FORECASTING, MODELING, AND CONTROL OF TIDAL CURRENTS ELECTRICAL ENERGY SYSTEMS

by

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To soul of those who loved me more than themselves, to my parents.

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ABSTRACT

The increasing penetration of renewable energy in the power system grid makes it one of the most important topics in electricity generation, now and into the future. Tidal current energy is one of the most rapidly growing technologies for generating electric energy. Within that frame, tidal current energy is surging to the fore. Forecasting is the first step in dealing with future generations of the tidal current power systems. The doubly-fed induction generator (DFIG) and the direct drive permanent magnet synchronous generator (DDPMSG) are the most commonly used generators associated with tidal current turbines. The aim of the present work is to propose a forecasting technique for tidal current speed and direction and to develop dedicated control strategies for the most commonly used generators, enabling the turbines to act as an active component in the power system.

This thesis is divided into two parts. The first part proposes a hybrid model of an artificial neural network (ANN) and a Fourier series model based on the least squares method (FLSM) for monthly forecasting of tidal current speed magnitude and direction. The proposed hybrid model is highly accurate and outperforms both the ANN and the FLSM alone. The model is validated and shown to perform better than other models currently in use. This study was done using data collected from the Bay of Fundy, Nova Scotia, Canada, in 2008.

The second part of the thesis describes the overall dynamic models of the tidal current turbine driving either a DFIG or a DDPMSG connected to a single machine infinite bus system, including controllers used to improve system stability. Two models are tested and validated, and two proportional integral (PI) controllers are proposed for each machine to control the output power of the tidal current turbine. The controllers are tested using a small signal stability analysis method for the models, and prove the robustness of the tidal current turbine using two different types of generators over those without controllers. The controller gain ranges are also investigated to establish zones of stability. Overall results show the advantages of using a DDPMSG over a DFIG.

LIST OF ABBREVIATIONS AND SYMBOLS USED

List of Abbreviations (in the order of appearance in the thesis)

DFIG	Doubly Fed Induction Generator
DDPMSG	Direct Drive Permanent Magnet Synchronous
ANN	Artificial Neural Network
FLSM	Fourier Series Model based on the Least Squares Method
PI	Proportional Integral
R.I.	Research Institute
IEA	International Energy Agency
FORCE	Fundy Ocean Research Centre for Energy
EU	The European Union
UK	United Kingdom
MW	Mega Watt
WWEA	World Wide Energy Association
BC	British Columbia
AB	Alberta
SK	Saskatchewan
MB	Manitoba
ON	Ontario
QC	Quebec
NB	New Brunswick
NS	Nova Scotia
FSIG	Fixed Speed Induction Generator
SSC	Supply Side Converter
GSC	Grid Side Converter
RSC	Rotor Side Converter
AVR	Automatic Voltage Regulator
DC	Direct Current
IGBT	Insulated Gate Bipolar Transistor

STATCOM	Static Synchronous Compensator
FMAC	Flux Magnitude Angle Controller
PSS	Power System Stabilizer
MCU	Master Control Unit
TSO	Transimission System Operator
UCS	Single Unit Control
TED	Tidal Energy Devices
MCT	Marine Current Turbines
UEK	Underwater Electric Kite
RTT	Rotech Tidal Turbine
ANN	Artificial Neural Network
FLSM	Fourier Series model based on the Least Squares Method
PBN	Back Propagation Neural Network
RBF	Radial Basis Function
MRA	multi-resolution analysis
GA	Genetic Algorithms
EOF	Empirical Orthogonal Function
PC	Principal Components
MLP	Multi Layer Perceptron
PCA	Principal Component Analysis
SOFM	Self Organizing Feature Map
RBF	Radial Basis Function
SLP	Single Layer Perceptron
OBD	Optimal Brain Damage
P E	Percentage of Error

List of Symbols (in the order of appearance in the thesis)

v_w	Wind speed signals model
v_{mw}	Mean wind speed
v_{rw}	Wind speed ramp
v_{gw}	Wind speed gust
v_{tw}	Turbulence
A_r	Amplitude of the wind speed ramp
T_{sr}	Starting time
T_{er}	Ending time
v_{gw}	Wind speed gust
C_p	Wind power coefficient
λ	Tip speed ratio
B	Pitch angle
R	The blade length in m
ρ	The density of the air
ω_t	The wind turbine rotational speed in rad/sec
C_f	The wind turbine blade design constant
P_w	Power extracted from the wind
T_m	Mechanical torque applied to the turbine
v_m	The turbine speed at hub height upstream the rotor
D_t	The turbine self-damping
D_g	The generator self damping
D_m	The mutual damping
H_t	The turbine inertia constant
H_g	The generator inertia constants
K_s	The shaft stiffness
ω_t	The turbine rotor speed
ω_g	The generator rotor speed
Θ_t	The turbine rotor angle
Θ_g	The generator rotor angles

H_m	The lumped inertia constant
ω_m	The rotational speed of the lumped system
D_m	The damping of the lumped system
$Y_j(t)$	Quantity computed by the first hidden neurons
$Y_k(t)$	Quantity computed by the second hidden neurons
$O_r(t)$	Network output
X & Z	Number of input and output neurons
H_1 & H_2	Number of first and second hidden neurons
Wij, W_{jk} & W_{kr}	Adjustable weights between input and first hidden layer, the first and Second layer and the second and output layer
b_i	Number of biases
f	Transfer function
E	Error
η	The learning rate
α	The momentum
V_{tide}	Tidal current speeds.
V_{nt}	Neap tide speed.
V_{st}	Spring tide speed.
C_s	Constant and equals 95 for spring, 45 for neap tide.
P_{ts}	Tidal in-stream power.
ρ	Density of the water (1025 kg/m^3)
A	Cross-sectional area perpendicular to the flow direction.
T_m	Mechanical torque applied to the turbine.
A	Cross-sectional area perpendicular to the flow direction.
C_p	Marine turbine blade design constant in the range of 0.35-0.5.
ω_s ,ω_r, ω_t	Stator, rotor electrical angular velocities, and turbine speed at hub height upstream the rotor.
T_e	Electrical torque of the generator.
D_s	Shaft stiffness damping.
H_t ,H_g	Turbine and generator inertia constants.

K_s	Shaft stiffness coefficient.
Θ_t ,Θ_r	Turbine and generator rotor angles.
B	Tidal turbine pitch angle.
S	Rotor slip.
d, q	Indices for the direct and quadrature axis components.
s, r	Indices of the stator and the rotor.
v, R, i, ψ	Voltage, resistance, current, and flux linkage of the generator.
K_{pt}, K_{it}	Coefficients for the proportional-integral controller of the pitch controller.
P_g, P_{DC}	Active power of the AC terminal at the grid side converter and DC link power respectively.
v_{Dg} , v_{Qg}	D and Q axis voltages of the grid side converter.
i_{Dg} ,i_{Qg}	D and Q axis currents of the grid side converter.
C	Capacitance of the capacitor.
v_{DC} , i_{DC}	Voltage and current of the capacitor.
K_{p1}, K_{p2}, K_{p3}	Proportional controller constants for the generator side converter controller
K_{i1}, K_{i} , K_{i3}	Integral controller constants for the generator side converter controller.
i_{Dg}, i_{Qg}	D and Q axis grid currents.
v_{Dg}, v_{Qg}	D and Q axis grid voltages.
K_{p4}, K_{p5}, K_{p6}	Proportional controller constants for the grid side converter.
K_{i4}, K_{i5}, K_{i6}	Integral controller constants for the grid side converter.
X_c	Grid side smoothing reactance.
$\dot{x}$	State variable.

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CHAPTER 1 INTRODUCTION

1.1 MOTIVATION

In recent years, conventional non-renewable electrical energy production has become an increasing concern due to its high costs, limited resources, and negative influence on global warming from CO2 emissions. In response to these challenges, scientists have begun to focus their research on renewable energy sources. Renewable energy is generally a clean source of supplying electrical loads, especially in remote and rural areas. Wind energy is one of the most common and rapidly growing renewable energy sources. Wind energy is produced from air motion caused by the uneven heating of the earth's surface by the sun. While wind turbines are associated with negative issues such as noise, visual impacts, erosion, birds and bats being killed, and radio interference, it is still an extremely useful form of energy for rural areas where access to utility transmission facilities is limited. Moreover, the use of wind energy reduces greenhouse gas emissions and positively impacts climate change due to fossil fuel replacement. Worldwide wind capacity is growing fast and may reach up to 1 million MW by 2050. This means that wind energy integration will become an important factor in the stability of the electric grid. Thus, there is a need for a 'smart' grid that is able to work through any disturbance and supply high quality electric energy to consumers. To date, however, wind power as an energy source is intermittent, challenging to predict, and requires using some form of storage to integrate it into the electric grid. New control techniques and improved forecasting methods are helpful in establishing operating practices that will increase the reliability of wind energy supply [1, 2].

In this thesis, a number of aspects of tidal in-stream (tidal current) energy is discussed. In many ways, tidal generation sources rely on the same technologies developed by wind generating electricity at offshore sites. Tidal current energy is the result of the gravitational influence of the moon and the sun on the earth. Due to the rotation of the earth relative to the moon and the sun, two high tides and two low tides are produced in most locations every day (semidiurnal tides), although some locations experience only one high and one low tide daily (diurnal tide). Figure (1.1) shows the gravitational influence of the moon and the sun on the earth due to the rotation of the earth relative to the moon. Tides run approximately six hours in one direction and then reverse for another six hours in the opposite direction [2, 3]. There are two tide types: spring tide (the speed of the spring tides varies from 3.5 to 4m/s), which happens when the moon and the sun are on the same line, and neap tide (the speed of the neap tides varies from 2 to 2.5m/s), which happens when the moon and the sun are at right angles and pull seawater in different directions. Nova Scotia's Bay of Fundy is characterized by high tides that can reach up to 17 meters [4-6].

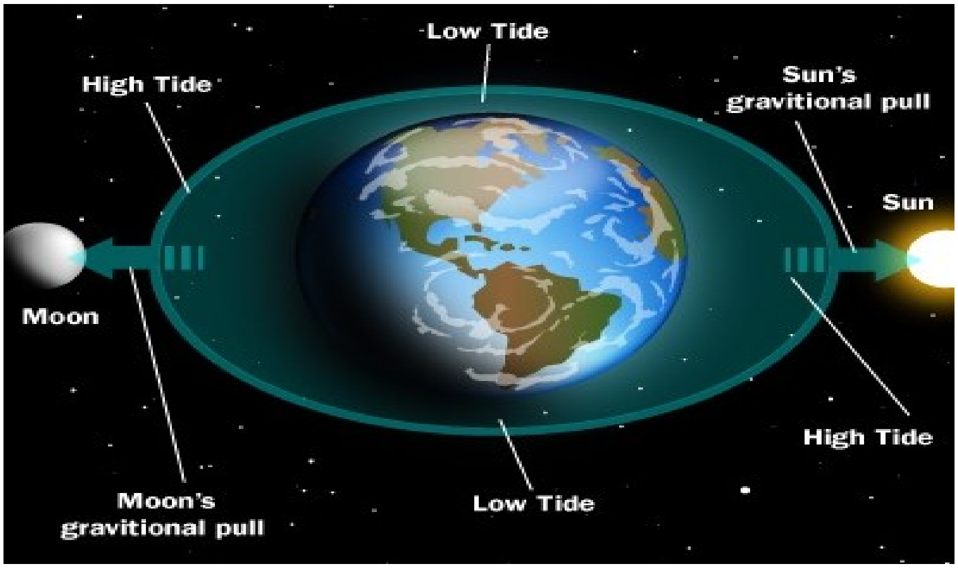


Figure (1.1) The gravitational influence of the moon and the sun on the earth [6].

The earliest methods for extracting tidal energy relied on tidal barrages and impoundments (lagoons). Like conventional hydro power plants, extracting ocean energy via tidal barrages involves drastically altering the environment at a tremendous cost to plant and marine life. In comparison, energy extraction using tidal in-stream turbines involves less disruption to the environment. Noting that the fixed cost of a barrage is very high, tidal in-stream energy extraction has become an attractive renewable source alternative [7-9].

This thesis deals with three models for tidal current forecasting as well as two variable-speed tidal current turbines and their modeling and control techniques for improving power system stability. The motivation for this thesis research is to propose a forecasting method for tidal current speed and direction that is fast and accurate, and to investigate the integration of tidal current energy into the grid. This research also proposes controllers for improving system stability and aims to determine appropriate range of values for the proposed controllers.

1.2 RENEWABLE ENERGY FROM CANADIAN AND NOVA SCOTIAN PERESPECTIVE

Various types of renewable energy are used at present. For instance, solar energy is used directly, usually via solar panels, to heat and power homes. Similarly, the heat of the sun drives the winds to produce wind energy. The wind and the sun cause water evaporation, which turns into rain and snow and contributes to rivers and waterfalls, whose energy can be captured through hydro power turbines. The sunlight and rain cause plants to grow, and these can eventually be harvested for biomass energy. Other renewable energy sources are geothermal energy, which is generated and stored in the earth, and marine energy, on which this research is based.

Canada is one of the world leaders in use of marine renewable energy due to its unique geography, abundant resources, and expertise in ocean engineering and offshore operations. Billions of tonnes of seawater ebb and flow every day along Canadian shorelines. Indeed, developing marine energy has become an integral part of government energy and economic strategy, according to one government minister who stated that “The Marine Renewable Energy Technology Roadmap demonstrates how government, industry and academics are working together to advance the commercialization of marine energy technologies in Canada while sharpening our global competitiveness” [10].

Being almost completely surrounded by seawater, the province of Nova Scotia has abundant marine renewable energy resources from offshore wind, waves and tides. The Bay of Fundy, located on the province’s western shore, has a 100 billion tonnes of seawater flowing into it each day, delivering a commercial potential of approximately

2,400 megawatts of power. This massive inflow of seawater exceeds the daily combined flow of the world's freshwater rivers. The energy potential is so huge compared to other countries that one industry expert has dubbed the Bay of Fundy the "Saudi Arabia" of marine renewable energy. The United States (U.S.)-based Electric Power Research Institute (EPRI) has also identified the Bay of Fundy as a prime site for potential tidal power generation. Ocean energy presents a significant opportunity for generating electrical energy, and tidal current and wave energy technologies are at the investigative stage. The development of renewable energy in Nova Scotia will help to contribute to the long-term renewable electricity mix, reducing greenhouse gases and other air pollutants, decreasing dependence on fossil fuels, reducing emissions, providing a diverse and more secure mix of energy, producing clean, green energy, and creating employment opportunities that build wealth and exports [11].

Despite the rosy picture being painted by industry and government investors, there are several issues that must be taken into consideration when dealing with marine renewable energy as a new source of energy. These issues include the following:

1. The protection of the marine ecosystem.
2. Health, safety and environmental protection.
3. The conservation of natural resources (not economic gain) as a top priority.
4. Sustainable industry development.

As well, there are environmental impacts that must be investigated and properly handled, such as [11, 12]:

1. The sediments, substrates and disruption of the currents and waves.
2. Electric and magnetic field effects.
3. Noise due to turbine blade rotation.
4. Navigation impacts and water quality changes.
5. Impacts on sea and land animal migration.

Renewable energy is needed to reduce dependence on imported fossil fuels, make Nova Scotia less susceptible to fluctuating market prices, and diversify the energy mix to bring stability to electricity rates. The total amount of renewable electricity in Nova Scotia based on 12,000 GWh/yr of total provincial electricity sales was 1100 GWh/yr (9%) pre-2001, 1300 GWh/yr (11%) at the end of 2009, and 1700 GWh/yr (14%) at 2011. It is expected to be 2300 GWh/yr (19%) by 2013, 3000 GWh/yr (25%) by 2015, and 4800 GWh/yr (40%) by 2020. Figure (1.2) shows the percentage of renewable energy compared to other sources in Nova Scotia for 2001 and 2009 and the expected percentage for 2015 and 2020 [12, 13].

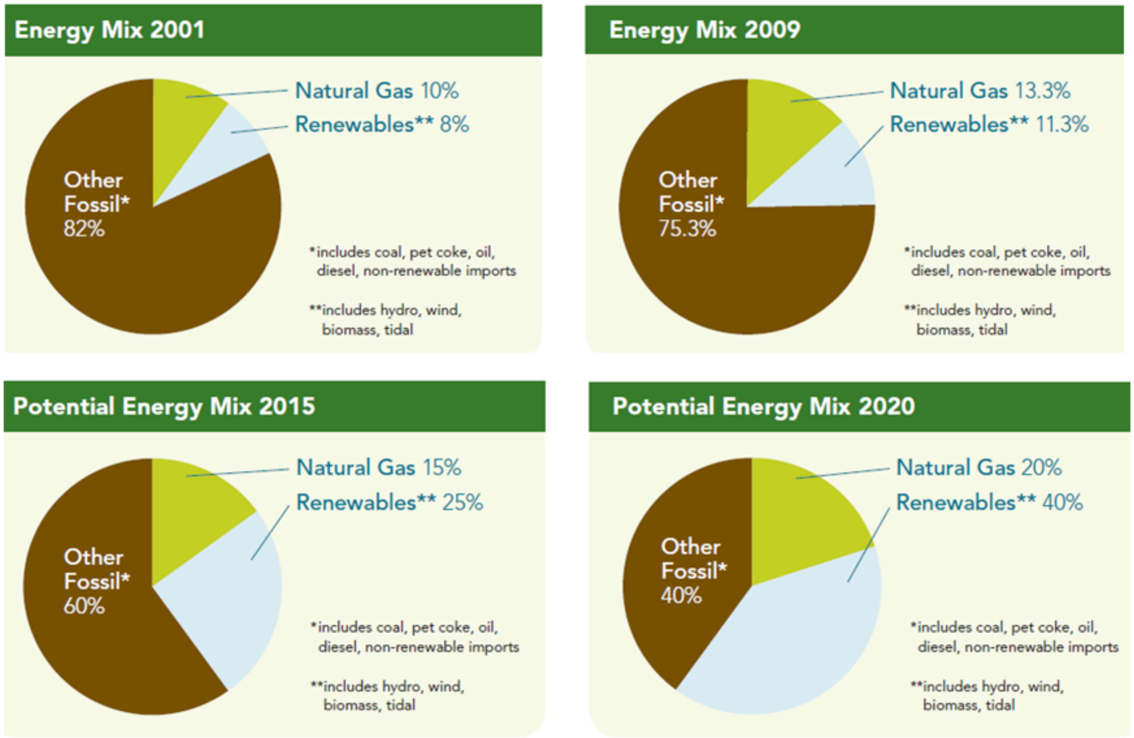


Figure (1.2) Potential energy mix in 2001 and 2009 and the expected potential energy mix in 2015 and 2020 [13].

Ocean waves produced by winds passing over the surface of the water are converted to electricity. There are approximately 50 competing designs being tested around the world in search of commercially viable wave-energy technology. The cost of wave energy is estimated by the International Energy Agency (IEA) to be in the range of \$0.20 to \$0.75 per kWh, depending on location. Nova Scotia's best wave resources are far from land, and so the overall cost will be relatively high. Hence, other parts of the world with better waves closer to shore have a competitive advantage and wave technology is therefore considered to be a lower priority for Nova Scotia [12].

Wind power is another attractive renewable energy source, but the best winds (off-shore) are expensive to harness. The cost of onshore wind power in Nova Scotia is in the range of $0.07 to $0.09 per kWh, but onshore winds are not as constant as offshore winds. A 2011 report by the International Energy Agency put the current costs of off-shore winds between $0.17 and $0.35 per kWh, making it far less economical than onshore winds due to the significantly higher construction and maintenance costs associated with these projects [11, 12].

Marine renewable energy is a new trend for generating electricity. It is expected to create jobs and grow the economy in the near future. Tidal current energy is an ideal renewable energy source because it is more predictable than wind and solar power, and this will reduce the back-up capacity and improve reliability, which potentially could be reflected in the cost.

The US-based Electric Power Research Institute estimated that underwater turbines could safely extract 300 megawatts of energy from the Minas Channel alone. In July 2011, the government of Nova Scotia announced a plan to create ‘winning conditions’ for the development of an in-stream tidal energy sector that will generate 65 MW by 2015 and an additional 300 MW in 5 to 10 years to replace approximately 10% of Nova Scotia’s current power supply. This amount would be more or less equivalent to Nova Scotia’s existing coal-fired generation. The province has recently introduced the Renewable Electricity Plan, which sets out a detailed program to move Nova Scotia away from carbon-based electricity generation towards greener, more local sources. Power from tidal current is expected to start contributing electricity around the middle of this decade and could make a significant contribution to electrical generation by 2020. The government currently provides support for tidal energy through FORCE (Fundy Ocean Research Centre for Energy). However, the cost of electricity from marine renewable energy resources is still so high that it is not yet competitive with other sources. This is because the technology is still in its infancy stage and many technical challenges remain to be resolved before large-scale commercial development can be implemented. Nevertheless, as the technology develops, the cost is expected to become competitive [14, 15].

Until now, there has been limited experience in assessing costs associated with large-scale tidal energy. As mentioned, current costs are generally high, averaging \$0.44 to \$0.51 per kWh for initial deployments. Costs are even higher for smaller projects (in the range of \$0.652 per kWh). Despite this financial hurdle, rising oil and coal prices along with the growing demand for clean and safe energy, are important issues bolstering the attractiveness of renewable energy. Moreover, the range of benefits and impacts created by the generation of marine renewable energy will differ depending on project location and technology used [14, 15]. Figure (1.3) shows a map of the mean power that can be easily extracted from tidal current passages around Nova Scotia while reducing the volume of water flowing through the passages by 5%. These values are calculated using simulation programs for tidal currents. In Cape Breton, the values are calculated using the characteristics of the flow and power extraction theory [12].

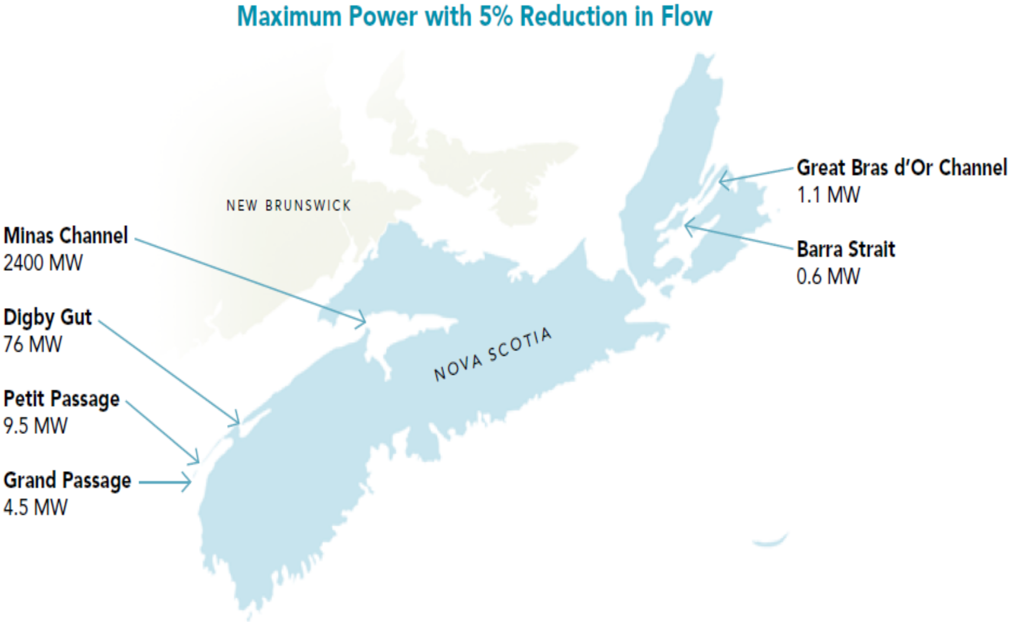


Figure (1.3) Map for the mean power that can be easily extracted from tidal current passages around Nova Scotia [12].

The federal and provincial governments have spent more than $75 million in support of marine renewable energy development projects over the past five years. An additional $100 million will be invested in phase 1 of FORCE, and the installation of technology arrays will involve a $500-million investment in the coming five years. From these projects, 75 MW will be installed by 2016, 250 MW will be installed by 2020, and 2,000 MW will be installed by 2030. It is worth noting that more than 50% of marine energy projects around the world use Canadian technology or expertise [16, 17].

The European Union (EU) member states have a target of deploying 1.95GW of marine energy by 2020. Figure (1.4) shows the marine targets for EU member states, most of which are situated along the Atlantic coast (UK, Ireland, France, Spain and Portugal) [18].

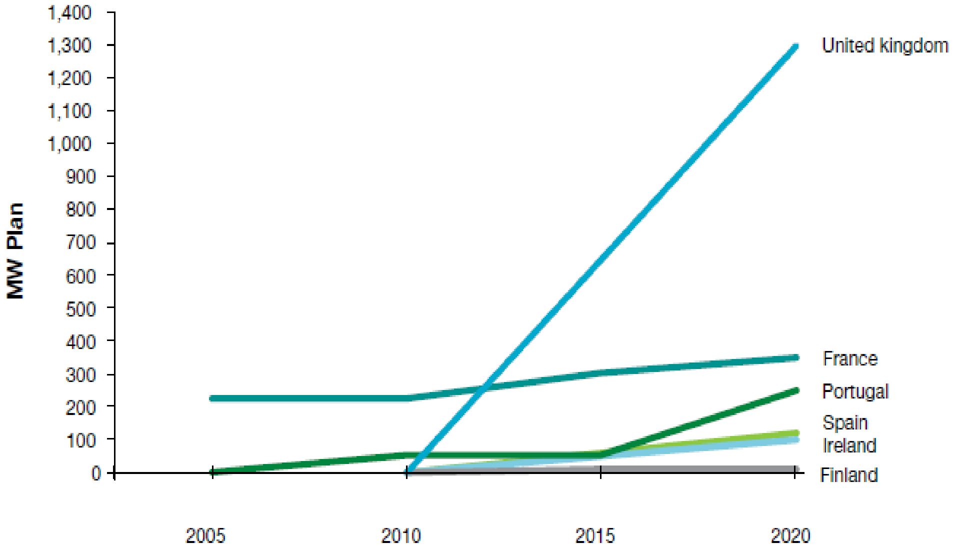


Figure (1.4) Marine targets for EU member states [18].

1.3 THESIS OBJECTIVES AND CONTRIBUTIONS

Tidal in-stream energy converters rely on the same principles involved in offshore wind turbines for generating electricity at offshore sites. The speed of water currents is slower than wind speed but water density is higher than air density. As a result, wind turbines operate at high rotational speeds and low torque. Tidal-in-stream turbines, in contrast, operate at low rotational speeds and high torque. Also, as the systems collecting the electricity may differ from each other, this will affect the methods used to deal with stability studies and the connection of the overall system. Generally speaking, tidal resources are more predictable than wind, a fact that will increase system stability and reliability. Even so, successful integration of any renewable power source into the electrical grid requires solving problems dealing with power flow, thermal limits, protection systems, and power quality to ensure system integrity. There are two main challenges for tidal integration into the power system: intermittency and grid reliability.

1.3.1 Some Issues Take into account When Dealing With Tidal Farms

1) Water depth: most existing devices operate at depths ranging between 25 and 45 m.

2) Choosing a location that has a high velocity during tides (the Bay of Fundy is one of the best locations for tides in Nova Scotia).

3) Choosing a location that is near to the grid in order to reduce the overall cost of energy extracted.

1.3.2 New Research Issues

1) Gauging optimal distance between turbines for harnessing optimal power output.

2) Calculating the optimal number of turbines in a string and string length.

3) Calculating optimal rotor size for harnessing optimal energy.

4) Using one large-sized rotor or using additional rotors on the same turbine.

5) Measuring maximum demand and power extracted during the spring tide to ascertain if they are at the same or different times, as this will affect overall cost.

6) Deciding on the control method used for the generator, as the tidal current fluctuates.

7) Estimating the transient response and the effect of inertia on the overall system during frequency changes in case of faulty loading conditions.

8) Coordinating tidal energy generation with other sources.

9) Integrating tidal energy onto the grid.

1.3.3. Objectives

This Ph.D. thesis research addresses various key aspects of tidal currents by:

1) Improving tidal currents forecasting accuracy of by proposing new techniques.
2) Developing dynamic models of the tidal current turbine using two different types of generators.
3) Improving the integration of tidal energy into the grid by proposing PI controllers to improve the system performance.

1.3.4. Contributions and methodology

This work develops improved models for the tidal current turbine and the control techniques used for the integration of tidal energy due to its fluctuation. The procedures used to achieve this task are summarized as follows:

1) Study the literature on wind turbines, as it uses approximately the same technologies used for tidal current turbines.
2) Review the various forecasting methods used in literature.
3) Review the ANN and Fourier based on the Least Square method for forecasting.
4) Review dynamic modelling for offshore wind turbines.
5) Review the control methods used for wind turbine grid integration.
6) Propose a forecasting technique for improving the tidal current speed and direction (Propose a hybrid model of ANN and FLSM for the tidal current speed and direction forecasting (never used before)).
7) Develop a dynamic model of a tidal current turbine driving two types of generators.
8) Design a methodology to improve the stability of the system in order to facilitate the integration of the tidal current energy into the grid without any distortions during

tidal current fluctuations (Propose two PI controllers for two types of machines for improving the system stability (never used before for tidal current turbines)).

9) Determine the stability ranges for the PI controllers coefficients used for improving the system performance of the tidal current turbines driving two types of generators.

1.4 THESIS OUTLINE

This thesis consists of five chapters. In this chapter (Chapter 1), the research motivation, a brief description of wind and tidal current turbine along with the thesis objectives are presented. The second chapter provides a literature review of offshore wind and tidal current turbines-based electric power generation. Chapter 3 discusses the development of the proposed ANN and FLSM hybrid model for tidal current magnitude and direction forecasting. The fourth chapter deals with small signal stability analysis of the tidal current turbine and the proposed controllers for improving this stability. Chapter 4 also addresses the development of the proposed controllers. The fifth and final chapter provides concluding remarks about the thesis work and suggests the scope of future work.

CHAPTER 2 LITERATURE REVIEW

2.1 INTRODUCTION

Recent publications related to this thesis are reviewed and summarised in this chapter which is organized in the following two sections:

- The first section reviews the literature on offshore wind turbines for generating electricity at offshore sites. A brief background of the impacts of offshore wind integration into the grid, various types of generators and their dynamic modeling, fault ride-through techniques used to improve generator and grid integration performance, the aggregated wind turbines modeling and finally highlight some stability and control issues.
- The second section reviews the literature on tidal in-stream energy as it relies on the same technologies developed from offshore wind turbines for generating electricity at offshore sites. A brief background of technologies, challenging issues, various types of generators, their modeling, grid integration performance, and finally the new research issues.

2.2 WIND ENERGY

Wind energy is produced by air motion caused by the uneven heating of the earth's surface by the sun. Although wind turbines are associated with negative issues such as audio noise, visual impacts, erosion, birds and bats killed and radio interference, but it is an extremely useful form of energy for rural areas where access to utility transmission facilities is limited and expensive. Moreover, wind energy reduces environmental damage (Green house Gas emissions) and climate change due to fossil fuel replacement. The wind power resource is intermittent and hard to predict. New control techniques and improved forecasting methods help to establish operating practices that will increase the reliability of the wind energy. The integration of wind energy into the grid is very important due to its fluctuations and intermittency [2, 19].

The wind energy integration has been increasing rapidly in the past few years as Table (2.1) shows worldwide cumulative capacity for wind energy until December 2010 and the percentage of top 10 countries to the total worldwide capacity [20]. Figure (2.1) shows a historical account of the total worldwide wind turbine capacity (2001-2011) [21]. As shown the wind capacity in the world wide on 2001 was 24,322 , on 2011 was 239,000 MW and the expected capacity by 2050 will be 1,000,000 MW. This means that the wind energy integration during the next forty years will be increased by four times of the exciting installed capacity. This huge amount of the wind energy will affect the stability of the electrical grid so there is a need for a smart grid which will be able to deal with disturbances and supply high quality electric energy to consumers. A great number of researchers are working on the stability of the power system grid due to the wind integration especially during a fault or any other disturbance but still much research needs to be done on this point to ensure quality of service of the electrical grid.

Table (2.1) Worldwide cumulative capacity for the wind energy (Dec 2010) [20]

Country	**Capacity (MW)**	**Percentage**
China	44,733	22.7
USA	40,180	20.4
Germany	27,214	13.8
Spain	20,676	10.5
India	13,065	6.6
Italy	5,660	2.9
France	5,797	2.9
UK	5,204	2.6
Canada	4,009	2
Denmark	3,752	1.9
Rest of the world	26,546	13.6
Total top 10	170,290	86.4
World total	197,039	100

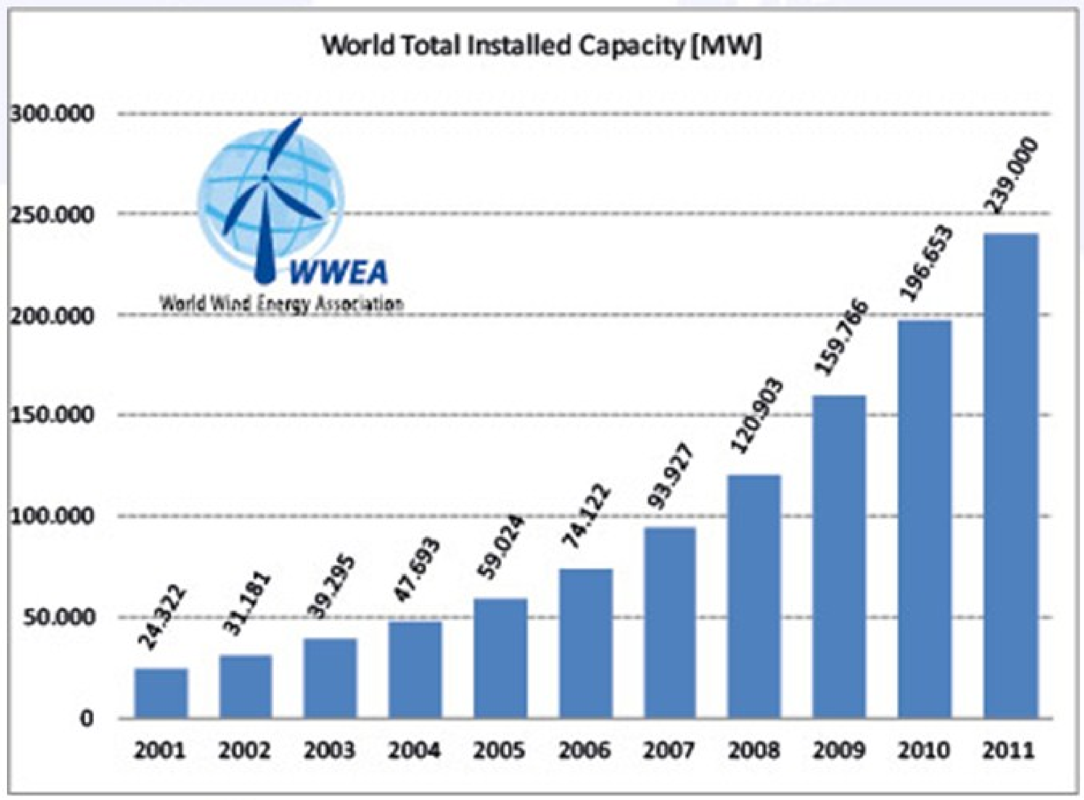


Figure (2.1) The historical of the total worldwide wind turbine capacity (2001-2011) [21]

In Canada wind energy integration has increased rapidly in the recent ten years. The electrical energy generated from wind is used for around 1.5 million homes and businesses. Around 1,267 MW of the new installed capacity in 2011 represented $ 3.1 billion. The current installed capacity of wind energy is 5,511 MW (2012). Figure (2.2) shows the historical wind turbine capacity all over Canada (2000-2012). The installed capacity across Canada was 137 MW in 2000 and became 5,511 MW in 2012 so it is increased around 40 times within twelve years. Canada became the ninth largest producer of wind energy in the world, it was representing 2 percent of the worldwide capacity in December 2010 with a capacity of 4,009 MW and now its installed capacity increased to 5,403 MW. 2.3 percent of Canada's total electricity demand is coming from the wind energy. Table (2.2) shows the new wind farms built in 2011 in different provinces. Figure (2.3) shows the current map of Canada's installed capacity from wind turbines [22].

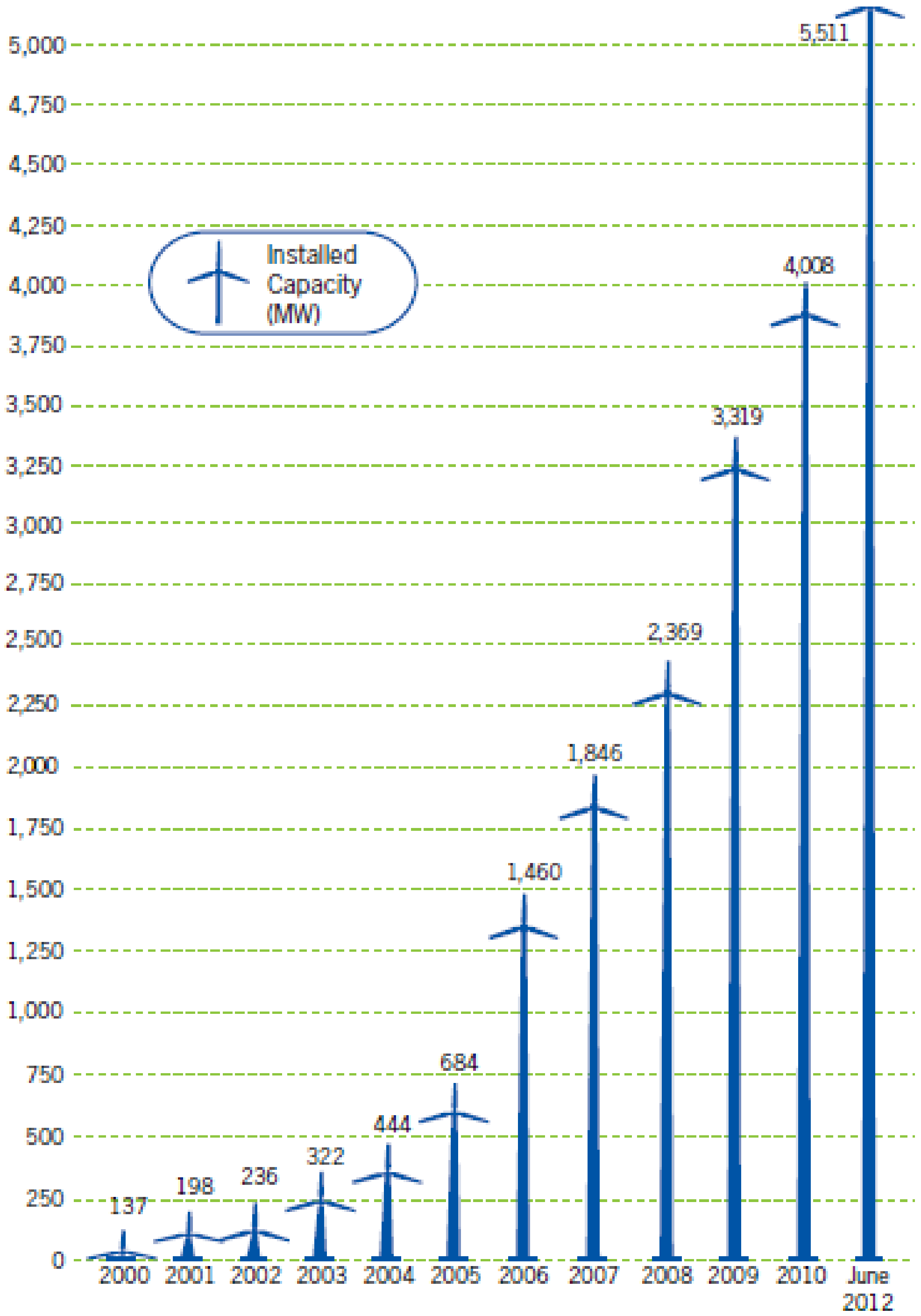


Figure (2.2) The historical wind turbine capacity in Canada (2000-2012) [22]

Table (2.2) New wind farms built in 2011 [22]

Wind Farm	**Province**	**No. of Turbines**	**Capacity (MW)**
Dokie Wind Project	BC	48	144
Wintering Hills	AB	55	88
Red Lilly Wind Energy Project	SK	16	26.4
St. Joseph	MB	60	138
North Maiden Wind Farm	ON	5	10
Kruger Energy Chatham Wind	ON	44	101.2
Raleigh Wind Energy Centre	ON	52	78
Kent Breeze Wind Farm	ON	8	20
Greenwich Renewable Energy Project	ON	43	98.9
Pointes Aux Roches	ON	27	48.6
Comber East	ON	36	82.8
Comber West	ON	36	82.8
Mont Louis	QC	67	100.5
Montagne-Sèche Wind Farm	QC	39	58.5
Gros Morne Phase I	QC	67	100.5
Lameque Wind Power Project	NB	30	45.00
Glen Dhu (2011 commissioned)	NS	18	41.4
Watts Wind	NS	1	1.5
Spiddle Hill Phase I	NS	1	0.80

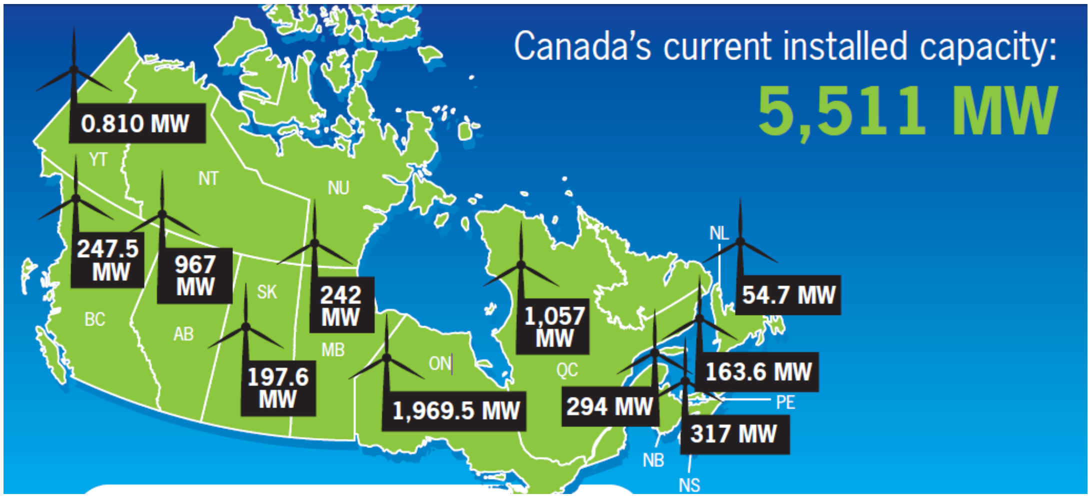


Figure (2.3) The current map of Canada's installed capacity from wind turbines [22].

2.2.1 Wind Turbine Types

In this section wind turbine types are discussed, dynamic modeling, integration, stability problems, its mitigation methods and finally wind farm aggregation as an introduction to tidal current turbines.

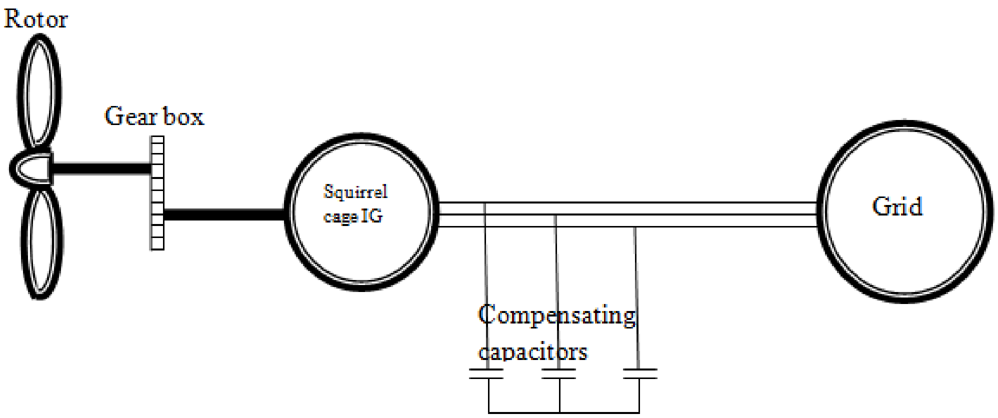
Most wind turbines systems are based on three main types depending on the electric generators used as shown in figure (2.4):

1) Fixed speed with direct grid-coupled squirrel cage induction generator (FSIG). The rotor side of the FSIG is connected to the wind turbine via a gearbox and the stator is connected directly to the grid. The speed varies within a very small range (it is considered as fixed speed). The drawbacks of this generator are the size, maintenance requirements, the noise, its lower reliability and efficiency, the voltage level at the grid cannot be controlled. Also the blade rotation is causing power variations and, affecting the voltage and varying the frequency from 1 to 2 Hz in the grid. The FSIG consumes reactive power and this causes voltage problems after clearing the fault [23].

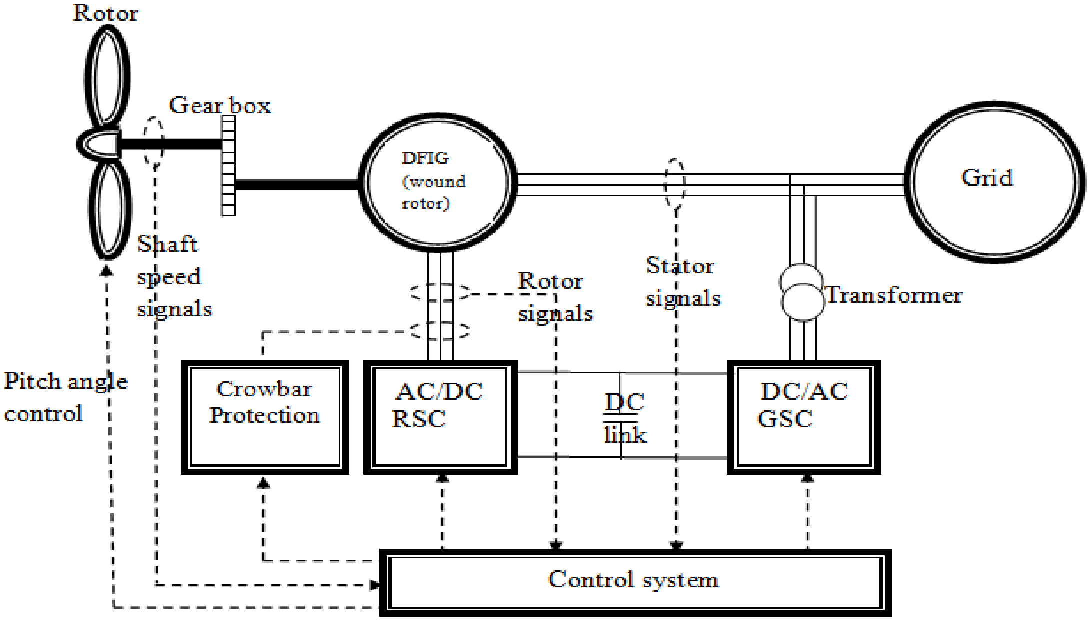
2) Variable speed with doubly fed induction generator (DFIG).This type uses a a partial scale power converter to feed or take power from the rotor and produces a variable speed. The rotor side of the DFIG is connected to the grid via a back to back converter. The converter at the side connected to the grid is called the supply side converter (SSC) or grid side converter (GSC) while the converter connected to the rotor is called the rotor side converter (RSC). The RSC operates in the stator flux reference frame. The direct axis component of the rotor current acts in the same way as the field current of a syn-

chronous generator and thus controls the change in reactive power and the quadrature component of the rotor current is used to control the speed by controlling the torque and the change in active power. Thus the RSC governs both the stator-side active and reactive powers independently. The GSC operates in the stator voltage reference frame. The *d*-axis current of the GSC controls the DC link voltage to a constant level, and the *q*-axis current is used for reactive power control. The GSC supplies or draws power from the grid according to the speed of the machine. If the speed is higher than the synchronous speed it supplies power, otherwise it draws power from the grid but its main objective is to keep the dc-link voltage constant regardless of the magnitude and direction of the rotor power [24]. DFIGs are more stable than FSIG as their rotor speeds are easier to control on the generators side. Also, the active power and reactive power are controlled independently by using the converter in the rotor side, and the fluctuation of the voltage is minimized [25]. By using DFIG the dynamic behavior of the turbine is improved, the noise at low speed is reduced, the power production is higher than FSIG and mechanical stresses are reduced. The power quality of the turbine using DFIG is improved but it is more complex than FSIG and the overall cost is increased due to the use of the power electronic devices for control [26, 27]. The DFIG is the most commonly used design for wind integration due to its high efficiency, fast reaction and robustness during the fault. This machine is able to supply a controlled reactive power to the grid [28].

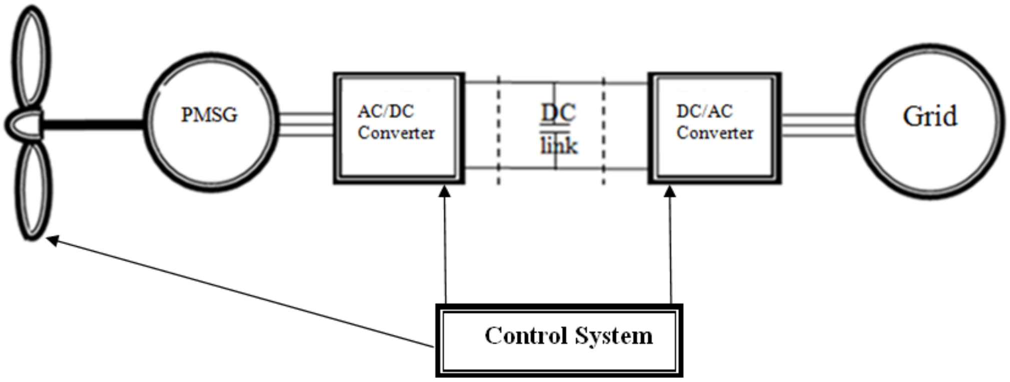
3) Variable speed based on a direct drive permanent magnet synchronous generator (DDPMSG). In DDPMSG, the generator and the grid are connected by means of a converter, which allows variable speed operation [26, 29]. The use of the gearbox between the generator and the turbine have some disadvantages because of increasing in the size of the turbine, the maintenance requirements, the lower reliability and the lower efficiency. Therefore, new designs depend on connecting the generator directly to the turbine by using numerous pairs of poles but at the same time use filters at the generator output because of high harmonic content caused by operating at low speeds and this advantage is not available to DFIG's [30]. Table (2.3) shows a comparison between the three types of generators. Figure (2.5) shows the overall wind turbine system and their interactions.



a. FSIG



c. DFIG



b. DDPMSG

Figure (2.4) Types of wind turbines

Table (2.3) A comparison between three types of generators.

Comparison	**FSIG**	**DFIG**	**PMSG**
Speed	Fixed	Variable	Variable
Converter scale	Zero	20-30%	100%
Power supplied to the grid	Directly	Partially via stator and the converter	Totally via the converter
Control	Poor	Good	Very good
Active & reactive control	Dependent each other	Independent	Independent
Voltage fluctution	High	Limited	Limited
Robustness	Small	High	Very high
Fault reaction	Slow	High	High
Efficiency	Poor	High	High
Cost	Low	High	Very high

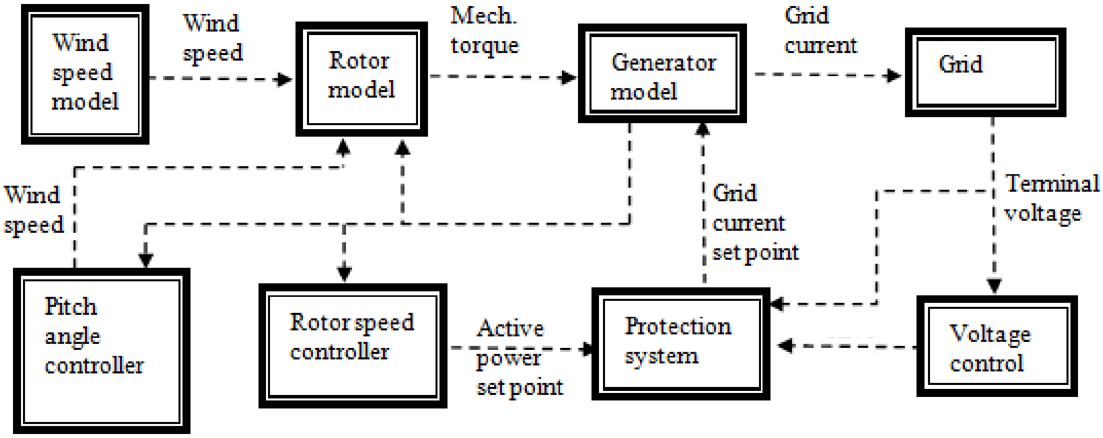


Figure (2.5) Overall wind turbine system and their interactions.

2.2.2 Subsystem Models

1) The Wind Speed Signals Model (v_w): This model consists of four components related to the mean wind speed (v_{mw}), the wind speed ramp *(v_{rw})* (which is considered as the

steady increase in the mean wind speed), the wind speed gust (v_{gw}), and the turbulence (v_{tw}).

$$v_w = v_{mw} + v_{gw} + v_{rw} + v_{tw}$$

The mean wind speed is a constant; a simple ramp function will be used for ramp component (characterized by the amplitude of the wind speed ramp (A_r (m/s)), the starting time (T_{sr}), and the ending time (T_{er})). The wind speed gust component is characterised by the amplitude of the wind speed gust (A_g (m/s)), the starting time (T_{sg}), and the ending time (T_{eg}). The wind speed gust may be expressed as a sinusoidal function.

The most used model is given by:

$v_{gw} = A_g(1-\cos(2\Pi(t/D_g - T_{sg}/D_g)))$ $\quad T_{sg} \le t \le T_{eg}$

$v_{gw} = 0$ $\quad t < T_{sg}$ or $t > T_{eg}$

$D_g = T_{eg} - T_{sg}$

A triangular wave is used to represent the turbulence function which has adjustable frequency and amplitude [31, 32].

2) The Rotor Model: The rotor model represents the conversion of kinetic energy to mechanical energy. The wind turbine is characterized by C_p (wind power coefficient), λ (tip speed ratio), and β (pitch angle). $\lambda = \omega_t R/v_w$, where R is the blade length in m, v_w is the wind speed in m/s, and ω_t is the wind turbine rotational speed in rad/sec. C_P-λ-β curves are manufacturer-dependent but there is an approximate relation expressed as

$$C_p = \frac{1}{2}\left(\frac{RC_f}{\lambda} - 0.026\,\beta - 2\right)e^{-0.295\frac{RC_f}{\lambda}},$$

C_f is the wind turbine blade design constant. Figure (2.7) shows the relation between the wind power efficiency and the tip speed ratio.

The rotor model may be represented by using the equation of the power extracted from the wind ($P_w = 0.5\rho\Pi R^2 C_p v_w^3$), or the mechanical torque applied to the turbine ($T_m = \frac{0.5\rho\Pi R^2 C_p v_w^3}{v_m}$), v_m is the turbine speed at hub height upstream the rotor, ρ is the density of the air [32].

The shaft system may be represented by a two mass system or by a single lumped mass system. The two mass systems may be represented as:

$2H_t\frac{d\omega_t}{dt} = T_t - K_s(\Theta_r\text{-}\Theta_t) - D_m\,(\omega_r\text{-}\ \omega_t)$,

$2H_g\frac{d\omega_g}{dt} = -T_e + K_s(\Theta_g\text{-}\Theta_t) - D_m\,(\omega_g\text{-}\ \omega_t)$,

D_t is the turbine self-damping, D_g is the generator self damping, D_m is the mutual damping, H_t and H_g are the turbine and generator inertia constants, respectively, K_s is the shaft stiffness, ω_t and ω_g the turbine and generator rotor speeds. Θ_t and Θ_g denote the turbine and generator rotor angles. There is a ratio for the torsion angles, damping and stiffness which must be considered when one uses a gear box. Calculations must be referred to the generator and calculated as: $a=\frac{\omega_g}{\omega_t}$, $\omega_t^{(t)} = \frac{\omega_t^{(g)}}{a}$, $\Theta_t^{(t)} = \frac{\Theta_t^{(g)}}{a}$, $K_s^{(t)} = a^2 K_s^{(g)}$, $D_m^{(t)} = a^2\, D_m^{(g)}$.

The shaft system as a single lumped mass represented as $2H_m\frac{d\omega_m}{dt} = T_m - T_e - D_m\,\omega_m$, H_m is the lumped inertia constant, ω_m is the rotational speed of the lumped system, and D_m is the damping of the lumped system [33]. Figure (2.6) shows the wind turbine nacelle components.

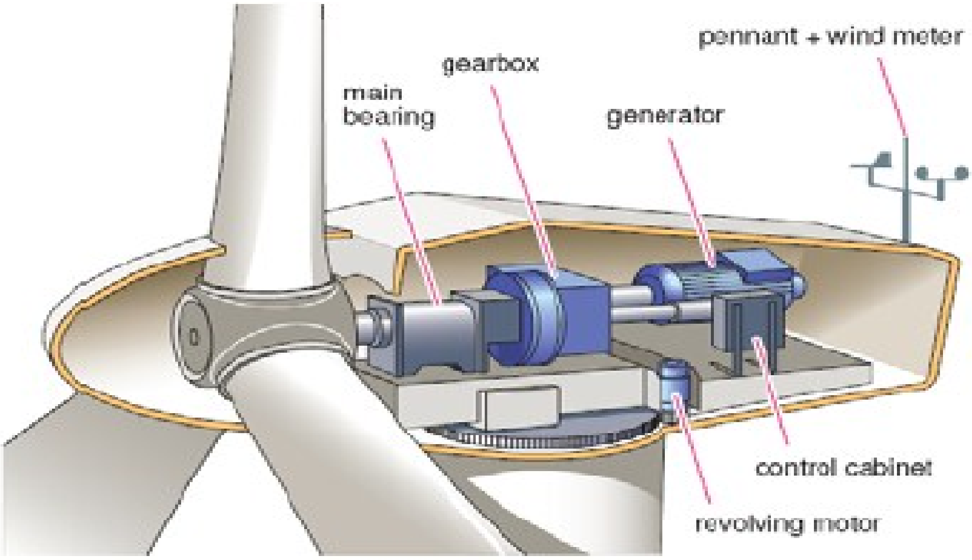


Figure (2.6) The wind turbine nacelle components [26].

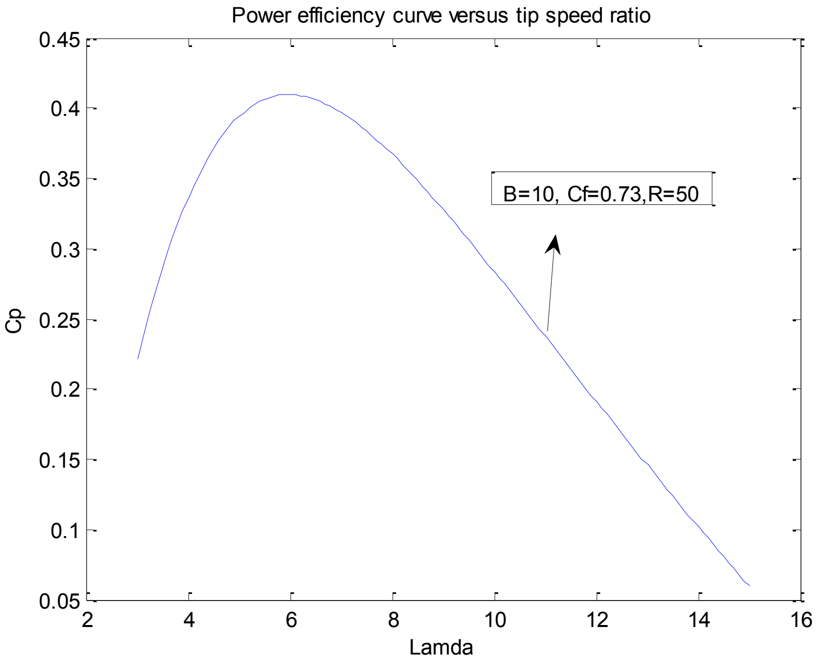


Figure (2.7) The relation between wind power efficiency and tip speed ratio.

3) The Generator Model

Two types of generators are used is this work and this is discussed in Chapter 4.

4) The rotor speed controller uses a power–speed curve to compute the reference power according to the actual speed.

5) The pitch angle controller model is active during the high wind speed to change the blade pitch angle to reduce C_p. The optimal pitch angle is zero below the nominal wind speed. The maximum rate of change is within 3 to 10 % [31].

6) The voltage controller model controls the value of the terminal voltage v_{dr} by controlling the value of reactive power which is proportionally related to terminal voltage [31]. The RSC is known as a controlled voltage source in which the q axis voltage v_{qr} controls the rotor speed and the d axis voltage v_{dr} controls the reactive power. The GSC is

represented by a controlled current source, and provides the exchange of active power from the rotor circuit to the grid with unity power factor [34].

7) The protection system model consists of two parts (to switch the wind turbine off for voltage or frequency) and a converter current limiter to protect the semiconductor switches. The aim of the control system of the DFIG is to maximize the extracted power for a wide range of the speed, limit the output power to the rated for high speeds, and adjust the active and the reactive powers to specified values as determined by the system operator [31].

2.2.3 Wind Integration

It is difficult to match wind generation to demand and the fluctuations of power may adversely impact the transmission system (the medium and low voltage subsystems). Hence the effect of increasing wind energy generation on the quality of power needs to be analyzed and the need for extra reserve generation, storage facilities, new control techniques, forecasting methods and the grid reliability should to be examined [35-37]. The induction generator which is coupled to wind turbines may consume reactive power and if there is no compensation method this will lead to voltage drop problems. These generators are different from conventional synchronous generators which are able to work during and after the fault is removed, which also affects the transmission capacity [38].

2.2.3.1 Grid Integration Aspects

Successful integration of wind power into the grid requires solving certain problems such as [39]:

1. Power flow to ensure that lines and equipments are not overloaded or that their thermal limits are not exceeded.
2. Short circuit levels and values must be re-evaluated.
3. Transient stability margins need to be re-evaluated
4. Protection schemes need to be re-adjusted.
5. A controllable energy source must be available in the system to compensate for the fluctuation of the wind power.

6. The power quality should be revaluated.

There are two main challenges for the wind integration into the power system, the intermittency and the grid reliability [40].

2.2.3.2 Dealing with Large Scale Wind Integration into the Grid

The following are potential approaches to enhance integrating wind power resources into an electric power grid.

1. Review of methods for calculation of available transmission capacity.
2. Transmission network reinforcement (by increasing the height of the towers, installing conductors with higher load carrying ability using capacitors, and using facts devices).
3. Convert from HVAC to HVDC to increase the rating of power transmitted 2-3 times and reduce line losses.
4. Coordination between wind and the hydro stations.

For wind farm applications, not all wind turbine generators work at the same speed and so the maximum power production of the wind farm is lower than the sum of the rated power production of each one. The peak of the wind turbine may not be at the same time of the peak of the transmission lines and this must be taken into account [41, 42].

2.2.4 Stability Issues of Wind Turbines, Mitigation Methods and Some Control Schemes

1. As the penetration of the FSIG increases, transient stability margins decrease specially without using AVR and this may lead to instability. In contrast, the DFIG and the DDPMSG are more stable with or without AVR as there is the ability to control the active, reactive power and the terminal voltage. The DDPMSG is more stable than the DFIG but it is more expensive. Using an AVR improves the stability margin in all types of generators. Under fault conditions as the FSIG penetration increases the swing angle of the conventional synchronous generator increases because the FSIG penetration increases the needed of reactive power and this will increase the amount of required current.

Consequently the voltage drop will be increased. But following fault removal, the FSIG is still able to take a large amount of reactive power due to its inertia and this reduces the voltage at the conventional generators, so the increased penetration of FSIG has an adverse effect on the stability. On contrary, the DFIG penetration does not decrease the voltage profile for the conventional generators during and after removing the fault [43].

2. For the FSIG, as the number of turbines increases, the voltage at the PCC will decrease. Also the torque speed characteristics will remain in a small zone, hence the stability will be worse. On contrary for the DFIG as the number of turbines increases, the stability will increase (because of the impedance change the DFIG will supply more reactive power around the synchronous slip) but at sub-synchronous speed (away from a zero slip) DFIG requires a higher voltage control [44].
3. In the FSIG the reactive power and the grid voltage level cannot be controlled, also the blade rotation causes power variations and, this will affect the voltage. FSIG consumes reactive power through the capacitors and this may cause voltage collapse after the fault is cleared.
4. The transient stability of FSIG is poor; FSIG may cause loss of synchronism and must be switched off during the fault.
5. Faults in the power system may cause a voltage sag at the connection point of the wind turbine and this will increase the current in the stator winding of DFIG, hence the current will also increase in the rotor due to the magnetic coupling, causing the destruction of the power electronic converters. As a result using DFIG needs a protection system called crowbars which will disconnect the connection to the grid [27, 45].
6. DFIGs improve the transient stability margins if they are connected to a low voltage ride through capability, reactive current boosting and fast voltage control. However, the wind source is connected to lower levels so the reactive losses are high, hence the reactive contribution of wind energy is limited, as a result its integration will have a negative impact on the transient stability. Their speed fluctuation is slow and it has no direct effect on the transient stability but it has an indirect effect as the wind energy is not easily predictable. Hence it requires a higher spinning reserve and this adds inertia to the system [2, 46].

7. The conversion control methods for the wind energy using converters affect its frequency specially frequencies between 2 and 8 Hz which may cause voltage flicker in the grid and it is preferred to dampen these frequencies in the output power. There are control methods used to mitigate this phenomenon; such as the optimal rotational speed control which concentrate on giving maximum power and the wind rotor at the rotor speed, torque control, average power control and stochastic dynamic optimization [47].

2.2.4.1 Stability Problems Mitigation Methods

There are a number of techniques to counteract the potential of stability problems.

1) The wind generation with energy storage devices in the distribution systems may result in reduced distribution losses and this depends on the ratio of the generation relative to the local load. If this ratio is high the losses will increase. The use of storage energy is important to optimize the operation and for improving the use of wind energy for security in the steady state [48, 49]

2) A DC link voltage boost scheme of insulated-gate bipolar transistors (IGBT) inverters for wind extraction is used to overcome the voltage sag due to the decreased wind energy by adding a switch between one of the rectifier input legs and the middle point of the dc link reservoir capacitor and this switch is turned on during the shortage and so double the value of the voltage. But this method results in unsymmetrical operation, and this will bring a mechanical vibration on the wind turbine due to unsymmetrical and unbalanced operation, so symmetrical double voltage rectifier is used [40].

3) Dealing with wind fluctuations: many methods are used to handle wind energy fluctuations. In terms of placement, the methods are divided into three categories[41]:

- ✓ At the wind turbine generator using two windings one of which is activated at high wind levels and the other is activated for low wind levels. Using shunt capacitors and/or another inverter to provide capacitive voltage support.
- ✓ At the dc link (DC step up chopper or voltage boost rectifier).
- ✓ At the inverter output by using a step up transformer.

4) During the fault if all wind turbines are disconnected from the grid this will affect the stability. A solution is to decrease the current through the rotor by using resistors. During longer voltage dips the rotor may feed a reactive power to the grid during the fault [27].

5) The wind farm stability is improved by increasing the shaft stiffness and/or the moment of inertia of generator, reducing the impedance of the line between the wind farm and the network, and improving the operating power factor of the farm [52, 53].

From the preceding discussion one concludes that faults on the power system are the most common problems that affect the operation of conventional and wind power generators unless there is a ride through facility. The impact of the fault on the wind power plant depends on the location, the type of the fault, the setting of the protection relay, the wind generator type (if there is a ride through or not), the overall characteristic of the network power system, the load distance from the generator, the grid configuration (radial or ring), the method of compensation, and the control algorithm in the grid [29].

During the fault, the response of the DFIG will be changed. The rotor current will be increased (the current may exceed 2-3 times the rated value). This leads to an increased DC-link voltage (it may reach 2-3 times the rated value), the GSC tries to stabilize the DC-voltage and this will lead to increase the GSC current (may reach up to 57% of the rated value), and the turbine will be exposed to an oscillating torque and this will reduce the turbine life time. The separation of the wind turbine from the grid during the fault is not preferred as it may lead to a voltage collapse [29, 54].

2.2.4.2 Control Schemes

Many control schemes are used for the DFIG focusing on the active and reactive power. The control variables are the rotor voltage or current and the blade pitch angle. One of these control systems depends on the quadrature and direct components of the rotor current and blade pitch angle for controlling the speed, reactive and active power respectively. The second control system depends on the quadrature and direct components of the rotor voltage and blade pitch angle for controlling the active, reactive power and the speed, respectively. The third control system is considered as a variant of the second control system in which there are two modes for the operation and so the speed is limited to its rated value by acting on the pitch angle [55].

Another voltage control strategy depends on both converters on the grid and rotor side to be coordinated in the DFIG to control operation under fault conditions. The RSC is usually used as the main reactive power source but the GSC is a supplementary one. During the fault conditions in the case of DFIG the current in the stator will increase rapidly as the stator is connected directly to the grid and this will increase the rotor current and voltage. As a result, this increased power will increase the energized power in the DC link as there is a fault on the grid side. The rotor is protected by the crowbar resistance and in this case it behaves like a squirrel cage induction generator with an increased rotor resistance. In this case the GSC is used as a STATCOM and delivers a limited amount of reactive power to the grid but the RSG is connected to the impedances in the crowbar. These impedances improve the dynamic stability of the DFIG under fault conditions but on the other hand it will affect the overall performance as the penetration of the wind farms is increased [29].

Reference [56] describes a new FMAC (flux magnitude angle controller) for the DFIG wind turbine to adjust the rotor voltage and the angle rotor for controlling the electric power. FMAC consists of AVR (for controlling the rotor voltage) and PSS (for controlling the rotor angle and using the stator electric power as its input signals). The use of PSS shiftes the eigenvalues to the left and has a positive influence on the damping.
For rotor speeds close to the synchronization DFIG control is limited, because the steady state rotor terminal voltage is affected by the slip value. At high value of the slip the rotor vector voltage is equal to the slip value times the internally generated vector voltage and as the magnitude of the internally generated voltage is approximately constant then the rotor voltage is proportional to the slip. At low slip value the magnitude of the rotor voltage is small and so the control for the DFIG is limited, the performance of the DFIG is near to the squirrel cage induction generator.

The voltage of the wind turbine during and after fault clearing is improved by using a STATCOM; hence improves the system reliability and stability. The system voltage has no effect on the maximum compensating current; as a result the STATCOM is able to be operated at any capacity at low voltages and this enhances the flexibility of this device.

The higher rating of a STATCOM the better recovery of the voltage during and after the fault removed but the overall cost will be increased [57, 58].

References [59, 60] describe a master control unit (MCU) to make a power schedule to reduce the effect of fluctuation of offshore wind energy and maintain the reliability of the power supply. This schedule may be received by transmission system operator (TSO) to use less wind power energy than it is available and so the control unit may be improved by making a commitment and system management depending on the power forecasting. There two control units: a primary and overall (MCU). The primary is the single unit control (UCS) which is the control unit for each windmill.

2.2.5 Equivalent Wind Farm Model

The aggregation of the wind turbines will be easy if all turbines receive the same wind. In this case the aggregate wind turbine is equal to the sum of the rated power of the individual wind turbines. The equivalent wind turbine will present the same model of the individual wind turbines. However, wind speed is not the same on all turbines. The wind farm may consist of many wind turbines arranged in rows and columns, hence the turbines in the same row may have the same wind but at the next row has a different wind because of the shadow and the parking effect [61].

The aggregation of wind turbine was developed for both variable and fixed speed based on aggregating the power for each individual wind turbine (using 3th order model for simplicity) and neglecting the turbulence (stochastic) term for wind speed signal model due to the smoothing effect of a large number of turbines and using sum assumptions (using the electrical power in case of variable speed instead of the mechanical power as compared to fixed speed, C_p replace by its maximum value, and the non-linear rotor speed versus control characteristic is replaced by a first order one) [62]. For different operating conditions of wind speed the aggregation of wind turbines may be easily calculated if the output mechanical torque of the individual turbine is used instead of the output power and by summing these torques one can find the total torque and used it as an input to the equivalent generator system, thus gives the equivalent output power at different wind conditions [61]. The wind farm control system consist of two controllers one for the power controller and the other for the dispatching controller that distributes the wind farm generation between the wind turbines and design the active and relative power for each wind turbine depending on the system operator [55]. Figure (10) shows the block diagram of the equivalent wind turbine model. The equivalent impedance for the aggregated series or parallel wind farm calculated by using the expression proposed in [63]. There are different techniques for calculating the equivalent impedance.

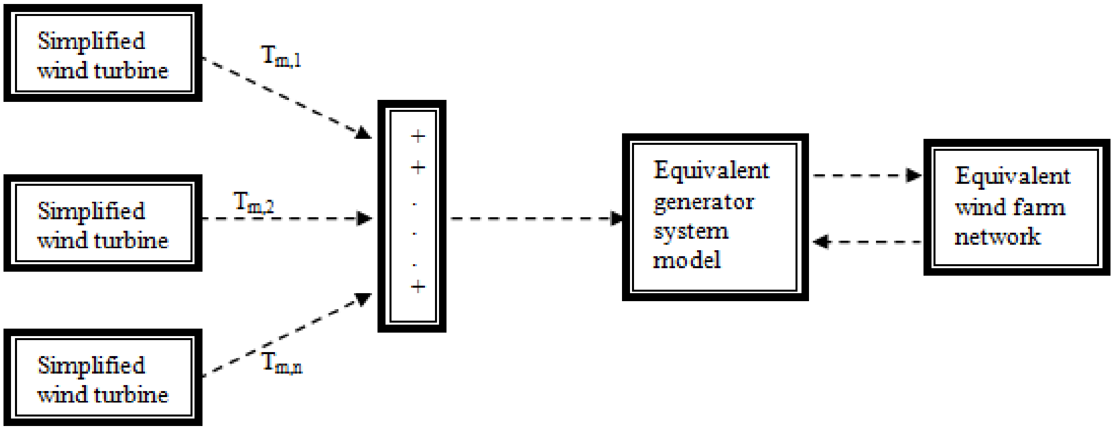


Figure (2.8) Block diagram of the equivalent wind

2.3 SIMILARITIES AND DIFFERENCES BETWEEN OFFSHORE WIND AND TIDAL CURRENTS TURBINES–HISTORIC OVERVIEW

The electrical layout and modeling approaches used in tidal in-stream systems are similar to those used for wind and offshore-wind systems. The speed of water currents is less than wind speed, while water density is higher than air density and as a result wind turbines operate at higher rotational speed and lower torque than tidal in-stream turbines which operate at lower rotational speed and high torque. Therefore in some tidal in-stream system designs the mechanical coupling between the turbine and generator is done through a gearbox.

Also the system collecting electricity may be different and this will influence the choice of methods used in stability studies and the connection of the overall system, but tidal currents are easier to predict than wind speed [2].

2.3.1 Advantages of Tidal In-stream Energy Resource Over Offshore Wind Energy Resource [64-74]

1-The better predictability of marine currents and energy patterns make it more valuable from a market pricing point of view as opposed to less predictable resources such as wind, wave and solar energy.

2- Marine current speed and direction predictions (to within 98% accuracy,) require shorter data records than those required for wind predictions.

3- The density of seawater is high (800 times that of air) compared to air and tidal in-stream currents have roughly four times the energy intensity compared to a good wind site. Thus tidal turbines need a quarter of the swept area of a wind turbines and this will reduce the cost of tidal turbines and also affect the turbine foot-print. Moreover, the higher energy intensity requires smaller and cheaper rotors compared to wind turbines for the same power rating.

4-Lower environmental impact in comparison with other renewable energy sources.

5-The slower moving rotor will have no discernible audio noise and cause fewer disturbances for under water marine-life as compared to the higher speed wind turbines which adversely affects bird and bat population.

6-Shipping and fishing lanes experience limited disturbance when blade tips are immersed at least 10 m below water level.

7-No green-house or other polluting emissions.

8-The “capacity factor” is the ratio of the average generation of an individual turbine to its rated output. A tidal energy turbine has larger capacity factor than the corresponding equivalent wind turbine and are thus more economic.

9- Fluid properties give the tidal current resource higher load factors.

10- Tides flow in only two directions and hence arrays of turbines are arranged in pre-determined rows, while wind comes from varying directions.

2.4 TIDAL IN-STREAM TECHNOLOGY CHALLENGES

Tidal in-stream turbines can use a wide variety of topologies such the vertical axis turbine with a synchronous generator, where the generator can be put above or below the turbine and so its size is not constrained [75].

The easier predictability of the tidal in-stream marine energy resource makes it is easier to integrate in an electric power grid. Recognizing that future ocean energy resources are available far from load centers and in areas with limited grid capacity will result in challenges and technical limitations. The authors of [76] list grid-integration issues that require attention. First, on the conversion process and resources side, the following considerations are important:

- Resource intermittency
- Plant remoteness/weak grid
- Plant size, type & behaviour
- Effects of multi-unit operation
- Switchgear ratings during faults
- Transmission line and cable thermal limits.
- Quality of the power delivered including flickers, harmonics, and voltage sag.
- Faults or harsh environmental events may cause generators to be disconnected from the network which is associated with sustained voltage drops and sags in the network.
- Reactive compensation may be required since induction generators consume reactive power (53-51% at idle and 60% at rated)
- Wind and tidal generation fluctuate on a daily basis and in the absences of energy storage devices, this causes cycling (turning on and off) of conventional electricity generating plants causing thermal stresses on the boiler, steam lines, turbines and auxiliary components which lead to component damage and shorter equipment life expectancy.
- The lower system inertia promotes opportunities for storage systems, such as batteries, compressed air, pumped-storage hydro and flywheels.

In addition, issues related to the scale of development are:

- Plant size (Pilot, Full-scale, Multi unit farm)

- Time-frame of implementation (Near-long term)
- Forecasted load/generation mix

Impact location considerations include:

- Area of impact (local, system-wide, or island)
- Network impact (distribution or transmission system, island grid, etc.)

The following sections discuss the problems facing marine turbines, the new research issues in marine, some of conversion trains, and some of the current technologies for the marine.

2.4.1 Problems Facing Tidal In-stream Turbines

1-The marine environment is harsh due to the presence of corrosive agents and debris which affects the system components. Hence turbine elements need be fabricated form special materials and this affects the overall cost.

2-Inspection, maintenance and repair would necessitate the use of a ship and could be difficult and hazardous

3-Due to the density of water, the turbine shaft is subject to high stress.

4-Cavitation is a potentially damaging phenomenon that takes place at low pressure. As a result, this effect must be considered on the design of the turbine. For example, adjusting the blade pitch may minimize cavitation [65, 76].

5-Generation and load unbalances cause frequency changes. For example, loss of generation (or increase in load) reduces system frequency and the remaining generators connected to the system will decelerate releasing some of their stored kinetic energy. This is referred to as the inertial response. The rotational speed of the synchronous machines connected to the network tracks frequency changes closely and is accompanied by change (release or gain) in part of its stored energy quickly acting as an initial arresting mechanism to the change (decrease or increase) in the system frequency. Synchronous machines are less desirable in renewable energy systems with fluctuating power output. In this case, induction machines are widely employed because they limit the speed variations and hence reducing the drive train stress. More recent renewable energy generation systems employ doubly-fed induction generators allowing more speed variation and greater power smoothing than a conventional induction machine. The inertial response of an induction machine differs from that of a synchronous machine which alters the frequency response of the power system to changes in generation and/or load. Moreover, the rate of change of frequency is critical since a slower change in frequency allows controllers sufficient time to respond to frequency unbalances. This is important for small isolated systems where system inertia is lower than for large grids [77].

6-Synchronizing the tidal current power station and the grid is an important consideration. This is more significant for asynchronous interfaces, e.g. power electronic converters, where frequency deviations in the power systems will be directly correlated with prime mover's speed variations [78].

7-Connecting to an electrically weak network may require reinforcing switchgear and cable thermal ratings as well as revising fault protection mechanisms.

8-Connecting a tidal in-stream-based generator to a distribution network will contribute to additional fault currents in the network and feeder circuits close-by.

9-Resource intermittency, start-up and shutdown conditions, and interactions with network control equipment may cause flicker which is one of the most common causes of nuisance and public complaints.

2.4.2 Tidal Farm Considerations

A tidal farm consists of an array or multiple arrays of individual tidal in-stream turbines. A tidal farm requires a large investment and it is crucial to arrange turbine placements so as to maximize the power extracted from the water channel to shorten the payback time. The arrangement should be such that downstream turbines are not placed in the wake of upstream ones.

Considerations involved in locating a tidal farm include water depth (most existing devices are designed for a depth between 25 and 45 m), high velocity during tides and choosing a location which near to the grid to reduce the overall cost of energy extracted.

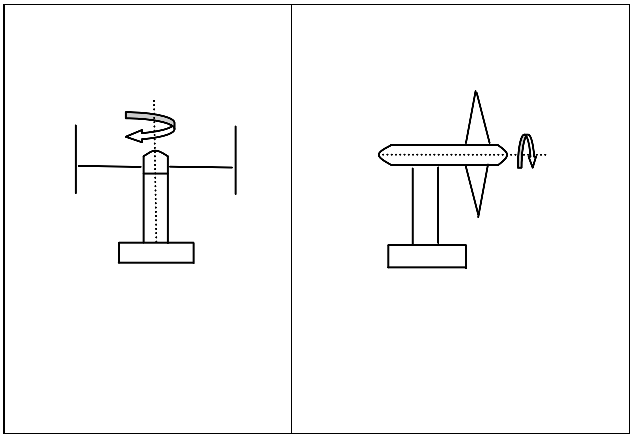
Turbines are interconnected in strings by sub-sea cables. The strings are then connected to the platform by feeder cables. The cables together with necessary switching equipment form the collection grid. Possible configurations for energy collection include:

- The radial design is the most straightforward arrangement. The maximum number of turbines on each string feeder is determined by the capacity of the generators and the maximum rating of the sub-sea cable. This design is simple and inexpsive because the total cable length is shorter. The major drawback of this design is its poor reliability as cable or switchgear faults at the platform end of a radial string would prevent all downstream turbines from exporting power.
- The ring design employs two strings interconnected in a ring system with a few sectionalizing breakers and the ring is connected to the platform by one breaker. If the full output power of the turbines in one of the strings were to be transferred through the other string during special situations, then the cable needs to be sized to a higher rating.
- The U-ring design is similar to the ring design. Each string of turbines is connected to the platform with a feeder cable, and the other end of one string is connected to the next forming a ring (U-ring).
- The redundancy offered by ringed designs is beneficial when the probability of a fault and the associated costs are higher than the costs associated with additional equipment, especially, when the repair downtimes are long. However, note that the fault current of a ring design will be higher than that of a radial design and could require higher switchgear rating [79].

2.4.3 Tidal In-Stream Types

Many types of turbine systems are available. Based on the alignment of the rotor axis with respect to the water flow tidal in-stream turbines may be classified as follows:

- The horizontal axis (alternately called as axial-flow): The rotational axis of the rotor is parallel to the incoming water flow (employing lift or drag type blades). The turbine's mooring structure may be either solid or buoyant. The former locates the generator unit near the seafloor; the latter may employ a non-submerged generator placed closer to the water surface.
- Vertical: Here the rotational axis of rotor is orthogonal to both the water surface and the incoming water stream. This category includes many designs such Darrieus , and H-Darrieus or Squirrel-cage Darrieus (straight bladed) turbines. The Gorlov and Savonious designs are vertical axis turbines, where in the former the blades are helical and the latter are drag type devices, which may consist of straight or skewed blades.
- Cross-flow: (Rotational axis of rotor is parallel to the water surface but orthogonal to the incoming water flow employing lift or drag type blades) . The latter are inherently less efficient than lift based counterparts. Darrieus turbines with cross flow arrangements may also fall under this category [80].



Vertical turbine type   Horizontal turbine type

Figure (2.9) Vertical and horizontal turbine types

Figure (2.9) shows vertical and horizontal turbine types. Vertical turbines work easily from any direction and have a larger area but the most commonly used turbines are the horizontal type as it uses almost the same technology as the wind turbines.

Tidal in-stream turbines may also be classified based on their lift/drag properties, and fixed/variable (active/passive) blade pitching mechanisms. Different types of rotors may also be hybridized (such as, Darrieus–Savonious hybrid) in attempts to craft specific desirable performance features.

The structure of a horizontal (axial) flow turbine can be constructed as either open or ducted (duct augmentation). While ducted turbines were unsuccessful in large-scale wind turbines due to storm loads, these conditions are not present underwater. Ducted turbines increase flow velocities over and on the rotor. An advantage of ducted turbines is streamlining fluid flow and reducing turbulence and its harmful effects on the rotor, which in turn may improve power conversion efficiency. Ducted turbines use smaller rotor for equivalent power output and operate at higher speeds (to facilitate direct-drive electrical generator operation). Individual rotor size is limited by water depth and blade root stresses which are overcome by ducting. However, using a duct requires a higher capital investment. The extra drag on the duct must be borne by the tower, and further study is required to identify the optimal duct for a farm of turbines in order to extract maximum aggregate energy [81, 82].

Table (2.4) Comparison between vertical and horizontal axis rotors

No	Type of comparison	Vertical	Horizontal
1	**Design simplicity**	Simple	Complex
2	**Cost**	Less	High
3	**Generator coupling**	Placed at one end of the shaft and may be above the water surface	Using right angles gear coupling
4	**Noise emission**	Less	High
5	**Floating and augmentation**	Easy	Not easy
6	**Skew flow**	More suitable	Faces problems
7	**Starting torque**	Poor	High (self starting)
8	**Output torque**	Contains ripples	Ripple-free
9	**Efficiency**	Low	High
10	**Control**	Not easy	Easy
11	**Installation**	Less hard	Hard
12	**Known technology**	Not well-known	Well known based on experience with wind

2.4.4 Power Conversion Train

There are three types of power conversions train described as follows:

1. Gear system which is the most commonly used in the wind turbines but its maintenance is more cumbersome and expensive.
2. Hydraulic system which depends on the pressure to increase the speed by using a hydraulic pump connected to the rotor of the turbine to convert the rotational speed into pressure then using a hydraulic motor to convert this pressure into higher speed connected to the generator.
3. Direct drive machine, where the generator is directly connected at lower speed. This is preferred in the tidal application because of the maintenance complexity in the ocean environment [82].

The model of the ocean system consists of three stages. The first stage contains the fluid mechanical process. The second stage consists of the mechanical conversion and depends on the motion between bodies. This motion may be mechanical transmission and then using mechanical gears or may be depending on the hydraulic pumps and hydraulic motors. The third stage consists of the electromechanical conversion and the electrical grid [83 - 85].

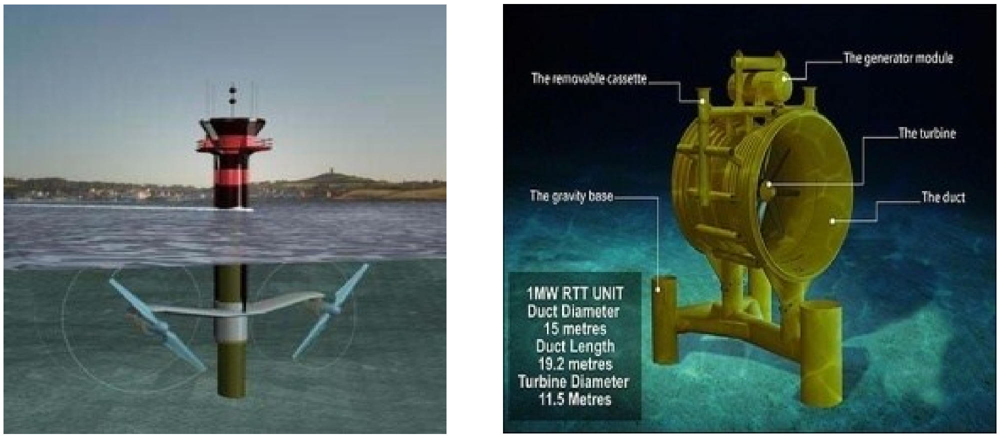
2.5 TIDAL IN-STREAM TECHNOLOGIES

Tidal in-stream turbines are under development, there are two types of these turbines depending on the axis of rotation horizontal axis (the axis of rotation is horizontal with respect to the ground and parallel to the flow direction) and vertical axis (the axis of rotation is perpendicular to the flow direction) [86].

Various projects deploy tidal energy devices (TED) in the world. Among these projects MCT (Marine Current Turbines) which is known as “SeaGen” ready for the use as shown in figure (2.10). MCT applies the same technology as offshore wind turbines and consists of twin axial flow rotors, each has a rotor diameter between 15 and 22 m (the size is depending on local site conditions), each driving a generator connected to the turbine through gear box and accommodated to work in bidirectional as their blades can be pitched through 180^{o}. The power units are easy to be raised above sea level for maintenance; this marine was tested in September 2005 and now they have a farm of turbines which may be used easily but it is still under development. The water currents will drive the rotor at speed of 10 and 22 revolution per minute and this speed is slow to affect the life time of the blades [70]. 1 MW prototype lunar energy turbine is shown in figure (2.10) was installed at European Marine Energy Center in 2007 [87]. Figure (2.10) shows another technology called an open hydro marine turbine technology. Open hydro is one of the first energy technologies used in the world. The first test (6m) produces energy to supply 153 average European homes and save 473 tones emission of CO_2 each year [89].

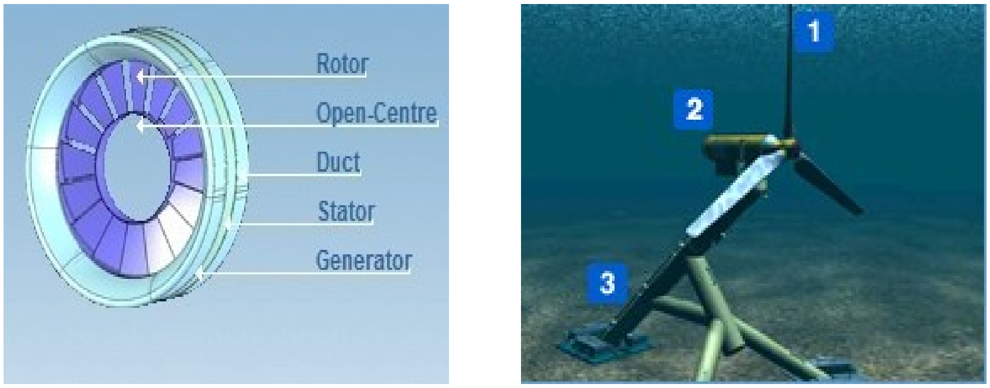
The Engineering Business “Stingray” generator was developed in the United Kingdom and used the oscillatory movement of hydroplanes driven by the water. The angle of the hydroplane is changed during the flowing of water (fall and rise) and the hydroplane is connected to a hydraulic cylinder. The movement will develop a pressure on the oil of a hydraulic cylinder; this pressure is used to drive a hydraulic motor which drives the electric generator. The Hammerfest Stroem generator which has a horizontal axis prototype generator (similar to Seaflow project) was installed in Norwegian in 2003 to develop 310 kW. North America (US and Canada) developed some small prototype technologies such as the Verdant Power and Underwater Electric Kite (UEK) [90].

The Rotech Tidal Turbine (RTT) is a prototype system tested to extract the power from tidal currents into electrical power in a unique and patented manner. This prototype used a symmetric duct and turbine blade sections to operate in both directions and this eliminate the used mechanics part in a reversing tide. The turbine is connected to a fixed displacement hydraulic pump. This pump converts the rotational energy into hydraulic flow and pressure, then this fluid energy is fed to a sealed pod which is used to drive two variable displacement hydraulic motors and these motors are used to drive a synchronous generator. By using the swashplate, the power extracted from the generator is adjusted at various tidal conditions. This prototype system is designed to produce 1 MW electrical power output at 11 KV as shown in figure (2.10) [91].



a. Marine Current Turbine [70]

b. Lunar Energy [87]



c. Open hydro [89]

d. Turbine components [90]

Figure (2.10) Some of tidal current turbines technology.

It was concluded that to get positive benefits for the tidal generation for a case studied in Ireland, the capital cost must be less than 664,000 euro per MW installed and this is very high as it is compare to conventional energy till now [92]. The main components of the turbine as shown in figure (2.10) are:

1) The blades system.

2) The nacelle which is called the production system contains the generator, gear box and control system.

3) The subsea cables which are used to transmit the electrical power from the off shore to the shore system. The turbine is able to work in two directions according to the direction of the flow.

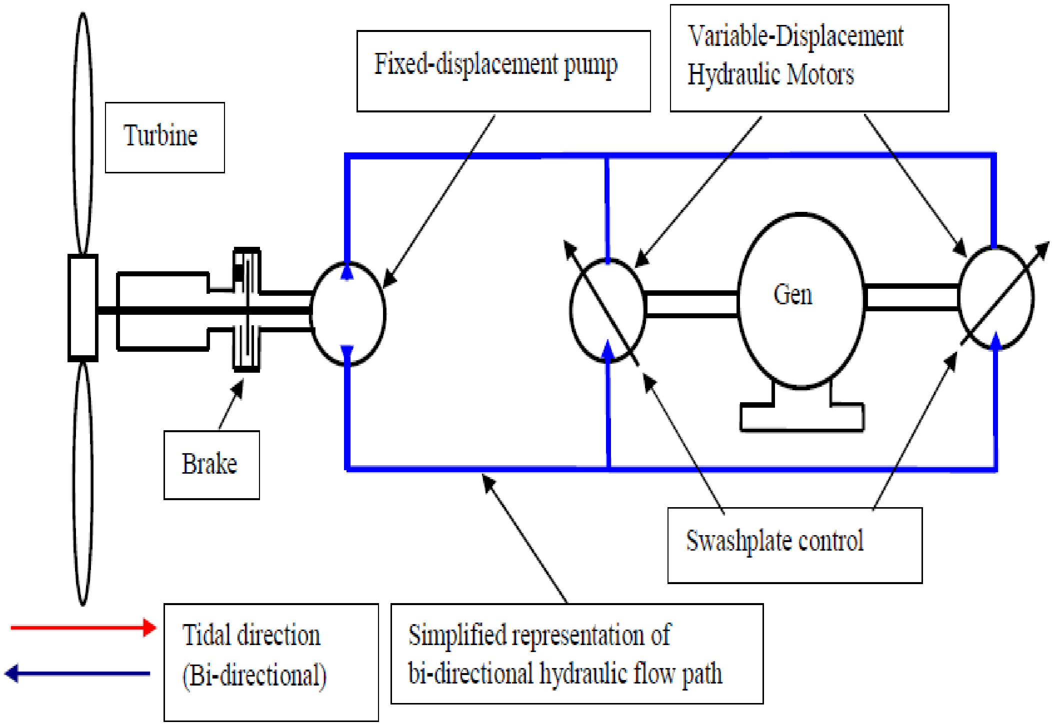
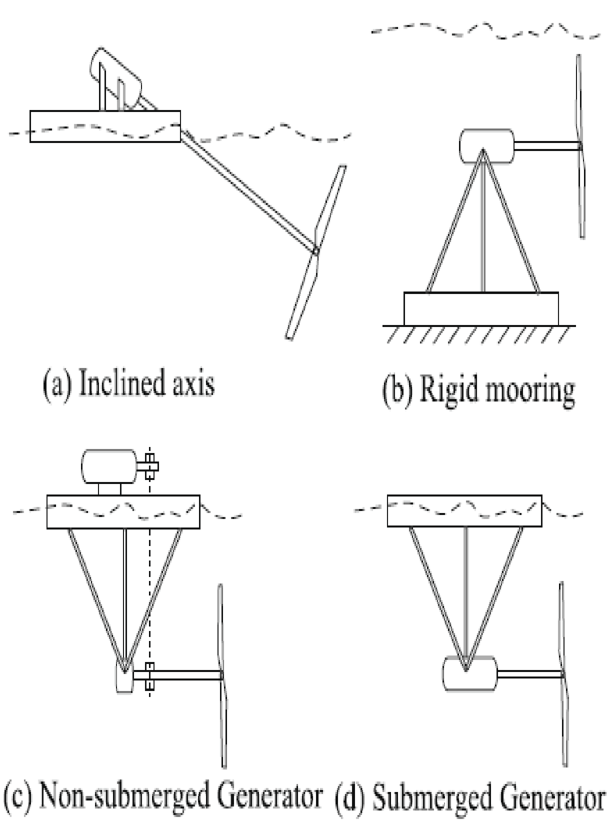


Figure (2.11) The Rotech Tidal Turbine (RTT) [91].

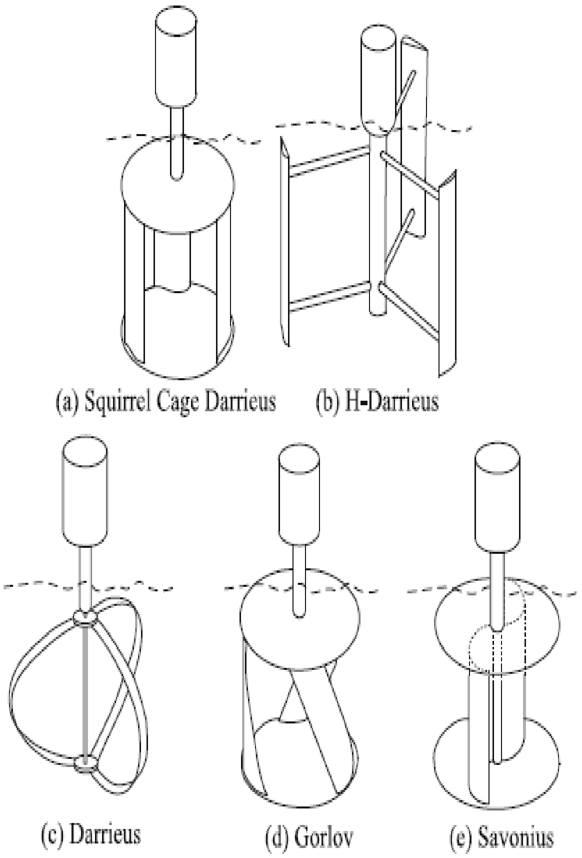
Various types of turbines are now available depending on the position of the rotating axis, horizontal axis and vertical axis as shown in Figures (2.12), and (2.13). The horizontal axis consists of straight and inclined axis. The straight axis contains two types, solid mooring and buoyant mooring. The buoyant mooring may be submerged or non-submerged. The vertical axis consists of four types SC-Darrieus (Straight Blade), H-Darrieus (Straight Blade) , Darrieus (Curved Blade), Gorlov (Helical Blade) and Savonius (Straight/Skewed)). The horizontal axis turbine is preferred due to its easy control and its high starting torque [90].



(a) Inclined axis (b) Rigid mooring

(c) Non-submerged Generator (d) Submerged Generator

Figure(2.12) Horizontal axis turbines [90].



(a) Squirrel Cage Darrieus (b) H-Darrieus

(c) Darrieus (d) Gorlov (e) Savonius

Figure (2.13) Vertical axis turbines[90].

2.5.1 Canadian Tidal Energy Technology

There are different types of turbines used all over the world for capturing the tidal in-stream energy. The most commonly used turbines in Canada as shown in Figure (2.14) are:

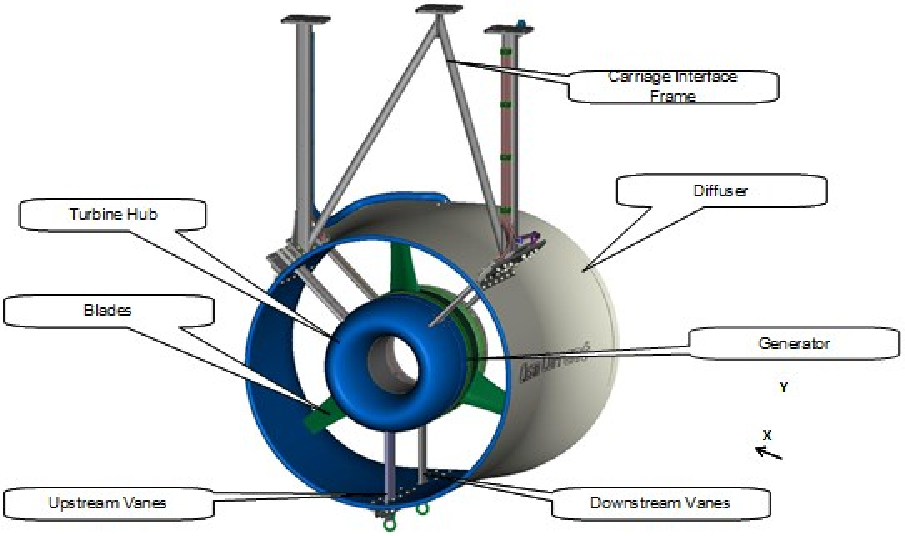
1) Blue Energy, this type is called eggbeater (this is a vertical ducted turbine and uses a permanent magnet generator above the water to facilitate the maintenance) [93].

2) Verdant Power (this is a horizontal flow turbine) [94].

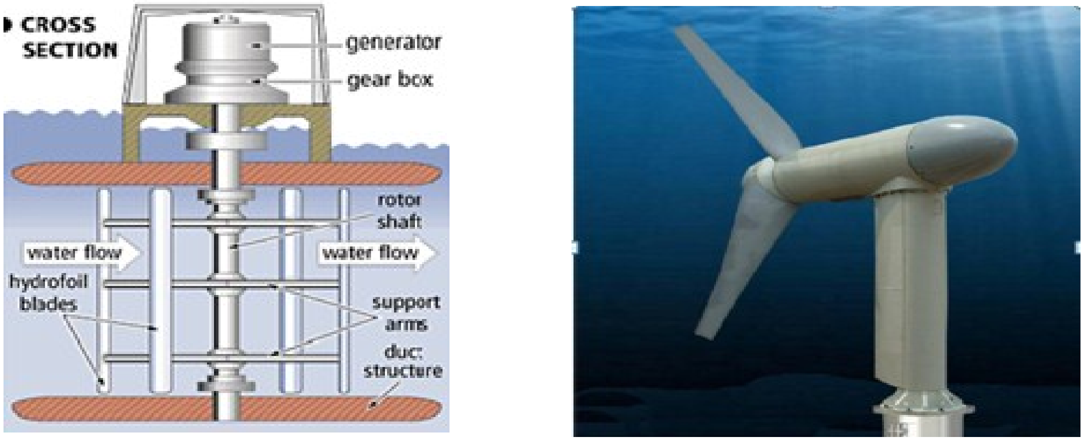
3) Clean current power (this type uses DDPMSG) [95].

4) Coastal Hydropower Corporation (this type uses a vertical turbine with helical or straight blades) [96].

5) Water wall turbine (this type uses DDPMSG) [97].

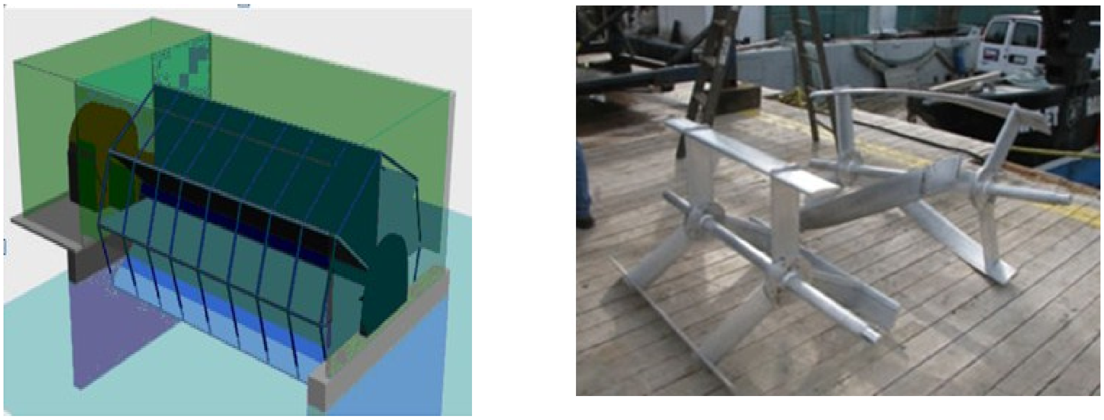


Clean current turbine [95]



Blue turbine [94]

Verdant energy [93]



Water wall turbine [97]

Coastal Hydropower Corporation [96]

Figure (2.14) Canadian tidal current turbine technologies.

Due to the fluctuation of the tidal energy during the day so there is cycling of turning on and off for the conventional stations and this will cause stresses on the boiler, steam lines, turbine and auxiliary components which leads to component damages [98]. Some research has been carried out related to this topic but they are still under development. In the following chapters the focus will be on the forecasting of tidal current speed and direction and on the stability of the tidal current turbine.

2.6 SUMMARY

In this chapter, offshore wind turbines types were discussed, Different generators types were addressed, stability problems of wind turbines, mitigation methods, some control schems and wind farm were shown as an introduction of the tidal current turbine. Then similarities and differences between tidal in-stream and offshore wind turbines, tidal in-stream technology and tidal in-stream turbines types were presented.

CHAPTER 3 A PROPOSED ANN AND FLSM HYBRID MODEL FOR TIDAL CURRENT MAGNITUDE AND DIRECTION FORECASTING

3.1 INTRODUCTION

Tidal current energy can be converted into electrical power. It is so hard to store the electrical energy for latter use and a control system is required to be connected directly to the consumer. It is very important to have advance knowledge for the tidal current energy to manage the production of the electrical power so that it may ensure that this power will be controlled in an efficient way to allow scheduling different electrical energy resources to minimize interruptions. Prior knowledge of future generated electrical energy or the tidal current energy is known as forecasting. Tidal flow causes somewhat predictable energy output patterns. Forecasting marine currents using data gathered for short periods of time is predictable to within 98% accuracy). On the other hand forecasting wind speed requires data gathered over a longer period. The marine resource is easier to integrate in the electrical grid. Forecasting is the first step in dealing with future generation of the tidal current power systems. The accuracy of the models used for tidal current forecasting is critical since a tidal in-stream forecast with sufficient accuracy can provide a stable and controlled electric power dynamic performance that allows better dispatching of grid resources and this evens out the use of battery storage and will affect the overall cost of electricity. In addition, tidal current prediction is useful in making operations- and planning related decisions such as towing of activities vessels, fisheries and recreational activities and monitoring of oil slick movements. In this chapter we review the previous work on the tidal current forecasting and propose a hybrid model of an artificial neural network (ANN) and Fourier series model based on the least squares method (FLSM) for monthly forecasting of tidal current magnitude and direction. The proposed hybrid model is highly accurate and outperforms either the ANN or FLSM when used alone. This study was done using data collected from the Bay of Fundy in 2008. By adjusting the period of the trained data, the accuracy will increase, especially if we utilize all changes in the trained data.

3.2 PREVIOUS RESEARCH FOR TIDAL CURRENTS FORECASTING

Sir G. H. Darwin [99] is credited with the idea that tidal oscillation of the ocean may be represented as the sum of a number of simple harmonic waves. Subsequently, Doodson [100-101] proposed using least squares estimation to determine the parameters of the harmonic series which has been widely used for tidal forecasting [102].

Artificial neural networks (ANN) have been used to overcome the problem of exclusive and nonlinear relationships. French, Krajewski & Cuykendall proposed an ANN model to predict rainfall intensity[103]. Raman & Sunilkumar proposed a multivariate modeling of water resourses time series by using ANN [104]. Dawson and Wilby considered the potential of using ANN for rainfall-runoff modelling and flood forecasting [105]. Coulibaly et al. used a modified ANN for daily resvoir inflow forecasting [106]. Lee and Jeng [107] used an ANN model for tidal level forecasting using short-term tidal records from three harbours in Taiwan. Campolo & Soldati applied ANN for river flood forecasting [108]. Lee [109] used the ANN Back Propagation with descent algorithm to forecast the tidal level for three different tide types, diurnal, semi-diurnal and mixed tides. This model was used for the short and long term forecasting. In [110], Lee , Tsai and Shieh applied the Back Propagation Neural Network (PBN) to predict long term semi-diurnal tidal levels. Based on the model, the different tide types for other two field data of diurnal and mixed types were used to test the performance of a PBN model.

Vijay and Govil [111] used radial basis function ANN networks (RBF) for tidal data prediction for high and low tides of any day of the year depending on the training data of only one month. They concluded that a Fourier series or a polynomial series alone do not give accurate results. They also reported that using Wavelets yielded approximately the same results as ANN but implementing the Wavelet approach required longer execution time. Chen, Wang and Chu [112] proposed a hybrid of wavelet and ANN models for tidal current prediction. The signal in the multi-resolution analysis (MRA) used in wavelet analysis consists of high and low frequency components. Chen et al. eliminated the high frequency components and used inverse wavelets to rebuild new signals. The input/output data that were used for the training of the ANN depended on the calculation of the tidal constituent time-lags. Adamowski [113] proposed a hybrid of ANN and wavelet and cross wavelet constituent components for short term river flood forecasting that gave accurate results compared to wavelet and cross wavelet constituent components alone.

In [114] genetic algorithms (GA), were used to carry out the prediction task. A preliminary empirical orthogonal function (EOF) analysis was used to compress the spatial variability into a few eigen-modes, so that GA could be applied to the time series of the dominant principal components (PC). Burrage et al. proposed an optimal multi linear regression model for the tidal current forecasting [115].

Harmonic tidal current constituent analysis or numerical hydrodynamic models are traditional models used for tidal current prediction. These models have their own limitations and nonlinear data adaptive approaches are gaining increased acceptance. Numerical hydrodynamic models require large computing resources and huge input information.

In this Chapter such an approach, known as a Hybrid model of ANN and FLSM, has been employed for the tidal prediction. The novelty of the method is the use of the ANN technique to forecast of the resulting principal components from a few observed tidal levels with the use of FLSM. The proposed model is easy to use and only depends on the input data (speed or direction) without knowing the tides' constituents because we covered all cycles without referring to the the type of the cycle so we used the model for predicting of the speed and the direction using time as an input. The proposed model accuracy is high compared to ANN or FLSM alone. This model is used for more than month (33.67 days) prediction and the results proved its robustness.

3.3 OVERVIEW OF SOME FORECASTING TECHNIQUES

In this section some most commonly used forecasting techniques will be outlined and the main focus will be on the techniques used in this work for tidal current forecasting. Many forecasting techniques are used nowadays ranging from Multiple Linear and Nonlinear Regression, Dynamic Techniques, General Exponential Smoothing Technique, Expert

System, Fourier Series Model based on the Least Squares Method, Time Series, Wavelet and An Artificial Neural Network.

3.3.1 Multiple Linear and Nonlinear Regression[116, 117]

Regression is a commonly used techniques for modeling. Regression is used to develop a mathematical model which is represented by an equation or a set of equations that represent the system behavior and treat one variable as a function of others. These equations may be linear or nonlinear and can be used to predict a response from the value of a given predictor(s). They can be used to consider more complex relationships than correlation by using more than two variables or combinations of different order equations. This technique is effective for the case of off line forecasting application and is generally unstable for the on-line forecasting application, because it requires many external variables. It is commonly used in experimental tests where a range of fixed predictor levels are set and one tests whether there is a significant increase or decrease in the response variable along the gradient of predictor levels.

In multiple linear regression, the most common estimation method is implemented using an equation of the form:

$$E(y_i) = \beta_0 + \sum_{i=1}^{N} \beta_i x_i\,(t) + r(t)$$

$E(y_i)$ is the forecasted variable at a certain time t (the dependent or response variable), β_0 is the intercept , β_i is the regression coefficient and r(t) is the residual.
The previous equation is a first order model with one predictor but sometimes there will be a need for increasing the order depending on the used model and the data. The least squares method is used for estimating the parameters for the model.

In the nonlinear model at least one of the parameters appears nonlinearly. Generally speaking in a nonlinear model at least one parameter should appear when a first order derivative with respect to that parameter. For example one may write the nonlinear model in the form of $E(y_i) = \exp(ax + bx^2)$

3.3.2 Expert System Approach[118]

The expert system method depends on statistical analysis of the past data and the knowledge of experts in the field of interest. The forecast model using this technique emulates the knowledge, experience and identifies the rules and the variables used by the experts. This technique is commonly used for the load forecasting.

3.3.3 Fourier Series based on Least Square Model Structure (FLSM) [119, 120]

The Fourier series based on least square model structure is a common model used for the harmonic identification. Since the shape of the tidal current waveform is similar to the sinusoidal wave containing some harmonics so it is natural to adopt the FLSM technique for tidal current forecasting using the following assumptions :

The estimated data may be expressed using Fourier series as:

$$Z_{0estimate}(K) = DC + \sum_{n=1}^{N}(a_i \sin(\omega_i k + \theta_i)) =$$

$$\mathrm{DC} + \sum_{i=1}^{N}(a_i \sin(\omega_i k) cos\theta_i + a_i \cos(\omega_i k) sin\theta_i)$$

DC = Constant value depending on the data (the average value),

k =discrete time index,

a= amplitude parameter,

i=number of harmonics in the wave,

θ= the phase shift. The Fourier series parameters may be determined using the LSM.

Now let us define the actual data as Z=DC+HX+e(k), where e(k)is the error (residual), then we may apply the least squares model to estimate the Fourier series parameters.

$X_{hat} = (H^T H)^{-1} H^T Z$,

$Z_{oestimate} = DC + HX_{hat}$,

$Z_{innovation} = Z - Z_{oestimate}$,

$$,H=\begin{bmatrix} sin\omega_1 & cos\omega_1 & sin\omega_2 & \dots\dots\dots. & sin\omega_i & cos\omega_i \\ sin2\omega_1 & sin2\omega_1 & \dots\dots.. & \dots\dots.. & sin2\omega_i & cos2\omega_i \\ sin3\omega_1 & \dots\dots\dots\dots.. & \dots\dots.. & \dots\dots.. & \dots\dots\dots\dots.. & cos3\omega_i \\ \dots\dots\dots. & \dots\dots\dots\dots.. & .. & .. & \dots\dots\dots\dots.. & \dots\dots\dots\dots \\ \dots\dots\dots\dots.. & \dots\dots\dots\dots.. & .. & .. & \dots\dots\dots\dots.. & \dots\dots\dots\dots \\ sinn\omega_1 & cosn\omega_1 & .. & .. & sinn\omega_i & cos8n\omega_i \end{bmatrix}$$

$$, X=\begin{bmatrix} a_1cos\theta_1 \\ a_1sin\theta_1 \\ a_2cos\theta_2 \\ \dots\dots \\ \dots\dots \\ a_isin\theta_i \end{bmatrix}$$

H is a matrix that has a number of rows equal to the number of the input data and number of columns depending on the number of harmonic used. X is a resulting vector coming from the matrix H and the input data.

3.3.4 An Artificial Neural Network Structure

An artificial neural network is a mathematical model inspired by the natural neurons interactions. It is based on simulating the function of human brain which consists of massive neural networks. The brain has the ability to compute, recognize faces, speech and control activities. The brain has a highly parallel computing structure, and the capability for processing the information. The human brain has more than 10 billion interconnected neurons. Each neuron in the human brain is a cell which uses the reactions to receive, process, and transmit information. The networks of nerve fibers are called dendrites which are connected to the cell body or soma, where the cell nucleus is located. The axon is a single long fiber extending from the cell body. This axon branches into strands and substrands, to connect to other neurons through synaptic terminals or synapses. The neurons receive signals through synapses. Figure (3.1) shows the mammalian neuron. The neurons start to activate and emit a signal through the axons when they receive strong signals, the potential of the signals reach a threshold, a pulse is sent down the axon and the cell is fired. Figure (3.2) shows the general structure of the neural network feed forward system [121, 122].

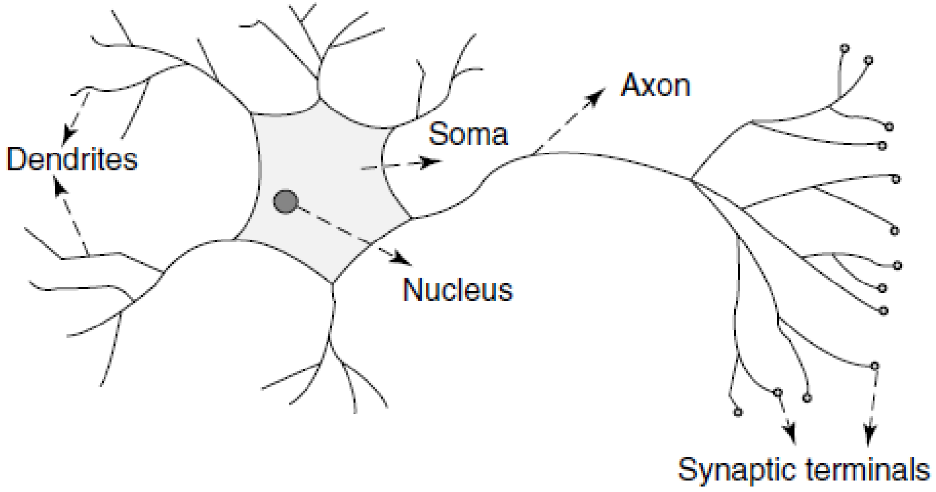


Figure (3.1) The mammalian neuron.

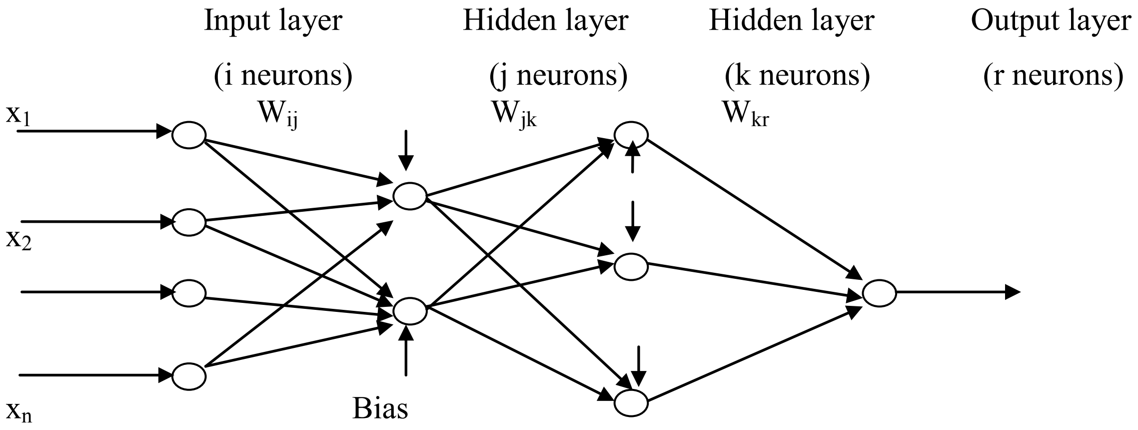


Figure (3.2) General structure of the neural network feed forward system.

In neural networks, the effects of the synapses are represented by connection weights that modulate the effect of the associated input signals. The transfer function is used to represent the nonlinear characteristic exhibited by neurons. The impulse of the neuron is equal to the weighted sum of the input signals that transformed by the transfer function. By adjusting the weights the artificial neuron starts to learn [122]. An artificial neural network is commonly used for forecasting. As the size of the input data increases, accuracy will increase. The neural network consists of one input layer, one output layer and one or more hidden layers. Each layer consists of a number of neurons. In feed forward networks, the signal flow is coming from input to output and there is no feedback connections. In the recurrent networks there is a feedback connection. There are several neural network structures like recurrent or Elman networks, adaptive resonance theory maps, competitive networks…., which are used according to the properties and requirements of the application.

The neural network has to be configured to produce the desired set of outputs for a certain set of inputs. There are many methods used to configure the ANN. A common way is to set the weights explicitly by using a priori knowledge. Another simple way is to train the neural network by feeding it teaching patterns and allowing it to change its weights according to some additional learning rule which is easier but requires additional processing time. The output of each neuron can be expressed as a function of the input signals as:

$$Y_j(t) = f\left(\sum_{i=1}^{x} W_{ij} X_i(t) \pm b_i\right) \qquad \text{for } j = 1,\dots H_1$$

$$Y_k(t) = f\left(\sum_{j=1}^{H1} W_{jk} Y_j(t) \pm b_i\right) \qquad \text{for } k = 1,\dots H_2$$

$$O_r(t) = f\left(\sum_{r=1}^{H2} W_{kr} Y_k(t) \pm b_i\right) \qquad \text{for } r = 1,\dots Z$$

$Y_j(t)$ & $Y_k(t)$ = Quantity computed by the first and second hidden neurons respectively.

$O_r(t)$ = Network output.

X & Z= Number of input and output neurons.

H1 & H2= Number of first and second hidden neurons.

W_{ij}, W_{jk} & W_{kr} = Adjustable weights between input and first hidden layer, the first and second layer and the second and output layer.

b_i = Biases.

f = Transfer function.

There are three types of learning, supervised learning, unsupervised learning, and reinforcement learning. For supervised learning, the input vector is presented at the input nodes together with a set of desired responses, one for each node, at the output layer. A forward path is used, and the errors are calculated which is the difference between the desired and actual data for each node in the output layer. The errors are used to determine weight changes in the network depending on the learning rule. The backpropagation algorithm, the perceptron rule, and the delta rule are typical supervised learning techniques. In unsupervised learning, the output unit is trained to respond to pattern clusters within the input. The system attempts to discover statistically salient features of the input. Here the system develops its own representations from the input. In reinforcement learning the system is taught what to do, and how to map situations to distinguish features of reinforcement learning. Trial and error search and delayed reward all characterize reinforcement learning. In this approach the learner is not informed which actions to take first for solving a certain problem, but it is informed to discover which actions yield the most reward by trying them [121]. There are some rules that should be considered while dealing with ANN like the selection of the raw data patterns for training, the topology of the network, and the training algorithm that has faster convergence properities and lower computational time [123].

3.3.4.1 Supervised Learning by Evolving Multi-layer Perceptron [124, 125]

This section discusses the evolving architecture neural networks depending on Multi Layer Perceptron (MLP) and contains some kind of evolution pattern. Two kinds of investigations are discussed; the first depends on starting as small scale and becomes bigger during learning and this is referred to as the constructive method. On the other hand, the second depends on starting big and becomes smaller, this is called the pruning method. Some people prefer to mix the two approaches.

3.3.1.1.1 Constructive Method

This method uses one hidden layer only and then growing the network till convergence is achieved. Four techniques have been used to achieve this:

a) Progressive error minimization: This depends on reducing the error rate by adding additional units and may be done either by adding layers or establishing the number of units as follows:

1) Fixed layer number networks: In some logical problems, it is suggested to add neurons in hidden layers while the error reduction is larger than to a certain threshold, and if the error does not decrease the training stopped. This method converges and needs less time, but its performance may not be able to classify real data and to generalize. Other approaches add new hidden unit if the error does not decrease by 1% over the last 100 epochs and this method has a satisfactory results and its validation for real data is acceptable . Other methods analyze the learning of the residual error committed at step k and proposed original stopping criterion.

2) Variable layer number networks: In the tiling algorithm the training of each layer is done using the pocket algorithm where the first neuron of each layer is called “master unit”. If the outcome is a mistake, then add new units to the layer being built. A layer is called full if its output is different for each pair of training. As a result create a new master unit and link it to the previous (Boolean function approximation is used for convergence) [125, 126].

b) Neural tree: This neural tree consists of neural networks connected in a tree architecture. In this method the networks are used to partition the feature space into subregions and the neural tree is grown by a learning algorithm [125].

c) Active data selection: This is done by selecting the effective data in one of two ways. The first defines a statistical criterion to determine a good summary else add other samples. The second is to select data using an incremental designed NN and this allows treating noisy data but is valid for small data [125].

d) Genetic Algorithms (GA): This is used at each level of the NN as it increases the computational speed, size and convergence. This is done through architecture determination (coding), weight training (to avoid local minima) and learning parameter determination [126].

3.3.1.1.2 Pruning Method [125, 126]

This method not only reduces the size but also improves the capability and is done through:

a) Progressive error minimization

b) Measure of a saliency, this finds units of an MLP which are the least influential. Saliency (the influence of a neuron) is computed for each neuron. The principle is to build a model of the error function, predict the effect on the weight vector, and then examine if the saliency is superior according to a given threshold.

C) Penalty term addition is the term which added to the error function during using BP and is proportional to the number of neurons.

D) Pruning using GA, design a fitness function taking into account the complexity (the number of units of the tested MLP).

3.3.4.2 Learning Linear Neural Networks [127]

This section contains most known results on linear networks, including BP, and the structure of the error function, learning algorithms, and the connections to classical statistical ideas, such as principal component analysis (PCA used to compress the high dimensional input data into something low dimensional without discarding too much relevant information. principal component analysis can be concluded in two purposes: data compression by projecting high-dimensional data into a lower-dimensional space and feature extraction by revealing, through the principal components, relevant but unexpected structures hidden in the data), and the effect of noise on BP networks. It emphasizes the importance of linear algorithms because nonlinear algorithms stress only input output relations and missed dynamics. Learning rules are algorithms altering the connection weights to achieve a desirable goal such as minimization of the error function and may be carried out off-line, on-line or in combinations.

3.3.4.2.1 Back Propagation [121, 126]

Back propagation is a supervised training technique most commonly used for determining the error derivative of the weights and biases. The simple perceptron is able to handle linearly separable or linearly independent problems. Taking the partial derivative of the error with respect to each weight, yields the direction in which the error of the network is changing. The negative of the partial derivative means that, the rate of change of the error as the value of the weight increases and the error will decrease until it reaches local minima. A positive derivative means that the error is increasing when the weight is increasing. So if we take the negative derivative and then add it to the weight. The backpropagation algorithm depends on taking partial derivatives and then applying them to each of the weights starting from the output layer to hidden layer weights. Subsequently repeat the process again in the backward direction updating the hidden layer to input layer weights.

The training of neural network is very important and this can be done in two modes, the online and the batch modes. The number of weight updates are different for both. In the case of online method the weight updates are computed for each input data sample, and then weights are modified after each one. In the batch training mode, compute the weight update for each input sample, and store these values during one pass through the training set (*epoch)* and then at the end of each epoch, add all contributions. This method adapts the weights with a cumulative weight update.

The average of all the squared errors (E) for the outputs should be computed, and the weights should be updated one by one. In the batch mode variant, the descent is based on the gradient ∇E for the total training set

$$\Delta w_{ij} (n) = - \eta * \delta E/\delta w_{ij} + \alpha * \Delta w_{ij} (n-1)$$

where η and α are the learning rate and momentum respectively. The momentum term is used to define the effect of past weight changes on the current direction of movement in the weight direction. By making a good choice of η and α the training will improve the speed of the neural network learning. Choosing the number of the hidden neurons is very important and has an effect on the ability of the network to distinguish the data. A large number of hidden neurons will enhance correct learning. In addition, the network will be able to predict the data that it has been trained on, but the performance for new data, and the ability to generalize, will not be improved.

In the case of a few hidden neurons, the network may be unable to learn the relationships amongst the data and the error will be high. The back propagation learning with adequate hidden neurons can converge in a short time and achieve high performance. The learning algorithm depends on a steepest descent technique, and this rolls straight downhill in weight space until the first valley is reached. This affects the choice of the initial starting point in the multidimensional weight space. Deep networks with multiple hidden layers are constrained as the hidden layer consists of small size p; imposing rank restriction on the map computed and the geometry of connections. In the cases of nonlinear, local connected linear network, then E is devoid of local minima. In the nonlinear case, local minima appear. Some networks consist of nonlinear elements and linear elements, the nonlinear elements in hidden layer while the linear elements are in the output layer and in this case the solution using nonlinear elements is close to PCA. Other networks use the bias with linear units instead of using the data to be centered.

The learning rate is used to control the size of the step that is taken in multidimensional weight space during the modification of each weight. There are two cases of learning rates: too large, or too small. If it is too high the local minimum will be overstepped constantly, and this will cause oscillations. As a result convergence will be low to the lower error state. But if the learning rate is too low then the number of epochs required will be too large and this will cause inferior performance.

3.3.4.2.2 Self Organizing Feature Map (SOFM) [121]

The Self Organizing Feature Map (SOFM) proposed by Kohonen in 1988. It is a data visualization technique used to reduce the dimensions of data through the use of self-organizing neural networks. A SOFM learns the topology, and distribution of input vectors and is used to orient more neurons to recognize parts of the input space where more input vectors happen and orient fewer neurons to parts of the input space where few input vectors appear. It detects regularities and correlations in their input and adapts itself for the future. SOFM has smoother transition of output vectors than that obtained with competitive layers because SOFM learning algorithm allows neurons that are neighbors to the winning neuron to be output values. SOFM reduces dimensionality and displays similarities but it takes a long time for the map to finally arrange itself.

3.3.4.2.3 Radial Basis Function Network [121, 126]

The Radial Basis Function (RBF) network is one of the most popular network models used in practical applications. It consists of a three layer feed forward network (input layer, hidden layer and output layer). It uses a linear transfer function for the output units and a nonlinear transfer function (normally Gaussian) for the hidden layer neurons. Radial basis networks require more neurons than standard feed forward back propagation networks, but it is characterized by its lesser time. In RBF the weights of the hidden layer basis units are set using some clustering technique. The output of the RBF has a maximum value of one if the input is zero and this means that the neuron produces one or near one when the input is identical to the weight vector and the distance between them is very small. When the input data moves away from the connection weights, the activation value is reduced. The output of the RBF has zero or near zero value when the input is far from the weight vector and the distance between them is large.

3.3.4.2.4 Recurrent Neural Networks [121, 125]

Recurrent networks are used in nonlinear time series forecasting, system identification, and pattern classification. The response of the network is dynamic and the output of the network at time *t* is used with a new input to help in calculating the output of the network at time *t* + 1. A simple recurrent neural network can be constructed by adding a context layer to the multilayered feed forward network. At each step, the inputs are fed to the network, passed into the context layer, and then fed back into the hidden layer in the next time step. At the beginning, the context layer has nothing. Weights are calculated in the same way as the previous step

3.3.4.3 Neural Networks for Classification [127, 128]

This section discusses classification in neural networks (the link between neural and traditional classifiers, learning and generalization, variable selection, and the misclassification cost effects). Conventional statistical classifications are limited because they work well only when the underlying assumptions are satisfied and so one must have good knowledge of both data properties and model capabilities. In contrast, neural network classification can self-adjust to the data without any explicit specification of functional or distributional form for the underlying model with arbitrary accuracy because of the universal functional approximation properties. They are nonlinear models, which makes them flexible in modeling real world complex relationships, and they are able to estimate a-posteriori probabilities which provides the basis for statistical analysis and classification.

3.3.4.3.1 Bayesian Classification Theory [127]

This theory is the basis of statistical classification; and it gives the fundamental probability model for statistical discriminate analysis but two problems arise in its application. (1) In most practical situations, the density functions are not known or cannot be assumed, consequently the a-posteriori probabilities cannot be determined directly. (2) The decision goal is simply to minimize the probability of misclassifying a new object. Interpretation of network outputs allows outputs from multiple networks to be combined for higher level decision making, which simplifies creating rejection thresholds, and makes it possible to compensate for the difference between pattern class probabilities in training and test data, allows the output to be used to minimize alternative risk functions.

3.3.4.3.2 Posteriori Probability Estimation [128]

In the classification problem, the desired output ***y*** is a vector of binary values and is the j^{th} basis vector $e_j = (0,\ldots,0,1,0,\ldots,)^t$. Hence the j^{th} element of F(x) is given by

$$F(x) = E[y_j/x] = 1 \,.\, P(y_j = 1 / x\,) + 0.P(y_j = 0 / x\,)= P(y_j = 1 / x\,)= P(W_j / x\,)$$

There is a local minima problem, suboptimal architecture and finite sample data in neural network training and so the mapping function is not perfect. Theoretically in order to get satisfactory approximations one needs large data, but empirically, it is found that sample size is critical in learning. The outputs of neural networks are also valid for other types of error function such as the cross entropy function which can be a more appropriate criterion than squared error cost because of their binary output characteristic, improved performance and reduced training time.

3.3.4.3.3 Neural Networks and Conventional Classifiers [121,127]

It was found that under some quite general conditions the hidden layers of an MLP project the input data into different clusters in a way that these clusters can be further aggregated into different classes. For linear MLPs, the projection performed by the hidden layer is shown to be theoretically equivalent to the linear discriminate analysis. The nonlinear MLPs, on the other hand, have demonstrated through experiments the capability in performing more powerful nonlinear discriminate analysis. It was shown that during the adaptive training process of Single Layer Perceptron (SLP), by purposefully controlling the SLP classifier complexity through adjusting the target values, learning-steps, and number of iterations and using regularization terms, the decision boundaries of SLP classifiers are equivalent or close to those of seven statistical classifiers. These statistical classifiers include the Enclidean distance classifier, the Fisher linear discriminate function, the Fisher linear discriminate function with pseudo-inversion of the covariance matrix, the generalized Fisher linear discriminate function, the regularized linear discriminate analysis, the minimum empirical error classifier, and the maximum margin classifier. Logistic regression is another important classification tool. It is a standard statistical approach used in medical diagnosis and epidemiologic studies. Logistic regression is often preferred over discriminate analysis in practice. Another connection is that the maximum likelihood function of logistic regression is essentially the cross-entropy cost function which is often used in training neural network classifiers. It was found that the added modeling flexibility of neural networks due to hidden layers does not automatically guarantee their superiority over logistic regression because of the possible overfitting and other inherent problems with neural networks. Links between neural and other conventional classifiers have been illustrated

3.3.4.3.4 Learning and Generalization [121, 127]

Learning is the ability to approximate the underlying behavior adaptively from the training data, while generalization is the ability to predict well beyond the training data. Powerful data fitting or the function approximation capability of neural networks also make them susceptible to the overfitting problem. Complex flexible models such as neural networks tend to overfit the data and cause the model unstable when extrapolating.

3.3.4.3.5 Bias and Variance [127,128]

A pre-specified model which is less dependent on the data may misrepresent the true functional relationship and have a large bias. On the other hand, a model-free or data-driven model may be too dependent on the specific data and have a large variance. Bias and variance are often incompatible. A good tradeoff between model bias and model variance is necessary and desired in building a useful neural network classifier $Y=F(x) +\varepsilon$. Given a particular training data set D_N of size N
$MSE = E[(y-f(x; D_N))^2]$

the overall prediction error of the model can be written as

$$E[(y-F(x))^2] + E[(f(x;D_N) - F(x))^2] \,,\; E[(y-F(x))^2] = E[(\varepsilon)^2],$$

$$E_D[(f(x;D) - E(y/x))^2] = E_D[(f(x;D) - E(y/x))]^2 + E_D[(f(x;D) - E_D(f(x;D)))^2]$$

Where E_D denotes the expectation over all possible random samples of sample size N. The first term on the right hand side is the square of the bias and is for simplicity called model bias while the second one is termed as model variance. The model bias measures the extent to which the average of the estimation function over all possible data sets with the same size differs from the desired function. The model variance, on the other hand, measures the sensitivity of the estimation function to the training data set. Although it is desirable to have both low bias and low variance, we cannot reduce both at the same time for a given data set because these goals are conflicting. A model that is less dependent on the data tends to have low variance but high bias if the model is incorrect. On the other hand, a model that fits the data well tends to have low bias but high variance when applied to different data sets.

3.3.4.3.6 Methods for Reducing Prediction Error

Neural networks often tend to fit the training data very well and thus have low bias. But the potential risk is overfitting which causes high variance in the generalization. A majority of effort has been devoted to developing methods to reduce the overfitting effect. Such methods include cross validation, training with penalty terms, and weight decay and node pruning [121].

Dietterich observed that improving the optimization algorithms in training does not have a positive effect on the testing performance and hence the overfitting effect may be reduced by “undercomputing.” He proposed a global smoothing training strategy by imposing monotonic constraints on network training, which seems to be effective in solving classification problems. There are many different ways of combining individual classifiers. The most popular approach to combining multiple classifiers is via simple average of outputs from individual classifiers. Wolpert proposes to use two (or more) levels of stacked networks to improve generalization performance of neural network classifiers. The first level networks include a variety of neural models trained with leave-one-out cross validation samples. The outputs from these networks are then used as inputs to the second level of networks that provide smoothed transformation into the predicted output [126-129].

The error reduction of the ensemble method is mainly due to the reduction of the model variance rather than the model bias. It has been observed that it is generally more desirable to have an error rate estimator with small variance than an unbiased one with large variance. Empirically a number of studies found that the prediction error reduction of the ensemble method is mostly accounted for by the reduction in variance. Those ensemble classifiers can perform better the if individual classifiers considerably disagree with each other [126-128].

3.3.4.3.7 Feature Variable Selection

The most important thing in the selection is to find a small amount of data that gives satisfactory performance. There are a lot of methods for the feature variable selection. PCA is the most used method. One problem with PCA is that this method is an unsupervised learning procedure and does not consider the correlation between target outputs and input features and, is a linear dimension reduction technique. It is not appropriate for complex problems with nonlinear correlation structures.

Neural networks are able to perform certain nonlinear PCA. Battiti proposes to use mutual information as the guide to evaluate each feature’s information content and select features with high information content. Several saliency measures of input variables explicitly consider both input, hidden weights and their interactions on the network output. For example, a pseudo weight is the sum of the product of weights from the input node to the hidden nodes and corresponding weights from the hidden nodes to the output node [130] .

An important saliency measure is proposed by Garson who partitions the hidden layer weights into components associated with each input node and then the percentage of all hidden nodes weights attributable to a particular input node is used to measure the importance of that input variable [131]. Glorfeld presents a backward elimination procedure to select more predictive feature variables, depending on Garson's measure of saliency [132]. Belue and Bauer propose a confidence interval method to select salient features. A confidence interval on the average saliency is constructed to discriminate between whether a feature has significant contribution to the classification ability weight elimination [133].

Prunings are techniques often used to remove unnecessary linking weights or input nodes during the network training. One of the earlier methods is the optimal brain damage (OBD). OBD is a technique used to remove weights without significantly lowering classification performance to improve the network performance. It is depending on reducing the network complexity by pruning to improve generalization by removing unwanted weights from the network by freezing them (setting them to 0). With this approach, a saliency measure is calculated for each weight based on a simplified diagonal Hessian matrix. Then the weights with the lowest saliency can be eliminated [127]. Mozer and Smolensky describe a node pruning method based on a saliency measure that is the difference of the error between when the node is removed and when the node is present. Selection with neural networks is heuristic in nature and lack rigorous statistical tests to justify the removal or addition of features [134].

3.4 PROPOSED FORECASTING NEURAL NETWORK CONSTRUCTION

The neural network consists of one input layer which is fed the time index and one output which is the tidal speed magnitude or the tidal wave direction and one hidden layer. Each layer consists of a number of neurons. The weight matrices, the number of layers, neurons, epochs of training, inputs and the transfer functions affect the ANN performance. The back propagation algorithm which is used in this work is an efficient method for changing the weights in a feed forward network, with differential activation function units and supervised training, to learn a training set of input/output examples. It depends on gradient descent that adjusts the weights to reduce the system error. Figure (3.3) shows the structure of the proposed ANN system.

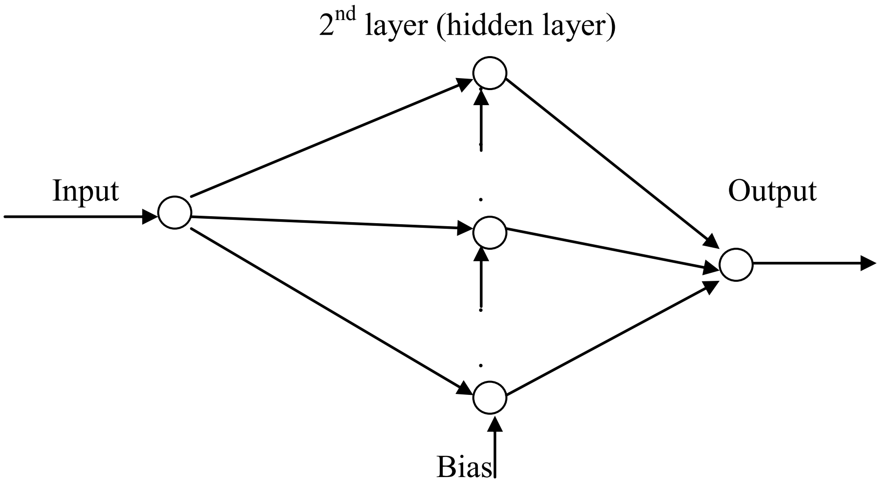


Figure (3.3) Neural network structure of the used model.

3.5 HYBRID MODEL OF ANN AND FLSM

This model consists of the tidal currents prediction using the FLSM at the first step and then find the error between the exact and the predicted data. This error is called innovations (Residuals). Secondly we use these innovations (residuals) to feed the ANN model as an input. Finally, the full model is equal to the ANN model plus the FLSM model. The flowchart shown in figure(3.4) illustrates the overall steps that are used in the hybrid model of ANN and FLSM.

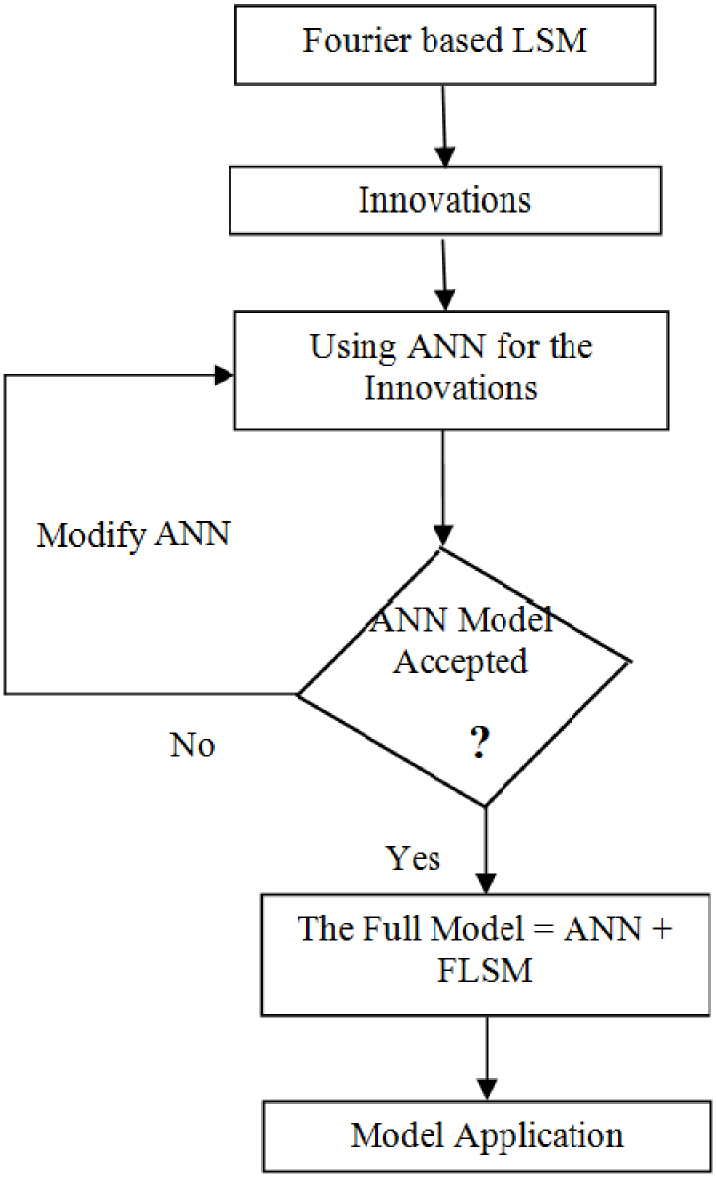


Figure (3.4) Hybrid model flowchart

The data that we used in this work is a field-collected (commercial) data subject to non-disclosure so we used it after multiplying by a factor and shifting. In the following sections we use the three models for the tidal current speed magnitude prediction then we will use them again for the tidal current direction prediction to improve the outcome of the proposed model. Three models are used in this work and we tried to compare between these models.

3.6 TIDAL CURRENT DATA IDENTIFICATION (TIDAL SPEED PREDICTIONS)

The forecasting error depends on the number of data points, and the time that the data taken as its shape will be different from time to time. We will use the percentage of error (P. E.) for comparing different proposed methods.

The percentage of error (P. E.) = $((Z_{\text{Actual}} - Z_{\text{Predicted}}) / Z_{\text{Actual}}) * 100$.

The input data for the model is the time index and the output is the tidal current speed magnitude. The time for the collected data used for training FLSM, ANN or the hybrid model is measured every ten minutes with end of time of 30,000 minutes from start time which is at 4:10 on 2/5/2008. The time for the data used for validating the model was measured also at each ten minutes after the end of the first time. This means that the time for the graphs of the validating data starts from the 3001*10 minutes which is after ten minutes from the end of the first graph (e.g. figure (3.5)) that used for the training data and this means that the time1 on the graph (e.g. figure (3.9)) for the validating data is equal to 3001*10 minutes.

3.6.1 Fourier Series Model based on Least Square Method (FLSM)

The FLSM model was discussed in section 3.3.3. In this section we apply the Fourier series based on the least square model for the tidal currents speed magnitude prediction.

Figure (3.5) shows the relation between the speed and the time of the tidal current for the actual data (70% of the whole data). The waveform of the tidal current appears to be similar to a sinusoidal wave that is super-imposed on some harmonics. Figure (3.6) shows the relation between the speed and the time of the tidal current for the forecasted data after using FLSM (70% of the whole data). From that figure we found that there is an error between the actual and the forecasted data and this error is shown in Figure (3.7). The percentage of that error is 0.6399%. We tried to draw the relation between the speed and the time for the actual and the forecasted data on the same graph as shown in figure (3.8). This proposed model is used for forecasting a new speed magnitude for the rest of the data (30% of the whole data that is used for validation) . This data was not used before for training the proposed model so we expect that the error will be high. The percentage of the error for the rest of the data (not trained data) is 0.817. Figure (3.9) shows the relation between speed and the time of the tidal current after using the FLSM for the exact(not trained) and the estimated data.

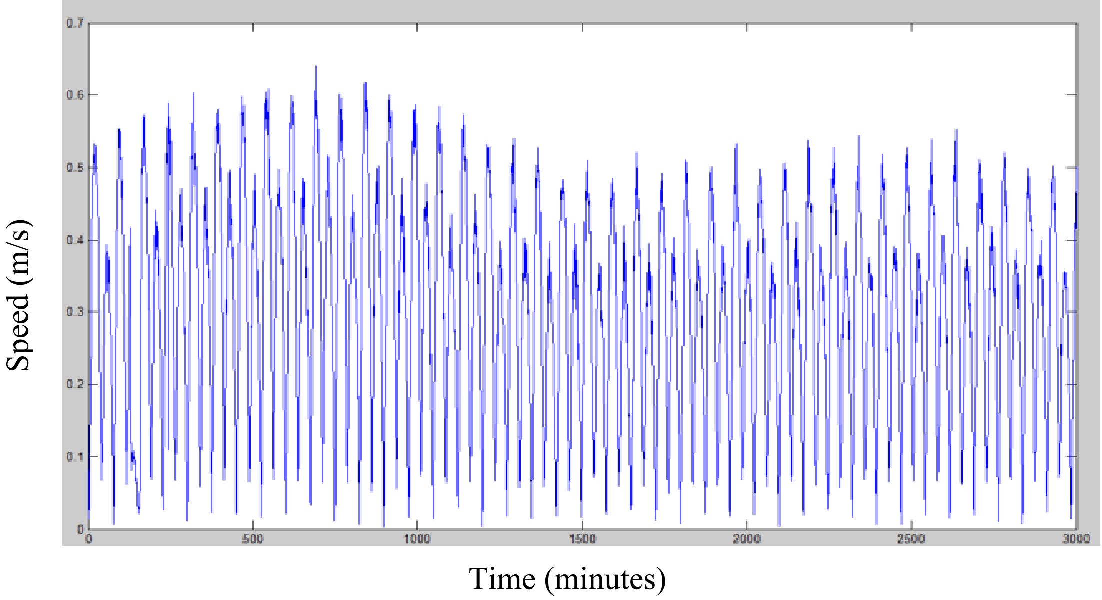


Figure (3.5) The relation between the speed and the time of the tidal current for the actual data (70% of the whole data).

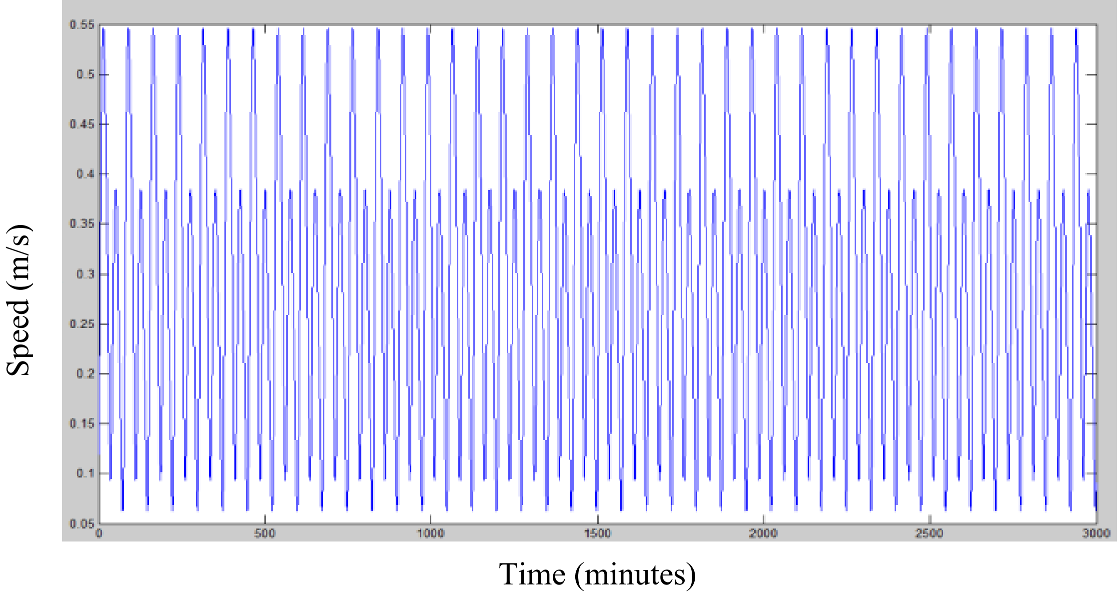


Figure (3.6) The relation between the speed and the time of the tidal current for the forecasted data using FLSM (70% of the whole data).

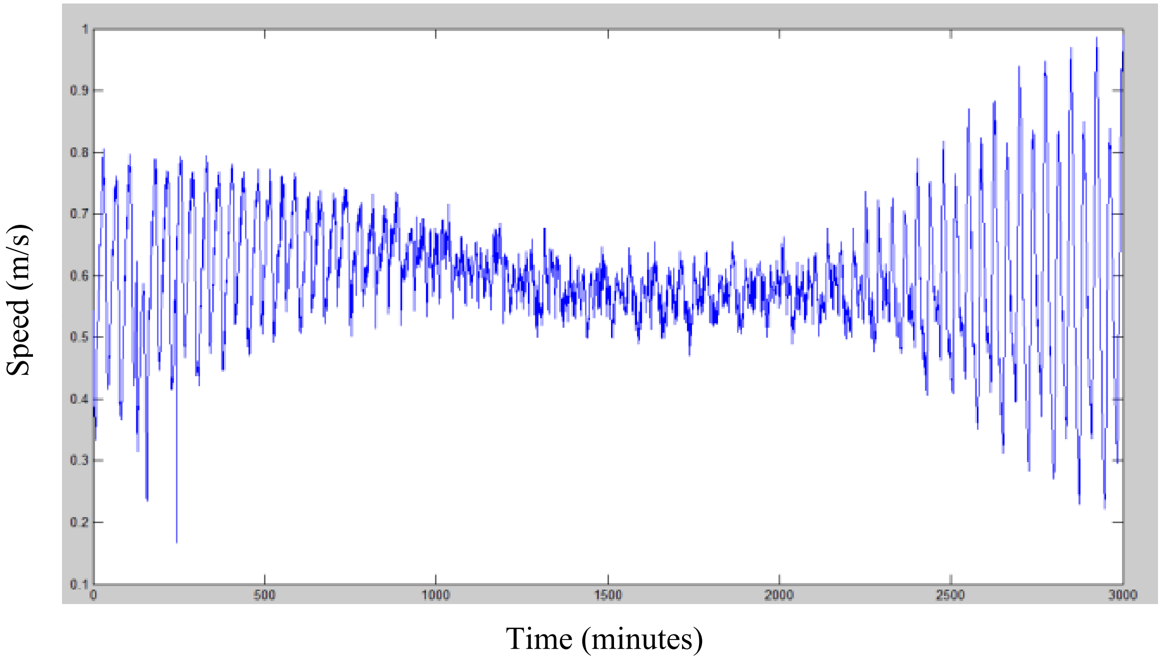


Figure (3.7) The relation between error in the speed (the actual minus the forecasted) for the tidal current and the time after using FLSM for the trained data.

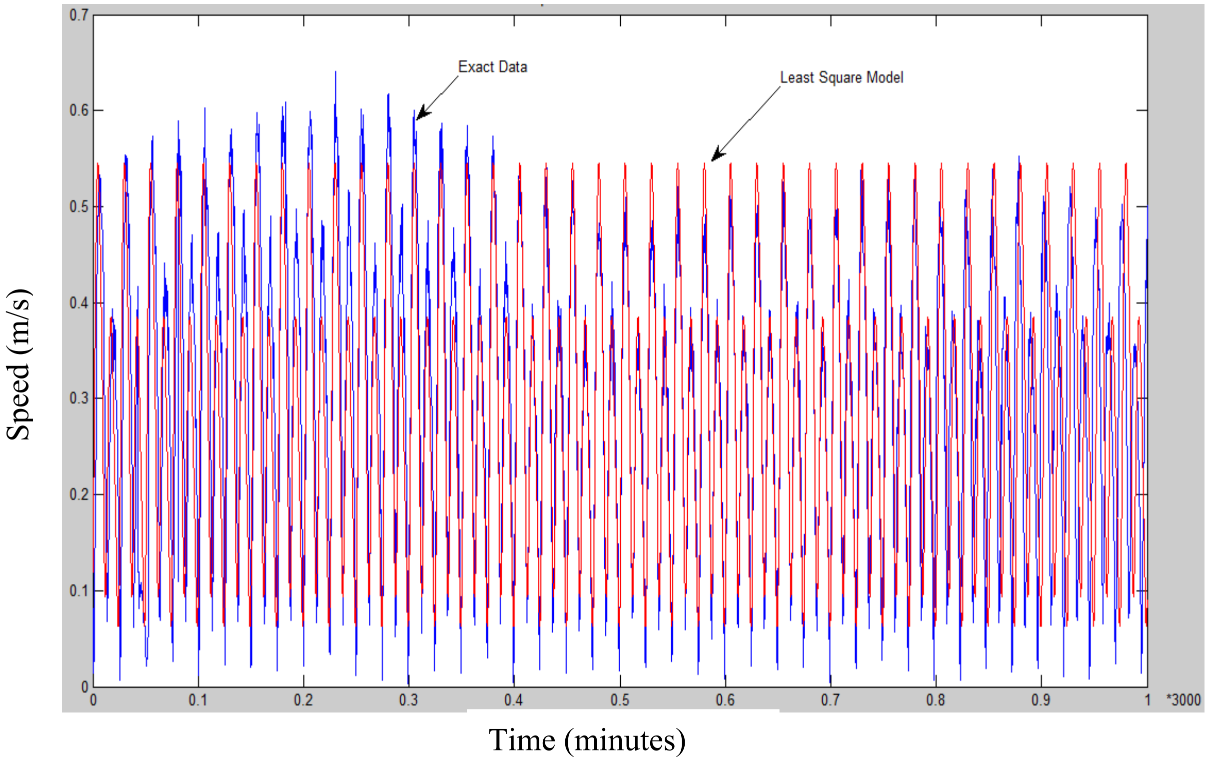


Figure (3.8) The relation between the speed and the time of the tidal current after using the FLSM for the exact trained and the estimated data.

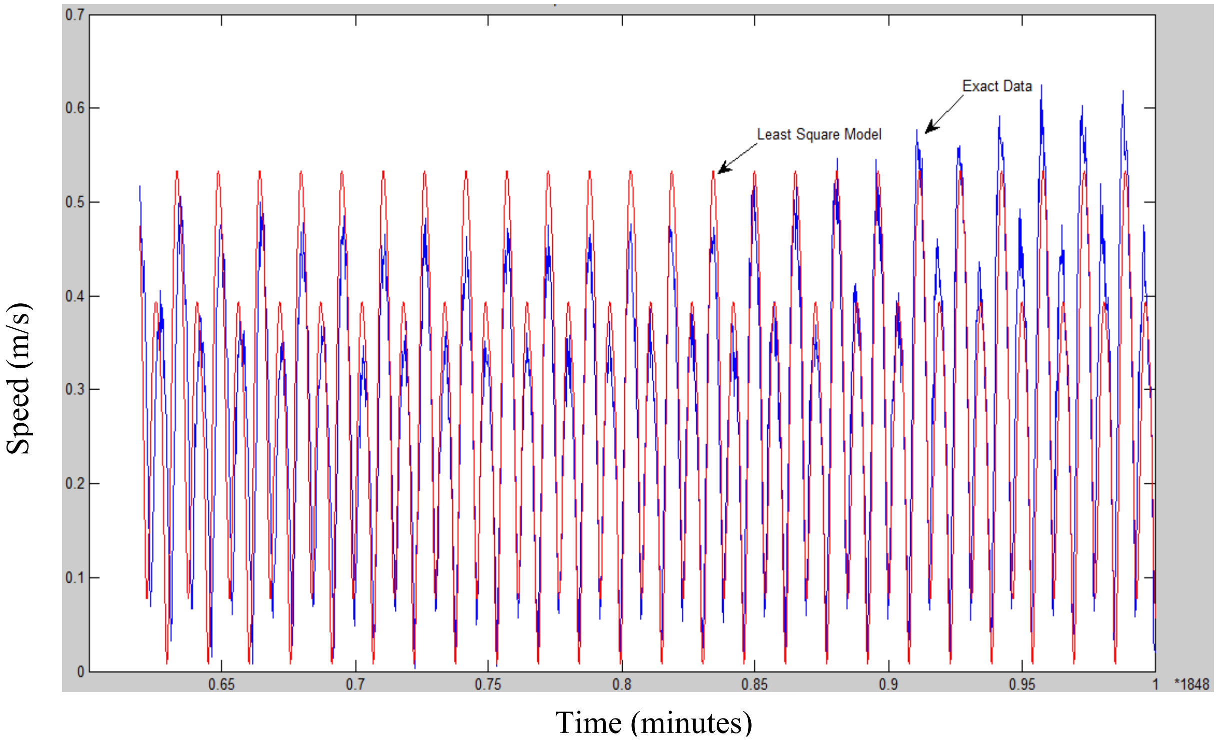


Figure (3.9) The relation between the speed and the time of the tidal current after using the FLSM for the exact (not trained) and the estimated data.

3.6.2 ANN Model

In this section we used the ANN for tidal currents speed prediction for the same data used in the previous section. We used the exact data (70% of the whole data)without modifications as an input to the ANN for trainng the model. After 20,000 epochs, 225 neurons in the first layer, the mean squared error became 0.000633. Figure (3.10) shows the relation between the speed and the time of the tidal current for the forecasted data (70% of the whole data) after using ANN. From that figure we found that there is an error between the actual and the forecasted data as shown in Figure (3.11). Figure (3.12) shows the regression line for the trainned speed data after using ANN. The R-value (the Coefficient of Determination for the regression line) from that figure is 0.99224 and this is a good indication for the forecasted model. We draw the relation between the speed and the time for the actual and the forecasted data on the same graph as shown in figure (3.13). The percentage of the error between the actual and the forecasted data is 0.3903%. The proposed model is used for forecasting a new speed magnitude for the rest of the data (30% of the whole data that is used for validation) . This data was not used before for training the proposed model so we expect that the error will be high. The percentage of the error for the rest of the data (not trained data) is 1.0946. Figure (3.14) shows the relation between the speed and the time of the tidal current after using the ANN for the exact(not trained) and the estimated data.

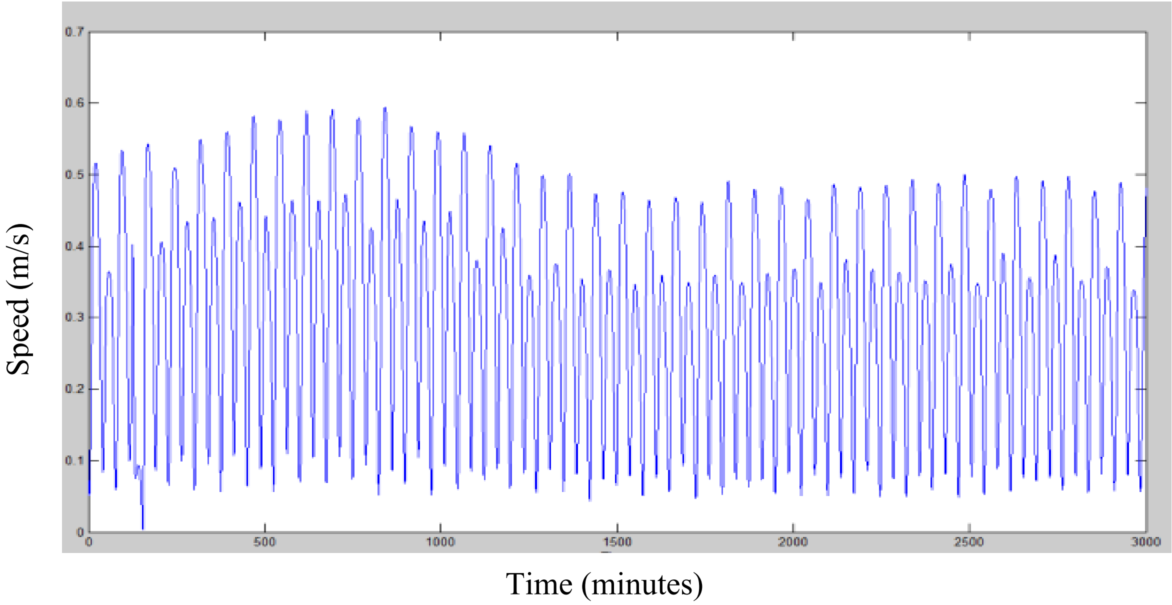


Figure (3.10) The relation between the speed and the time of the tidal current for the forecasted trained data using ANN (70% of the whole data).

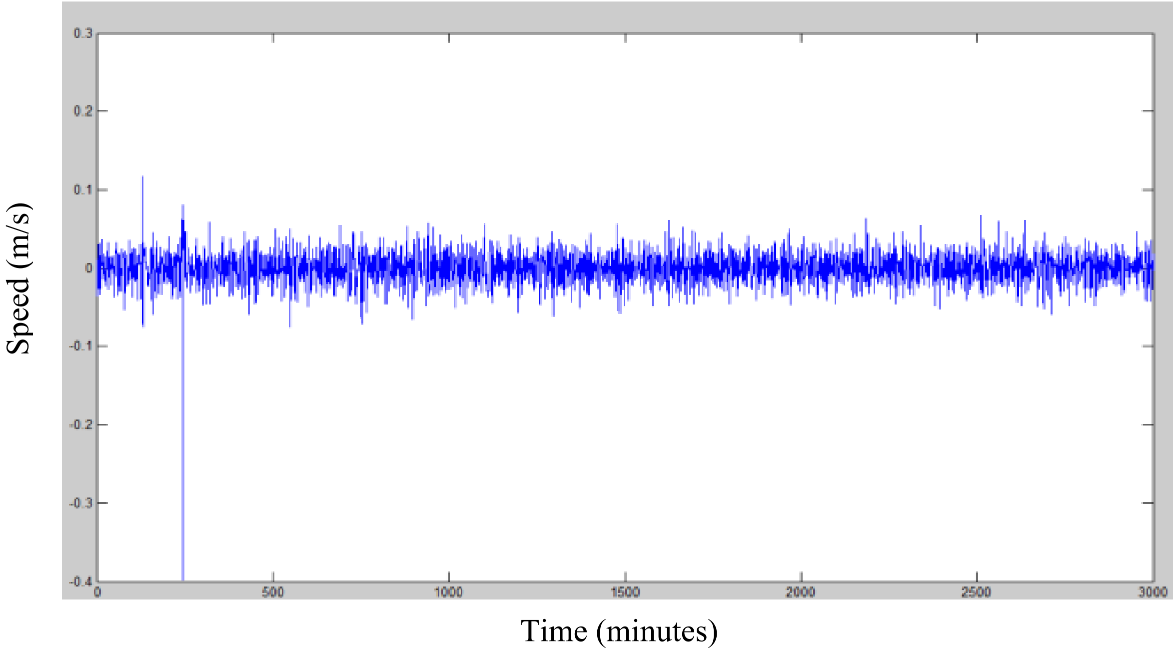


Figure (3.11) The relation between error (the actual minus the forecasted trained speed of the tidal currents) and the time after using ANN (70% of the whole data).

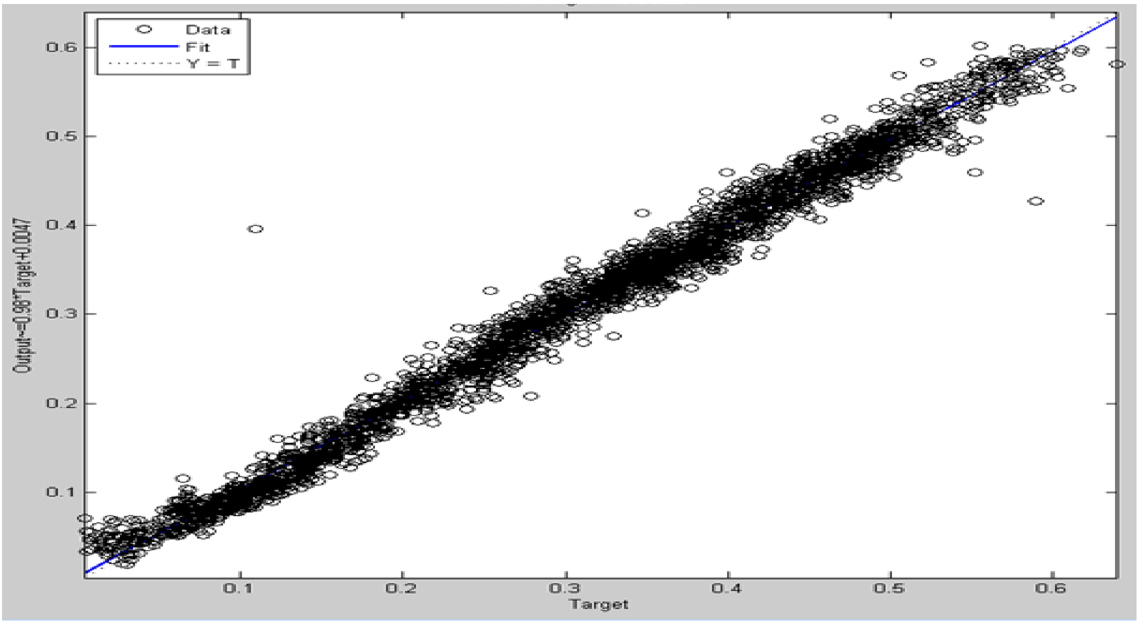


Figure (3.12) The regression line for the trained speed data after using ANN.

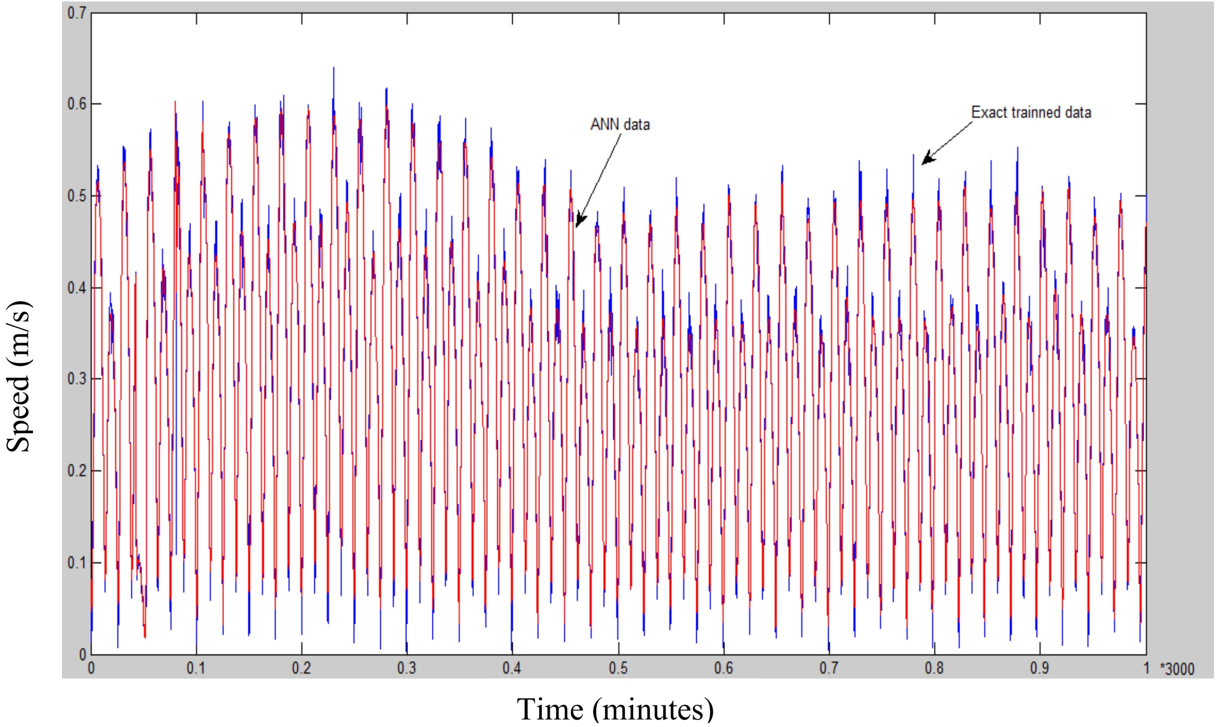


Figure (3.13) The relation between the speed and the time for the tidal currents after using the predicted ANN and the exact trained data.

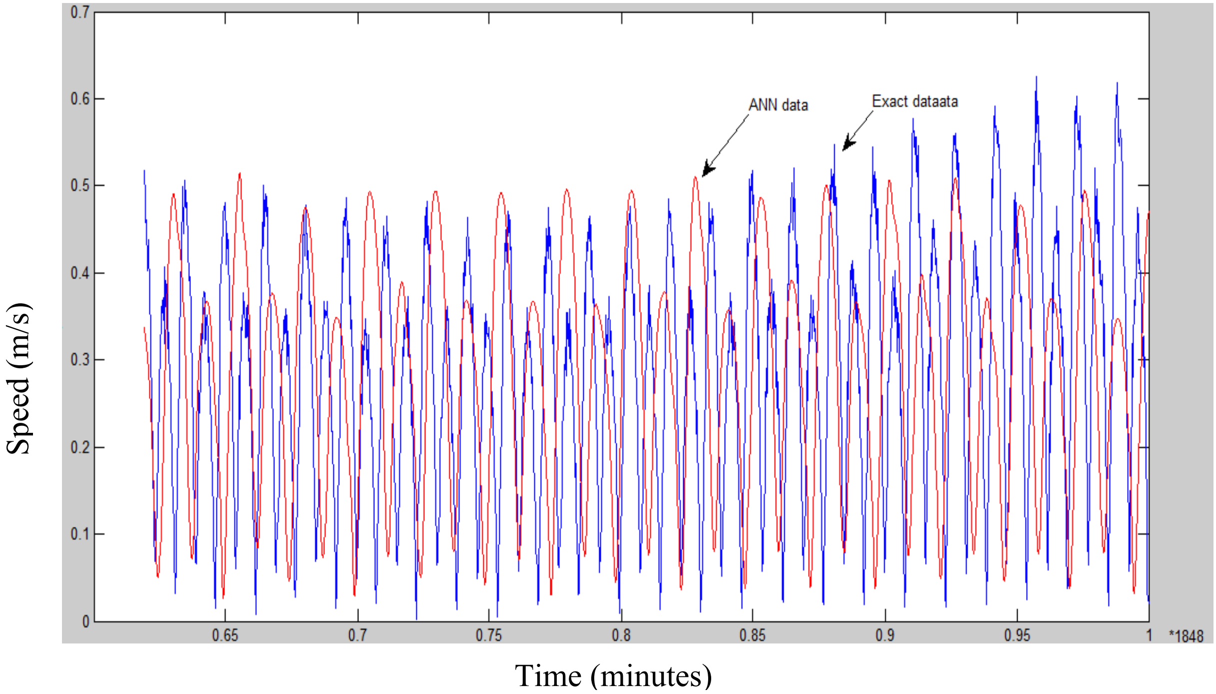


Figure (3.14) The relation between the speed and the time for the tidal currents after using the predicted ANN and the exact not trained data.

3.6.3 Hybrid model of ANN and Fourier Series based on LSM

The models used in the case of FLSM and ANN give a percentage of error for the predicted not trained data so we proposed a hybrid of ANN and FLSM. In the hybrid model we tried to find what we call the innovation data (Innovation data = Actual data – Forecasted data after using the FLSM) and then use this innovation as an input to the ANN that's why we called this proposed model as a hybrid model. We used 70% of the whole data for training the model and 30% for validating the data as did in the previous sections. After 20,000 epochs, 225 neurons in the hidden layer, the mean squared error for the innovation data became 0.000380. The percentage of error for the innovation of the trained data is 0.1304. Figure (3.15) shows the relation between the speed and the time of the tidal current for the forecasted data (70% of the whole data) after using the hymrid model. From that figure we found that there is a small error between the actual and the forecated data and this error is shown in Figure (3.16). Figure (3.17) shows the regression line for the trainned innovation data after using the hybrid model. The R-value (the Coefficient of Determination for the regression line) for the trained forecasted data is 0.999817 and this is a good indication for the forecasted model. We tried to draw the relation between the speed and the time for the actual and the forecasted data on same graph as shown in figure (3.18). The percentage of the error between the actual and the forecated data is 0.3328%. The proposed model is used for forecasting a new speed magnitude for the rest of the data (30% of the whole data that is used for validation) . This data was not used before for training the proposed model so we expect that the error will be high. The percentage of the error for the rest of the data (not trained data) is 0.4737. Figure (3.19) shows the relation between the speed and the time of the tidal current after using the hybrid model for the exact and the estimated data.

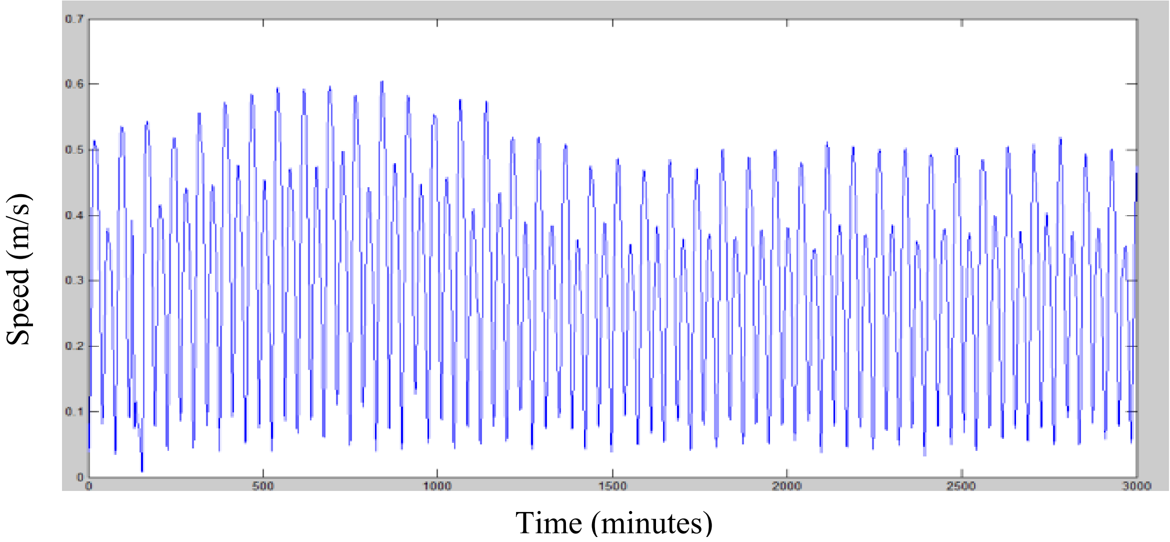


Figure (3.15) The relation between the speed and the time of the tidal currents for the forecasted trained data using the hybrid model.

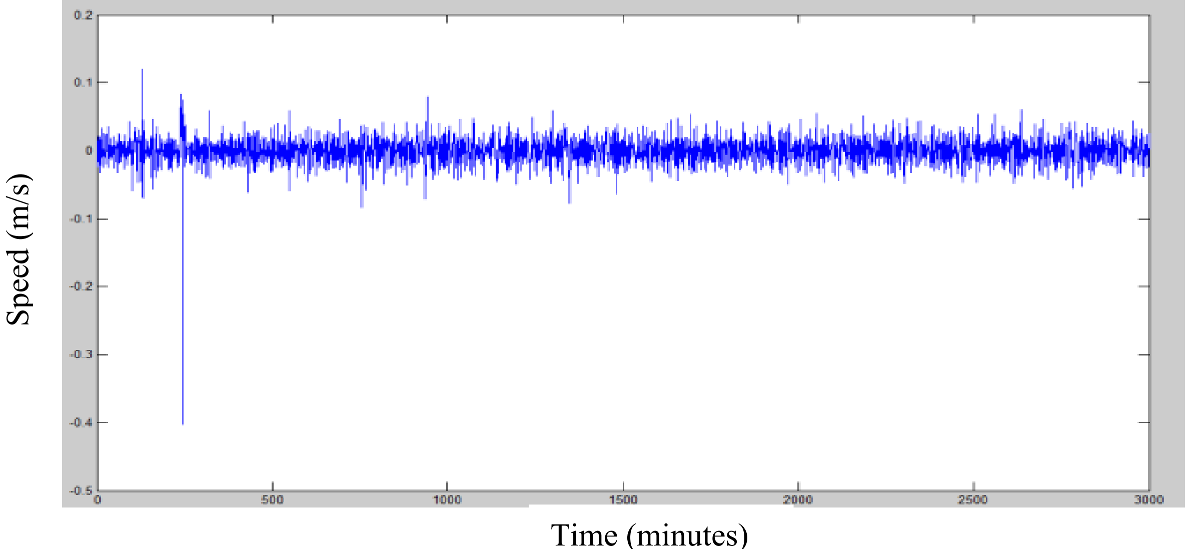


Figure (3.16) The relation between error (the actual minus the forecasted trained speed of the tidal currents) and the time after using the hybrid model.

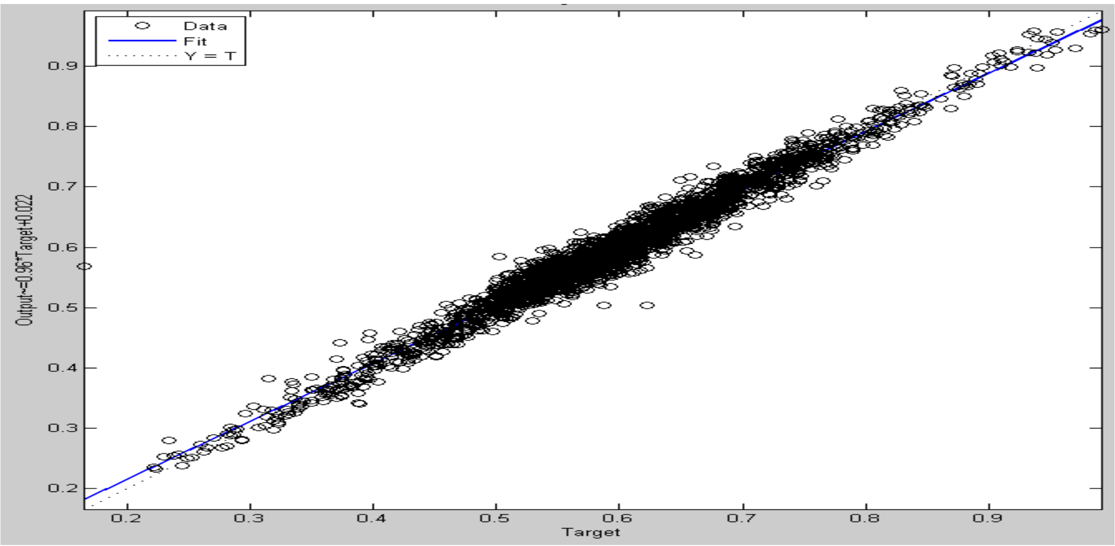


Figure (3.17) The regression line for the trainned innovation data for the hybrid model.

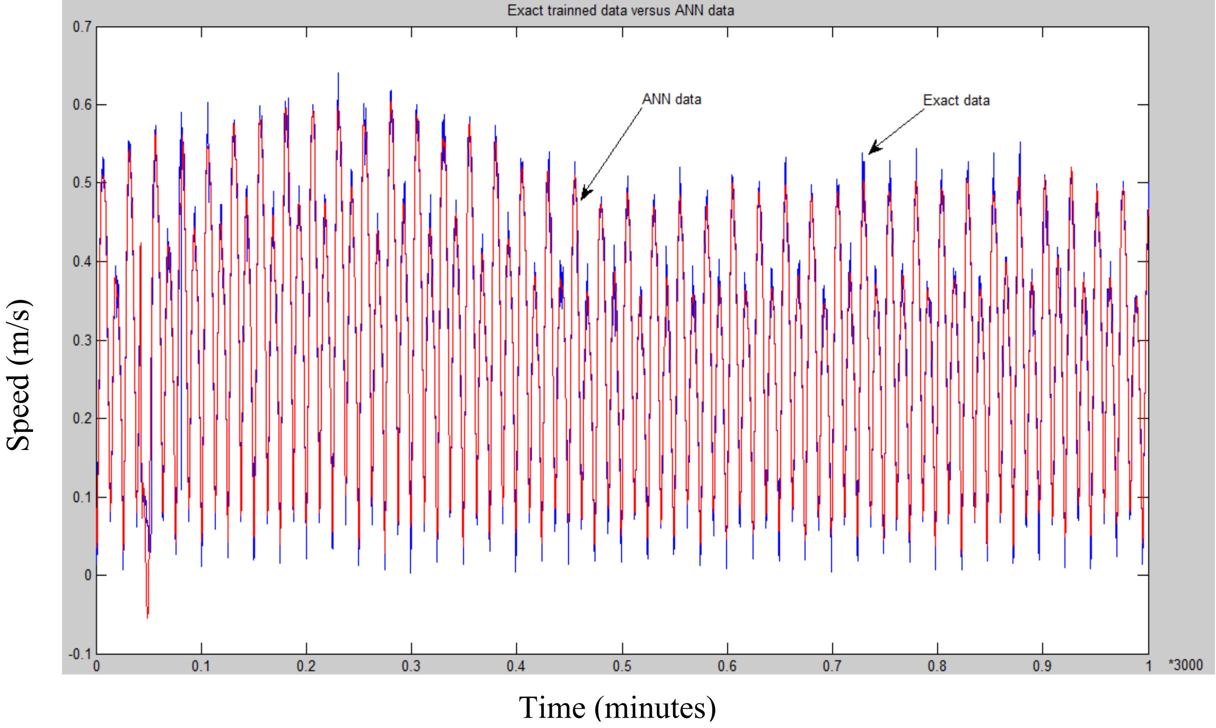


Figure (3.18) The relation between the speed and the time for the tidal currents after using the hybrid model and the exact trained data.

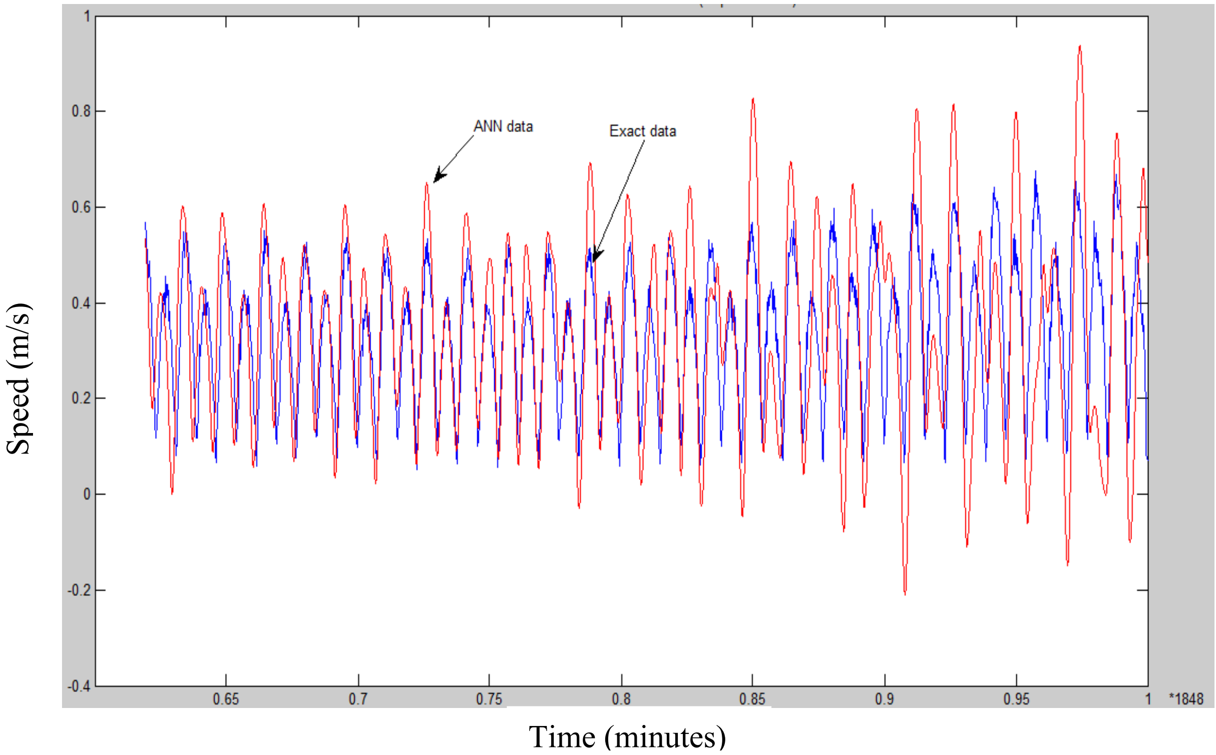


Figure (3.19) The relation between the speed and the time for the tidal currents after using the hybrid model and the exact not trained data.

Table (3.1) summarizes the preceding analysis. We found that the percentage error for the hybrid model is the smallest one in case of the trained or the predicted data, so it is better to use the hybrid model instead of using either ANN or FLSM alone. In the next section we will try to use the same methodology for the tidal current direction forecasting to prove the validity of the proposed model for another type of data.

Table (3.1) Comparison between different used models for speed prediction

Comparison between different models used			
Type of comparison	**FLSM**	**ANN**	**Hybrid**
% Error for the exact trained data (70% of the whole data)	0.6399	0.3903	***0.3328***
% Error for the predicted data (30% of the whole data)	0. 817	1.0946	***0.4737***

3.7 VALIDATION OF THE PROPOSED MODEL (TIDAL DIRECTION PREDICTIONS)

In this section we apply the proposed technique to the prediction of direction magnitude for the tidal currents. The data that we used in this work is a field-collected (commercial) data subject to non-disclosure so we used it after multiplying by a factor and shifting.

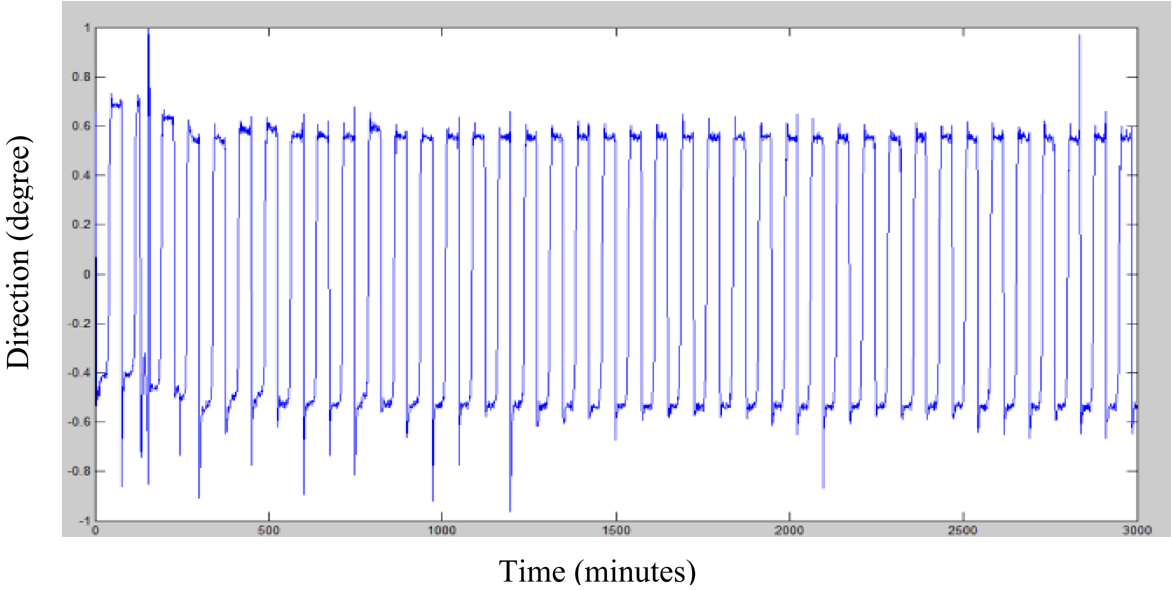


Figure (3.20) The relation between the direction and the time of the tidal currents for the actual data (70% of the whole data).

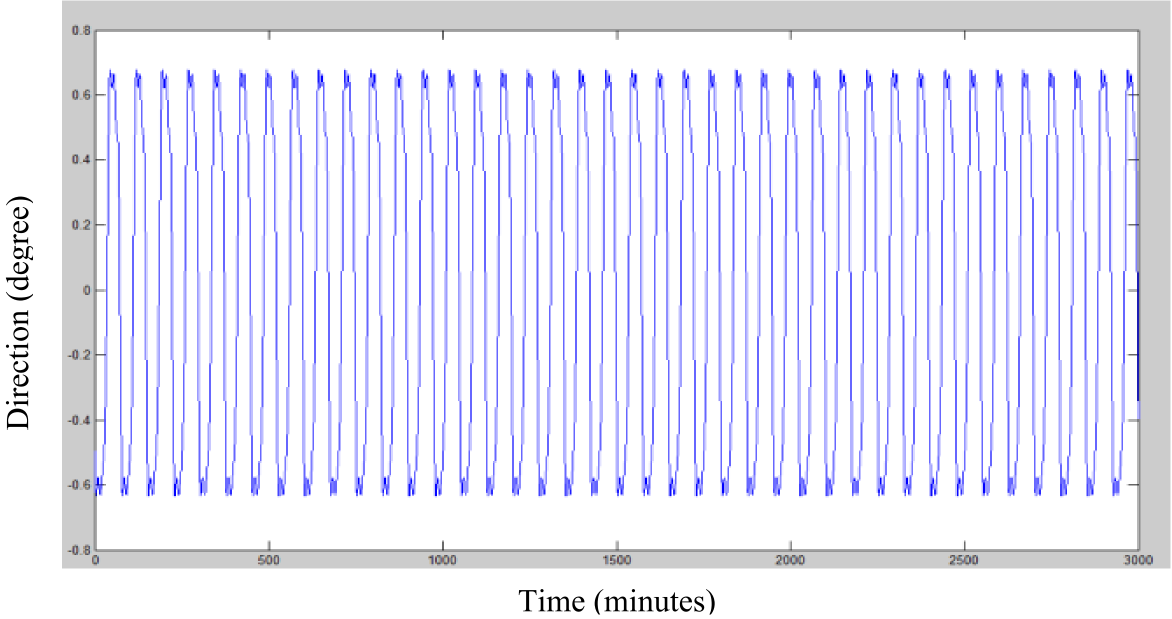


Figure (3.21) The relation between the direction and the time of the tidal currents for the forecasted data using FLSM (70% of the whole data).

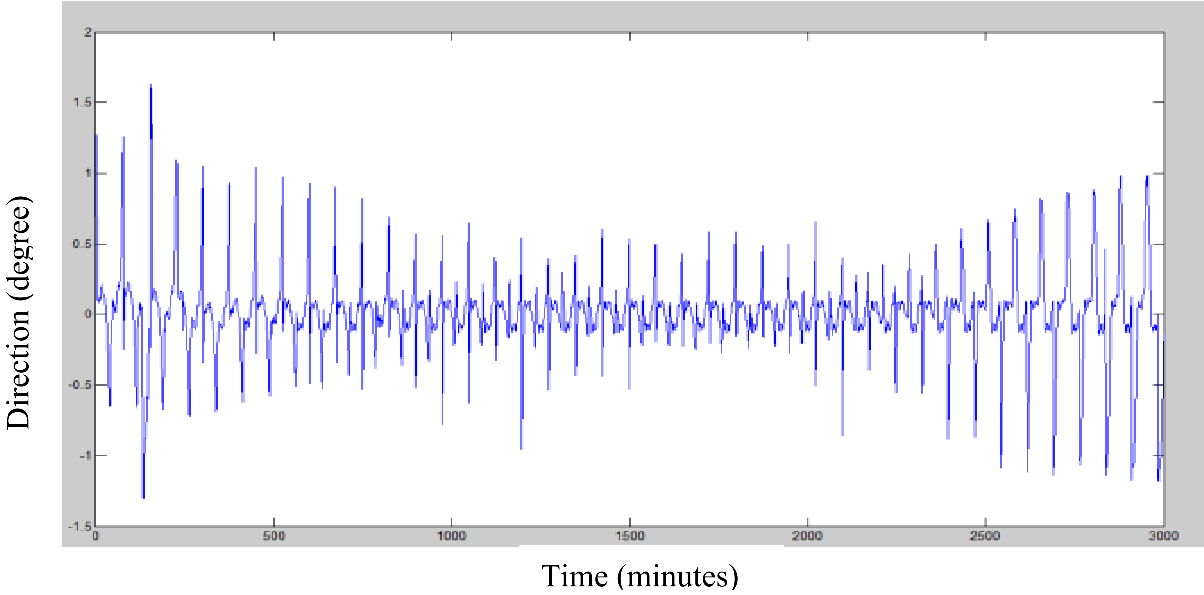


Figure (3.22) The relation between error (the actual minus the forecasted direction of the tidal currents) and the time after using FLSM (70% of the whole data).

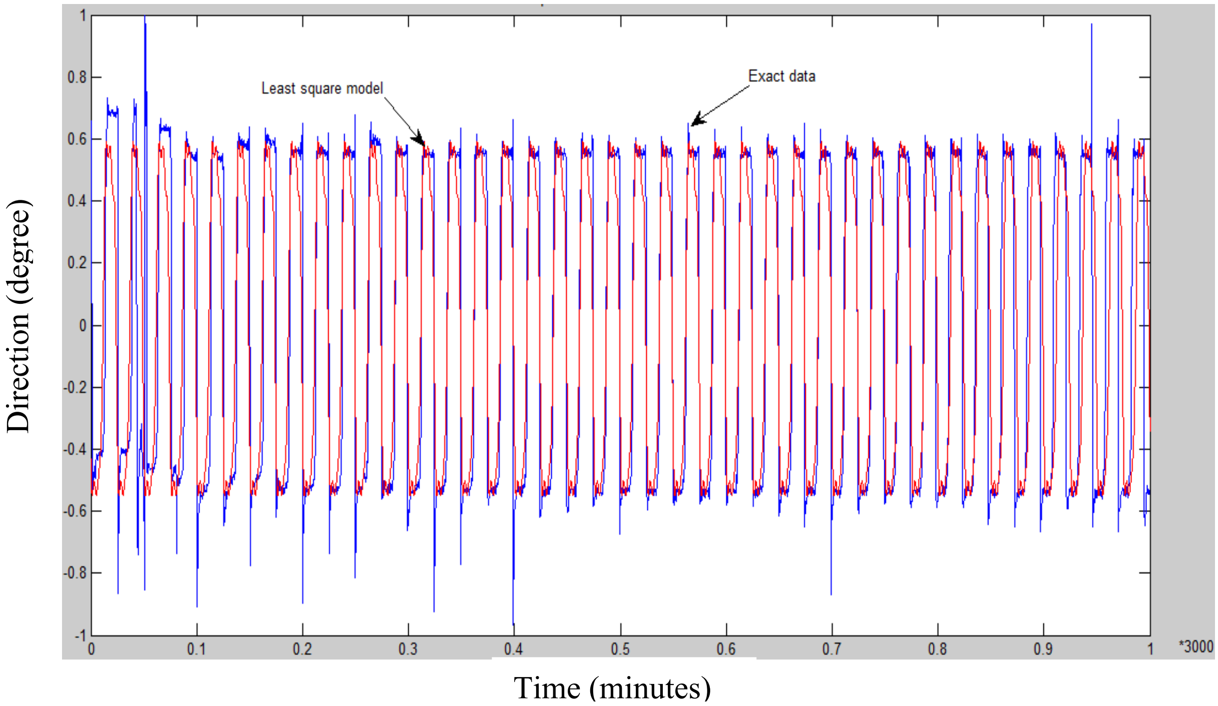


Figure (3.23) The relation between the direction and the time for the tidal currents after using the FLSM and the exact trained data.

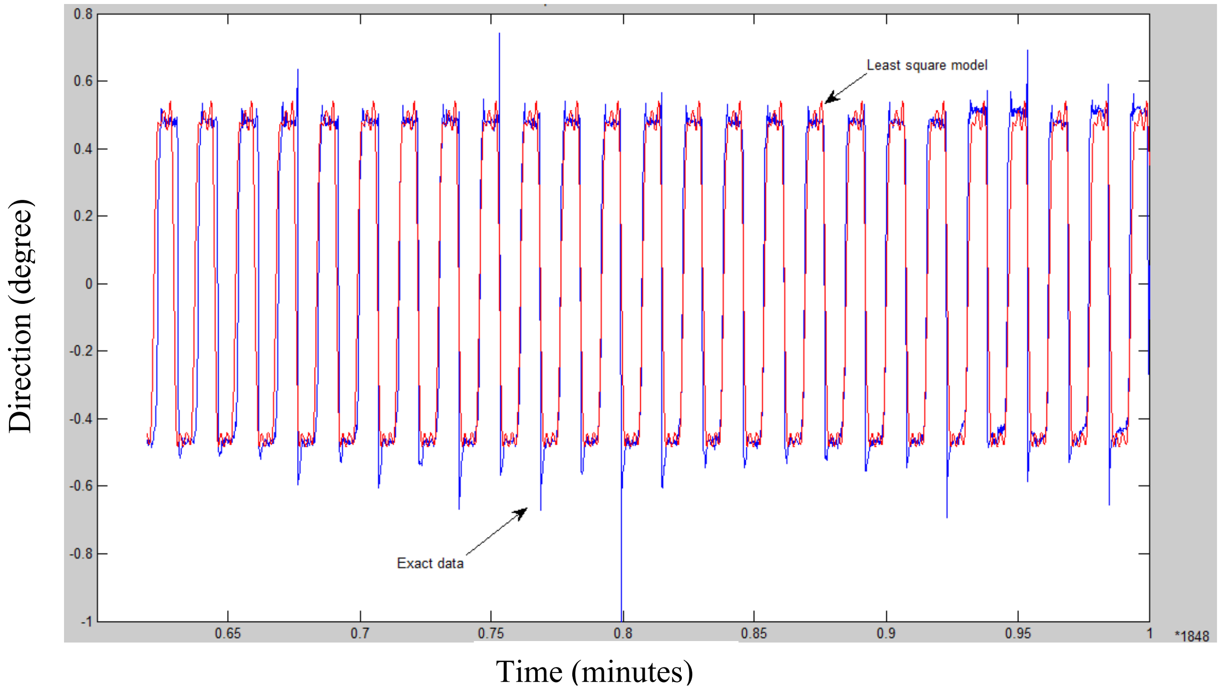


Figure (3.24) The relation between the direction and the time of the tidal currents after using the FLSM and the exact data not trained data.

3.7.1 Fourier Series Model based on Least Square Method for Tidal Current Direction

We used the FLSM model for the tidal direction forecasting for the same period and site that was used for the speed forecasting. Figure (3.20) shows the relation between the direction and the time of the tidal current for the actual data (70% of the whole data). The waveform of the tidal current looks like a sinusoidal wave that is imposed by some harmonics that why we proposed FLSM model to be used for the tidal current magnitude and direction forecasting. Figure (3.21) shows the relation between the direction and the time of the tidal current for the forecasted data after using FLSM (70% of the whole data). From that figure we found that there is an error between the actual and the forecasted data and this error is shown in Figure (3.22). The percentage of that error is 0.7339%. We tried to draw the relation between the direction and the time for the actual and the forecasted data on the same graph as shown in figure (3.23). This proposed model is used for forecasting a new direction magnitude for the rest of the data (30% of the whole data that is used for validation). This data wasn't used before for training the proposed model so we expect that the error will be high. The percentage of the error for the rest of the data (not trained data) is 0.917. Figure (3.24) shows the relation between the direction and the time of the tidal current after using the FLSM for the exact(not trained) and the estimated data.

3.7.2 ANN Model for Tidal Current Direction

In this section we used the ANN for tidal currents direction prediction for the same data used in the previous section. We used the exact data (70% of the whole data) without modifications as an input to the ANN for training the model. After 20,000 epochs, 225 neurons in the first layer, the mean squared error became 0.000379. Figure (3.25) shows the relation between the direction and the time of the tidal current for the forecasted data (70% of the whole data) after using ANN. From that figure we found that there is an error between the actual and the forecasted data and this error is shown in Figure (3.26). Figure (3.27) shows the regression line for the trained speed data after using ANN. The R-value (the Coefficient of Determination for the regression line) from that figure is 9960 and this is a good indication for the forecasted model.

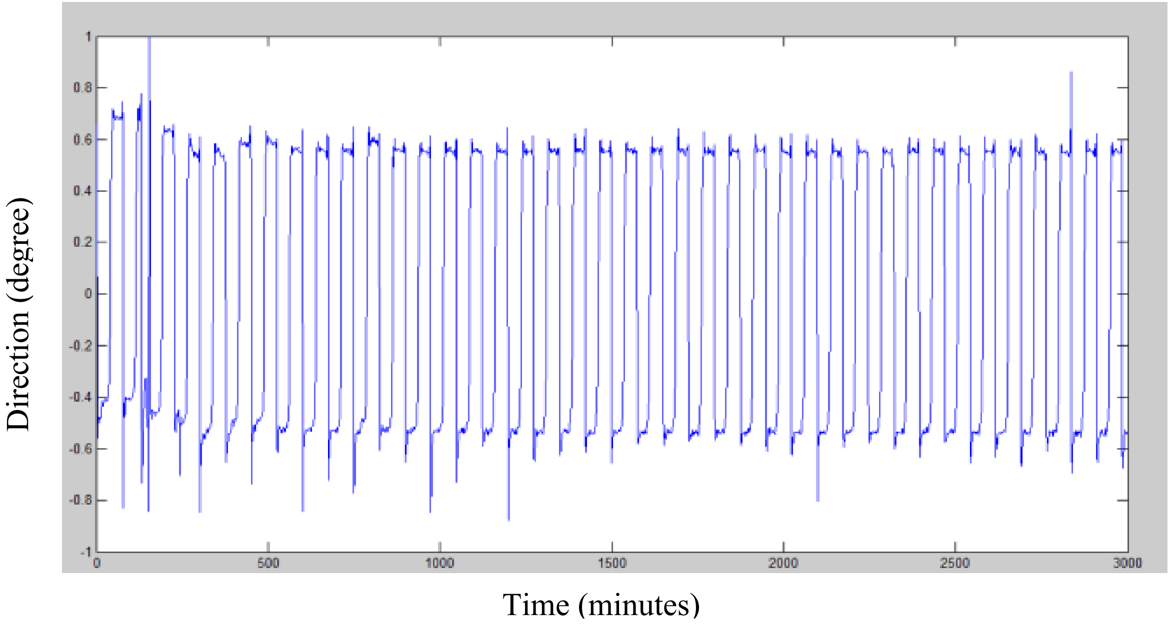


Figure (3.25) The relation between the direction and the time of the tidal currents for the forecasted trained data using ANN.

We tried to draw the relation between the speed and the time for the actual and the forecasted data on the same graph as shown in figure (3.28). The percentage of the error between the actual and the forecasted data is 0.3167%. The proposed model is used for forecasting a new speed magnitude for the rest of the data (30% of the whole data that is used for validation) . This data was not used before for training the proposed model so we expect that the error will be high. The percentage of the error for the rest of the data (not trained data) is 1.0896. Figure (3.29) shows the relation between the speed and the time of the tidal current after using the ANN for the exact (not trained) and the estimated data.

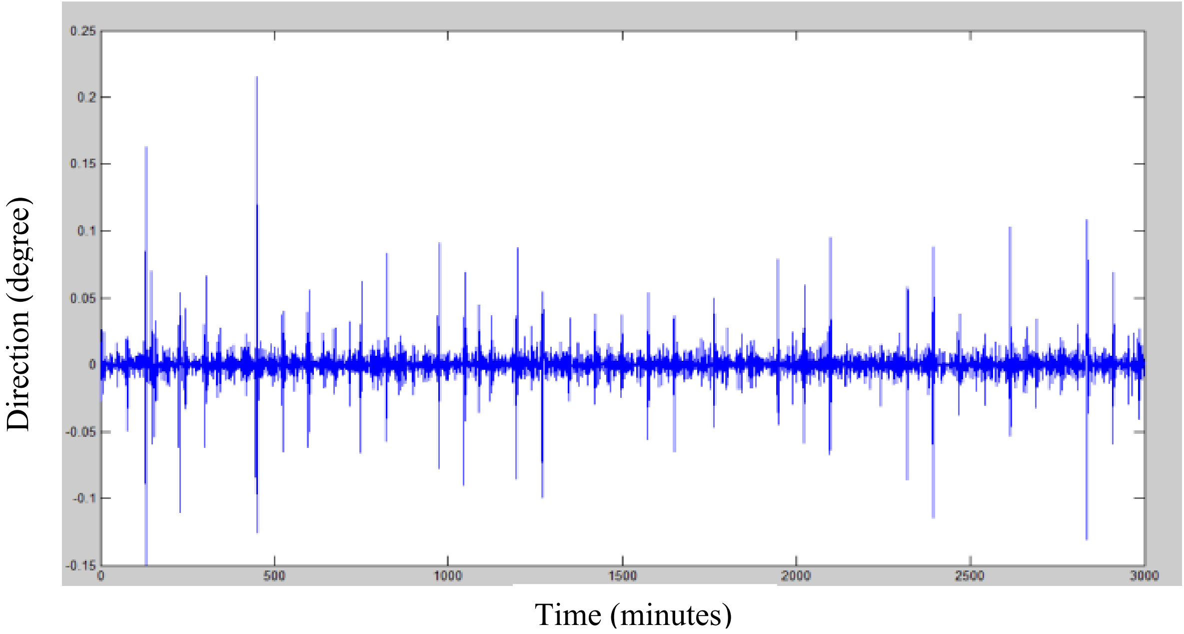


Figure (3.26) The relation between error (the actual minus the forecasted trained direction of the tidal currents) and the time after using ANN.

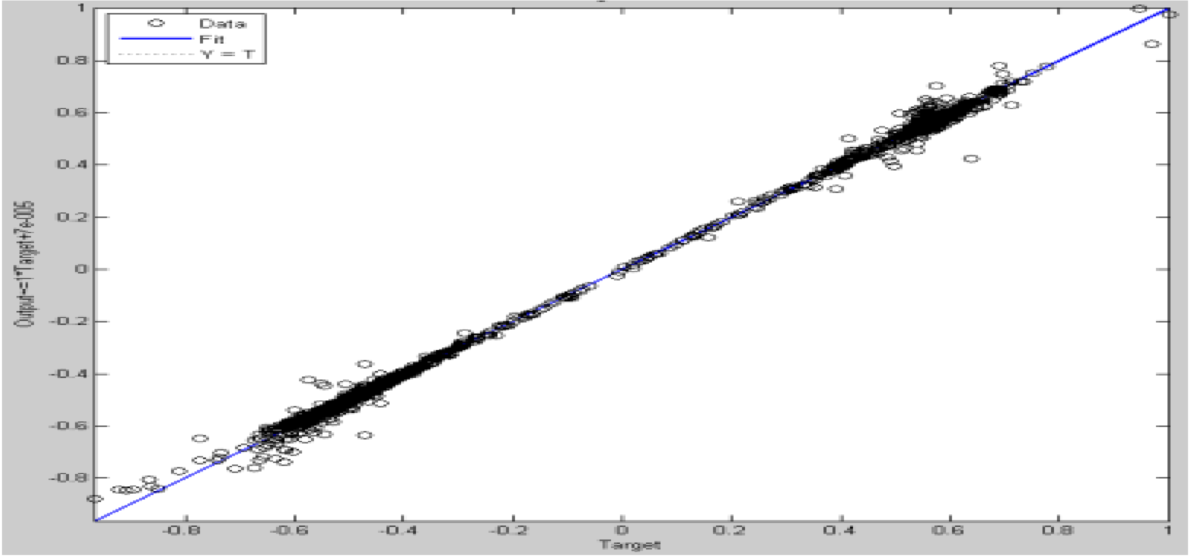


Figure (3.27) The regression line for the trained direction data after using the ANN.

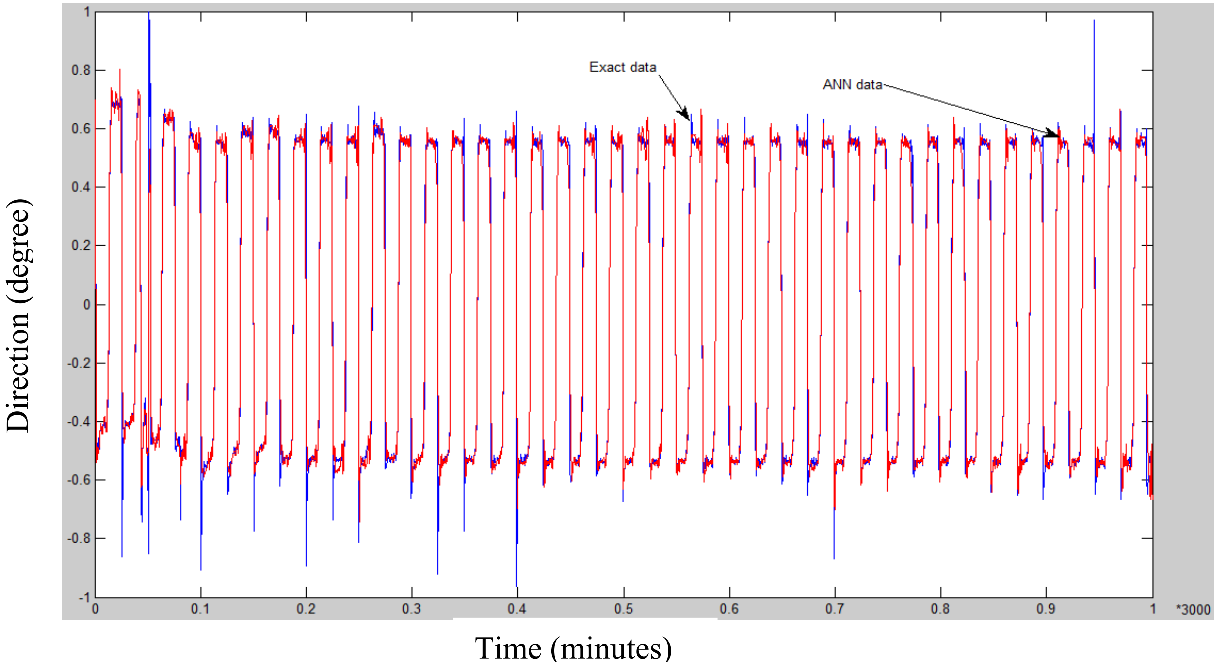


Figure (3.28) The relation between the direction and the time for the tidal currents after using the predicted ANN data and the exact trained data.

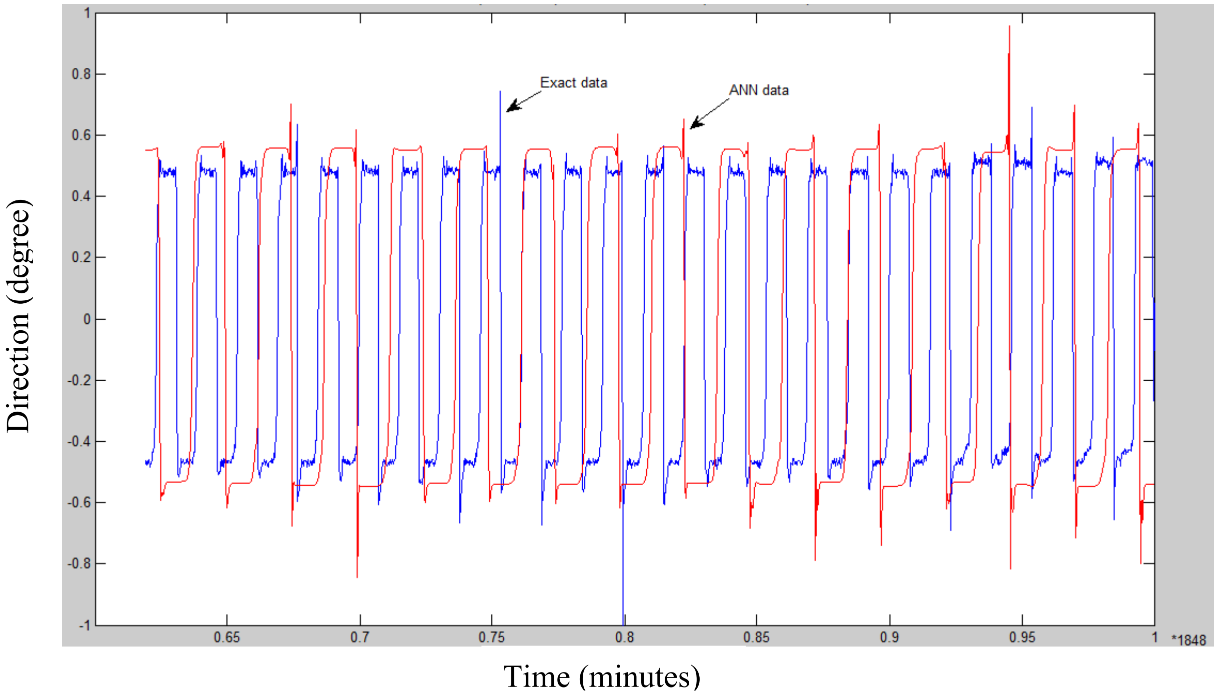


Figure (3.29) The relation between the direction and the time for the tidal currents after using the predicted ANN data and the exact not trained data.

3.7.3 Hybrid model of ANN and Fourier series based on LSM for Tidal Current Direction

In the hybrid model as we discussed before we find the innovation data (Innovation data = Actual data – Forecasted data after using the FLSM) and then use this innovation as an input to the ANN that's why we called this proposed model as a hybrid model. We used 70% of the whole data for training the model and 30% for validating the data as did in the previous sections. After 20,000 epochs, 225 neurons in the hidden layer, the mean squared error for the innovation data became 0.000579. The percentage of error for the innovation of the trained data is 0.1304. Figure (3.30) shows the relation between the direction and the time of the tidal current for the forecasted data (70% of the whole data) after using the hybrid model. From that figure we found that there is a small error between the actual and the forecasted data and this error is shown in Figure (3.31). Figure (3.32) shows the regression line for the trained innovation data after using the hybrid model. The R-value (the Coefficient of Determination for the regression line) for the trained forecasted data is 0.9974 and this is a good indication of the forecasted model. We tried to draw the relation between the direction magnitude and the time for the actual and the forecasted data on the same graph as shown in figure (3.33). The percentage of the error between the actual and the forecasted data is 0.316728%. The proposed model is used for forecasting a new direction magnitude for the rest of the data (30% of the whole data that is used for validation) . This data was not used before for training the proposed model so we expect that the error will be high. The percentage of the error for the rest of the data (not trained data) is 0.4970. Figure (3.34) shows the relation between the speed and the time of the tidal current after using the hybrid model for the exact(not trained) and the estimated data.

Table (3.2) summarized the previous analysis. We found that the percentage of error for the hybrid model is the smallest one in case of the trained or the predicted data, so as we said before, it is better to use the hybrid model instead of using either ANN or FLSM alone.

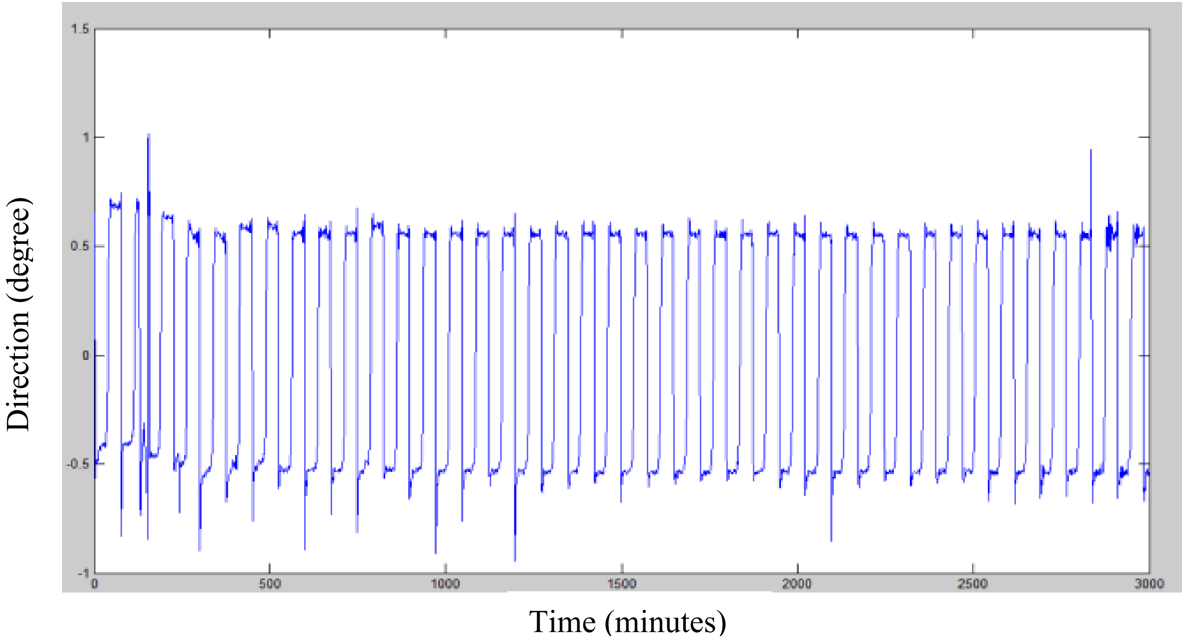


Figure (3.30) The relation between the direction and the time of the tidal currents for the forecasted trained data using the hybrid model.

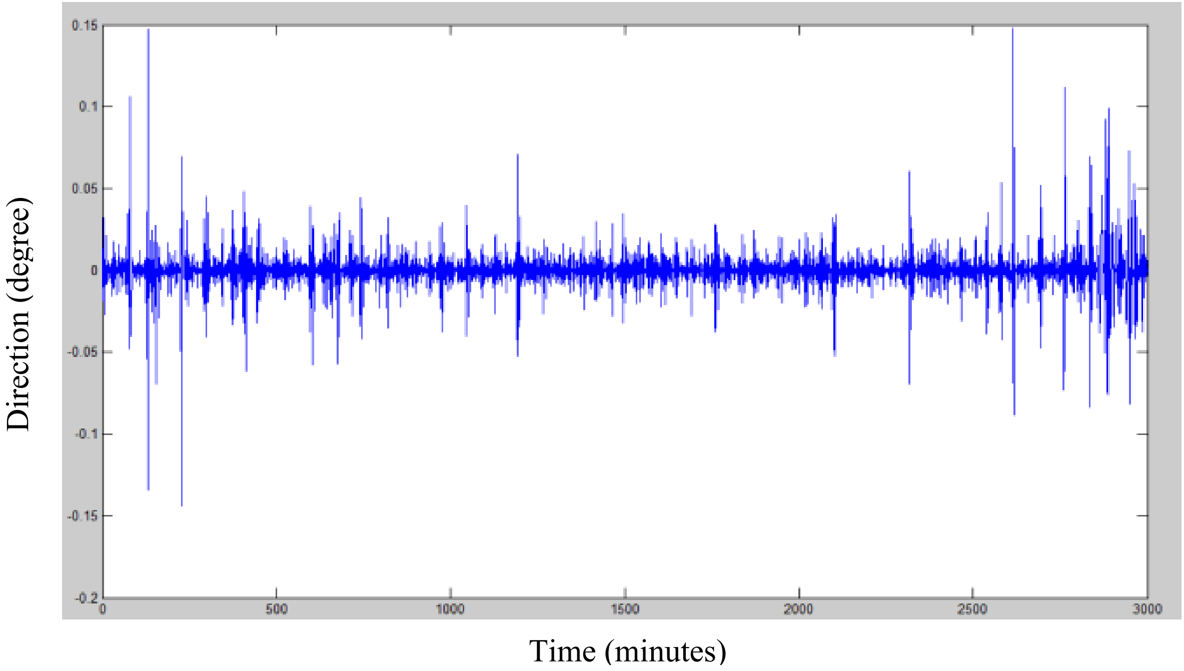


Figure (3.31) The relation between error (the actual minus the forecasted trained direction of the tidal currents) and the time after using the hybrid model.

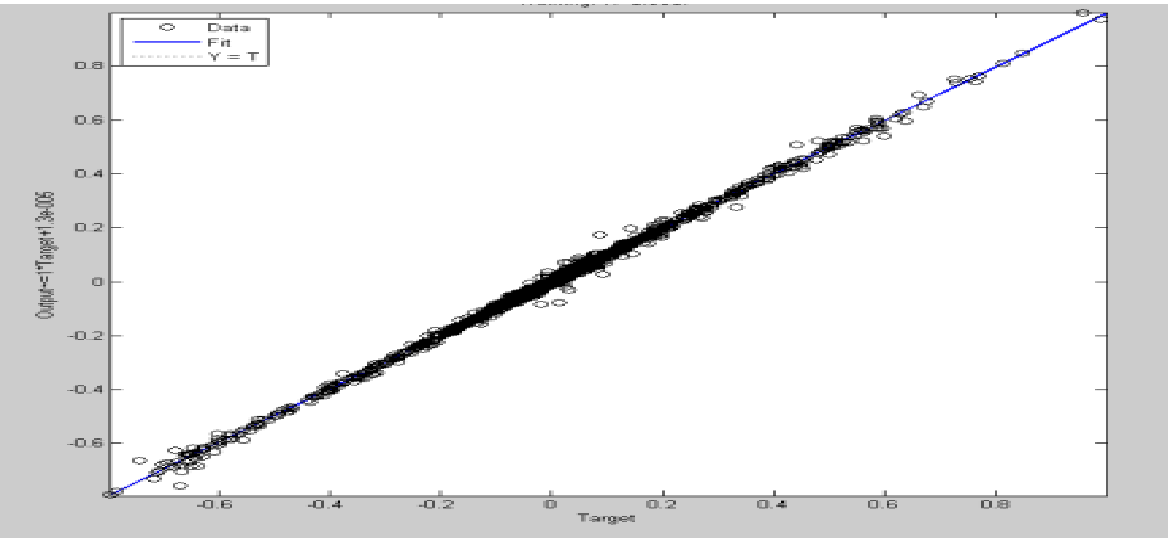


Figure (3.32) The regression line for the trained innovations of the direction data after using the hybrid model.

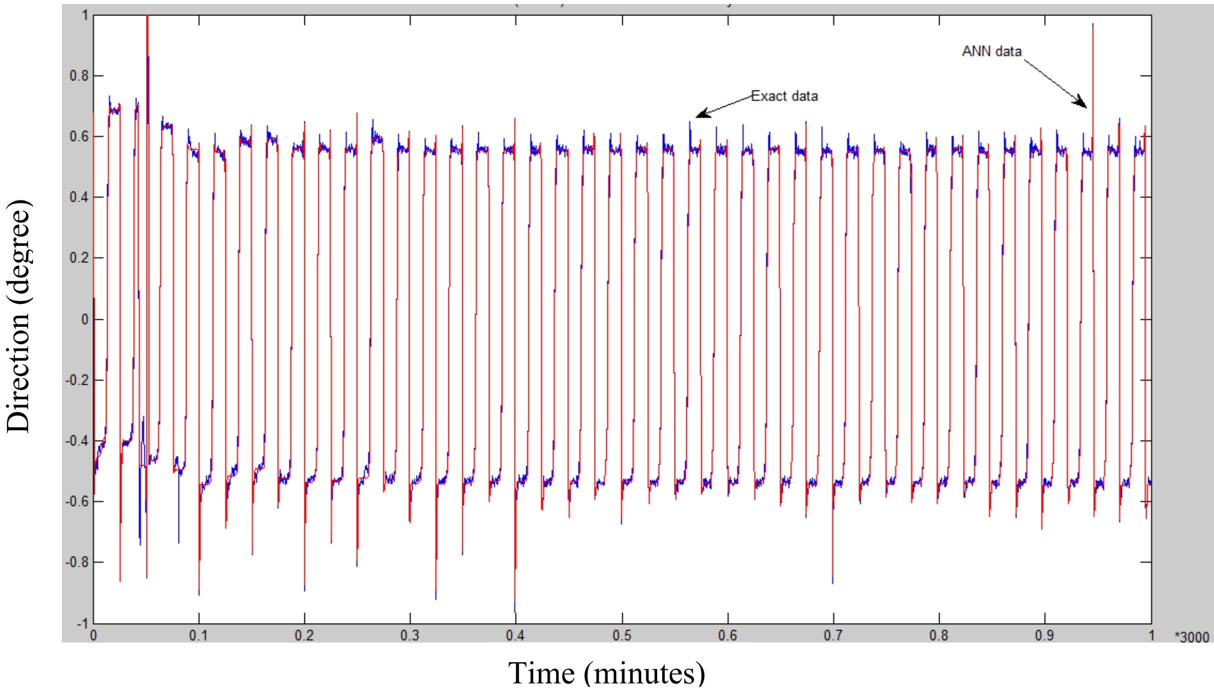


Figure (3.33) The relation between the direction and the time for the tidal currents after using the hybrid model and the exact trained data.

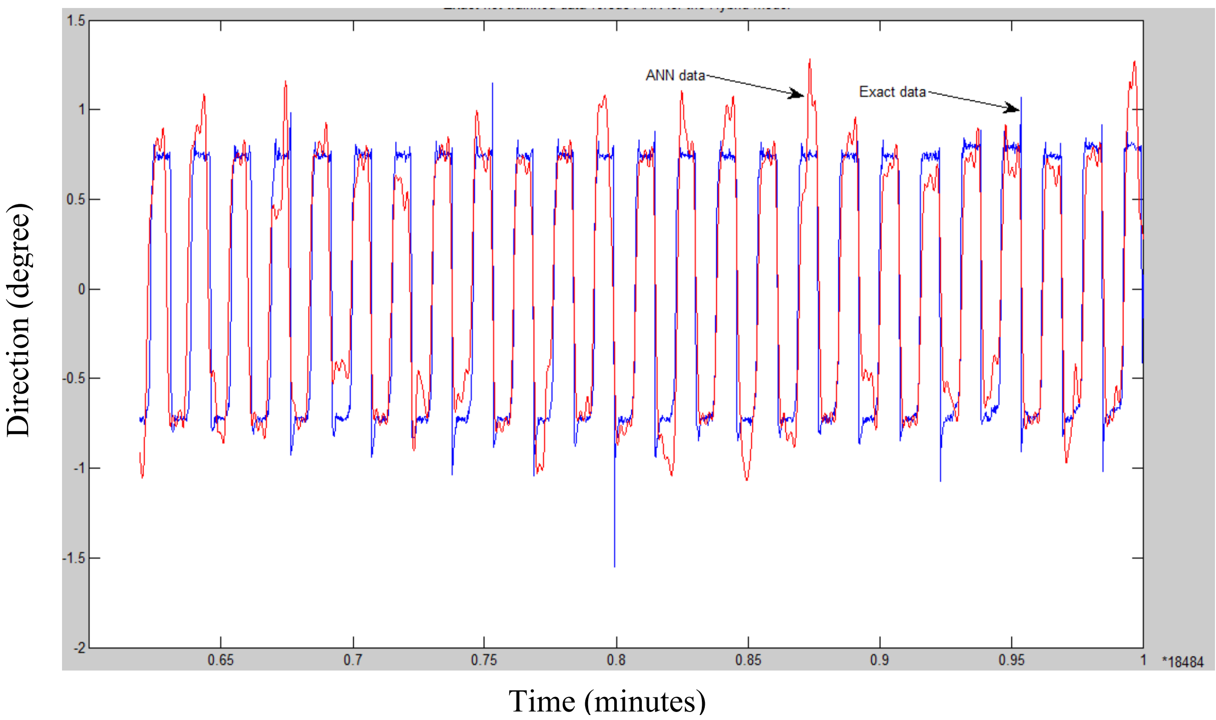


Figure (3.34) The relation between the direction and the time for the tidal currents after using the hybrid model and the exact not trained data.

Table (3.2) Comparison between different used models for direction prediction

Comparison between different used models			
Type of comparison	**FLSM**	**ANN**	**Hybrid**
% Error for the exact trained data (70% of the whole data)	0.7339	0.3167	***0.1169***
% Error for the exact not trained data (30% of the whole data)	0.917	1.0896	***0.4970***

3.8 SUMMARY

Harmonic tidal current constituent analysis and numerical hydrodynamic models are the most commonly models used for tidal current prediction. Recently artificial neural networks (ANN) were used in many areas to handle problems of unknown nonlinear relationships. This thesis proposed a hybrid model of ANN and FLSM for tidal current prediction. It is proved that using either FLSM or ANN alone to predict tidal current magnitudes and direction is not recommended. Instead the hybrid of ANN and FLSM offers an improved facility for tidal currents prediction with high accuracy. The procedure of back propagation of neural network (BPN) repeatedly adjusts the weights of the connections in the network so as to minimize the measure of the difference between the actual output vector and the desired output vector. In this chapter we used the proposed model for the speed and direction prediction of the tidal currents and the model gives good results.

CHAPTER 4 DYNAMIC MODELING AND CONTROL OF TIDAL CURRENT TURBINE DRIVEN DIRECT DRIVE PERMANENT MAGNET SYNCHRONOUS AND DOUBLY FED INDUCTION GENERATORS

4.1 INTRODUCTION

DFIG and DDPMSG are commonly used generators for offshore wind turbines and also for tidal current turbines. Grid codes require that generators continue to work during faults. The fault ride-through compensator can easily be connected to the full scale converter rather than with a partial scale converter. Presently, the DFIG with partial scale frequency converter in the rotor circuit is the most commonly used generator for off-shore wind turbine applications due to its cost advantags compared to DDPMSG with a full scale converter. But in the case of grid faults the partial scale converter needs to be protected against the transient currents and voltages. This is why it is important to devise a control strategy to improve system stability following a fault. During grid faults a transient current will flow through the rotor circuit. This current may damage the rotor. In addition, the DC link capacitor may be overcharged. A crowbar (external rotor resistance) is used to short circuit the rotor to protect the generator when the rotor current or the DC link voltage exceeds a certain limit. But the drawback of this method is the loss of active and reactive power controllability of the generator. Some grids require that rated reactive current component be provided during the fault so that for these grids it is preferred to use DDPMSG with full scale converter as it is easier to ride-through the fault with full scale converters than with partial converters [128-136].

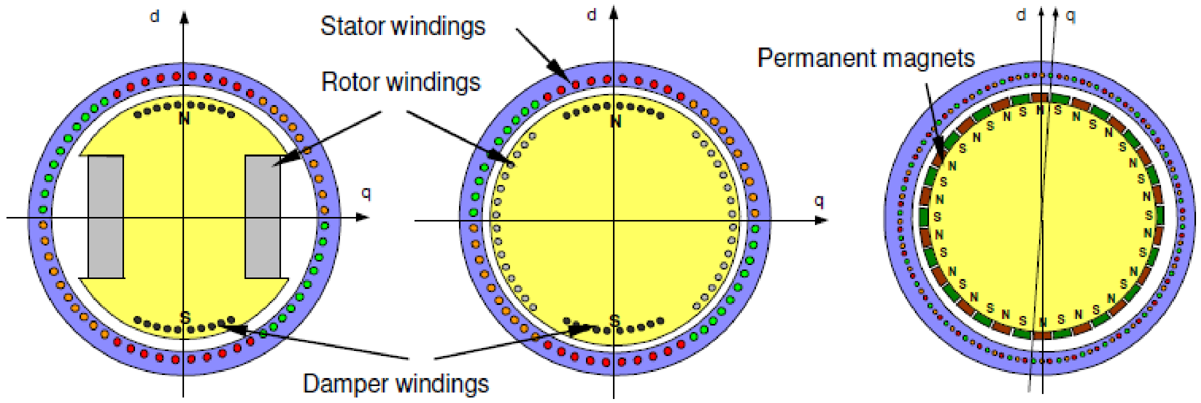
In DDPMSG, the generator is connected via a full-scale IGBT converter to the grid. This connection decouples the generator from the frequency of overall system and gives a range of variable speed operation. Also, the reactive power supplied by the converter is independent of the reactive power operational point of the generator. This generator has multi-poles so it provides the ability to remove the gear box and also because of using permanent magnets, there is no need for DC excitation. As a result the generator weight, and losses, will be less and this increases the efficiency but its cost is still high compared to DFIG due to the permanent magnet excitation and the full scale converters [137].

As a result the new trends are to use the DDPMSG instead of DFIG. In practice three types of synchronous generators exist [135,136]:

1. **Salient Pole Synchronous Gennerator (SPSG)**
   In the (SPSG) the windings of the rotor are placed as a concentrated coil around the pole shoe and so the rotor reluctance will be different in the d and q axes (x_d and x_q are not equal, $x_d > x_q$). A damper winding is needed for this type of machines and it is placed in the pole shoe. This type of machine is used in hydro power plants as the hydro plants need a machine with lower speed.

2. **Round Rotor Synchronous Gennerator (RRSG)**
   In the (RRSG) the windings of the rotor are equally distributed in the rotor slots, so the reluctances will be the same in the d and q axis ($x_d = x_q$). This type of machines is used in thermal power plants as they need machines with higher speed (around 1500 rpm, 3000 rpm).

3. **Multi-pole Permanent Magnet Synchronous Generator (MPSG)**
   This type of machines is preferred for very low speed applications and they need a high number of poles and there is no need for a damper winding. This type of machine uses a permanent magnet instead of DC excitation in the rotor circuit. The distribution of surface mounted magnets are equal and the permeability of the magnet material is high. There is a very small difference in the reactances between the d and q axes so it is normal to consider this machine as a round rotor machine ($x_d = x_q$). Figure (4.1) shows different synchronous generator types.



Salient pole

Round rotor

Multi-pole permanent magnet

Figure (4.1) Different synchronous generator types [135].

Different controllers are used for stabilizing purposes of DDPMSG and DFIG for both grid side converter and generator side converter. Some of these controllers use the generator side converter controller to maintain the rotating speed of the DDPMG at optimal speed value, and to minimize core losses; and use the grid side converter controller to maintain the voltage of the DC-link, and control the output reactive power to a certain reference value. Other controllers use the generator side converter controller to control the output active power and reactive power of the DDPMG, while using the grid side converter controller to control the DC-link voltage and the terminal voltage of the turbine system. The concept of DDPMSG is to use a full scale IGBT voltage source frequency converter to connect the generator to the grid. This converter decouples the generator from the electrical frequency of the grid and allows a variable speed operation and supplies the grid by reactive power which is independent of the reactive power of the generator operation. This chapter describes the overall dynamic models of tidal current turbine driving the two types of generators doubly fed induction generator and direct drive permanent magnet synchronous generator connected to a single machine infinite bus system. In this chapter two controllers are proposed to improve system stability.

Stability analysis of these two generators with the proposed controllers is discussed to highlight the important role of these controllers. Testing with ranges of controllers gains is carried out to establish zones of stability for both controllers and the model is validated to conclude this chapter.

4.2 MODEL OF TIDAL CURRENT TURBINE DRIVEN DFIG

4.2.1 The Speed Signal Resource Model

In Chapter three we proposed a model for the tidal current speed prediction. Tidal current speed may be expressed as a function of spring tide speed, neap tide speed and tides coefficient (Cs). Hence knowing the prevailing tides' coefficient, it is easy to derive a simple and practical model for tidal current speeds as follows [138, 80]: $V_{tide} = V_{nt} + \frac{(Cs-45)+(V_{st}-V_{nt})}{95-45}$.

4. 2.2 The Rotor Model

The tidal current power (P_{ts}) may be found using $P_{ts} = ½ \rho A(v_{tide})^3$. The turbine harnesses a fraction of this power, hence the power output may be expressed as $P_t = ½ \rho C_p A(v_{tide})^3$. The power output is proportional to the cube of the velocity. The velocity at the bottom of the channel is lower than at the water column above seabed. The mechanical torque applied to the turbine (T_m) can be expressed as [80, 139-142]:

$$T_m = \frac{0.5\rho\Pi R^2 C_p v_{tide}^3}{\omega_t} \tag{4.1}$$

The shaft system may be represented by two masses one for the turbine and the other for the generator as shown:

$$2H_t\frac{d\omega_t}{dt} = T_t - K_s(\Theta_r-\Theta_t) - D_s(\omega_r-\omega_t) \tag{4.2}$$

$$2H_g\frac{d\omega_r}{dt} = T_e - K_s(\Theta_r-\Theta_t) - D_s(\omega_r- \omega_t) \tag{4.3}$$

$$\Theta_{tr} = \Theta_r-\Theta_t \tag{4.4}$$

$$\frac{d\Theta\Theta tr}{dt} = \omega_r- \omega_t \tag{4.5}$$

There are ratios for the torsion angles, damping and stiffness that need to be considered when one adds a gear box as all above calculations must be referred to the generator side and calculated as : $a=\frac{\omega_r}{\omega_t}$, $\omega_r^{(t)} = \frac{\omega_r^{(g)}}{a}$, $\Theta_t^{(t)} = \frac{\Theta_t^{(g)}}{a}$, $K_s^{(t)} =a^2K_s^{(g)}$, $D_m^{(t)}=a^2 D_m^{(g)}$. The same model used for the offshore wind is used for tidal in-stream turbines; however, there is a number of differences in the design and operation of marine turbines due to the changes in force loadings, immersion depth, and different stall characteristics. Since the extracted power from the tidal currents is proportional to the area and the cube of the velocity, hence narrow channels are preferred for tidal turbines to extract higher power levels as the velocity is higher in this case.

4.2.3 Dynamic Model of The DFIG

Figure (4.1) shows the modelling scheme and control concept of the variable speed tidal current turbine with DFIG. The DFIG model is developed using a synchronously rotating d-q reference frame with the direct-axis oriented along the stator flux position. The reference frame rotates at the same speed as the stator voltage. The stator and rotor active and reactive powers are given by [80, 139-146]:

$$P_s=3/2(v_{ds}\ i_{ds} + v_{qs}\ i_{qs}) \quad , \quad P_r= 3/2(v_{dr}\ i_{dr} + v_{qr}\ i_{qr}) \tag{4.6}$$

$$P_g= P_s + P_r \tag{4.7}$$

$$Q_s=3/2(v_{qs}\ i_{ds} - v_{ds}\ i_{qs}) \quad , \quad Q_r=3/2 (v_{qr}\ i_{dr} - v_{dr}\ i_{qr}) \tag{4.8}$$

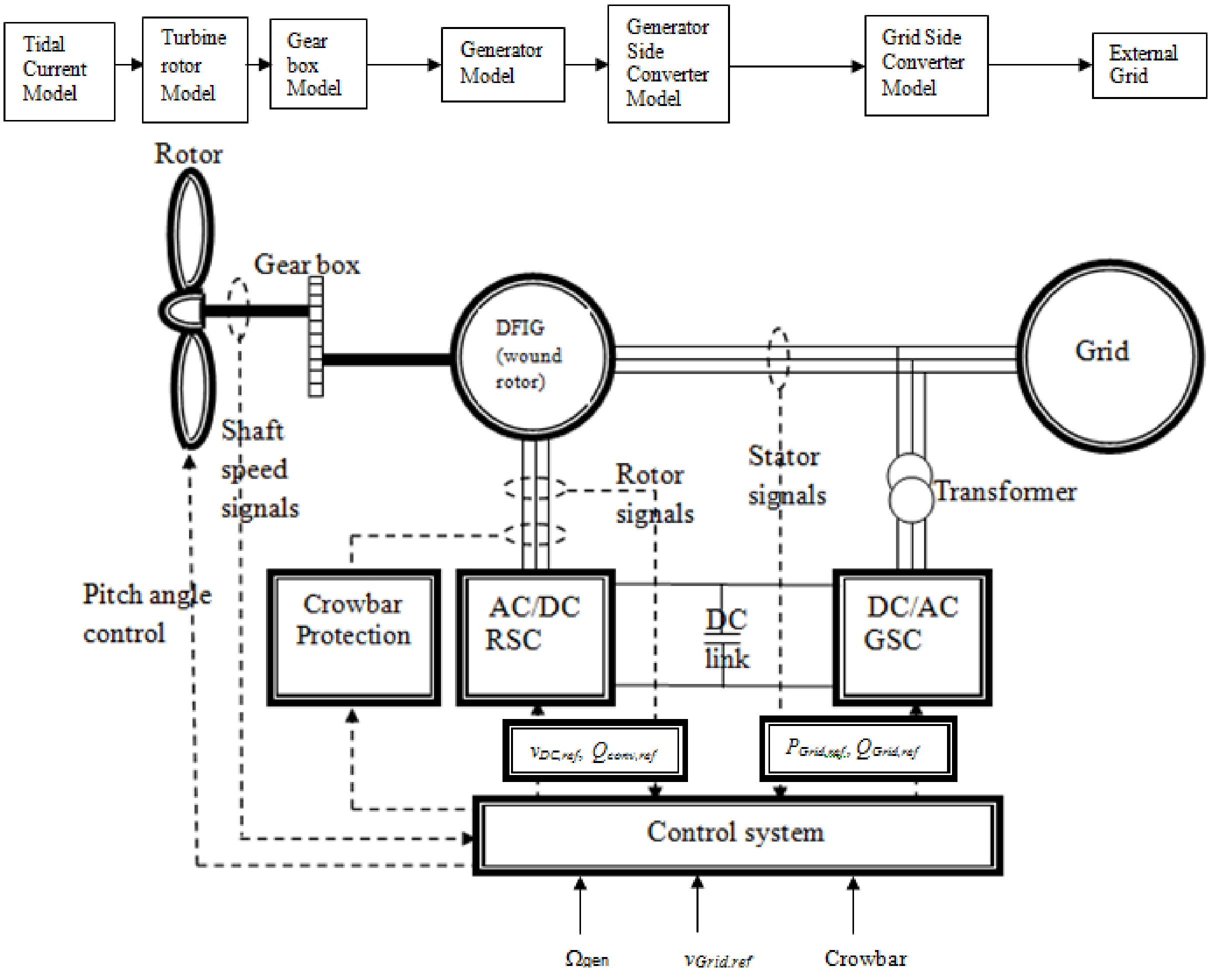


Figure (4.2) Modelling scheme and control concept of the variable speed tidal current turbine with DFIG.

The model of the DFIG can be described as:

$$v_{ds} = -R_s\ i_{ds} - \omega_s\ \psi_{qs} + \frac{d}{dt}\psi_{ds} \tag{4.9}$$

$$v_{qs} = -R_s\ i_{qs} + \omega_s\ \psi_{ds} + \frac{d}{dt}\psi_{qs} \tag{4.10}$$

$$v_{dr} = -R_r\ i_{dr} - s\ \omega_s\ \psi_{qr} + \frac{d}{dt}\psi_{dr} \tag{4.11}$$

$$v_{qr} = -R_r\ i_{qr} + s\ \omega_s\ \psi_{dr} + \frac{d}{dt}\psi_{qr} \tag{4.12}$$

$$\Psi_{ds} = -L_{ss}\ i_{ds} - L_m\ i_{dr} \quad , \quad \Psi_{qs} = -L_{ss}\ i_{qs} - L_m\ i_{qr} \tag{4.13}$$

$\Psi_{dr} = -L_{rr}\ i_{dr} - L_m\ i_{ds}$, $\Psi_{qr} = -L_{rr}\ i_{qr} - L_m\ i_{qs}$ (4.14)

$s = (\omega_s - \omega_r)/\omega_s$ (4.15)

$$\frac{d\omega_r}{dt} = -\omega_s \frac{ds}{dt} \qquad (4.16)$$

$L_{ss} = L_s + L_m$, $L_{rr} = L_r + L_m$, L_s, L_r and L_m are the stator leakage, rotor leakage and mutual inductances, respectively. The previous model may be reduced by neglecting stator transients and is described as follows:

$v_{ds} = -R_s\ i_{ds} + X'\ i_{qs} + e_d$ (4.17)

$v_{qs} = -R_s\ i_{qs} - X'\ i_{ds} + e_q$ (4.18)

$$\frac{de_d}{dt} = -\frac{1}{T_0}\left(e_d + (X - X')i_{qs}\right) + s\ \omega_s\ e_q - \omega_s \frac{L_m}{L_{rr}} v_{qr} \qquad (4.19)$$

$$\frac{de_q}{dt} = -\frac{1}{T_0}\left(e_q - (X - X')i_{ds}\right) - s\ \omega_s\ e_d + \omega_s \frac{L_m}{L_{rr}} v_{dr} \qquad (4.20)$$

The components of the voltage behind the transient (the internal voltage components of the induction generator) are $e_d = -\frac{\omega_s L_m}{L_{rr}}\ \psi_{qr}$ and $e_q = \frac{\omega_s L_m}{L_{rr}}\ \psi_{dr}$. The stator reactance $X = \omega_s\ L_{ss} = X_s + X_m$, and the stator transient reactance $X' = \omega_s\ (L_{ss} - L_m^2/L_{rr}) = X_s + (X_r\ \ X_m)/\ (X_r + X_m)$. The transient open circuit time constant is $T_o = L_{rr}/R_r = (L_r + L_m)/R_r$, and the electrical torque is $T_e = (i_{ds}i_{qr} - i_{qs}i_{dr})X_m/\omega_s$.

4.2.4 The Pitch Controller Model

The pitch controller is used to adjust the tidal current turbine to achieve a high speed magnitude by changing the location of the turbine depending on the tidal current speed magnitude. This may be represented by a PI controller with a transfer function $K_{pt} + \frac{K_{it}}{S}$ shown in Figure (4.3).

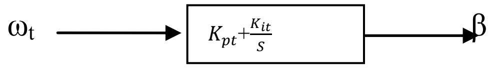


Figure (4.3) Pitch angle control block

$$\beta=\left(K_{pt}+\frac{K_{it}}{s}\right)\omega_t \tag{4.21}$$

$$\frac{d\beta}{dt}=K_{pt}\frac{d\omega t}{dt}+K_{it}\omega_t \tag{4.22}$$

4.2.5 The Converter Model

A converter feeds or takes power from the rotor circuit and produces variable speed (a partial scale power converter used). The rotor side of the DFIG is connected to the grid via a back to back converter. The converter at the side connected to the grid is called the supply side converter (SSC) or grid side converter (GSC) while the converter connected to the rotor is the rotor side converter (RSC). The RSC operates in the stator flux reference frame. The direct axis component of the rotor current acts in the same way as the field current as in the synchronous generator and thus controls the reactive power change. The quadrature component of the rotor current is used to control the speed by controlling the torque and the active power change. Thus the RSC governs both the stator-side active and reactive powers independently. The GSC operates in the stator voltage reference frame. The *d*-axis current of the GSC controls the DC link voltage to a constant level, and the *q*-axis current is used for reactive power control. The grid side converter is used to supply or draw power from the grid according to the speed of the machine but its main objective is to keep the dc-link voltage constant regardless of the magnitude and direction of the rotor power. The back to back converter using a DC link is shown in Figure (4.4). The power balance equation is given by [147, 148]:

$$P_r=P_g+P_{DC} \tag{4.23}$$

$$P_{DC}=v_{DC}i_{DC}=-Cv_{DC}\frac{dv_{DC}}{dt}, \quad P_g=v_{Dg}i_{Dg}+v_{Qg}i_{Qg} \tag{4.24}$$

(24.5)

$$Cv_{DC}\frac{dv_{DC}}{dt} = v_{Dg}i_{Dg}+v_{Qg}i_{Qg} - v_{dr}\ i_{dr} - v_{qr}\ i_{qr}$$

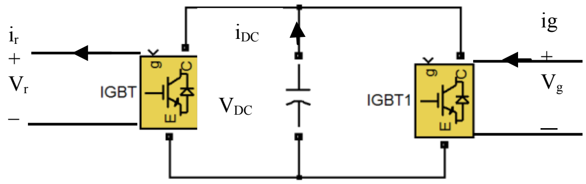


Figure (4.4) Back to back converter

4.2.6 The Proposed Rotor Side Converter Controller Model

In this section we modified the grid side converter controller that was used for offshore wind turbine (never used before for tidal current turbine) to be used for tidal current turbine. The rotor side converter controller used here is represented by four states ($\dot{x}_1$, $\dot{x}_2$, $\dot{x}_3$ and $\dot{x}_4$), $\dot{x}_1$ is related to the difference between the generated power of the stator and the reference power that is required at a certain time, $\dot{x}_2$ is related to the difference between the quadrature axis generator rotor current and the reference current that is required at a certain time, $\dot{x}_3$ is related to the difference between the stator terminal voltage and the reference voltage that is required at a certain time, and $\dot{x}_4$ is related to the difference between the direct axis generator rotor current and the reference current that is required at a certain time [147, 148]. Figure (4.5) shows the rotor side converter controller. This is described by equations (4.26 - 4.34).

$$\dot{x}_1= P_{ref}\ -P_s \tag{4.26}$$

$$\dot{x}_1= - K_{i1}/ K_{p1}x_1 + 1/ K_{p1}\, i_{qr\_ref} \tag{4.27}$$

$$\dot{x}_2= i_{qr\_ref}\ -i_{qr} \tag{4.28}$$

$$\dot{x}_2 = K_{p1}\dot{x}_1 + K_{i1}\, x_1 - i_{qr} \qquad (4.29)$$

$$\dot{x}_2 = -K_{i2}/K_{p2}x_2 + 1/K_{p2}\, v_{qr} - \omega_s L_m/K_{p2}\, i_{ds} - \omega_s L_{rr}/K_{p2} i_{dr} + (L_m/K_{p2})\, i_{ds}\omega_r + (L_{rr}/K_{p2}) i_{dr}\omega_r \qquad (4.30)$$

$$\dot{x}_3 = v_{s\_ref} - v_s \qquad (4.31)$$

$$\dot{x}_3 = -K_{i3}/K_{p3}x_3 + 1/K_{p3}\, i_{dr\_ref} \qquad (4.32)$$

$$\dot{x}_4 = i_{dr\_ref} - i_{dr} \qquad (4.33)$$

$$\dot{x}_4 = -K_{i2}/K_{p2}x_4 + 1/K_{p2}\, v_{dr} - \omega_s L_m/K_{p2}\, i_{qs} - \omega_s L_{rr}/K_{p2} i_{qr} + (L_m/K_{p2})\, i_{qs}\omega_r + (L_{rr}/K_{p2}) i_{qr}\omega_r \qquad (4.34)$$

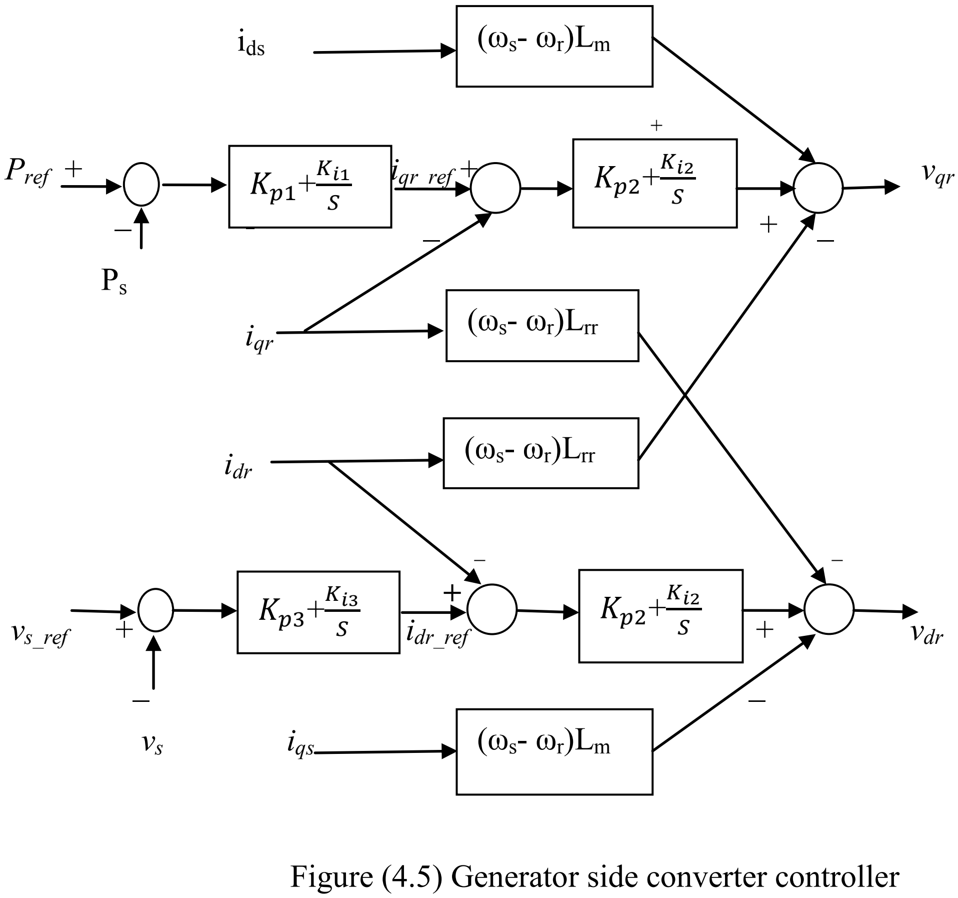


Figure (4.5) Generator side converter controller

4.2.7 The Proposed Grid Side Converter Controller Model

The grid side converter controller used here is represented by four states ($\dot{x}_5$, $\dot{x}_6$, $\dot{x}_7$ and $\dot{x}_8$), x_5 is related to the difference between the DC voltage and the reference DC voltage required at a certain time, x_7 related to the difference between the grid terminal voltage and the reference terminal voltage required at a certain time, x_6 is a combination of x_5 and direct axis grid current and x_8 is a combination of x_6 and quadrature axis grid current as shown in equations (4.35 – 4.40). Figure (4.6) shows the grid side converter controller.

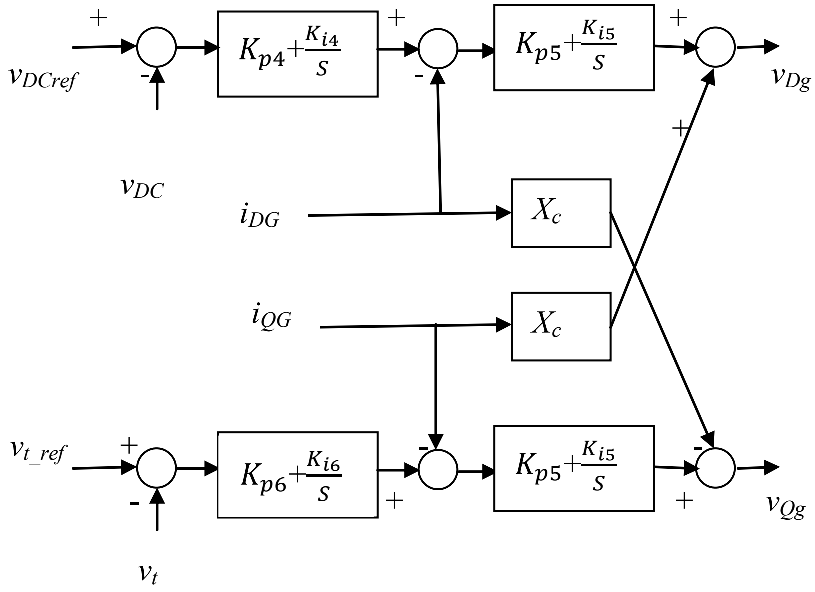


Figure (4.6) Grid side converter controller

$$\dot{x}_5 = v_{DC\_ref} - v_{DC} \tag{4.35}$$

$$\dot{x}_6 = K_{p4}\dot{x}_5 + K_{i4}x_5 - i_{Dg} \tag{4.36}$$

$$\dot{x}_7 = v_{t\_ref} - v_t \tag{4.37}$$

$$\dot{x}_8 = K_{p6}\dot{x}_7 + K_{i6}x_7 - i_{Qg} \tag{4.38}$$

$$v_{Dg}=K_{p5}\dot{x}_6+K_{i5}x_6+X_c i_{Qg} \tag{4.39}$$

$$v_{Qg}=K_{p5}\dot{x}_8 +K_{i5}x_8- X_c i_{Dg} \tag{4.40}$$

4.3 MODEL OF TIDAL CURRENT TURBINE DRIVEN DDPMSG

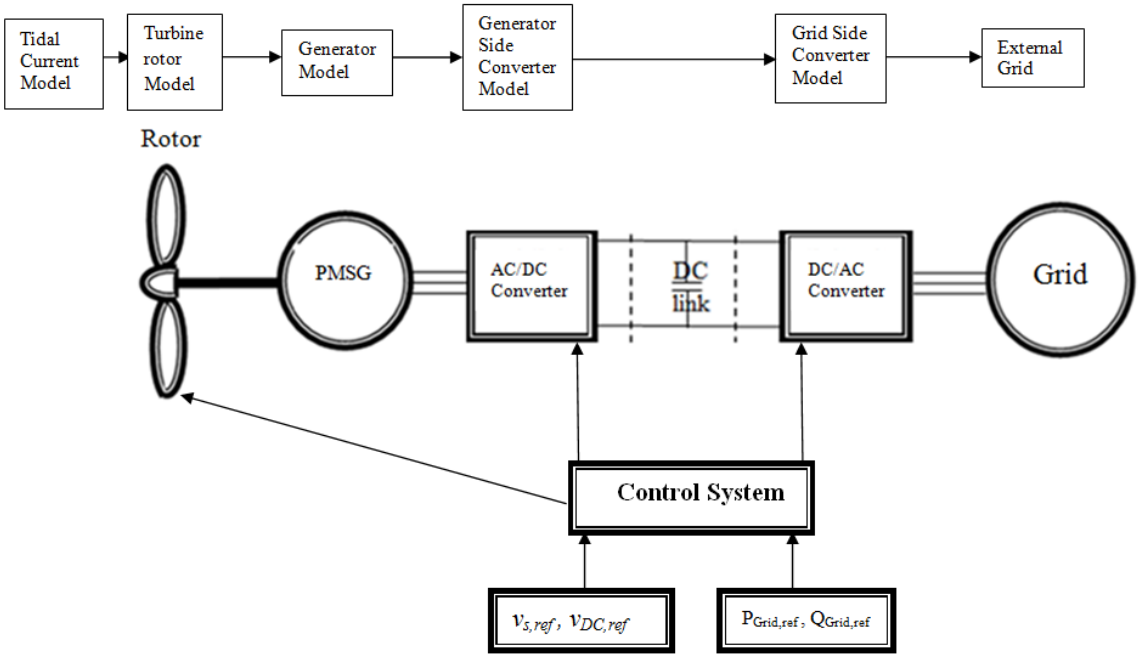


Figure (4.7) Modelling scheme and control concept of the tidal current turbine with DDPMSG

In this section we review the dynamic model of the direct drive permanent magnet synchronous generator, the converter and the proposed controllers. Figure (4.7) shows the modelling scheme and control concept of the tidal current turbine with DDPMSG. We use the same signal resource model and the one mass model for the rotor model without gear box as described in the previous secion for the DFIG.

4.3.1 The Dynamic Model of the DDPMSG

The DDPMSG can be modeled as follows [138, 147]:

$$v_{ds} = -R_s \times i_{ds} - \omega_s \times \psi_{qs} + \frac{d}{dt}\psi_{ds} \tag{4.41}$$

$$v_{qs} = -R_s \times i_{qs} + \omega_s \times \psi_{ds} + \frac{d}{dt}\psi_{qs} \tag{4.42}$$

The flux linkages and the torque can be expressed as:

$$\Psi_{ds} = -L_d \times i_{ds} + \psi_f \tag{4.43}$$

$$\Psi_{qs} = -L_q \times i_{qs} \tag{4.44}$$

$$T_e = (3/2)p\, i_{qs}\left((L_d - L_q)\, i_{ds} + \psi_f\right) \tag{4.45}$$

L_d, and L_q are the direct and quadrature inductances of the stator. Ψ_f is the excitation field linkage, and p is the number of pole pairs. Figure (4.8) shows the d-q axis component of the DDPMSG. In this work for simplicity we assume that $L_d=L_q=L_s$, because the difference is very small as we discussed in the introduction before, and so the generator model can be rewritten in a state space representation as:

$$L_s \frac{d}{dt} i_{ds} = -v_{ds} - R_s \times i_{ds} + L_s \times \omega_s \times i_{qs} \tag{4.46}$$

$$L_s \frac{d}{dt} i_{qs} = -v_{qs} - R_s \times i_{qs} - L_s \times \omega_s \times i_{ds} + \omega \times \psi_f \tag{4.47}$$

The converter models used for the DFIG are the same converters that are used for the DDPMSG keeping in mind that a full scale power converter is used. Figure (4.8) shows the d-q axis component of the PMSG.

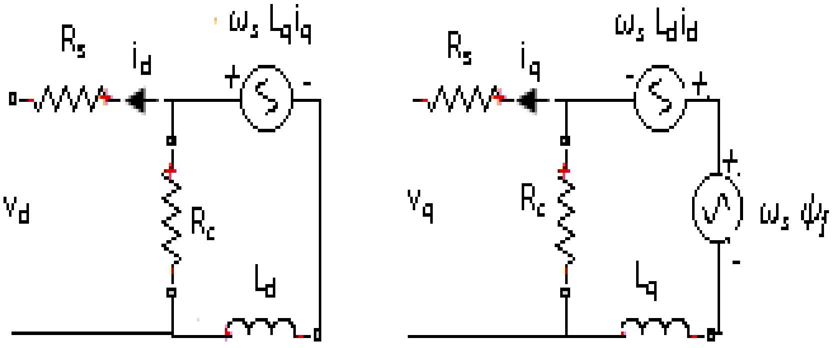


Figure (4.8) The d-q axis component of the PMSG

4.3.2 The Proposed Generator Side Converter Controller Model for The DDPMSG

The generator side converter controller proposed here is represented by two states only (x_1, and x_2), x_1 related to the difference between the generated power and the reference power that required at a certain time and x_2 related to the difference between the direct axis generator current and the reference current that required at a certain time [147, 148]. Figure (4.9) shows the generator side converter controller described by:

$$\dot{x}_1 = P_s - P_{ref} \tag{4.48}$$

$$\dot{x}_2 = i_{ds} - i_{ds\_ref} \tag{4.49}$$

$$v_{qs} = K_{p1}\dot{x}_1 + K_{i1}x_1 - L_s w i_{ds} \tag{4.50}$$

$$v_{ds} = K_{p2}\dot{x}_2 + K_{i2}x_2 + L_s w i_{qs} \tag{4.51}$$

Where:

K_{p1}, K_{p2}, represent the proportional controller constants and K_{i1}, K_{i2} represent the integral controller constants for the generator side converter controller.

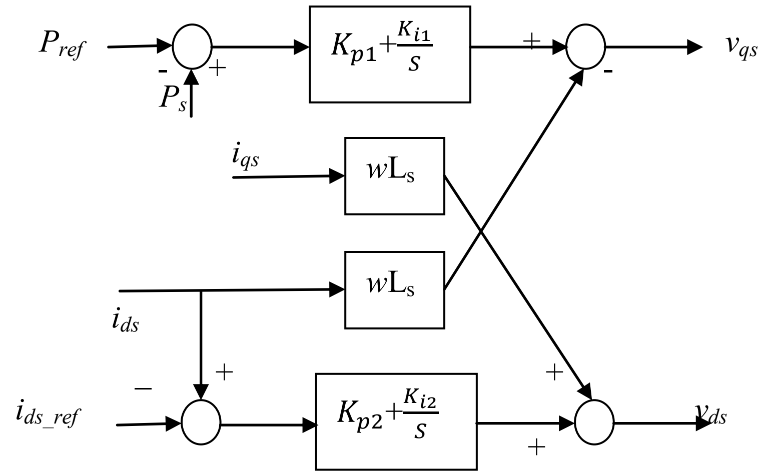


Figure (4.9) Generator side converter controller for DDPMSG

4.3.2 The Proposed Grid Side Converter Controller Model for the DDPMSG

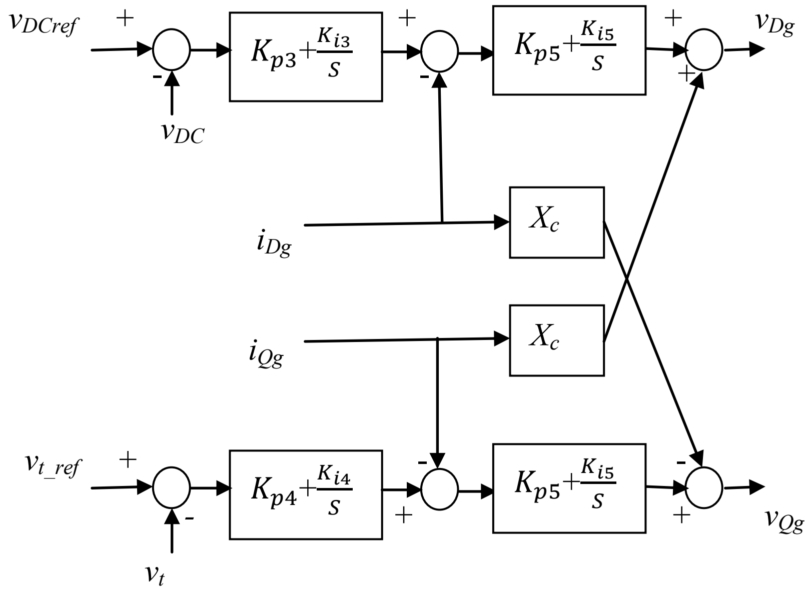


Figure (4.10) Grid side converter controller for DDPMSG

The grid side converter controller proposed here is represented by four states (x_3, x_4, x_5, x_6), x_3 is related to the difference between the DC voltage and the reference DC voltage that required at a certain time, x_5 related to the difference between the terminal voltage and the reference terminal voltage that required at a certain time, x_4 is a combination of x_3 and direct axis grid current and x_6 is a combination of x_4 and quadrature axis grid current. Figure (4.10) shows the grid side converter controller.

$$\dot{x}_3 = v_{sDC\_ref} - v_{DC} \tag{4.52}$$

$$\dot{x}_4 = K_{p3}\dot{x}_3 + K_{i3}x_3 - i_{Dg} \tag{4.53}$$

$$\dot{x}_5 = v_{t\_ref} - v_t \tag{4.54}$$

$$\dot{x}_6 = K_{p4}\dot{x}_4 + K_{i4}x_5 - i_{Qg} \tag{4.55}$$

$$v_{Dg} = K_{p5}\dot{x}_4 + K_{i5}x_4 + X_c i_{Qg} \tag{4.56}$$

$$v_{Qg} = K_{p5}\dot{x}_6 + K_{i5}x_6 - X_c i_{Dg} \tag{4.57}$$

V_{DC} is the DC link voltage, i_{Dg}, i_{Qg} are the D and Q axis grid currents, v_{Dg}, v_{Qg} are the D and Q axis grid voltages, K_{p3}, K_{p4}, K_{p5} represent the proportional controller constants, X_c is the grid side smoothing reactance, and K_{i3}, K_{i4}, K_{i5} represent the integral controller constants for the grid side converter.

The rotor speed controller uses a power–speed curve shown in figure (4.11) to compute the reference power according to the actual speed. The extracted tidal for variable pitch tidal machines may be calculated using this curve [82].

I. Zero to cut-in speed
II. Cut-in speed to rated speed
III. Greater than rated speed

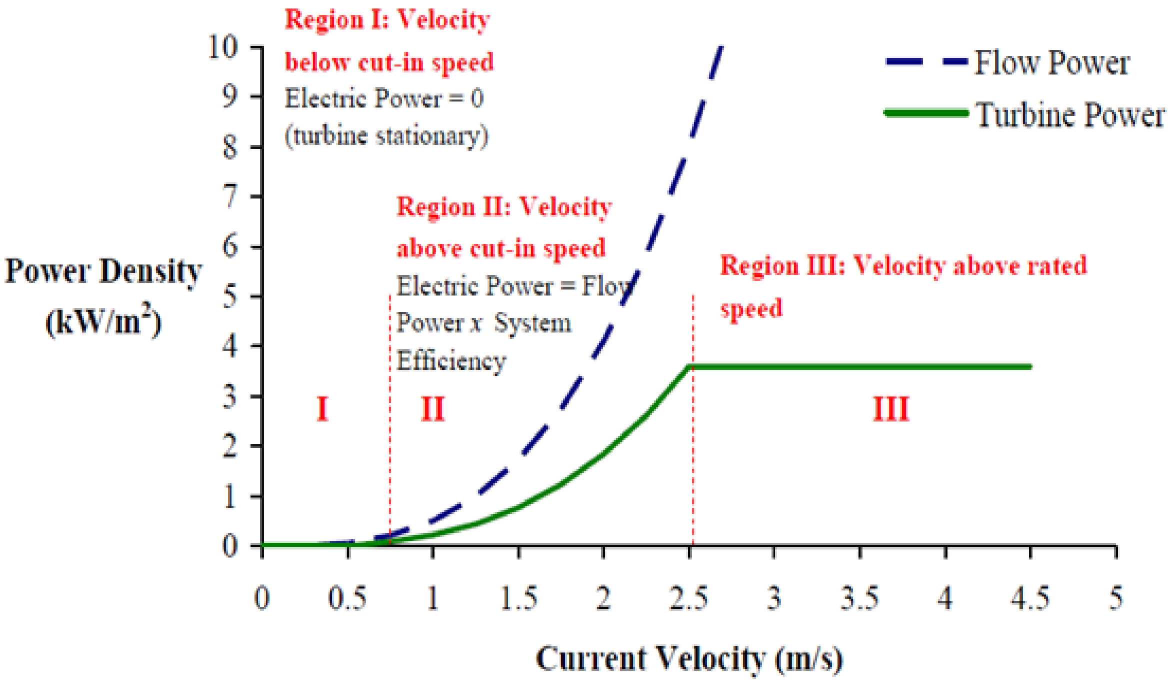


Figure (4.11) Power speed curve for tidal in-stream turbines.

4.4 STATE SPACE REPRESNTATION AND SMALL SIGNAL STABILITY ANANLYSIS FOR THE OVERALL SYSTEM DRIVING DFIG AND DDPMSG

In this section we describe the state space representation of the whole system and apply small signal stability analysis of a single machine infinite bus system for tidal current turbine using DFIG and DDPMSG. Small signal stability is the ability of the power systems to remain in synchronism under small disturbances. Small signal stability analysis for the power system determines the properties of operation of the system due to small disturbance in the system. This is done by finding the eigenvalues of the system for a small change that may have happened. In this section we perturb each state of the system by a small increment Δ, keeping in mind some assumptions [149]. These assumptions are:

$\Delta^2=0$, $\sin\Delta=0$ and $\cos\Delta=1$ and then linearized the equations to find the small change equations.

4.4.1 DFIG Linearized Equations

From equation(4.1): $T_m = \frac{0.5\rho\Pi R^2 C_p v_{tide}^3}{\omega_t} = K\frac{v_{tide}^3}{\omega_t}$, so linearizing this equation yields:

$$T_m + \Delta T_m = K\frac{v_{tide}^3\,(\omega_t - \Delta\omega_t)}{(\omega_t + \Delta\omega_t)(\omega_t - \Delta\omega_t)}$$

$$\Delta T_m = -K\frac{v_{tide}^3}{\omega_t^2}\Delta\omega_t$$

Linearizing equations(4.2), (4.5), (4.3), (4.19), (4.20) and (4.22) yield:

$$\Delta\dot{\omega}_t = \left(-K\frac{V_{tide}^3}{2H_t\,\omega_t^2} - \frac{D_s}{2H_t}\right)\Delta\omega_t + \frac{D_s}{2H_t}\Delta\omega_t - \frac{K_s}{2H_t}\Delta\theta_{tr} \tag{4.58}$$

$$\Delta\dot{\beta} = \left(-\frac{K_{pt}KV_{tide}^3}{2H_t\,\omega_t^2} + \frac{K_{pt}D_s}{2H_t} + K_{it}\right)\Delta\omega_t - \frac{K_{pt}D_s}{2H_t}\Delta\omega_t - \frac{K_{pt}K_s}{2H_t}\Delta\theta_{tr} \tag{4.59}$$

$$\Delta\dot{\theta}_{tr} = -\Delta\omega_t + \Delta\omega_r \tag{4.60}$$

$$\Delta\dot{\omega}_r = -\frac{1}{2H_g}[v_{ds}\Delta i_{ds} + [v_{ds}\Delta i_{ds} + i_{ds}\Delta v_{ds} + v_{qs}\Delta i_{qs} + i_{qs}\Delta v_{qs}] - \frac{K_s}{2H_g}\Delta\theta_{tr} - \frac{D_s}{2H_g}\Delta\omega_t - \frac{D_s}{2H_g}\Delta\omega_r \tag{4.61}$$

$$\Delta\dot{e}_d = -\frac{1}{T_o}\Delta e_d - \frac{X-\grave{X}}{T_o}\Delta i_{qs} + \omega_s\Delta e_q - \omega_r\Delta e_q - e_q\Delta\omega_r - \frac{L_m}{L_{rr}}\omega_s\Delta v_{qr} \tag{4.62}$$

$$\Delta\dot{e}_q = -\frac{1}{T_o}\Delta e_q - \frac{X-\grave{X}}{T_o}\Delta i_{ds} - \omega_s\Delta e_d + \omega_r\Delta e_d - e_d\Delta\omega_r - \frac{L_m}{L_{rr}}\omega_s\Delta v_{dr} \tag{4.63}$$

Linearizing equation (4.25) yields:

$$\Delta\dot{V}_{DC} = -\left(\frac{V_{Dg}i_{Dg} + V_{Qg}i_{Qg} + V_{ds}i_{ds} + V_{qs}i_{qs}}{CV_{DC}^{2}}\right)\Delta V_{DC} + \frac{V_{Dg}}{CV_{DC}}\Delta i_{Dg} + \frac{i_{Dg}}{CV_{DC}}\Delta V_{Dg} + \frac{V_{Qg}}{CV_{DC}}\Delta i_{Qg} + \frac{V_{Qg}}{CV_{DC}}\Delta V_{Qg} + \frac{v_{ds}}{CV_{DC}}\Delta i_{ds} + \frac{i_{ds}}{CV_{DC}}\Delta v_{ds} + \frac{v_{qs}}{CV_{DC}}\Delta i_{qs} + \frac{i_{qs}}{CV_{DC}}\Delta v_{qs} \tag{4.64}$$

Linearizing equations(4.29), (4.30), (4.32), (4.34), (4.36), (4.39), (4.38) and (4.40) yield:

$$\Delta\dot{X}_1 = -\frac{K_{i1}}{K_{p1}}\Delta X_1 + \frac{1}{K_{p1}}\Delta\dot{X}_2 + \frac{1}{K_{p1}}\Delta i_{qr} \tag{4.65}$$

$$\Delta\dot{X}_2 = -\frac{K_{i2}}{K_{p2}}\Delta X_2 + \frac{1}{K_{p2}}\Delta v_{qr} - \frac{L_m}{K_{p2}}\omega_s\Delta i_{ds} - \frac{L_{rr}}{K_{p2}}\omega_s\Delta i_{dr} + \frac{L_m}{K_{p2}}i_{ds}\Delta\omega_r + \frac{L_m}{K_{p2}}\omega_r\Delta i_{ds} + \frac{L_{rr}}{K_{p2}}i_{dr}\Delta\omega_r + \frac{L_{rr}}{K_{p2}}\omega_r\Delta i_{dr} \tag{4.66}$$

$$\Delta\dot{X}_3 = -\frac{K_{i3}}{K_{p3}}\Delta X_3 + \frac{1}{K_{p3}}\Delta\dot{X}_4 + \frac{1}{K_{p3}}\Delta i_{dr} \tag{4.67}$$

$$\Delta\dot{X}_4 = -\frac{K_{i2}}{K_{p2}}\Delta X_4 + \frac{1}{K_{p2}}\Delta v_{dr} - \frac{L_m}{K_{p2}}\omega_s\Delta i_{qs} - \frac{L_{rr}}{K_{p2}}\omega_s\Delta i_{qs} + \frac{L_m}{K_{p2}}\omega_r\Delta i_{qs} + \frac{L_m}{K_{p2}}i_{qs}\Delta\omega_r + \frac{L_{rr}}{K_{p2}}i_{qr}\Delta\omega_r + \frac{L_{rr}}{K_{p2}}\omega_r\Delta i_{qr} \tag{4.68}$$

$$\Delta\dot{X}_5 = \frac{1}{K_{p4}K_{p5}}\Delta v_{Dg} - \frac{K_{i5}}{K_{p5}K_{p4}}\Delta X_6 - \frac{X_c}{K_{p5}K_{p4}}\Delta i_{Qg} - \frac{K_{i4}}{K_{p4}}\Delta X_5 + \frac{1}{K_{p4}}\Delta i_{Dg} \tag*{(4.68)}$$

$$\Delta\dot{X}_6 = \frac{1}{K_{p5}}\Delta v_{Dg} - \frac{K_{i5}}{K_{p5}}\Delta X_6 - \frac{X_c}{K_{p5}}\Delta i_{Qg} \tag{4.69}$$

$$\Delta\dot{X}_7 = \frac{1}{K_{p6}K_{p5}}\Delta v_{Qg} - \frac{K_{i5}}{K_{p5}K_{p6}}\Delta X_6 + \frac{X_c}{K_{p5}K_{p6}}\Delta i_{Dg} - \frac{K_{i6}}{K_{p6}}\Delta X_7 - \frac{1}{K_{p6}}\Delta i_{Qg} \tag{4.70}$$

$$\Delta\dot{X}_8 = \frac{1}{K_{p5}}\Delta v_{\mathrm{Qg}} - \frac{K_{i5}}{K_{p5}}\Delta \mathrm{X}_8 + \frac{X_c}{K_{p5}}\Delta \mathrm{i}_{\mathrm{Dg}} \tag{4.71}$$

4.4.2 DDPMSG Linearized Equations

From the equation of motion

$$2H_{tot}(\dot{\omega}_t + \Delta\dot{\omega}_t) = T_m + \Delta T_m - (T_e + \Delta T_e) \tag{4.72}$$

$$, \Delta T_e = -[\psi_f \, \Delta i_q + (L_d - L_q)\Delta i_q \Delta i_d] \tag{4.73}$$

$$, \; L_d = L_q \tag{4.74}$$

$$\Delta\dot{\omega}_t = \frac{\Delta T_m - \Delta T_e}{2H_{tot}} = \frac{\Delta T_m + \Delta 1.5 p \Delta i_q}{2H_{tot}} \tag{4.75}$$

Linearizing equations (4.46) and (4.47) yields:

$$\dot{\Delta\imath}_{ds} = \frac{1}{L_s}(-\Delta v_{ds} - R_s \Delta i_{ds} + pL_s\,[\Delta\omega_t i_{qs} + \Delta i_{qs}\omega_t + \Delta i_{qs}\,\Delta\omega_t] \tag{4.76}$$

$$\dot{\Delta\imath}_{qs} = \frac{1}{L_s}(-\Delta v_{qs} - R_s \Delta i_{qs} + p\psi_f\,\Delta\omega_t - pL_s\,[\Delta\omega_t i_{ds} + \Delta i_{ds}\omega_t + \Delta i_{ds}\,\Delta\omega_t] \tag{4.77}$$

The last two terms in the previous two equations tend to zero so we can rewrite these equations again as:

$$\dot{\Delta\imath}_{ds} = \frac{1}{L_s}(-\Delta v_{ds} - R_s \Delta i_{ds} + pL_s\,[\Delta\omega_t i_{qs} + \Delta i_{qs}\omega_t] \tag{4.78}$$

$$\dot{\Delta\imath}_{qs} = \frac{1}{L_s}(-\Delta v_{qs} - R_s \Delta i_{qs} + p\psi_f\,\Delta\omega_t - pL_s\,[\Delta\omega_t i_{ds} + \Delta i_{ds}\omega_t] \tag{4.79}$$

Linearizing equation (4.25) yields:

$$\Delta\dot{V}_{DC} = -\left(\frac{V_{Dg}i_{Dg}+V_{Qg}i_{Qg}+V_{ds}i_{ds}+V_{qs}i_{qs}}{CV_{DC}^{2}}\right)\Delta V_{DC}+ \frac{V_{Dg}}{CV_{DC}}\Delta i_{Dg} + \frac{i_{Dg}}{CV_{DC}}\Delta V_{Dg} + \frac{V_{Qg}}{CV_{DC}}\Delta i_{Qg} + \frac{V_{Qg}}{CV_{DC}}\Delta V_{Qg} + \frac{v_{ds}}{CV_{DC}}\Delta i_{ds} + \frac{i_{ds}}{CV_{DC}}\Delta v_{ds} + \frac{v_{qs}}{CV_{DC}}\Delta i_{qs} + \frac{i_{qs}}{CV_{DC}}\Delta v_{qs} \quad (4.80)$$

Linearizing equations (4.50), (4.51), (4.53), (4.55), (4.56) and (4.57) yields:

$$\Delta\dot{X}_1 = -\frac{1}{K_{p1}}\left[\left(p\psi_f - pL_s\, i_{ds}\right)\Delta\omega_t - \Delta v_{qs} + K_{i1}\Delta X_1 - pL_s\,\omega_t\Delta i_{ds}\right] \quad (4.81)$$

$$\Delta\dot{X}_2 = -\frac{1}{K_{p2}}\left[pL_s\, i_{qs}\Delta\omega_t + pL_s\,\omega_t\Delta i_{qs} + K_{i2}\Delta X_2 - \Delta v_{ds}\right] \quad (4.82)$$

$$\Delta\dot{X}_3 = \frac{1}{K_{p3}K_{p5}}\left(-\Delta v_{Dg} - K_{i5\,\Delta}X_4 + X_c\,\Delta i_{Qg}\right) + \frac{1}{K_{p3}}\left(K_{i3}\,\Delta X_3 - \Delta i_{Dg}\right) \quad (4.83)$$

$$\Delta\dot{X}_4 = -\frac{1}{K_{p5}}\left[-\Delta V_{Dg} + K_{i5}\Delta X_4 + X_c\Delta i_{Qg}\right] \quad (4.84)$$

$$\Delta\dot{X}_5 = \frac{1}{K_{p4}K_{p5}}\left[-\Delta V_{Qg} + K_{i5}\Delta X_6 - X_c\,\Delta i_{Dg}\right] + \frac{1}{K_{p4}}\left[K_{i4}\Delta X_5 - \Delta i_{Qg}\right] \quad (4.85)$$

$$\Delta\dot{X}_6 = \frac{1}{K_{p5}}\left[\Delta V_{Qg} - K_{i5}\Delta X_6 + X_c\Delta i_{Dg}\right] \quad (4.86)$$

Using the previous linearized equations for DFIG and DDPMSG allow rewriting the state space equations as:

$$\Delta\dot{x}=A\Delta x+B\Delta u$$

Δx for DFIG = $[\Delta w_t, \Delta\beta,\ \Delta w_r,\ \Delta\Theta_{tr},\ \Delta e_d\ ,\ \Delta e_q\ ,\ \Delta\, V_{DC},\ \Delta x_1,\ \Delta x_2,\ \Delta x_3,\ \Delta x_4,\ \Delta x_5,\ \Delta x_6,\ \Delta x_7,\ \Delta x_8\ ]^{T}$

Δx for DDPMSG = $[\Delta w_t,\ \Delta i_{ds},\ \Delta i_{qs},\ \Delta V_{DC},\ \Delta x_1,\ \Delta x_2,\ \Delta x_3,\ \Delta x_4,\ \Delta x_5,\ \Delta x_6]^{T}$

The fifteenth states of the DFIG are w_t , β , w_r , θ_{tr}, e_d , e_q , V_{DC}, x_1, x_2, x_3 , x_4, x_5, x_6, x_7 and x_8. Equations (4.2), (4.3), and (4.5) are used for the drive train. Equations (4.19) and (4.20) are used for the generator. Equations (4.23), (4.24), and (4.25) for the DC link give v_{DC} state. Equations from (4.26) to (4.34) are used for the generator side converter controller model and give the states x_1 and x_2. Equations (4.35) to (4.40) are used for the grid side converter controller.

The ten states of the DDPMSG are w_t, i_{ds}, i_{qs}, v_{DC}, x_1, x_2, x_3, x_4, x_5, and x_6. Using equations (4.41) and (4.42) for the generator. Equations (4.23), (4.24), and (4.25) for the DC link give v_{DC} state. Equations (4.48), (4.49), (4.50) and (4.51) for the generator side converter controller model and give the states x_1 and x_2. Equations (4.52), (4.53), (4.54), (4.55), (4.56) and (4.57) for the grid side converter controller and give states x_3, x_4, x_5 and x_6.

4.5 EFFECT OF CHANGING THE CONTROLLERS COFFECIENTS

As the values of the controller coefficients change, the stability will change. In this section we change the values of the controller coefficients independently and find the relation between the increasing or decreasing of these coefficients independently and the degree of the stability. Also we rank the importance of these coefficients for the stability analysis.

4.5.1 DFIG Controllers Coefficients

In this section we compare the effects of specific parameters change on stability for DFIG. At the end of this section we discuss the preferred ranges of values of the controllers for stability of the system. Table (4.1) gives the eigenvalues of the 15th order model of the whole system using DFIG for different values of the proportional coefficient controller K_{p1}. From Table (4.1) we concluded that the system is asymptotically stable. The eigenvalues related to the voltage states (e_d, e_q) have imaginary parts equal to 50 and -50 and real parts equal to -1 and +1.

Tables (4.1- 4.6) show the effect of changing the values of the proportional controllers coefficients for DFIG on stability analysis. The coefficients may be ranked depending on their effects on the stability. The most effective proportional coefficient controller is K_{p2}. This coefficient affects two modes of states and made a huge change on the locations of their two poles. The six proportional coefficients may be ranked from the most effective to the least effective depending on the changes that they made on the eigenvalues compared to the changes on their own values as K_{p2}, K_{p3}, K_{p1}, K_{p4}, K_{p6}, K_{p5}.

Tables (4.7- 4.12) show the effect of changing the values of the integral controllers coefficients for DFIG on stability analysis. The coefficients may be ranked depending on their effect on the stability. The most effective proportional coefficient controller is K_{i3}. The integral coefficients may be ranked from the most effective to the least effective depending on the changes that they made on the eigenvalues compared to the change on their own values as K_{i3}, K_{i1}, K_{i2}, K_{i4}, K_{i5}, K_{i6}. Table (4.13) shows the range of values for the controllers coefficients for DFIG.

Table (4.1) shows the eigenvalues of the DFIG for changing the proportional coefficient value K_{p1}. From that table we concluded that, changing the value of K_{p1} will affect the value of λ_8 which is related to the state variable x_1. The state variable x_1 describes the relation between the reference power and the generated power so by changing the value of K_{p1} the value of the generated power will be changed. Table (4.2) shows the Eigenvalues of the DFIG for changing the proportional coefficient value K_{p2}. From that table we concluded that, changing the value of K_{p2} will affect the value of λ_9 which is related to the state variable x_2. The state variable x_2 is describing the relation between the reference quadrature current and the generated quadrature current so by changing the value of K_{p2} the value of the generated quadrature current will be changed.

Table (4.1) Eigenvalues of the DFIG for changing proportional coefficient value K_{p1}

Eigen Value	**σ**	**ω**	**σ**	**ω**	**σ**	**ω**	**σ**	**ω**
	$K_{p1} = 0.5$		**$K_{p1} = 0.75$**		**$K_{p1} = 1$**		**$K_{p1} = 1.25$**	
λ_1	-10	-	-10	-	-10	-	-10	-
λ_2	-1542.9	-	-1542.9	-	-1542.9	-	-1542.9	-
λ_3	-1	+j50	-1	+j50	-1	+j50	-1	+j50
λ_4	-1	-j50	-1	-j50	-1	-j50	-1	-j50
λ_5	-2	+j3	-2	+j3	-2	+j3	-2	+j3
λ_6	-2	-j3	-2	-j3	-2	-j3	-2	-j3
λ_7	-1444	-	-1444	-	-1444	-	-1444	-
λ_8	**-200**	-	**-133**	-	**-100**	-	**-80**	-
λ_9	-27	-	-27	-	-27	-	-27	-
λ_{10}	-175	-	-175	-	-175	-	-175	-
λ_{11}	-27	-	-27	-	-27	-	-27	-
λ_{12}	-10	-	-10	-	-10	-	-10	-
λ_{13}	-8	-	-8	-	-8	-	-8	-
λ_{14}	-10	-	-10	-	-10	-	-10	-
λ_{15}	-27	-	-27	-	-27	-	-27	-

Table (4.2) Eigenvalues of the DFIG for changing proportional coefficient value K_{p2}

Eigen Value	**σ**	**ω**	**σ**	**ω**	**σ**	**ω**	**σ**	**ω**
	$K_{p2} = 0.05$		**$K_{p2} = 0.15$**		**$K_{p2} = 0.3$**		**$K_{p2} = 0.45$**	
λ_1	-10	-	-10	-	-10	-	-10	-
λ_2	-1542.9	-	-1542.9	-	-1542.9	-	-1542.9	-
λ_3	-1	+j50	-1	+j50	-1	+j50	-1	+j50
λ_4	-1	-j50	-1	-j50	-1	-j50	-1	-j50
λ_5	-2	+j3	-2	+j3	-2	+j3	-2	+j3
λ_6	-2	-j3	-2	-j3	-2	-j3	-2	-j3
λ_7	-1444	-	-1444	-	-1444	-	-1444	-
λ_8	-100	-	-100	-	-100	-	-100	-
λ_9	**-160**	-	**-53**	-	**-27**	-	**-18**	-
λ_{10}	-175	-	-175	-	-175	-	-175	-
λ_{11}	**-160**	-	**-53**	-	**-27**	-	**-18**	-
λ_{12}	-10	-	-10	-	-10	-	-10	-
λ_{13}	-8	-	-8	-	-8	-	-8	-
λ_{14}	-10	-	-10	-	-10	-	-10	-
λ_{15}	-27	-	-27	-	-27	-	-27	-

Table (4.3) shows the eigenvalues of the DFIG for changing the proportional coefficient value K_{p3}. From that table we found that, changing the value of K_{p3} will affect the eigenvalue value of λ_{10} which is related to the state variable x_3. The state variable x_3 is describing the relation between the reference stator voltage and the generated stator voltage so by changing the value of K_{p3} the value of the generated voltage will be changed.

Table (4.4) shows the eigenvalues of the DFIG for changing the proportional coefficient value K_{p4}. From the table we find that, changing the value of K_{p4} will affect the value of λ_{15} which is related to the state variable x_5. The state variable x_5 is describing the relation between the reference DC voltage and the generated DC voltage so by changing the value of K_{p4} the value of the generated DC voltage will be changed.

Table (4.3) Eigenvalues of the DFIG for changing proportional coefficient value K_{p3}

Eigen Value	**σ**	**ω**	**σ**	**ω**	**σ**	**ω**	**σ**	**ω**
	K_{p3} = 0.75		**K_{p3} =1**		**K_{p3} = 1.25**		**K_{p3} = 1.5**	
λ_1	-10	-	-10	-	-10	-	-10	-
λ_2	-1542.9	-	-1542.9	-	-1542.9	-	-1542.9	-
λ_3	-1	+j50	-1	+j50	-1	+j50	-1	+j50
λ_4	-1	-j50	-1	-j50	-1	-j50	-1	-j50
λ_5	-2	+j3	-2	+j3	-2	+j3	-2	+j3
λ_6	-2	-j3	-2	-j3	-2	-j3	-2	-j3
λ_7	-1444	-	-1444	-	-1444	-	-1444	-
λ_8	-100	-	-100	-	-100	-	-100	-
λ_9	-27	-	-27	-	-27	-	-27	-
λ_{10}	**-293**	-	**-219**	-	**-175**	-	**-146**	-
λ_{11}	-27	-	-27	-	-27	-	-27	-
λ_{12}	-10	-	-10	-	-10	-	-10	-
λ_{13}	-8	-	-8	-	-8	-	-8	-
λ_{14}	-10	-	-10	-	-10	-	-10	-
λ_{15}	-27	-	-27	-	-27	-	-27	-

Table (4.4) Eigenvalues of the DFIG for changing proportional coefficient value K_{p4}

Eigen Value	**σ**	**ω**	**σ**	**ω**	**σ**	**ω**	**σ**	**ω**
	K_{p4} = 0.05		**K_{p4} = 0.15**		**K_{p4} = 0.3**		**K_{p4} = 0.45**	
λ_1	-10	-	-10	-	-10	-	-10	-
λ_2	-1542.9	-	-1542.9	-	-1542.9	-	-1542.9	-
λ_3	-1	+j50	-1	+j50	-1	+j50	-1	+j50

λ_4	-1	-j50	-1	-j50	-1	-j50	-1	-j50
λ_5	-2	+j3	-2	+j3	-2	+j3	-2	+j3
λ_6	-2	-j3	-2	-j3	-2	-j3	-2	-j3
λ_7	-1444	-	-1444	-	-1444	-	-1444	-
λ_8	-100	-	-100	-	-100	-	-100	-
λ_9	-27	-	-27	-	-27	-	-27	-
λ_{10}	-175	-	-175	-	-175	-	-175	-
λ_{11}	-27	-	-27	-	-27	-	-27	-
λ_{12}	-10	-	-10	-	-10	-	-10	-
λ_{13}	-8	-	-8	-	-8	-	-8	-
λ_{14}	-10	-	-10	-	-10	-	-10	-
λ_{15}	**-160**	-	**-53**	-	**-160**	-	**-53**	-

Table (4.5) shows the eigenvalues of the DFIG for changing the proportional coefficient value K_{p5}. From that table we found that, changing the value of K_{p5} will affect the value of λ_{12} which is related to the state variable x_7 and λ_{12} which is related to the state variable x_4.The state x_7 is describing the relation between the reference terminal voltage and the actual terminal voltage and the state variable x_4 describes the relation between the reference direct current and the generated direct current at the rotor so by changing the value of K_{p5} the values of the actual terminal voltage and the generated direct current at the rotor will be changed.

Table (4.6) shows the eigenvalues of the DFIG for changing the proportional coefficient value K_{p6}. From that table we found that, changing the value of K_{p6} will affect the value of λ_{13} which is related to the state variable x_8. The state variable x_8 describes the relation between the state variable x_7 and the quadrature current at the grid side so by changing the value of K_{p6} the value of the actual quadrature current will be changed.

Table (4.5) Eigenvalues of the DFIG for changing proportional coefficient value K_{p5}

Eigen Value	**σ**	**ω**	**σ**	**ω**	**σ**	**ω**	**σ**	**Ω**
	$K_{p5} = 5$		$K_{p5} = 7.5$		$K_{p5} = 10$		$K_{p5} = 12.5$	
λ_1	-10	-	-10	-	-10	-	-10	-
λ_2	-1542.9	-	-1542.9	-	-1542.9	-	-1542.9	-
λ_3	-1	+j50	-1	+j50	-1	+j50	-1	+j50
λ_4	-1	-j50	-1	-j50	-1	-j50	-1	-j50
λ_5	-2	+j3	-2	+j3	-2	+j3	-2	+j3
λ_6	-2	-j3	-2	-j3	-2	-j3	-2	-j3
λ_7	-1444	-	-1444	-	-1444	-	-1444	-
λ_8	-100	-	-100	-	-100	-	-100	-
λ_9	-27	-	-27	-	-27	-	-27	-
λ_{10}	-175	-	-175	-	-175	-	-175	-
λ_{11}	-27	-	-27	-	-27	-	-27	-
λ_{12}	**-20**	-	**-13**	-	**-20**	-	**-13**	-
λ_{13}	-8	-	-8	-	-8	-	-8	-
λ_{14}	**-20**	-	**-13**	-	**-20**	-	**-13**	-
λ_{15}	-27	-	-27	-	-27	-	-27	-

Table (4.6) Eigenvalues of the DFIG for changing proportional coefficient value K_{p6}

Eigen Value	**σ**	**ω**	**σ**	**ω**	**σ**	**ω**	**σ**	**Ω**
	$K_{p6} = 5$		**$K_{p6} = 10$**		**$K_{p6} = 15$**		**$K_{p6} = 20$**	
λ_1	-10	-	-10	-	-10	-	-10	-
λ_2	-1542.9	-	-1542.9	-	-1542.9	-	-1542.9	-
λ_3	-1	+j50	-1	+j50	-1	+j50	-1	+j50
λ_4	-1	-j50	-1	-j50	-1	-j50	-1	-j50
λ_5	-2	+j3	-2	+j3	-2	+j3	-2	+j3
λ_6	-2	-j3	-2	-j3	-2	-j3	-2	-j3
λ_7	-1444	-	-1444	-	-1444	-	-1444	-

λ_{8}	-100	-	-100	-	-100	-	-100	-
λ_{9}	-27	-	-27	-	-27	-	-27	-
λ_{10}	-175	-	-175	-	-175	-	-175	-
λ_{11}	-27	-	-27	-	-27	-	-27	-
λ_{12}	-10	-	-10	-	-10	-	-10	-
λ_{13}	**-24**	-	**-12**	-	**-8**	-	**-6**	-
λ_{14}	-10	-	-10	-	-10	-	-10	-
λ_{15}	-27	-	-27	-	-27	-	-27	-

Table (4.7) shows the eigenvalues of the DFIG for changing the proportional coefficient value K_{i1}. From that table we concluded that, changing the value of K_{i1} will affect the value of λ_8 which is related to the state variable x_1. The state variable x_1 describes the relation between the reference power and the generated power so by changing the value of K_{p1} the value of the generated power will be changed. So from tables (4.1) and (4.7) by adiusting the values of K_{p1} and K_{i1}, the value of the generated power will be adjusted depending on the desired power required during a certain condition of operation for the tidal cureent turbine.

Table (4.8) the eigenvalues of the DFIG for changing the proportional coefficient value K_{i2}. From that table we concluded that, changing the value of K_{i2} will affect the value of λ_9 which is related to the state variable x_2. The state variable x_2 describes the relation between the reference quadrature current and the generated quadrature current so by changing the value of K_{p2} the value of the generated quadrature current will be changed. So from tables (4.2) and (4.8) by adjusting the values of K_{p2} and K_{i2}, the generated quadrature current will be adjusted depending on the reference quadrature current that be needed during a certain contion.

Table (4.7) Eigenvalues of the DFIG for changing integral coefficient value K_{i1}

Eigen Value	**σ**	**ω**	**σ**	**ω**	**σ**	**ω**	**σ**	**Ω**
	$K_{i1} = 50$		**$K_{i1} = 75$**		**$K_{i1} = 100$**		**$K_{i1} = 125$**	
λ_1	-10	-	-10	-	-10	-	-10	-
λ_2	-1542.9	-	-1542.9	-	-1542.9	-	-1542.9	-
λ_3	-1	+j50	-1	+j50	-1	+j50	-1	+j50
λ_4	-1	-j50	-1	-j50	-1	-j50	-1	-j50
λ_5	-2	+j3	-2	+j3	-2	+j3	-2	+j3
λ_6	-2	-j3	-2	-j3	-2	-j3	-2	-j3
λ_7	-1444	-	-1444	-	-1444	-	-1444	-
λ_8	**-50**	-	**-75**	-	**-100**	-	**-125**	-
λ_9	-27	-	-27	-	-27	-	-27	-
λ_{10}	-175	-	-175	-	-175	-	-175	-
λ_{11}	-27	-	-27	-	-27	-	-27	-
λ_{12}	-10	-	-10	-	-10	-	-10	-
λ_{13}	-8	-	-8	-	-8	-	-8	-
λ_{14}	-10	-	-10	-	-10	-	-10	-
λ_{15}	-27	-	-27	-	-27	-	-27	-

Table (4.8) Eigenvalues of the DFIG for changing integral coefficient value K_{i2}

Eigen Value	**σ**	**ω**	**σ**	**ω**	**σ**	**ω**	**σ**	**Ω**
	$Ki_2 = 4$		**$Ki_2 = 6$**		**$Ki_2 = 8$**		**$Ki_2 = 10$**	
λ_1	-10	-	-10	-	-10	-	-10	-
λ_2	-1542.9	-	-1542.9	-	-1542.9	-	-1542.9	-
λ_3	-1	+j50	-1	+j50	-1	+j50	-1	+j50
λ_4	-1	-j50	-1	-j50	-1	-j50	-1	-j50
λ_5	-2	+j3	-2	+j3	-2	+j3	-2	+j3

λ_6	-2	-j3	-2	-j3	-2	-j3	-2	-j3
λ_7	-1444	-	-1444	-	-1444	-	-1444	-
λ_8	-100	-	-100	-	-100	-	-100	-
λ_9	**-13**	-	**-20**	-	**-27**	-	**-33**	-
λ_{10}	-175	-	-175	-	-175	-	-175	-
λ_{11}	-27	-	-27	-	-27	-	-27	-
λ_{12}	**-13**	-	**-20**	-	**-27**	-	**-33**	-
λ_{13}	-8	-	-8	-	-8	-	-8	-
λ_{14}	-10	-	-10	-	-10	-	-10	-
λ_{15}	-27	-	-27	-	-27	-	-27	-

Table (4.9) shows the eigenvalues of the DFIG for changing the proportional coefficient value K_{i3}. From that table we found that, changing the value of K_{i3} will affect the value of λ_{10} which is related to the state variable x_3. The state variable x_3 describes the relation between the reference stator voltage and the generated stator voltage so by changing the value of K_{i3} the value of the generated voltage will be changed. So from tables (4.3) and (4.9) by adjusting the values of K_{p3} and K_{i3}, the generated stator voltage will be adjusted to a certain value depending on the value of the reference stator voltage during a certain condition of operation.

Table (4.10) shows the eigenvalues of the DFIG for changing the proportional coefficient value K_{i4}. From that table we found that, changing the value of K_{i4} will affect the value of λ_{11} which is related to the state variable x_6 and that will affect the direct generated current at the grid by increasing of decreasing its value depending on the reference value that needed during a certain operation.

Table (4.9) Eigenvalues of the DFIG for changing integral coefficient value K_{i3}

Eigen Value	**σ**	**ω**	**σ**	**ω**	**σ**	**ω**	**σ**	**Ω**
	K_{i3} = 140		**K_{i3} = 180**		**K_{i3} = 220**		**K_{i3} = 260**	
λ_1	-10	-	-10	-	-10	-	-10	-
λ_2	-1542.9	-	-1542.9	-	-1542.9	-	-1542.9	-
λ_3	-1	+j50	-1	+j50	-1	+j50	-1	+j50
λ_4	-1	-j50	-1	-j50	-1	-j50	-1	-j50
λ_5	-2	+j3	-2	+j3	-2	+j3	-2	+j3
λ_6	-2	-j3	-2	-j3	-2	-j3	-2	-j3
λ_7	-1444	-	-1444	-	-1444	-	-1444	-
λ_8	-100	-	-100	-	-100	-	-100	-
λ_9	-27	-	-27	-	-27	-	-27	-
λ_{10}	**-112**	**-**	**-144**	**-**	**-176**	**-**	**-208**	**-**
λ_{11}	-27	-	-27	-	-27	-	-27	-
λ_{12}	-10	-	-10	-	-10	-	-10	-
λ_{13}	-8	-	-8	-	-8	-	-8	-
λ_{14}	-10	-	-10	-	-10	-	-10	-
λ_{15}	-27	-	-27	-	-27	-	-27	-

Table (4.10) Eigenvalues of the DFIG for changing integral coefficient value K_{i4}

Eigen Value	**σ**	**ω**	**σ**	**ω**	**σ**	**ω**	**σ**	**Ω**
	K_{i4}= 4		**K_{i4} = 6**		**K_{i4} = 8**		**K_{i4} = 10**	
λ_1	-10	-	-10	-	-10	-	-10	-
λ_2	-1542.9	-	-1542.9	-	-1542.9	-	-1542.9	-
λ_3	-1	+j50	-1	+j50	-1	+j50	-1	+j50
λ_4	-1	-j50	-1	-j50	-1	-j50	-1	-j50
λ_5	-2	+j3	-2	+j3	-2	+j3	-2	+j3

λ_{6}	-2	-j3	-2	-j3	-2	-j3	-2	-j3
λ_{7}	-1444	-	-1444	-	-1444	-	-1444	-
λ_{8}	-100	-	-100	-	-100	-	-100	-
λ_{9}	-27	-	-27	-	-27	-	-27	-
λ_{10}	-175	-	-175	-	-175	-	-175	-
λ_{11}	**-13**	-	**-20**	-	**-27**	-	**-33**	-
λ_{12}	-10	-	-10	-	-10	-	-10	-
λ_{13}	-8	-	-8	-	-8	-	-8	-
λ_{14}	-10	-	-10	-	-10	-	-10	-
λ_{15}	-27	-	-27	-	-27	-	-27	-

Table (4.11) shows the eigenvalues of the DFIG for changing the proportional coefficient value K_{i5}. From that table we found that, changing the value of K_{i5} will affect the value of λ_{12} which is related to the state variable x_7 and λ_{12} which is related to the state variable x_4. The state variable x_7 is describing the relation between the reference terminal voltage and the actual terminal voltage and the state variable x_4 is describing the relation between the reference direct current and the generated direct current at the rotor so by changing the value of K_{i5} the values of the actual terminal voltage and the generated direct current at the rotor will be changed. So from tables (4.5) and (4.11) by adjsuting the values of K_{p5} and K_{i5}, the generated terminal voltage and generated direct current at the rotor will be adjusted.

Table (4.12) shows the eigenvalues of the DFIG for changing the proportional coefficient value K_{i6}. From that table we found that, changing the value of K_{i6} will affect the value of λ_{13} which is related to the state variable x_7 and that will affect the quadrature generated current at the grid. λ_1 is related to the value of ω_t . λ_2 is related to β (Tidal turbine pitch angle). λ_3, and λ_4 are related to e_d, and e_q. λ_5 is related to ω_r (rotor electrical angular velocities). λ_6 is related to the DC voltage (Voltage of the capacitor). λ_7 is related to θ_{tr} (the difference between the turbine and generator rotor angles).

Table (4.11) Eigenvalues of the DFIG for changing integral coefficient value K_{i5}

Eigen Value	**σ**	**ω**	**σ**	**ω**	**σ**	**ω**	**σ**	**Ω**
	K_{i5} = 50		**K_{i5}= 75**		**K_{i5} = 100**		**K_{i5} = 125**	
λ_1	-10	-	-10	-	-10	-	-10	-
λ_2	-1542.9	-	-1542.9	-	-1542.9	-	-1542.9	-
λ_3	-1	+j50	-1	+j50	-1	+j50	-1	+j50
λ_4	-1	-j50	-1	-j50	-1	-j50	-1	-j50
λ_5	-2	+j3	-2	+j3	-2	+j3	-2	+j3
λ_6	-2	-j3	-2	-j3	-2	-j3	-2	-j3
λ_7	-1444	-	-1444	-	-1444	-	-1444	-
λ_8	-100	-	-100	-	-100	-	-100	-
λ_9	-27	-	-27	-	-27	-	-27	-
λ_{10}	-175	-	-175	-	-175	-	-175	-
λ_{11}	-27	-	-27	-	-27	-	-27	-
λ_{12}	**-5**	**-**	**-7**	**-**	**-10**	**-**	**-13**	**-**
λ_{13}	-8	-	-8	-	-8	-	-8	-
λ_{14}	**-5**	**-**	**-7**	**-**	**-10**	**-**	**-13**	**-**
λ_{15}	-27	-	-27	-	-27	-	-27	-

Table (4.12) Eigenvalues of the DFIG for changing integral coefficient value K_{i6}

Eigen Value	**σ**	**ω**	**σ**	**ω**	**σ**	**ω**	**σ**	**Ω**
	K_{i6}= 80		**K_{i6}=100**		**K_{i6}= 120**		**K_{i6} = 140**	
λ_1	-10	-	-10	-	-10	-	-10	-
λ_2	-1542.9	-	-1542.9	-	-1542.9	-	-1542.9	-
λ_3	-1	+j50	-1	+j50	-1	+j50	-1	+j50
λ_4	-1	-j50	-1	-j50	-1	-j50	-1	-j50
λ_5	-2	+j3	-2	+j3	-2	+j3	-2	+j3
λ_6	-2	-j3	-2	-j3	-2	-j3	-2	-j3

λ_{7}	-1444	-	-1444	-	-1444	-	-1444	-
λ_{8}	-100	-	-100	-	-100	-	-100	-
λ_{9}	-27	-	-27	-	-27	-	-27	-
λ_{10}	-175	-	-175	-	-175	-	-175	-
λ_{11}	-27	-	-27	-	-27	-	-27	-
λ_{12}	-10	-	-10	-	-10	-	-10	-
λ_{13}	**-5**	**-**	**-7**	**-**	**-8**	**-**	**-9**	**-**
λ_{14}	-10	-	-10	-	-10	-	-10	-
λ_{15}	-27	-	-27	-	-27	-	-27	-

Table (4.13) The preferred range of values for the controllers coefficients for DFIG for the stability of the system.

Proportional Controllers Coefficients Range			**Integral Controllers Coefficients Range**		
Coefficient	**Max**	**Min**	**Coefficient**	**Max**	**Min**
K_{p1}	200	0.002	K_{i1}	99999	0.5
K_{p2}	16	0.00009	K_{i2}	29999	0.2
K_{p3}	438	0.003	K_{i3}	12499999	0.7
K_{p4}	17	0.0009	K_{i4}	299999	0.2
K_{p5}	200	0.009	K_{i5}	999999	5
K_{p6}	240	0.009	K_{i6}	1499999	8

4.5.2 DDPMSG Controllers Coefficients

This section compares the effects of specific parameters change on stability but using another generator (DDPMSG). At the end of this section we discuss the preferred ranges of values of the controllers for the stability of the system. Table (4.14) gives the eigenvalues of the 10th order model using DDPMSG. From table (4.14) we concluded that the system is asymptotically stable for a small signal stability analysis. The eigenvalues related to the speed and the DC voltage states (w_t, V_{DC}) have a real parts equal to -5 and -48537 and have zero imaginary part and this enhance the stability degree compared to

DFIG values. Tables (4.14 - 4.18) show the effect of changing the proportional controllers coefficients values for DDPMSG on stability analysis. The most effective proportional coefficient controller is K_{p5}. This coefficient affects two modes of states. The proportional coefficients may be ranked from the most effective to the least effective depending on the changed that they made on the eigenvalues compared to the change of their own values as K_{p5}, K_{p4}, K_{p1}, K_{p3}, K_{p2}.

Table (4.14) Eigenvalues of the DDPMSG for changing proportional coefficient value K_{p1}

Eigen Value	**σ**	**ω**	**σ**	**Ω**	**σ**	**ω**	**σ**	**Ω**
	K_{P1}= 0.3		**K_{P1}= 3**		**K_{P1}=30**		**K_{P1}= 201**	
λ_1	-5	-	-5	-	-5	-	-5	-
λ_2	-1	J250	-1	J250	-1	J250	-1	J250
λ_3	-1	-j250	-1	-j250	-1	-j250	-1	-j250
λ_4	-48537	-	-48537	-	-48537	-	-48537	-
λ_5	**-333**	-	**-33**	-	**-3**	-	**-0**	-
λ_6	-16	-	-16	-	-16	-	-16	-
λ_7	-25	-	-25	-	-25	-	-25	-
λ_8	-100	-	-100	-	-100	-	-100	-
λ_9	-240	-	-240	-	-240	-	-240	-
λ_{10}	-100	-	-100	-	-100	-	-100	-

Table (4.14) shows the eigenvalues of the DDPMSG for changing the proportional coefficient value K_{p1}. From that table we concluded that, changing the value of K_{p1} will affect the value of λ_5 which is related to the state variable x_1. The state variable x_1 describes the relation between the reference power and the generated power so by changing the value of K_{p1} the value of the generated power will be changed.

Table (4.15) shows the eigenvalues of the DDPMSG for changing the proportional coefficient value K_{p2}. From that table we concluded that, changing the value of K_{p2} will affect the value of λ_6 which is related to the state variable x_2. The state variable x_2

describes the relation between the reference direct current and the generated direct current so by changing the value of K_{p2} the value of the generated direct current will be changed.

Table (4.15) Eigenvalues of the DDPMSG for changing proportional coefficient value K_{p2}

Eigen Value	**σ**	**ω**	**σ**	**ω**	**σ**	**ω**	**σ**	**ω**
	K_{P2}= 0.25		**K_{P2}= 0.5**		**K_{P2}=5**		**K_{P2}= 16.1**	
λ_1	-5	-	-5	-	-5	-	-5	-
λ_2	-1	J250	-1	J250	-1	J250	-1	J250
λ_3	-1	-j250	-1	-j250	-1	-j250	-1	-j250
λ_4	-48537	-	-48537	-	-48537	-	-48537	-
λ_5	-333	-	-333	-	-333	-	-333	-
λ_6	**-32**	**-**	**-16**	**-**	**-2**	**-**	**-0**	**-**
λ_7	-25	-	-25	-	-25	-	-25	-
λ_8	-100	-	-100	-	-100	-	-100	-
λ_9	-240	-	-240	-	-240	-	-240	-
λ_{10}	-100	-	-100	-	-100	-	-100	-

Table (4.16) shows the eigenvalues of the DDPMSG for changing the proportional coefficient value K_{p3}. From that table we found that, changing the value of K_{p3} will affect the value of λ_7 which is related to the state variable x_3. The state variable x_3 describes the relation between the reference DC voltage and the generated DC voltage so by changing the value of K_{p3} the value of the generated DC voltage will be changed.

Table (4.17) shows the eigenvalues of the DDPMSG for changing the proportional coefficient value K_{p4}. From that table we found that, changing the value of K_{p4} will affect the value of λ_9 which is related to the state variable x_4 and that will affect the direct generated current at the grid.

Table (4.16) Eigenvalues of the DDPMSG for changing proportional coefficient value K_{p3}

Eigen Value	**σ**	**ω**	**σ**	**ω**	**σ**	**ω**	**σ**	**ω**
	K_{P3}= 0.002		**K_{P3}= 0.005**		**K_{P3}=0.008**		**K_{P3}=0.01**	
λ_1	-5	-	-5	-	-5	-	-5	-
λ_2	-1	J250	-1	J250	-1	J250	-1	J250
λ_3	-1	-j250	-1	-j250	-1	-j250	-1	-j250
λ_4	-48537	-	-48537	-	-48537	-	-48537	-
λ_5	-333	-	-333	-	-333	-	-333	-
λ_6	-16	-	-16	-	-16	-	-16	-
λ_7	**-25**	**-**	**-10**	**-**	**-6**		**-5**	**-**
λ_8	-100	-	-100	-	-100	-	-100	-
λ_9	-240	-	-240	-	-240	-	-240	-
λ_{10}	-100	-	-100	-	-100	-	-100	-

Table (4.17) Eigenvalues of the DDPMSG for changing proportional coefficient value K_{p4}

Eigen Value	**σ**	**ω**	**σ**	**ω**	**σ**	**ω**	**σ**	**ω**
	K_{P4}= 1.25		**K_{P4}= 2.5**		**K_{P4}=3.75**		**K_{P4}=5**	
λ_1	-5	-	-5	-	-5	-	-5	-
λ_2	-1	J250	-1	J250	-6	J250	-12	J250
λ_3	-1	-j250	-1	-j250	-6	-j250	-12	-j250
λ_4	-48537	-	-48537	-	-48537	-	-48537	-
λ_5	-333	-	-333	-	-333	-	-333	-
λ_6	-16	-	-16	-	-16	-	-16	-
λ_7	-25	-	-25	-	-25	-	-25	-
λ_8	-100	-	-100	-	-100	-	-100	-
λ_9	**-240**	**-**	**-120**	**-**	**-80**	**-**	**-60**	**-**
λ_{10}	-100	-	-100	-	-100	-	-100	-

Table (4.18) Eigenvalues of the DDPMSG for changing proportional coefficient value K_{p5}

Eigen Value	**σ**	**ω**	**σ**	**ω**	**σ**	**ω**	**σ**	**ω**
	K_{P5}= 0.1		**K_{P5}= 0.2**		**K_{P5}=0.4**		**K_{P5}=0.8**	
λ_1	-5	-	-5	-	-5	-	-5	-
λ_2	-1	J250	-1	J250	-1	J250	-1	J250
λ_3	-1	-j250	-1	-j250	-1	-j250	-1	-j250
λ_4	-48537	-	-48537	-	-48537	-	-48537	-
λ_5	-333	-	-333	-	-333	-	-333	-
λ_6	-16	-	-16	-	-16	-	-16	-
λ_7	-25	-	-25	-	-25	-	-25	-
λ_8	**-100**	-	**-50**	-	**-25**	-	**-13**	-
λ_9	-240	-	-240	-	-240	-	-240	-
λ_{10}	**-100**	**-**	**-50**	**-**	**-25**	**-**	**-13**	**-**

Table (4.18) shows the Eigenvalues of the DDPMSG for changing the proportional coefficient value K_{p5}. From that table we found that, changing the value of K_{p5} will affect the value of λ_8 which is related to the state variable x_5 and λ_{10} which is related to the state x_6.The state variable x_5 is controlling the relation between the direct current and voltage and x_4 is controlling the relation between the quadrature current and voltage so by changing the value of K_{p5} the values of the direct and quadrature of the current and voltage will be changed.

Tables (4.19 – 4.23) show the effect of changing the values of the integral controllers coefficients on stability analysis. The coefficients may be ranked depending on their effects on the stability. The most effective proportional coefficient controller is K_{i5}. This coefficient affects on two modes. The integral coefficients may be ranked from the most effective to the least effective as K_{i5}, K_{i1}, K_{i4}, K_{i3}, K_{i2}. Table (4.24) shows the range of values for the controllers coefficients for DDPMSG.

Table (4.19) Eigenvalues of the DDPMSG for changing integral coefficient value K_{i1}

Eigen Value	**σ**	**ω**	**σ**	**ω**	**σ**	**ω**	**σ**	**ω**
	K_{i1}= 10		**K_{i1}= 50**		**K_{i1}=100**		**K_{i1}=150**	
λ_1	-5	-	-5	-	-5	-	-5	-
λ_2	-1	J250	-1	J250	-1	J250	-1	J250
λ_3	-1	-j250	-1	-j250	-1	-j250	-1	-j250
λ_4	-48537	-	-48537	-	-48537	-	-48537	-
λ_5	**-33**	**-**	**-167**	**-**	**-333**	**-**	**-667**	**-**
λ_6	-16	-	-16	-	-16	-	-16	-
λ_7	-25	-	-25	-	-25	-	-25	-
λ_8	-100	-	-100	-	-100	-	-100	-
λ_9	-240	-	-240	-	-240	-	-240	-
λ_{10}	-100	-	-100	-	-100	-	-100	-

Table (4.19) shows the eigenvalues of the DDPMSG for changing the proportional coefficient value K_{i1}. From that table we concluded that, changing the value of K_{i1} will affect the value of λ_5 which is related to the state variable x_1. The state variable x_1 describes the relation between the reference power and the generated power so by changing the value of K_{p1} the desired value of the generated power will be changed. So from tables (4.14) and (4.19) by adjusting the values of K_{p1} and K_{i1}, the value of the generated power will be adjusted depending on the desired power.

Table (4.20) shows the eigenvalues of the DDPMSG for changing the proportional coefficient value K_{i2}. From that table we concluded that, changing the value of K_{i2} will affect the value of λ_6 which is related to the state variable x_2. The state variable x_2 describes the relation between the reference direct current and the generated direct current so by changing the value of K_{i2} the desired value of the generated direct current will be changed. So from tables (4.15) and (4.20) by adjusting the values of K_{p2} and K_{i2}, the generated direct current will be adjusted depending on the desired direct current.

Table (4.20) Eigenvalues of the DDPMSG for changing integral coefficient value K_{i2}

Eigen Value	**σ**	**ω**	**σ**	**ω**	**σ**	**ω**	**σ**	**ω**
	K_{i2}= 2		**K_{i2}= 4**		**K_{i2}=8**		**K_{i2}=12**	
λ_1	-5	-	-5	-	-5	-	-5	-
λ_2	-1	J250	-1	J250	-1	J250	-1	J250
λ_3	-1	-j250	-1	-j250	-1	-j250	-1	-j250
λ_4	-48537	-	-48537	-	-48537	-	-48537	-
λ_5	-333	-	-333	-	-333	-	-333	-
λ_6	**-4**	**-**	**-8**	**-**	**-16**	**-**	**-24**	**-**
λ_7	-25	-	-25	-	-25	-	-25	-
λ_8	-100	-	-100	-	-100	-	-100	-
λ_9	-240	-	-240	-	-240	-	-240	-
λ_{10}	-100	-	-100	-	-100	-	-100	-

Table (4.21) shows the eigenvalues of the DDPMSG for changing the proportional coefficient value K_{i3}. From that table we found that, changing the value of K_{i3} will affect the value of λ_7 which is related to the state variable x_3. The state variable x_3 is describing the relation between the reference DC voltage and the generated DC voltage so by changing the value of K_{i3} the value of the generated DC voltage will be changed. So from tables (4.16) and (4.21) by adjusing the values of K_{p3} and K_{i3}, the desired value of the generated DC voltage will be adjusted depending on the desired value.

Table (4.22) shows the eigenvalues of the DDPMSG for changing the proportional coefficient value K_{i4}. From that table we found that, changing the value of K_{i4} will affect the value of λ_9 which is related to the state variable x_4 and that will affect the direct generated current at the grid. So from tables (4.17) and (4.22) by adjusting the values of K_{p4} and K_{i4}, the desired value of direct generated current at the grid will be adjusted depending on the desired value.

Table (4.21) Eigenvalues of the DDPMSG for changing integral coefficient value K_{i3}

Eigen Value	**σ**	**Ω**	**σ**	**ω**	**σ**	**ω**	**σ**	**ω**
	K_{i3}= 0.0125		**K_{i1}= 0.025**		**K_{i1}=0.05**		**K_{i1}=0.075**	
λ_1	-5	-	-5	-	-5	-	-5	-
λ_2	-1	J250	-1	J250	-1	J250	-1	J250
λ_3	-1	-j250	-1	-j250	-1	-j250	-1	-j250
λ_4	-48537	-	-48537	-	-48537	-	-48537	-
λ_5	-333	-	-333	-	-333	-	-333	-
λ_6	-16	-	-16	-	-16	-	-16	-
λ_7	**-6**	**-**	**-13**	**-**	**-25**	**-**	**-37**	**-**
λ_8	-100	-	-100	-	-100	-	-100	-
λ_9	-240	-	-240	-	-240	-	-240	-
λ_{10}	-100	-	-100	-	-100	-	-100	-

Table (4.22) Eigenvalues of the DDPMSG for changing integral coefficient value K_{i4}

Eigen Value	**σ**	**ω**	**σ**	**ω**	**σ**	**ω**	**σ**	**ω**
	K_{i4}= 100		**K_{i4}=200**		**K_{i4}=300**		**K_{i4}=400**	
λ_1	-5	-	-5	-	-5	-	-5	-
λ_2	-1	J250	-1	J250	-6	J250	-12	J250
λ_3	-1	-j250	-1	-j250	-6	-j250	-12	-j250
λ_4	-48537	-	-48537	-	-48537	-	-48537	-
λ_5	-333	-	-333	-	-333	-	-333	-
λ_6	-16	-	-16	-	-16	-	-16	-
λ_7	-25	-	-25	-	-25	-	-25	-
λ_8	-100	-	-100	-	-100	-	-100	-
λ_9	**-80**	**-**	**-160**	**-**	**-240**	**-**	**-320**	**-**
λ_{10}	-100	-	-100	-	-100	-	-100	-

Table (4.23) shows the eigenvalues of the DDPMSG for changing the proportional coefficient value K_{i5}. From that table we found that, changing the value of K_{p5} will affect the value of λ_8 which is related to the state variable x_5 and λ_{10} which is related to the state variable x_6.The state variable x_5 is controlling the relation between the direct current and voltage and the state variable x_4 is controlling the relation between the quadrature current and voltage so by adjusting the value of K_{p5} and K_{i5} the values of the direct and quadrature of the current and voltage will be adjusted to the desired value. λ_1 is related to the state variable of ω_t (the turbine speed at hub height upstream the rotor). λ_2 is related to the state variable of the stator direct current. λ_3 is related to the state variable of the stator quadrature current. λ_4 is related to the state variable of the DC voltage (Voltage of the capacitor). Table (4.24) shows the range of values for the controllers coefficients using DDPMSG for the system stability.

Table (4.23) Eigenvalues of the DDPMSG for changing integral coefficient value K_{i5}

Eigen Value	**σ**	**ω**	**σ**	**ω**	**σ**	**ω**	**σ**	**ω**
	K_{i5}= 2.5		**K_{i5}=5**		**K_{i5}=10**		**K_{i5}=15**	
λ_1	-5	-	-5	-	-5	-	-5	-
λ_2	-1	J250	-1	J250	-1	J250	-1	J250
λ_3	-1	-j250	-1	-j250	-1	-j250	-1	-j250
λ_4	-48537	-	-48537	-	-48537	-	-48537	-
λ_5	-333	-	-333	-	-333	-	-333	-
λ_6	-16	-	-16	-	-16	-	-16	-
λ_7	-25	-	-25	-	-25	-	-25	-
λ_8	**25**	**-**	**50**	**-**	**100**	**-**	**150**	**-**
λ_9	-240	-	-240	-	-240	-	-240	-
λ_{10}	**25**	**-**	**50**	**-**	**100**	**-**	**150**	**-**

Table (4.24) The range of values for the controllers coefficients using DDPMSG for the system stability.

Proportional Controllers Coefficients Range			**Integral Controllers Coefficients Range**		
Coefficient	**Max**	**Min**	**Coefficient**	**Max**	**Min**
K_{p1}	200	0.002	**K_{i1}**	29999	0.2
K_{p2}	16	0.005	**K_{i2}**	49999	0.3
K_{p3}	0.18	0.000001	**K_{i3}**	199	0.0001
K_{p4}	600	0.004	**K_{i4}**	99999	0.7
K_{p5}	20	0.001	**K_{i5}**	9999	0.05

4.6 EFFECT OF CHANGING THE GENERATOR PARAMETERS ON STABILITY (MODEL VALIDATION)

As the value of the resistance or inductance changes the degree of stability will change. In this section we will try to find the relation between the increasing or decreasing these values and the stability degree as a way of validating the model. Table (4.25) shows different values of the resistance and the corresponding eignvalues for DFIG. Figure (4.12) shows the relation between different values of the rotor resistance and the eigenvalues of the changed mode in case of DFIG. Table (4.26) shows different values of the resistance and the corresponding eignvalues for DDPMSG. Figure (4.13) shows the relation between different values of the stator resistance and the eigenvalues of the changed mode in case of DDPMSG. From Figures (4.13, 4.14), (as we expected), as the machine resistance value increases, the stability degree will increase.

Table (4.25) Eigenvalues of DFIG for different values of resistance.

Eigen Value	**σ**	**ω**	**σ**	**ω**	**σ**	**ω**	**σ**	**Ω**
	Rr = 0.5		**Rr = 0.05**		**Rr = 0.01**		**Rr = 0.005**	
λ_1	-10	-	-10	-	-10	-	-10	-
λ_2	-1542.9	-	-1542.9	-	-1542.9	-	-1542.9	-

λ3	-19	+j50	-10	+j50	-5	+j50	-1	+j50
λ4	-1	-j50	-10	-j50	-5	-j50	-1	-j50
λ5	-2	+j3	-2	+j3	-2	+j3	-2	+j3
λ6	-2	-j3	-2	-j3	-2	-j3	-2	-j3
λ7	**-3578**	**-**	**-2911**	**-**	**-2244**	**-**	**-1444**	**-**
λ8	-100	-	-100	-	-100	-	-100	-
λ9	-27	-	-27	-	-27	-	-27	-
λ10	-175	-	-175	-	-175	-	-175	-
λ11	-27	-	-27	-	-27	-	-27	-
λ12	-10	-	-10	-	-10	-	-10	-
λ13	-8	-	-8	-	-8	-	-8	-
λ14	-10	-	-10	-	-10	-	-10	-
λ15	-27	-	-27	-	-27	-	-27	-

Table (4.26) Eigenvalues of DDPMSG for different values of resistance.

Eigen Value	**σ**	**ω**	**σ**	**ω**	**σ**	**ω**	**σ**	**Ω**
	Rs = 0.05		**Rs = 0.1**		**Rs = 1**		**Rs = 2**	
λ1	-5	-	-5	-	-5	-	-5	-
λ2	**-0**	**J250**	**-1**	**J250**	**-6**	**J250**	**-12**	**J250**
λ3	**-0**	**-j250**	**-1**	**-j250**	**-6**	**-j250**	**-12**	**-j250**
λ4	-48537	-	-48537		-48537	-	-48537	-
λ5	-333	-	-333	-	-333	-	-333	-
λ6	-16	-	-16	-	-16	-	-16	-
λ7	-25	-	-25	-	-25	-	-25	-
λ8	-100	-	-100	-	-100	-	-100	-
λ9	-240	-	-240	-	-240	-	-240	-
λ10	-100	-	-100	-	-100	-	-100	-

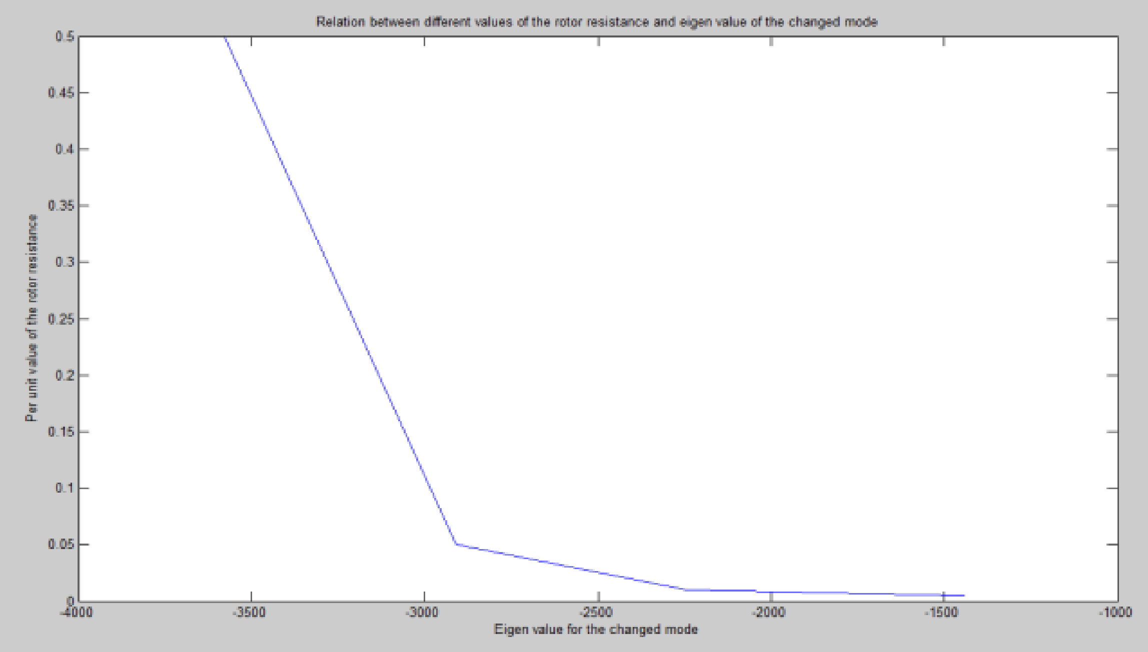


Figure (4.12) The relation between different values of the rotor resistance and the eigen-values of the changed mode in case of DFIG.

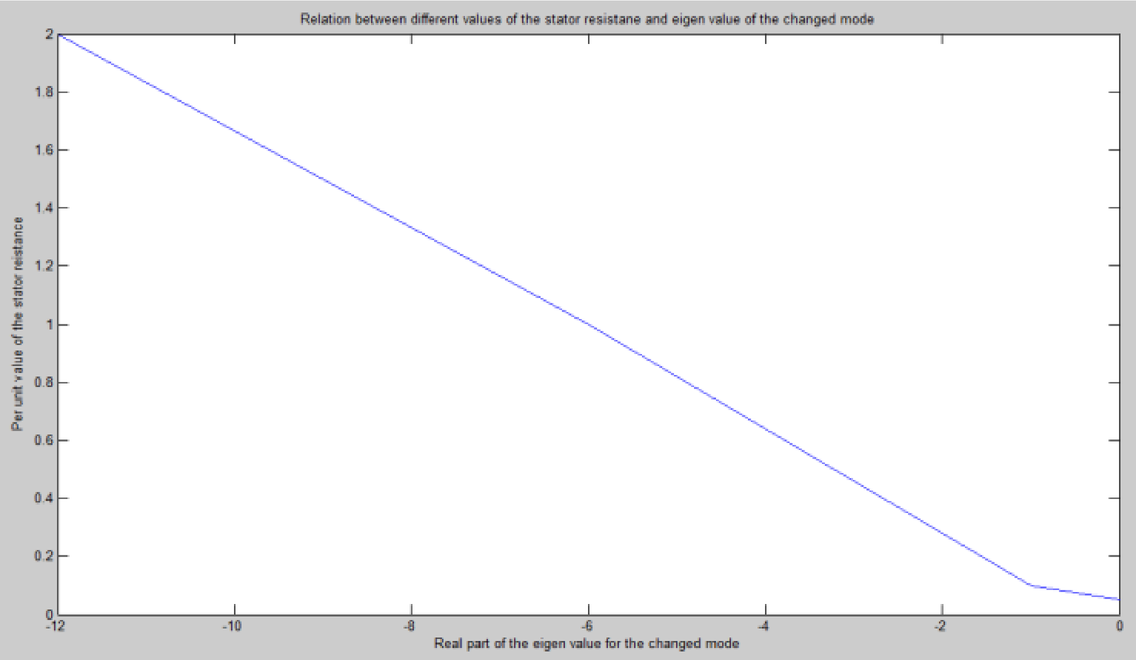


Figure (4.13) The relation between different values of the stator resistance and the eigenvalues of the changed mode in case of DDPMSG.

Table (4.27) Eigenvalues of DFIG for different values of inductance.

Eigen Value	**σ**	**ω**	**σ**	**ω**	**σ**	**ω**	**σ**	**Ω**
	Ls = 0.01		**Ls = 0.1**		**Ls = 1**		**Ls = 2**	
λ_1	-10	-	-10	-	-10	-	-10	-
λ_2	-1542.9	-	-1542.9	-	-1542.9	-	-1542.9	-
λ_3	-1	+j50	-1	+j50	-1	+j50	-1	+j50
λ_4	-1	-j50	-1	-j50	-1	-j50	-1	-j50
λ_5	-2	+j3	-2	+j3	-2	+j3	-2	+j3
λ_6	-2	-j3	-2	-j3	-2	-j3	-2	-j3
λ_7	**-1822**	**-**	**-1750**	**-**	**-1556**	**-**	**-1444**	**-**
λ_8	-100	-	-100	-	-100	-	-100	-
λ_9	-27	-	-27	-	-27	-	-27	-
λ_{10}	-175	-	-175	-	-175	-	-175	-
λ_{11}	-27	-	-27	-	-27	-	-27	-
λ_{12}	-10	-	-10	-	-10	-	-10	-
λ_{13}	-8	-	-8	-	-8	-	-8	-
λ_{14}	-10	-	-10	-	-10	-	-10	-
λ_{15}	-27	-	-27	-	-27	-	-27	-

Table (4.28) Eigenvalues of DDPMSG for different values of inductance.

Eigen Value	**σ**	**ω**	**σ**	**ω**	**σ**	**ω**	**σ**	**Ω**
	Ls = 0.001		**Ls = 0.01**		**Ls = 0.05**		**Ls = 0.1**	
λ_1	-5	-	-5	-	-5	-	-5	-
λ_2	**-100**	**J250**	**-10**	**J250**	**-2**	**J250**	**-1**	**J250**
λ_3	**-100**	**-j250**	**-10**	**-j250**	**-2**	**-j250**	**-1**	**-j250**
λ_4	-48537	-	-48537	-	-48537	-	-48537	-
λ_5	-333	-	-333	-	-333	-	-333	-
λ_6	-16	-	-16	-	-16	-	-16	-

λ_7	-25	-	-25	-	-25	-	-25	-
λ_8	-100	-	-100	-	-100	-	-100	-
λ_9	-240	-	-240	-	-240	-	-240	-
λ_{10}	-100	-	-100	-	-100	-	-100	-

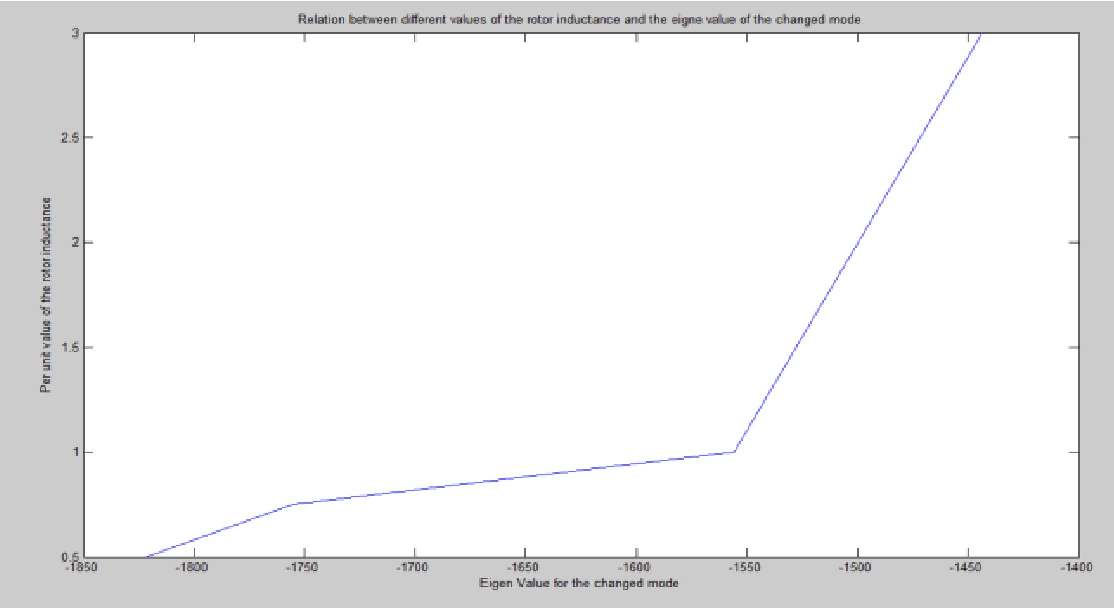


Figure (4.14) The relation between different values of the rotor inductance and the eigenvalues of the changed mode in case of DFIG.

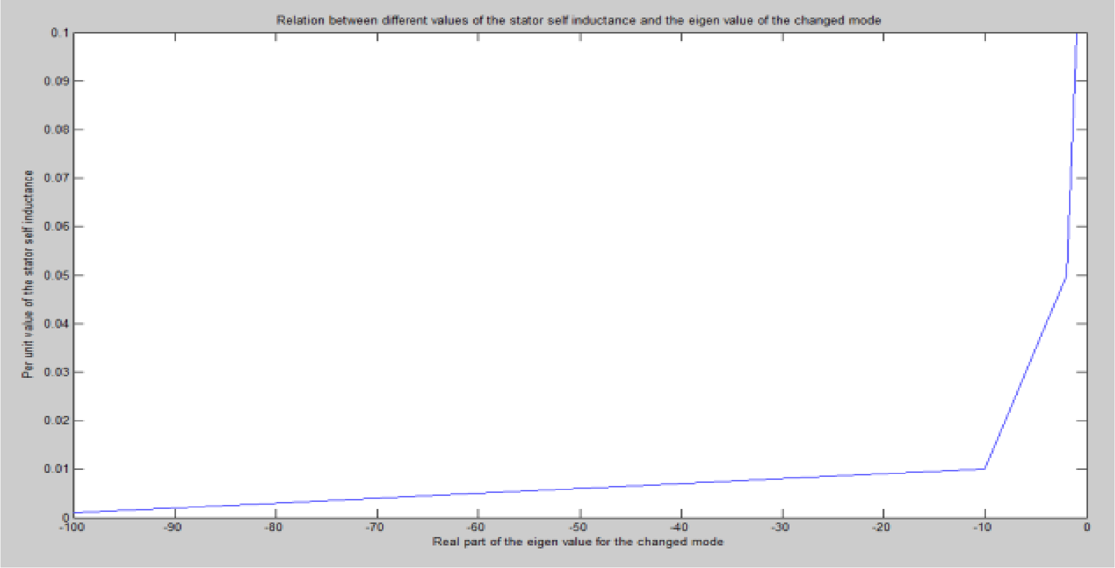


Figure (4.15) The relation between different values of the stator self inductance and the eigenvalues of the changed mode in case of DDPMSG.

Table (4.27) shows different values of the inductance and the corresponding eigenvalues for DFIG. Figure (4.14) shows the relation between different values of the rotor inductance and the eigenvalues of the changed mode in the case of DFIG. Table (4.28) shows different values of the inductance and the corresponding eigenvalues for DDPMSG. Figure (4.15) shows the relation between different values of the stator inductance and the eigenvalues of the changed mode in case of DDPMSG. From Figures (4.14, 4.15), (as we expected), as the inductance value increases the stability will decrease because of increasing the delay time.

4.7 TIDAL CURRENT TURBINE WITH AND WITHOUT THE PROPOSED PI CONTROLLERS

In this section we find the eigenvalues for the overall system using the two types of generators with and without controllers. Table (4.29) gives the eigenvalues of the 7th order model for the system without using the grid side or the rotor side controllers for DFIG. From that we concluded that the system without controllers is marginally stable for a small signal stability analysis. The eigenvalues related to the voltage states (e_d, e_q) have imaginary parts equal to 100 and -100 and zero real parts.

Table (4.29) Eigenvalues of the system without using PI controllers for DFIG.

Eigen Value	**Real part**	**Imaginary part (ω)**	**Freq. (Hz)**
λ_1	-8	-	-
λ_2	-1500	-	-
λ_3	0	+j100	15.9
λ_4	0	-j100	15.9
λ_5	-2	+j3	0.48
λ_6	-2	-j3	0.48
λ_7	-1179	-	-

Table (4.30) shows the eigenvalues of the system using PI controllers for DFIG. From that table we conclude that the system with controllers for DFIG is asymptotically stable. The eigenvalues related to the voltage states (e_d, e_q) have imaginary parts equal to 50 and -50 and real parts equal to -1 and +1. Also some poles of the system are shifted toward the left and this means that the stability of the system is improved by adding the controllers.

Table (4.30) Eigenvalues of the system using PI controllers for DFIG

Eigen Value	**Real part (σ)**	**Imaginary part (ω)**	**Freq. (Hz)**
λ_1	-10	-	-
λ_2	-1542.9	-	-
λ_3	-1	+j50	7.96
λ_4	-1	-j50	7.96
λ_5	-2	+j3	0.48
λ_6	-2	-j3	0.48
λ_7	-1444	-	-
λ_8	-100	-	-
λ_9	-27	-	-
λ_{10}	-175	-	-
λ_{11}	-27	-	-
λ_{12}	-10	-	-
λ_{13}	-8	-	-
λ_{14}	-10	-	-
λ_{15}	-27	-	-

Table (4.31) gives the eigenvalues of the 4th order model for the system using DDPMSG without the controllers. From Table (4.31) we concluded that the system without a controller is marginally stable for a small signal stability analysis. The eigenvalues related to the speed and the DC voltage states (w_t, v_{DC}) have a real parts equal to -4 and -2047.7 and have zero imaginary parts. The eigenvalues related to the direct and the quadrature current of the generator (i_{ds}, i_{qs}) have eigenvalues with imaginary parts only as shown in Table (4.31).

Table (4.31) Eigenvalues of the system without using controllers for DDPMSG.

Eigen Value	**Real part (σ)**	**Imaginary part (ω)**	**Freq. (Hz)**
λ₁	-4	-	-
λ₂	0	+j250	39.79
λ₃	0	-j250	39.79
λ₄	-2047.7	-	-

Table (4.32) shows the eigenvalues of the system using PI controllers for DDPMSG. From Table (4.32) we concluded that the system with the proposed controllers is asymptotically stable. The eigenvalues related to the speed and the DC voltage states (w_t, v_{DC}) have real parts equal to -15 and -48,537 and have zero imaginary part. The eigenvalues related to the direct and the quadrature current (i_{ds}, i_{qs}) have values with real and imaginary parts hence these two states affect system stability after using the controller. Also the poles of the system are shifted towards the left and this means that the stability increased by adding the controller.

Table (4.32) Eigenvalues of the system using PI controllers for DDPMSG.

Eigen Value	**Real part (σ)**	**Imaginary part (ω)**	**Freq. (Hz)**
λ₁	-15	-	-
λ₂	-1	J200	31.8
λ₃	-1	-j200	31.8
λ₄	-48537	-	-
λ₅	-333	-	-
λ₆	-16	-	-
λ₇	-25	-	-
λ₈	-100	-	-
λ₉	-240	-	-
λ₁₀	-100	-	-

From the previous tables for DDPMSG and DFIG we found that using the proposed PI controllers increases the system stability for both types of generators used. Also we concluded that the turbine based on DDPMSG is more stable than the turbine based on DFIG as the eigenvalues for the turbine based on DDPMSG are more negative than the eigenvalues for the turbine based on DFIG. The generator speed and the DC voltage are more stable for the turbine based on DDPMSG than for the turbine based on DFIG. Hence the power fed to the grid using DDPMSG is more stable than the power fed to the grid using DFIG because the power depends on the DC voltage. Maintenance for the DDPMSG is easier than the DFIG as there is no gearbox. Consequently, using of DDPMSG is more beneficial than DFIG for tidal current turbine.

4.8 SUMMARY

The overall dynamic system of the tidal current turbine based on two different types of generators for a single machine infinite bus system and the controllers used for improving the power system stability has been modeled. The equations for a small signal stability analysis for the two generators types have been formulated. The results of the small signal stability analysis show the better performance of the tidal current turbines using a DDPMSG compared to DFIG. Tidal current turbines without controllers do have the capability to sustain a small disturbance for a long period but it is more beneficial to use PI controllers with the tidal current turbines to improve system stability. As the value of the coefficients of the PI controllers change, the stability degree will change. For DFIG the most effective proportional coefficient controller is K_{p2} and the most effective integral coefficient controller is K_{i3}. For DDPMSG the most effective proportional coefficient controller is K_{p5} and the most effective integral coefficient controller is K_{i5}. The preferred ranges of the controllers coefficients values for the system stability are concluded for both types of machines used in this work. The model is validated by finding the relation between the increasing or decreasing the generator parameters and the stability degree (As the resistance value for both types of generators increases, the stability degree will increase but the system efficiency will decrease. In contrast, as the inductance value of the machine increases, the stability degree will decrease).

CHAPTER 5 CONCLUSIONS AND FUTURE WORK

5.1 CONTRIBUTIONS AND CONCLUSIONS

Among renewable sources, tidal current energy shows great promise for satisfying future energy needs. However, as technology related to the energy sources is still in its infancy, vast improvements need to be made before it can truly become a commercially viable alternative. For instance, it is important to accurately forecast tidal current energy and to modify the control system depending on the forecasted model to adjust the output power. Also, during the faulty behavior, generators used for converting renewable energy will be different compared to generators used for the nonrenewable energy conversion. In this thesis, a proposed model for forecasting the tidal current was covered in Chapter 3, and proposed controllers for tidal current turbine driving two types of machines was discussed in Chapter 4.

Harmonic tidal current constituent analysis and numerical hydrodynamic models are the two most commonly used models for tidal current prediction. Recently, an artificial neural network is being widely used in to overcome the problem of nonlinear relationships. However, these models have significant limitations, and nonlinear data adaptive approaches are consequently gaining increasing acceptance. Numerical hydrodynamic models require large computing resources and huge input information. This thesis proposed a hybrid model of ANN and FLSM for tidal current prediction. It was proved that using either FLSM or ANN alone to predict tidal current speed magnitude and direction is not recommended. Instead, a hybrid of ANN and FLSM provides a more suitable model for tidal current data prediction and also has a high accuracy. The procedure of back propagation of neural network (BPN) used in this work repeatedly adjusts the weights of the connections in the network so as to minimize the measure of the difference between the actual output vector and the desired output vector. In this work we used the proposed model for the speed and direction prediction of the tidal currents, with the model giving good results. The novelty of this model is the use of the ANN technique to forecast resulting principal components from a few observed tidal levels with the use of

FLSM. Its accuracy is also very high compared to ANN or FLSM alone. The proposed model is easy to be used and only depends on the input data (speed or direction) without knowing the tides constituents because we covered all cycles without keeping in mind the type of the cycle so we didn't need more analysis of the data, just use the model for predicting of the speed and the direction using the time as an input. This model is used for more than month (33.67 days) prediction and the results proved its robustness. This model is validated by using another type of data for the tidal current direction.

In the second part of the thesis the overall dynamic system of a tidal current turbine based on two different types of generators for a single machine infinite bus system and the controllers used for improving the power system stability has been modeled. As well, the equations for a small signal stability analysis for the two generators types have been formulated. The results of the small signal stability analysis show the better performance of the tidal current turbines using a DDPMSG compared to DFIG. While tidal current turbines without controllers do have the capability to sustain a small disturbance for a long period, it is more beneficial to use the proposed PI controllers with the tidal current turbines to improve system stability. It has been shown that tidal current turbines equipped with the presented control strategy for normal operation and for grid fault operation can contribute to power system stability.

The coefficients of the proposed PI controllers have a great effect on the system stability. As the value of the coefficients of the PI controllers change, the stability degree will also change. For DFIG, the most effective proportional coefficient controller is K_{p2} and the most effective integral coefficient controller is K_{i3}. For DDPMSG, the most effective proportional coefficient controller is K_{p5} and the most effective integral coefficient controller is K_{i5}. The preferred ranges of the controller coefficient values for system stability are concluded for both types of machines used in this work. The model is validated by finding the relation between increasing or decreasing generator parameters and the stability degree. We found that as the resistance value for both types of generators increases, the stability degree will increase but the system efficiency will decrease. Conversely, as the inductance value of the machine increases, the stability degree will decrease. These PI controllers are used for both types of machines used with tidal current turbines for a wide range of values and the results proved the robustness of the tidal current turbine with the proposed PI controllers over those without controllers during a fault condition.

5.2 FUTURE WORK

The forecasting for the tidal current turbine presented in this work can be further extended and enhanced. The following subjects may shed some light on the intended work extensions:

- The error between the forecasted data from the hybrid model and the actual data can be fed again to another forecasting program like Wavelet. The hybrid model for that case will consist of three models: FLSM, ANN and Wavelet.
- The overall error will be affected by the order of the used programmes (i.e., FLSM, ANN, then Wavelet or FLSM, Wavelet, then ANN or ANN, FLSM, then Wavelet or Wavelet, FLSM, then ANN, and so on). Thus, we have nine models and should rank these models depending on their accuracy and ability to provide the best model for tidal current forecasting.
- Extending this work to forecast solar energy will be easy because the input for the model will be not only one compared to the tidal current, so the accuracy will be high.

The proposed PI controllers for the tidal current turbine have numerous parameters that will affect system stability and the zone of the stability. These include the following considerations:

- Future work should focus on optimal values for PI controller coefficients in order to enhance system stability using heuristic or non-heuristic tools for future work. Several heuristic tools have evolved over the past few years (e.g., ant colony optimization, bacteria swarm foraging optimization method, and bee algorithm) that have shown the capability of solving different optimization problems.

- The fuzzy set theory can be used for the proposed controllers for the tidal current turbine. It can also be used for PI controllers coefficients optimization.

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APPENDIX A

DATA USED FOR TIDAL CURRENT FORECASTING

Training data for tidal current direction for FLSM model

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P = [1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25
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Validating data for tidal current current for FLSM model

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Training data for tidal current direction for ANN

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0.507426 0.473021 0.438052 0.473585 0.474149 0.447077 0.400263 0.421508
0.361534 0.339538 0.305321 0.276556 0.244407 0.166761 0.144200
0.139500....
0.077646 0.056214 0.084038 0.105471 0.123143 0.128596 0.176349 0.258695
0.289904 0.274676 0.300620 0.318481 0.329009 0.342922 0.378267
0.380147....
0.394999 0.369054 0.362850 0.402707 0.344614 0.370934 0.348562 0.359466
0.308329 0.354390 0.325813 0.342170 0.313593 0.280880 0.236699
0.243655....
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0.015980 0.049069 0.100207 0.145140 0.165445 0.201730 0.248919....
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0.576612 0.550855 0.553487 0.535627 0.555744 0.555180 0.520211
0.510058....
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0.318669 0.310397 0.276744 0.213198 0.188757 0.128032 0.079714
0.065802....
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0.376011 0.422824 0.396315 0.406279 0.451401 0.439932 0.460989
0.444256....
0.450085 0.409663 0.416056 0.416432 0.383155 0.392743 0.394999 0.373190
0.361910 0.350442 0.304381 0.273548 0.245159 0.246287 0.239519
0.198346....
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0.138184 0.119947 0.078962 0.030457 0.016920 0.058470 0.114871 0.157172
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0.489942....
0.496710 0.522467 0.557436 0.555368 0.547659 0.555932 0.559504 0.538635
0.541455 0.527355 0.509870 0.540139 0.513254 0.482422....
0.473585 0.464373 0.431472 0.395939 0.359842 0.326941 0.297424 0.261891
0.217898 0.160745....
0.112239 0.064674 0.054334 0.089867 0.113931 0.174093 0.171649 0.243843
0.255123 0.282384 0.310961 0.351194 0.362662 0.384659 0.373002
0.394999....
0.420756 0.431284 0.436360 0.426960 0.405339 0.377891 0.407031 0.386915
0.388795 0.354766 0.354954 0.347622 0.301560 0.323745 0.316225
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0.072006 0.117315 0.156044 0.187817 0.237451 0.291972 0.298928
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0.566084 0.568904 0.554428 0.552923 0.544839 0.563264 0.533747
0.532619....
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0.268472 0.223726 0.140628 0.104907 0.066366 0.096071 0.116939
0.155480....
0.170145 0.239895 0.257755 0.279376 0.344238 0.394999 0.402895 0.410980
0.424140....
0.430532 0.482986....
0.421320 0.492386 0.471329 0.439368 0.418876 0.451777 0.410415 0.444632
0.389547 0.387479 0.366798 0.371122 0.373002 0.348186 0.294980
0.272608....
0.248731 0.198534 0.155292 0.144952 0.092499 0.064298 0.024817 0.040421
0.095131 0.150592 0.176161 0.215454 0.236135 0.266027 0.336529
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0.625306 0.571912 0.588080 0.572852 0.525099 0.551607 0.552171
0.523971....
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0.236699 0.215266 0.162249 0.130100 0.074074 0.059222 0.095319
0.156796....
0.214890 0.193457 0.287272 0.309457 0.271480 0.326001 0.387855 0.354578
0.409287 0.440872 0.433916 0.442752 0.435044 0.476029 0.422824
0.429404....
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0.325813 0.306261 0.278624 0.238767 0.184997 0.167137 0.126528
0.073886....
0.050761 0.037037 0.039857....
0.101335 0.152096 0.184245 0.231434 0.256815 0.321865 0.399699....
0.446324 0.482610 0.494078 0.512690 0.521715 0.582064 0.591089 0.571348
0.602557 0.580748 0.564016 0.541643 0.563076 0.544463 0.579808
0.515886....
0.486746 0.489190 0.474525 0.436736 0.439368 0.402143 0.343298 0.293100
0.269976 0.225982 0.199286 0.164317 0.094755 0.064110 0.101711
0.127844....
0.167701 0.195901 0.290468 0.293288 0.309645 0.348186 0.365670 0.396503
0.429780 0.442188 0.519835 0.456101 0.463809 0.495958 0.453657
0.435608....
0.460989 0.457981 0.399323 0.413424 0.386351 0.385223 0.398571 0.397067
0.332393 0.304569 0.341042 0.297612 0.238767 0.212822 0.144012
0.128032....
```

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0.086670 0.048505 0.017672 0.072006 0.128784 0.159616 0.200978 0.235195
0.281820 0.303440 0.388231 0.423764 0.485054 0.523407 0.526415
0.558000....
0.599173 0.590149 0.618913 0.600113 0.585072 0.554804 0.545591 0.545403
0.563828 0.564204 0.547847 0.539387....
0.518519 0.453093 0.432224 0.421320 0.395187 0.357962 0.341606 0.284828
0.232187 0.210942 0.152848 0.119947 0.057530....
0.072006 0.124647 0.175221 0.218462 0.225794 0.318857 0.280316 0.313781
0.368678 0.357210 0.365482 0.390111 0.397255 0.437676 0.454221
0.475277....
0.463809 0.411168 0.415492 0.408347 0.398383 0.391427 0.366234 0.328821
0.326565 0.316977 0.291408 0.327881 0.280880 0.265275 0.239143
0.178041....
0.150216 0.033277 0.026509 0.018801];
```

APPENDIX B

PARAMETERS

Tidal current turbine parameters

R=18 m, R_s= 0.01 pu, C_p=0.46, V_{tide}=4 m/s,H_t=3 s, H_g= 0.5 s, K_s=0.171, K_{pt}=10, K_{it}=100, K_s= 10 pu, D_s= 3.14 pu.

Generator parameters

L_m=2.9pu, L_r=0.156 pu, L_s=0.171 pu, R_r=0.005pu.

Converter parameters

V_{DC}=1.5 pu, C=0.0001 pu.

Controller parameters for DFIG

K_{p1}=1 pu, K_{p2}=0.3 pu, K_{p3}=1.25 pu, K_{p4}=0.3 pu, K_{p5}=10 pu, K_{p6}=15 pu, K_{i1}=100 s^{-1}, K_{i2}=8 s^{-1}, K_{i3}=219 s^{-1}, K_{i4}=8 s^{-1}, K_{i5}=100 s^{-1}, K_{i6}=120 s^{-1}.

Controller parameters for DDPMSG

K_{p1}=0.3 pu, K_{p2}=0.5 pu, K_{p3}=0.002 pu, K_{p4}=1.25 pu, K_{p5}=0.1pu, K_{i1}=100s^{-1}, K_{i2}=8 s^{-1}, K_{i3}=0.05 s^{-1}, K_{i4}=300 s^{-1}, K_{i5}=10 s^{-1}.