A Power System Reliability Evaluation Technique and Education Tool for Wind Energy Integration

by

Anubhav Sinha

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Graduate Supervisory Committee:

Gerald Heydt, Co-Chair
Vijay Vittal, Co-Chair
Raja Ayyanar
George Karady

ARIZONA STATE UNIVERSITY

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ABSTRACT

This thesis is focused on the study of wind energy integration and is divided into two segments. The first part of the thesis deals with developing a reliability evaluation technique for a wind integrated power system. A multiple-partial outage model is utilized to accurately calculate the wind generation availability. A methodology is presented to estimate the outage probability of wind generators while incorporating their reduced power output levels at low wind speeds. Subsequently, power system reliability is assessed by calculating the loss of load probability (LOLP) and the effect of wind integration on the overall system is analyzed.

Actual generation and load data of the Texas power system in 2008 are used to construct a test case. To demonstrate the robustness of the method, reliability studies have been conducted for a fairly constant as well as for a largely varying wind generation profile. Further, the case of increased wind generation penetration level has been simulated and comments made about the usability of the proposed method to aid in power system planning in scenarios of future expansion of wind energy infrastructure.

The second part of this thesis explains the development of a graphic user interface (GUI) to demonstrate the operation of a grid connected doubly fed induction generator (DFIG). The theory of DFIG and its back-to-back power converter is described. The GUI illustrates the power flow, behavior of the electrical circuit and the maximum power point tracking of the machine for a variable wind speed input provided by the user. The tool, although developed on MATLAB software platform, has been constructed to work as a standalone application on

Windows operating system based computer and enables even the non-engineering students to access it.

Results of both the segments of the thesis are discussed. Remarks are presented about the validity of the reliability technique and GUI interface for variable wind speed conditions. Improvements have been suggested to enable the use of the reliability technique for a more elaborate system. Recommendations have been made about expanding the features of the GUI tool and to use it to promote educational interest about renewable power engineering.

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TABLE OF CONTENTS

Page

LIST OF TABLES……………………………………………………………..viii

LIST OF FIGURES…………………………………………………………....ix

NOMENCLATURE…………………………………………………………..xii

CHAPTER

1 INTRODUCTION TO WIND ENERGY RELIABILITY AND WIND GENERATION CONFIGURATIONS…………………………………..…………1

1.1 Objectives…………………………………………………………....1

1.2 Motivation……………………………………………………………2

1.2.1 Reliability studies for wind integrated power systems……………...2

1.2.2 A "hands on" educational tool for DFIG wind energy systems……..3

1.3 Literature survey: partial outage representation in conventional generation system…..…………………………………………………..…….4

1.4 Literature survey: impact of wind generation on LOLP…………………..6

1.5 Literature survey: wind generation configurations for wind turbines.........8

1.6 Organization of thesis…………………………………………………....10

2 THEORY AND ANALYSIS OF POWER SYSTEM RELIABILITY STUDIES…………………………………………………………..….........12

2.1 System reliability and its measurement……………………………........12

CHAPTER Page

2.2 The capacity outage table (COT)……………………………………...13

2.3 The load duration curve (LDC)…………………………………………..14

2.4 Loss of load probability………………………………………….........17

2.5 Problems in developing reliability indices for wind generation................18

2.6 LOLP calculation methodology for wind generation profile……….........19

2.7 Segregation of wind generation profile into intervals……………………20

2.8 EFOR calculation…………………………………………………...22

3 TEST BED, SIMULATION AND RESULTS………………………………25

3.1 Reliability calculation through proposed method………………………..25

3.2 Choice of the Texas power system as test case…………………………..25

3.3 Description of test case……………………………………………..26

3.4 Simulation showing LOLP and EFOR variation for the test case…..........29

3.4.1 Case #1: 9th June 2008……………………………………………..29

3.4.2 Case #2: 23rd December 2008……………………………………...34

3.5 Results depicting the effect of increased wind penetration……………...39

3.5.1 Case #1: 9th June 2008……………………………………………..39

3.5.2 Case #2: 23rd December 2008……………………………………...40

CHAPTER Page

4 THEORY OF WIND GENERATION TECHNOLOGIES AND THE DFIG POWER CONVERTER TOPOLOGY…………………………………….....42

4.1 Overview: wind turbine configurations…………………………….........42

4.2 The doubly fed induction generators…………………………….........45

4.2.1 Power flow in a DFIG machine……………………………………45

4.2.2 The rotor side converter……………………………………………49

4.2.3 The grid side converter…………………………………………….51

4.2.4 Equivalent circuit for a DFIG……………………………………...51

4.2.5 Phasor diagram of a DFIG machine………………………………..53

5 CONSTRUCTION OF A GRAPHICAL USER INTERFACE FOR THE DFIG GENERATION SYSTEM……………………………………........55

5.1 Choice of MATLAB for GUI construction……………………………...55

5.2 Features of the GUI for simulation of a DFIG system…………………...56

5.2.1 The power flow interface…………………………………………..57

5.2.2 The equivalent circuit interface……………………………………59

5.2.3 The phasor diagram interface………………………………………60

5.2.4 Maximum power point tracking interface………………………….62

CHAPTER Page

6 CONCLUSIONS AND RECOMMENDATIONS…………………………..65

6.1 Reliability assessment technique……………………………………...65

6.2 GUI construction for a DFIG system……………………………........66

REFERENCES……………………………………………………………..67

APPENDIX

A MATLAB CODE FOR RELIABILITY STUDY IMPLEMENTATION ON TEXAS POWER SYSTEM……………………….…………...............72

B MATLAB CODE FOR THE DFIG OPERATION GUI……………..……...93

C INSTALLATION INSTRUCTIONS FOR STAND ALONE GUI………...129

LIST OF TABLES

Table Page

3.1 Installed capacity of Texas power system in 2008……………..……………26

3.2 Typical values of forced outage rates for some major sources…………..…..27

3.3 Test case for analysis…………………………………………..……….27

4.1 Parameters for a 1.5 MW General Electric wind turbine……………….....…..50

4.2 List of abbreviations used in Figure 4.9…………………………………...52

5.1 Specification of wind turbine used as test case for GUI design……………..56

LIST OF FIGURES

Figure Page

1.1 Motivation and approach for the thesis……………………………………..2

2.1 Typical capacity outage table…………………………………………...14

2.2 Example of a load curve………………………………………………..15

2.3 Load duration curve derived from Figure 2.2………………………………..15

2.4 Load duration curve for a high load factor…………………………………..16

2.5 Load duration curve for a low load factor…………………………………...16

2.6 Wind generation profile of Texas in June 2008……………………………...20

2.7 Derivation of additional data points by using cubic splines…………………22

2.8 Flowchart depicting proposed methodology of LOLP calculation…………..24

3.1 Load duration curve for load in Texas in year 2008…………………………27

3.2 Hourly wind generation of Texas on 9th June 2008………………………….29

3.3 Individual generation profile of wind generators in test case………………..30

3.4 Derivation of additional data points by implementing cubic spline for 72 inte-
vals……………………..………………………………………...………..31

3.5 Variation of LOLP with change in number of intervals……………………..33

3.6 Variation of EFOR with change in number of intervals……………………..33

3.7 Hourly wind generation of Texas on 23rd December 2008…………………..35

Figure Page

3.8 Individual generation profile of wind generators in test case #2…………….35

3.9 Derivation of additional data points by implementing cubic spline for 72 inte-
vals..……………………………………………………………………...…..36

3.10 Variation of LOLP with change in number of intervals for case #2………..37

3.11 Variation of EFOR with change in number of intervals for case #2……….38

3.12 LOLP variation with change in wind penetration level for case #1………..39

3.13 EFOR variation with change in wind penetration level for case #1………..40

3.14 LOLP variation with change in wind penetration level for case #2………..40

3.15 EFOR variation with change in wind penetration level for case #2………..41

4.1 Type 1 wind turbine configuration………………………………………..43

4.2 Type 2 wind turbine configuration………………………………………..43

4.3 Type 3 wind turbine configuration………………………………………..44

4.4 Type 4 wind turbine configuration………………………………………..44

4.5 Power flow in a DFIG based configuration (Type 3)………………………..45

4.6 Power flow in a DFIG machine in subsynchronous mode…………………..48

4.7 Power flow in a DFIG machine in supersynchronous mode………………...48

4.8 Turbine tracking characteristics…………………………………………...51

4.9 Equivalent circuit of a DFIG machine…………………………………….52

Figure Page

4.10 Phasor diagram of a DFIG machine for a unity power factor………………54

4.11 Phasor diagram of a DFIG machine for a lagging power factor……………54

5.1 Power flow GUI showing subsynchronous operation……………………….58

5.2 Power flow GUI showing supersynchronous operation……………………..58

5.3 DFIG equivalent circuit GUI interface for unity power factor operation at wind speed 7 m/s……………………..………………………………………59

5.4 DFIG equivalent circuit GUI interface for unity power factor operation at wind speed 10 m/s………………..……………………………………….60

5.5 Wind speed 14 m/s and unity power factor………………………………….61

5.6 Wind speed 14 m/s and power factor angle -35 degrees…………………….61

5.7 Wind speed 14 m/s and power factor angle 35 degrees……………………...62

5.8 Maximum power point tracking GUI at wind speed 6 m/s…………………..63

5.9 Maximum power point tracking GUI at wind speed 9 m/s………………......63

5.10 Maximum power point tracking GUI at wind speed 12.5 m/s……………...64

NOMENCLATURE

A	Area swept by wind turbine blades
ARMA	Autoregressive moving average
c_i	Constants used to calculate wind turbine power coefficient
C_p	Wind turbine power coefficient
CDF	Cumulative probability density
COT	Capacity outage table
DF	Derating factor
DFIG	Doubly fed induction generator
E	Generator internal EMF
EFOR	Equivalent forced outage rate
EFORd	Equivalent demand forced outage rate
EMF	Electro motive force
ERCOT	Electric Reliability Council of Texas
f_0	Probability of full capacity outage
FOH	Forced outage hours
FOR	Forced outage rate
GE	General Electric Co.
GUI	Graphic user interface
I_m	DFIG magnetizing current
I_r'	DFIG rotor current reflected to primary
I_s	DFIG stator current
L_{lr}	Rotor leakage inductance
L_{ls}	Stator leakage inductance
L_m	Magnetizing inductance
LDC	Load duration curve
LOLE	Loss of load expectation
LOLP	Loss of load probability
P_{gap}	Power transferred trough air gap
P_{loss_rotor}	Power loss in the rotor circuit
P_{loss_stator}	Power loss in the stator circuit
P_m	Power input into rotor from wind turbine
P_{m_pu}	Per unit power input into rotor from turbine

P_{mech}	Mechanical power output of wind turbine
P_r	Power transferred between the rotor and rotor converter
P_s	Power into the stator
PMSG	Permanent magnet synchronous generator
R_r'	Equivalent resistance of the rotor circuit reflected to stator side
R_s	Equivalent resistance of the stator circuit
RPS	Renewable portfolio standards
s	Generator operating slip
SCIG	Squirrel cage induction generator
SH	Service hours
SVPWM	Space vector pulse modulated wave
t_i	Duration of reduced output in the ith interval
TSR	Tip speed ratio
v	Wind speed
V_{rotor}	Voltage across the rotor circuit of DFIG (per phase)
V_{stator}	Voltage across the stator circuit of DFIG (per phase)
WRIG	Wound rotor induction generator
X_r'	Equivalent reactance of the rotor circuit reflected to the stator side
X_s	Equivalent reactance of the stator circuit
θ	Pitch angle of wind turbine blades
λ	Tip speed ratio
λ_i	Constant used in power coefficient calculation
ρ	Air density
ω_r	Rotor electrical frequency
ω_{ref}	Rotor speed reference
ω_s	Stator electrical frequency
ω_t	Angular turbine speed in per unit

CHAPTER 1

INTRODUCTION TO WIND ENERGY RELIABILITY AND WIND GENERATION CONFIGURATIONS

1.1 Objectives

Reliability analysis in power system planning and power electronics is the key driving force to enable an enhanced wind generation penetration in the future. To realistically visualize the effect of increased wind penetration and to estimate the extent of penetration possible, accurate power system reliability analysis techniques are necessary. Additionally, to realize a targeted level of wind energy penetration, efficient power electronics technology is instrumental for large scale wind integration. A further objective of this thesis is to provide an educational tool as a framework and motivating element for students who might make their careers in the electric energy area. The main objectives of this thesis are to evaluate the role of reliability analysis and power electronics and to provide an educational tool relating to wind energy by:

- Developing an accurate reliability representation for wind integrated power systems and to enable power systems planning.
- Developing an educational tool to promote an understanding of contemporary wind generator technology including power electronics.

Figure 1.1 pictorially describes the motivation and approach of this thesis.

1.2 Motivation

1.2.1 Reliability studies for wind energy integrated power systems

A reliable electricity infrastructure is a key factor in driving any economy. Power outages reflect directly into the production costs of industries. It is estimated that owing to unreliable power delivery, US businesses incur a loss of approximately $100 billion annually [1]. Nonetheless, industrial customers are willing to pay more for a continuous and reliable power supply and thereby reduce their outage expense which could result in higher costs. Such economic emphasis makes the need for an accurate power systems reliability study more important.

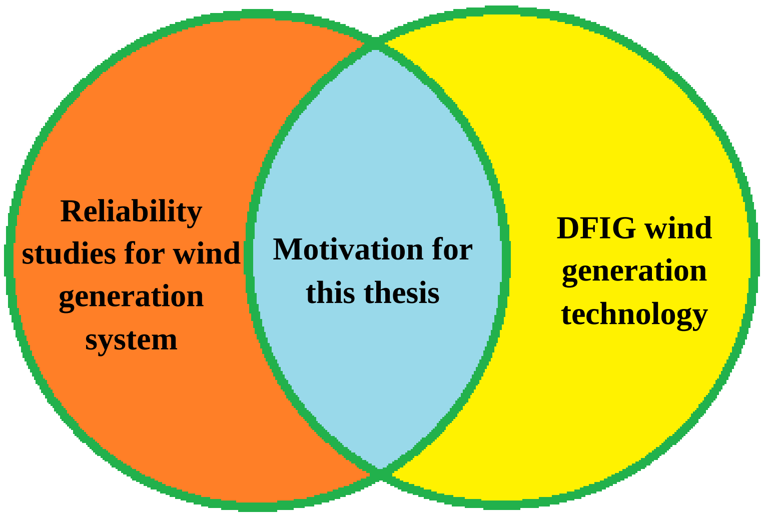

Reliability studies for wind generation system
Motivation for this thesis
DFIG wind generation technology

Figure 1.1 Motivation and approach for the thesis

Reliability studies provide an indication of the capabilities of a power system to supply electricity without failure and constitute an important ingredient of power system planning studies. They aid in formulating a predictive assessment of customer outage cost and thus help towards designing a ‘fail-safe’ infrastructure that meets the desired level of expectancy of power delivery [2].

While conducting reliability studies for any typical power system, calculation of an index such as the loss of load probability (LOLP) requires three ingredients:

- An accurate model of the generating unit availability,
- An estimate of the generating unit outages and
- Information about the behavior of the load.

Although all of these quantities are subject to variation, they are fairly predictable for analysis of conventional generation systems. However, such calculations become inaccurate if there is a significant share of variable sources such as wind generators.

In recent decades, there has been an increased penetration of renewable energy (especially wind energy) into the electrical power system. For instance, in the US, the installed wind generation capacity rose from 6456 MW (0.67% of total installed generation) in 2004 [3] to 43461 MW (4.18% of installed generation) in 2011 [4], [5]. Further, with US states establishing renewable portfolio standards (RPS) goals for the decade, steep increase in wind generation installation is expected [6].

This thesis discusses the challenges of using the existing reliability study model (applicable to conventional generation) for the wind energy systems and proposes a methodology to include the effect of partial power outputs of wind generators (e.g., during low wind conditions) while still using the existing reliability indices to measure system reliability. The performance of the proposed methodology is further analyzed by implementing it on the Texas power system and observing its response to a rise in the wind generation penetration level from 5 to 10 % of the total installed generation capacity.

1.2.2 A "hands on" educational tool for DFIG wind energy systems

A significant integration of wind energy in the future would require a dedicated power engineering workforce having an in-depth knowledge of wind generation technology. Planning for the future, a focused approach has been devised in this project which was funded by the U.S Department of Energy [7]. This project aims to educate high school and undergraduate electrical engineering students and motivate them to pursue a career in the field of wind power engineering.

This thesis, which is a part of the above mentioned project, contributes to the initiative by developing a simplified graphic user interface (GUI) that demonstrates the operation of a doubly fed induction generator (DFIG) based wind generation systems. The GUI is constructed using the MATLAB software.

1.3 Literature survey: partial outage representation for conventional generation

For a conventional generation system having a static capacity, a binary representation may be employed to denote the availability of a generating unit where the random failures of generating units is expressed in terms of forced outage rate (FOR). However, in such a representation, neglecting partial outages or defining them as full outages leads to inaccurate results for reliability study calculations - especially for generating units with large size or having a variable pattern of generation.

Extensive literature is available that propose techniques of representing the availability of a partially loaded generation unit as well as its outage probability. By utilizing the Markov approach, reference [8] develops a single partial outage model to calculate transient outage probability. In this context, the Markov approach relies on the analysis of system states and transitions between system states with the assumption that transition probabilities are fixed. The author categorizes the service of a generator into three states of operation namely, a fully operational state, a derated state and a complete outage state and discusses the treatment of derating in probability calculations. The paper proceeds to evaluate the effect of the method on LOLP calculations.

In reference [9], a multiple-partial outage model is used for static capacity planning studies. Partial outages over a time interval create a number of capacity levels. The derated levels are grouped into some selected capacity levels which are defined on the basis of the probability of occurrence of the outage event. The paper expresses the outage probability in terms of an equivalent forced outage rate (EFOR). The effect of EFOR representation on calculation accuracy and economic benefits is analyzed for a selected test case.

Reference [10] discusses the improvement in reliability study calculation by using a multi-state representation of generation unit availability (for cases of partial outages) as compared to modeling the outage probability as an EFOR.

Reference [11] evaluates system reliability by calculating LOLP for a power system with partially loaded machines governed by economic dispatch algorithms. A multi-state model is used to represent the partial commitment of generating units. The effect of load variation on partial loading of machines is incorporated by using a convolution technique to derive an equivalent load curve for each committed unit on the basis of the available hourly load data.

1.4 Literature survey: impact of wind generation on LOLP

LOLP is an index used to measure power system reliability. An elaborate description of the classical LOLP calculation methodology for conventional generation system is discussed in reference [12]. Reference [13] demonstrates LOLP calculation for a chosen power system test case and proceeds to compare its performance as compared to the load-loss frequency and duration index.

Wind generation is variable and its higher penetration into power systems leads to a fluctuating and inaccurate estimation of generation availability and outage probability formulation. Hence, LOLP calculation for wind energy integrated power systems by use of methods described in references [12] and [13] would lead to unreliable results.

Studies in recent times have proposed numerous models to derive generation availability for wind integrated systems. Reference [14] uses a Monte Carlo method to simulate wind conditions and appropriately represent the generation availability. The author takes into account the wind speed dynamics and implements an autoregressive moving average (ARMA) wind model [15] for analysis.

The use of a time series wind model is discussed in reference [16] which computes the wind generator power output based on the hourly wind speeds. Such analysis includes the chronological characteristics of the generated wind energy. However, the method requires exhaustive wind data for the site under analysis.

Reference [17] employs a multi-state model of wind speed to calculate the wind generation with the aid of power curves at various output states. This reference proceeds to construct the cumulative probability density function (CDF) of each of the wind generators. The paper formulates an equivalent CDF of a wind farm total output which is derived from the characteristics of the individual wind generators on in the farm. Subsequently, LOLP is calculated for the system under study and the effect of increased wind penetration is investigated. In a similar study, the short-term impact of wind generation on LOLP is presented in reference [18]. It constructs an instantaneous multi-state model to characterize the wind generation output.

Although there has been an intensive research for deriving a generation availability model for wind integrated power systems, industry and academia seem divided over an exact approach for estimating the probability of total outage. Reference [16] simulates reliability studies for a selected test bed by using time series model. The author, however, does not derive any definite model for calculating outage probability for the wind integrated system and simply uses a fixed value of 0.05 for FOR and assumes that the units operate in binary states. Reference [19] provides a list of the average values of equivalent demand forced outage rate (EFORd) used by ISO New England for reliability analysis. The document also illustrates the use of the values of EFORd of hydro generating units for analysis of wind generating systems.

A more pragmatic approach is followed by reference [20] which models the entire wind park as a single unit and devises an equivalent FOR to account for wind uncertainty. The FOR is defined in terms of ‘interval numbers’ which indicate a range of possible values the wind generators under study may assume. The authors also propose the scope to expand the work by the use of fuzzy logic to formulate outage uncertainty. This approach is taken in order to aid in a more intuitive approach for decision making in the expansion planning process.

1.5 Literature survey: wind generation configurations for wind turbines

Before the advent of efficient power electronics technologies, the wind turbine driven induction generators were directly connected to the electrical grid through a mechanical gearbox. Popularly known as the ‘Danish Concept’ of interconnection [21] such a topology is a fixed speed turbine system. Although it is an inexpensive technology, such turbines are incapable of accurately controlling the power quality of injected power [22] or delivering optimum power transfer unless the wind blows near its designed operational speed [23]. On the other hand, a variable speed turbine uses power electronics converters to overcome most of such issues. However, they are costlier in comparison to the fixed speed systems.

A variety of literature exists that aims at improving the performance of fixed and variable speed turbines. Reference [24] discusses the influence of mechanical characteristics of turbine (such as the inertial constant) and grid parameters (like the short circuit power) on the transient voltage stability of a fixed speed wind turbine. The paper evaluates the response of the turbine for a simulated fault condition. An application of power electronics to fixed speed systems is demonstrated in reference [25] which discusses a method to improve the transient voltage stability of fixed speed turbines by installing a power converter next to the induction generators. Reference [26] proposes a novel design for equipment that improves the power quality of fixed speed generators by utilizing power electronics converters to cancel harmonic content in the power output.

For variable speed systems, a number of configurations have been proposed and implemented. The performance of a variable speed turbine topology is evaluated in reference [27] where a cascaded rectifier and inverter combination is connected between the grid and the wind generator. The paper implements a unique algorithm to eliminate voltage and frequency fluctuation in the output. In a different approach, reference [28] illustrates the implementation of a cascaded multilevel converter for variable speed turbines by using multiple permanent magnet synchronous generator (PMSG) drive configuration and highlights its benefits.

Power quality enhancement of variable speed generator output by the use of an AC-AC matrix converter is demonstrated in reference [29]. The author highlights the benefit of the configuration to attain a smoother speed control and an increased efficiency as compared to the DC-link voltage source converter.

The dynamic response of a DFIG based turbine technology and its ability to control the active and reactive power injection into grid by the use of a space vector pulse wave modulated (SVPWM) converter is discussed in reference [30]. Reference [31] proposes a fault detection scheme for back-to-back converters in DFIG-based wind generation system.

1.6 Organization of thesis

This thesis has been organized into six chapters. Chapter 1 discusses the objective and motivation of the thesis. It also details a literature summary on topics of partial outage representation of generation systems, wind integration impact on power system reliability and different wind turbine configurations prevalent.

Chapter 2 outlines the theory and calculation methodology to evaluate power system reliability. It explains the demerits of using the conventional reliability technique for wind integrated power systems. It proceeds to propose a methodology for computing the outage probability of the wind generators and the overall reliability of wind connected systems.

The proposed technique is simulated on a realistic test case in Chapter 3. The values of LOLP and outage probabilities of wind generators are calculated and remarks are made to demonstrate an increase in reliability study accuracy by using the new methodology. The case of an increased wind generation penetration is also simulated and its effect on overall power system reliability is discussed.

Chapter 4 explains the theory of the prevalent wind turbine technologies. The working of the grid connected DFIG machine is outlined and the operation mechanism of the power converters is elaborated in detail. Equations related to power flow equation and maximum power point tracking mechanism are also elaborated upon.

Chapter 5 focuses on describing the construction of the GUI for the DFIG system. It discusses the basis of choosing MATLAB as the software to construct the GUI. It also illustrates the different components of the GUI and explains its features.

Conclusions, recommendations and future scope of the presented work are provided in Chapter 6. The appendices A and B contain the MATLAB code used to develop the reliability model calculation for the test case and the GUI tool. Appendix C describes the instructions to install the standalone version of the GUI on a Windows operating system based computer.

CHAPTER 2

THEORY AND ANALYSIS OF POWER SYSTEM RELIABILITY STUDIES

2.1 System reliability and its measurement

The ability of a device or system to perform a required function under stated conditions for the desired period of time is termed as reliability [32]. A myriad of system abnormalities such as protection component failures, control or communication failures, accidents or operational errors make the power system vulnerable. Loss of service of generating units has a significant effect on the performance of utility systems as well as on the consumer and result in revenue losses amounting to tens of millions of dollars [33]. This amount increases appreciably if partial outages are also accounted for in the cost analysis and accurately represented. Therefore, to perceive the cost of unreliable operation of a power system, indices have been formulated to accurately represent the service availability.

Mathematically, reliability is the probability that a device would perform its required function for a specified period of time under the stated operational conditions. For conventional generators, the FOR serves as its reliability indicator and is defined as,

$$FOR = \frac{FOH}{(SH + FOH)} \tag{2.1}$$

where, *SH*: service hours, *FOH*: forced outage hours. Neglecting partial outages altogether or representing them as a full outage leads to an incorrect forced outage rate. Therefore, a multistate derated model is used where the partial outage probability is weighted by the fraction of the capacity lost and added to the probability of total outage [9]. The ‘weighted’ forced outage rate thus obtained is defined as an EFOR.

On the basis of service availability data of each individual generating unit, their outage probability (expressed in terms of FOR or EFOR) and the load profile data, the overall reliability of the entire power system is usually assessed in terms of the following reliability indicators [34]:

- LOLP: It is the probability that generation will be insufficient to meet the demand at some point over a specific time window.
- Loss of load expectation (LOLE): It is a measure of how long the available capacity is likely to fall short of demand. It is obtained by calculating the probability of daily peak demand exceeding the available capacity for each day and adding these probabilities for all days in a year.

LOLP, unlike LOLE, quantifies the extent to which supply fails to meet demand. Of course, LOLE refers to the energy not served whereas LOLP is the probability of failure to meet the load. This thesis uses LOLP to evaluate the system reliability.

2.2 The capacity outage table (COT)

For a fixed capacity level, the COT is used to compute the probability for which the total generation capacity is unavailable due to forced outages exceeding a particular threshold [35]. Figure 2.1 depicts the layout of a COT. The first column of the table contains all the capacity states in ascending order of outage magnitude. If the system contains identical units then binomial distribution can be used to calculate the COT. The second column lists the corresponding probability of outages for a particular capacity state.

Available generation capacity	**Probability of outage**
Lists the combination of possible capacity states	Lists the corresponding probability for the capacity state to have outage

Figure 2.1 Typical capacity outage table

For a system having a large number of machines, the COT is generated by interpolation. With the aid of the load duration curve, the COT is used to calculate the LOLP. Also the COT indicates the expected generation margin which is defined as the difference between the available generation and the load.

2.3 The load duration curve (LDC)

The LDC depicts the relation between capacity utilization and the duration for which a load is served. It is a load curve in which the demand data is arranged in descending order of magnitude. Figure 2.2 shows a load curve versus time (showing load variation for 10 hours) and the LDC derived from it is shown in Figure 2.3. Note that some LDCs as depicted in Fig. 2.3 are represented with the abscissa and ordinate reversed.

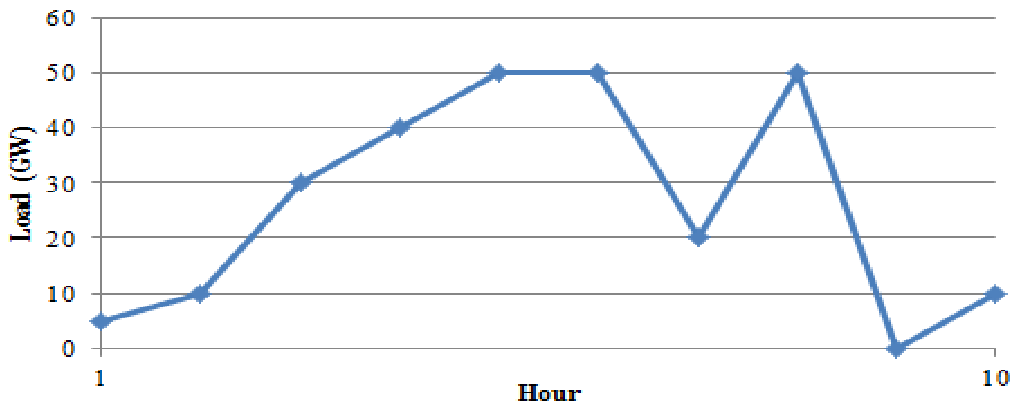


Figure 2.2 Example of a load curve

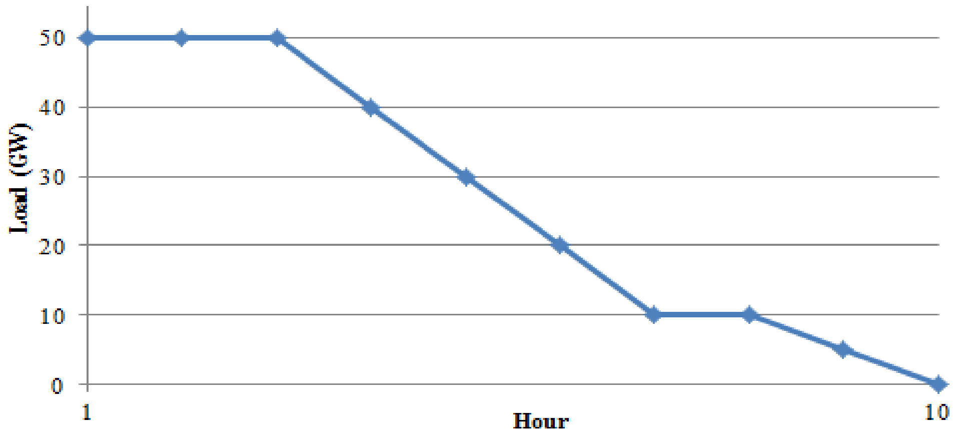


Figure 2.3 The load duration curve derived from Figure 2.2

Load factor, which is calculated as the ratio of the average load to the peak load in a power system during a period [36], indicates the nature of a load profile. For example, a high load factor signifies a fairly constant load profile since the average load is same as the peak load.

On the other hand, a LDC is a graphical representation and provides an objective idea about the magnitude as well as the nature of load profile. For instance Figures 2.4 and 2.5 give a quick visual idea about LDCs for a load profile having a high and a low load factor.

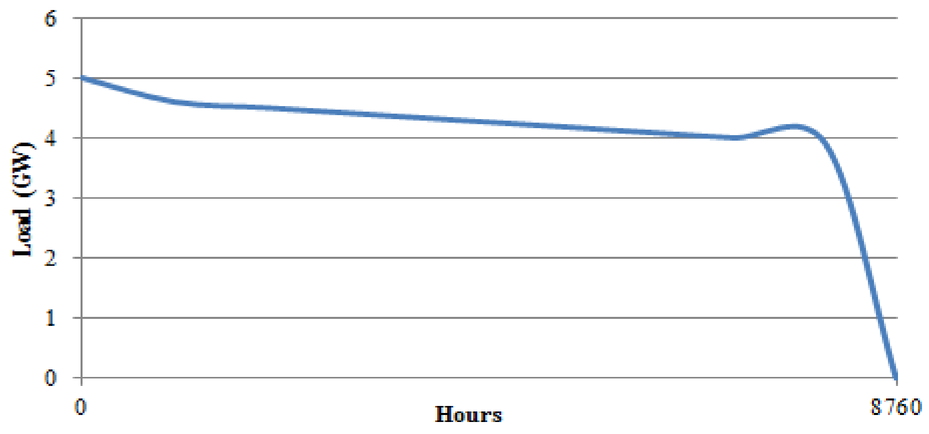


Figure 2.4 Load duration curve for a high load factor

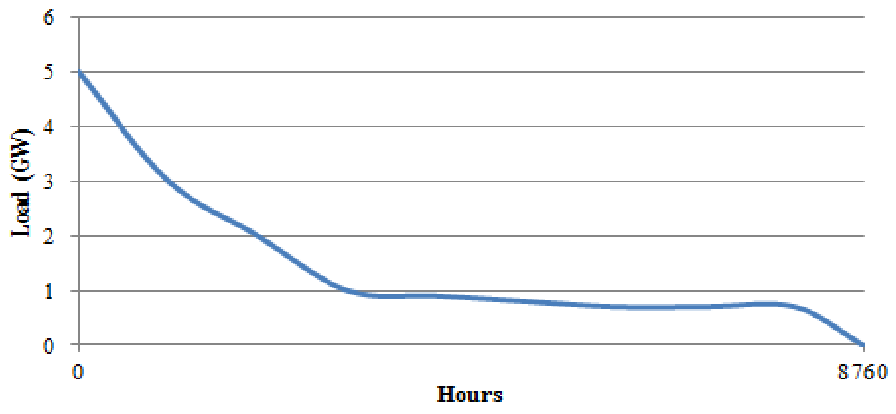


Figure 2.5 Load duration curve for a low load factor

The LDC is used in the analysis of electric power systems for estimating the operating cost of resource plans, and as a tool to integrate demand side management in the planning of electricity generation [37]. The LDC may also be used as a tool to illustrate the mix of various generation technologies serving load in the same power system [38]. For each capacity level of a COT, the percentage of time for each demand level is inferred from the LDC and subsequently used to calculate the LOLP of the power system under study.

2.4 Loss of load probability

The LOLP is a probabilistic measure of load unavailability within a specified period of time. Based on the size of the system under evaluation and the extent of input data (generation availability model, outage probability and load data) available, any of the following approaches can be employed to calculate LOLP:

- Instead of building an equivalent generation distribution model first, the load probability distribution may be convolved with the individual generation distribution one at a time and the resultant be convolved with the load curve [20].
- An equivalent generation capacity table can be constructed and the LOLP can be deduced with the aid of the LDC.

The first method is suited for a system having a large number of generators. On the other hand, the second method may involve extensive calculation for a system having a large number of generators or multiple operating states.

As explained in the later sections, the LOLP calculation methodology proposed in this thesis is accurately calculated using the second method since a fewer number of generators is incorporated while constructing the test case and a different approach has been undertaken to handle the existence of multiple operating states of generating units. Hence to calculate the LOLP, the following simplistic procedure is followed:

a) On the basis of the available generation data and the FOR of individual generators connected to the power system under study, the capacity outage table is constructed as depicted in Section 2.2.

b) The first column of the COT tabulates the combination of the generation states possible. For each of the available generation states, the LDC is used to find the amount of 'time' for which the load exceeds the available generation. This adds a third column to the COT.

c) The probability of generation availability (column 2) is multiplied with the corresponding values of time for which load exceeds generation (column 3). The cumulative sum of all such products yields the LOLP. The unit of LOLP depends on the unit of time used in the LDC.

2.5 Problems in developing reliability indices for wind generation

Wind is a variable form of energy and is continuously changing in an unpredictable manner. Using the conventional LOLP calculation method for wind generation systems would result in inaccurate results. This is primarily due to the following approximations for wind systems which result in large deviations:

a) Inaccurate representation of wind generation availability data

Wind varies with the time of day (blows harder in night than in day) and is influenced by seasonal variations. For example, in many parts of Texas, the average wind speed in March is around 14 m/s while it reduces to around 10 m/s in September [39]. Hence the actual output of any wind farm is lower than its installed capacity and may never generate continuously up to its nameplate rating.

As illustrated in Section 2.4, for conventional generation systems the LOLP is calculated by utilizing the available generation states from the COT along with the LDC. Assuming the most ideal case where no partial loading of generating units exists (except for wind generators), the generation states are in turn derived from the values of installed generation capacity of individual machines. For wind generation the output is below its installed capacity most of the time; therefore the LOLP calculation methodology requires a different approach and is discussed in the subsequent sections.

b) Inaccurate FOR representation

Due to the variable non availability of the wind generator output, a binary representation of forced outage rates for each wind generator would lead to erroneous results in LOLP calculation. Also neglecting the reduced output of wind generators altogether would result in large errors too. In such a scenario, the cases of reduced output of the wind generators must be visualized as cases of partial outage and a model is needed to be developed accordingly. This thesis uses the EFOR over a time interval to accurately denote the FOR.

2.6 LOLP calculation methodology for wind generation profile

LOLP calculation requires accurate data of the available generation and the FOR of each generating unit. This section proposes a method to calculate LOLP for wind integrated systems.

The approach followed is based on calculating the LOLP based on generation data available for a 24 hour period (other desired time spans may also be suitably chosen). Within a day, the available generation changes enormously and creates uncertainty regarding which precise value of generation should be chosen to construct the COT. To tackle this problem, it is proposed to segregate the analysis period (24 hours used here) into multiple time intervals. Depending upon the length of each time interval chosen, the available generation and the equivalent forced outage rate is approximated as described in subsequent sections.

2.7 Segregation of wind generation profile into intervals

Figure 2.6 shows the wind generation profile of entire state of Texas for 6th September 2008 [40]. It is noteworthy to observe the large variation in wind generation data in daytime as compared to the night.

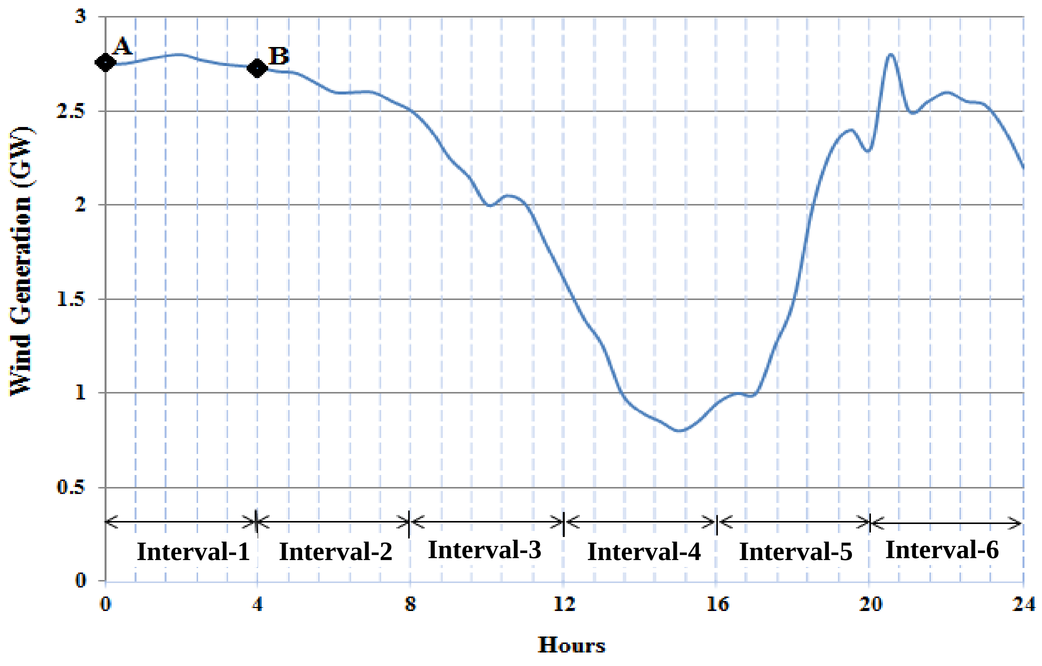


Figure 2.6 Wind generation profile of Texas in 6th September 2008

In Figure 2.6, the day long wind generation profile is divided in six intervals. For each interval, a wide variation in wind generation is observed. To avoid excessive calculations while analyzing a large system, the 'average' generation during the interval may simply be approximated by the arithmetic mean of the generation at the start and end points of the chosen interval. For example, in Figure 2.6, the arithmetic mean of generation output at point A and B may be used to denote the available generation during the period 0-4 hours. However, due to wide variation, such an approach neglects the subtlety of the generation profile and yields gross and inaccurate results.

Alternatively, in order to approximate the non-linear generation output curve, curve-fitting techniques may be used. The curve may be approximated by using a piece-wise cubic spline. A cubic spline is preferred since they are twice differentiable polynomial curves and do not exhibit the oscillatory behavior observed for higher order curves [41]. Further, being a lower order curve, splines are easier to compute.

As an illustration, a cubic spline is implemented (using MATLAB) for some wind profile for 96 intervals and data points in addition to the 24 points historically available are obtained as shown in Fig. 2.7. By segregation of the highly variable non-linear generation output curve into multiple time intervals and approximating it by using cubic splines, a more accurate representation of the available wind generation can be obtained.

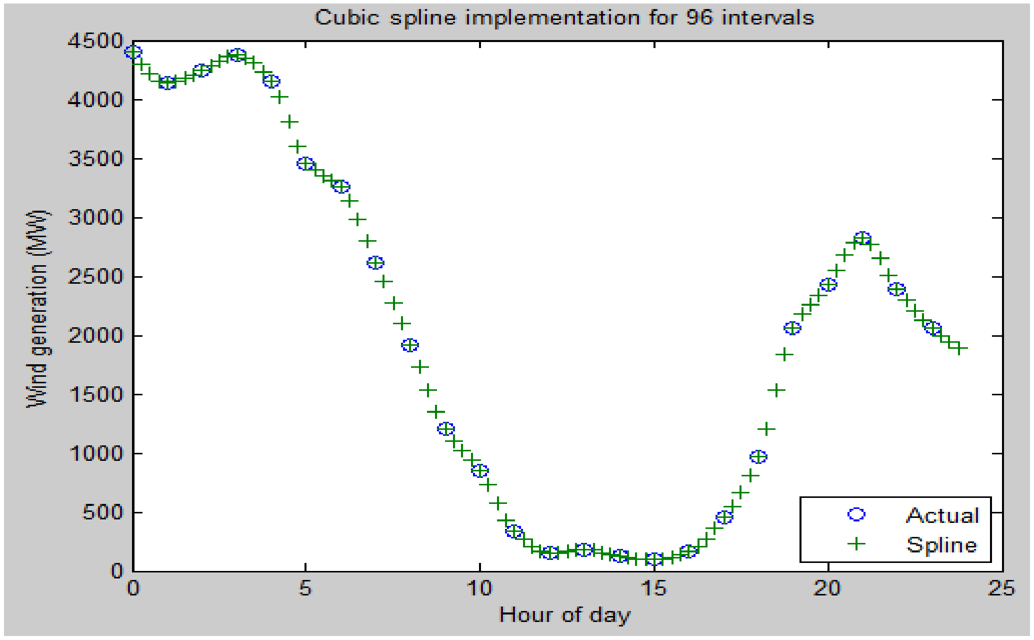


Figure 2.7 Derivation of additional data points by using cubic splines

2.8 EFOR calculation

For conventional generators, a generating unit is derated to compensate for its inability to deliver up to its nameplate capacity due to some physical constraints. The derating factor (DF) is defined as,

$$DF = \frac{Actual\_Output}{Rated\_Output} \tag{3.1}$$

For a wind generator, a reduced output (during low wind speeds) compared to its nameplate capacity is not a case of full capacity outage and must be viewed as a case of partial outage. By analyzing Figure 3.1, the generator output in each of the six intervals is visualized as a derated output and an EFOR is deduced [9],

$$EFOR = f_0 + \sum \frac{(t_i.DF)}{T} \tag{3.2}$$

where, f_o: probability of full capacity outage, t_i: duration of the reduced output in i^{th} interval and T: total duration of analysis. f_o is zero for the wind generation profile shown in Figure 2.7 since there is no full outage anytime during the day.

Summarizing, for a chosen number of intervals, the available generation is determined and DF calculated by the use of cubic splines in each interval. Next, the EFOR is calculated as the weighted mean of the DF of each interval (assuming there is no total outage). Figure 2.8 shows a flowchart describing the step by step approach of the proposed LOLP calculation methodology.

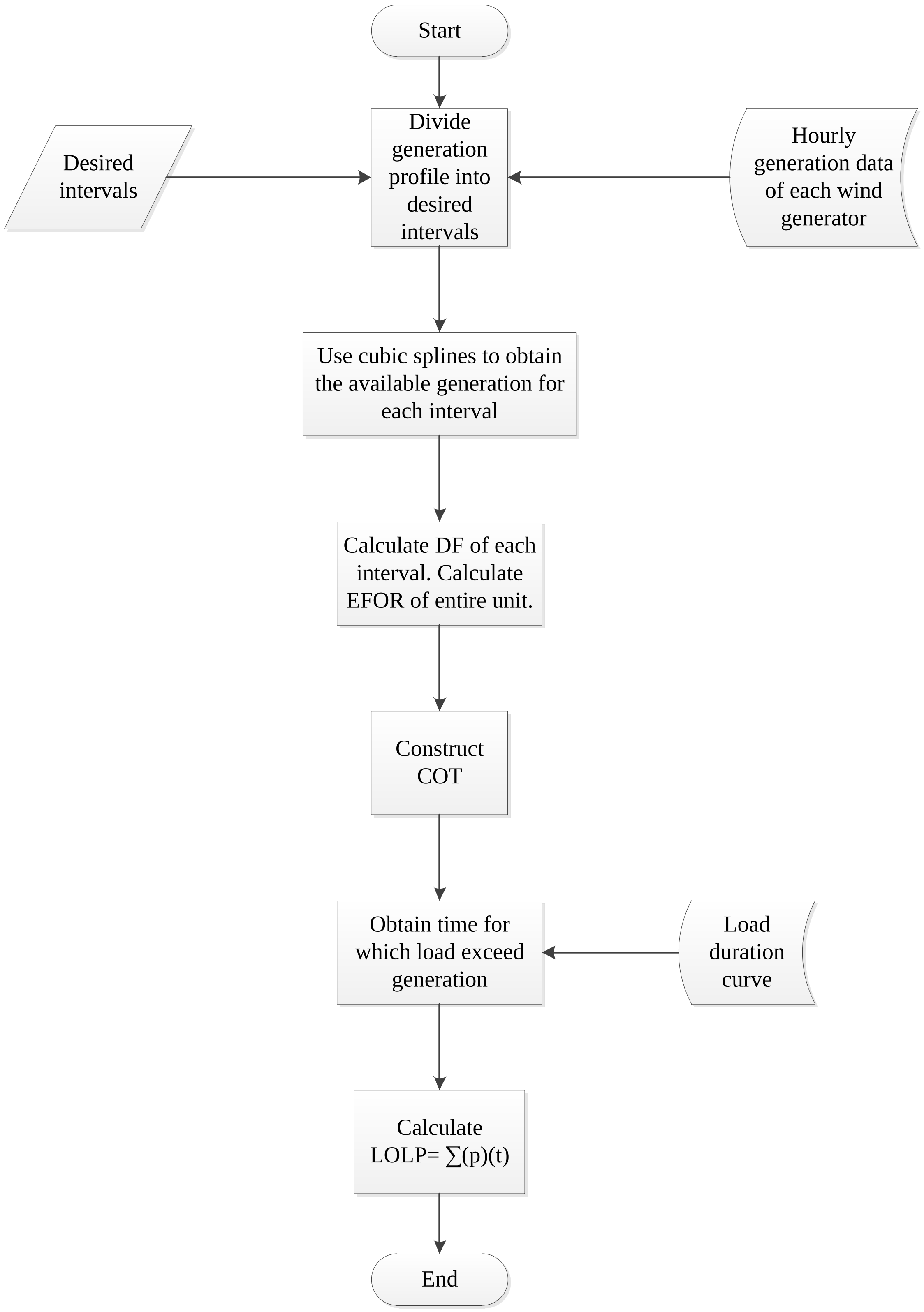

Start
Desired intervals
Divide generation profile into desired intervals
Hourly generation data of each wind generator
Use cubic splines to obtain the available generation for each interval
Calculate DF of each interval. Calculate EFOR of entire unit.
Construct COT
Obtain time for which load exceed generation
Load duration curve
Calculate LOLP= ∑(p)(t)
End

Figure 2.8 Flowchart depicting the proposed methodology of LOLP calculation

CHAPTER 3

TEST BED, SIMULATION AND RESULTS

3.1 Reliability calculation through proposed method

In this chapter, the reliability calculation methodology, which was discussed in the preceding section, is implemented on an existing power system test case to illustrate the following:

- Application and efficiency of the method to calculate the EFOR and subsequently obtaining the LOLP for the system under study
- The effect on LOLP due to increase in the installed capacity of wind energy generation
- The variation of the EFOR and LOLP due to the change in the number of intervals while implementing the algorithm
- Dependency of LOLP on the type of wind generation profile

To successfully demonstrate the performance of the proposed method, a test case having a fairly large size, a sufficiently high level of wind penetration and a diverse variation of wind generation profile over the day is chosen to provide realistic results. Incorporating all such features, the Texas power system has been used as a test case.

3.2 Choice of the Texas power system as test case

Texas is blessed with a plentiful of wind energy resource. With a high average wind speed ranging from 10 to 14 m/s in most parts of the state throughout the year [42], one of the largest wind energy installations in the US is located in Texas. The installed capacity of the Texas power system was around 105 GW in 2008 of which the installed wind generation capacity was nearly 7.5 GW [43] - a wind penetration level of 6.8%. Further, according to the RPS goals, Texas has an aggressive target of increasing wind energy installation in coming years [44]. This factor makes Texas a better fit for conducting a realistic experiment to analyze the effect of increased wind penetration on reliability of the expanded system.

For conducting LOLP calculations on the Texas power system, actual hourly wind generation data [40] and hourly load profile [45] for the year 2008 have been procured from Electrical Reliability Council of Texas (ERCOT).

3.3 Description of test case

While constructing the test bed, an attempt has been made to simulate a case most identical with the actual data of the Texas power system. Table 3.1 depicts the installed capacity of the chief energy sources serving Texas in 2008 [46] and Table 3.2 lists the typical values of FORs [47] for those energy sources.

Table 3.1 Installed capacity of Texas power system in 2008

Energy source name	**Installed capacity (GW)**
Nuclear	4.927
Coal	20.189
Natural gas	70.856
Wind	7.427
	Total= 103.4

Table 3.2 Typical values of forced outage rates for some major sources

Energy source name	**Typical FOR**
Nuclear	0.02 – 0.03
Coal	0.06 – 0.07
Natural gas	0.08 - 0.09

On the basis of the generation and outage probability data mentioned in Tables 3.1 and 3.2, the Texas test system is reduced to a simpler equivalent system comprising of 10 generators having specifications as listed in Table 3.3.

Table 3.3 Test case for analysis

Generation type	**Units**	**Installed rating (GW)**	**FOR**
Coal	Unit #1	10.1	0.06
	Unit #2	10.1	
Natural gas	Unit #3	24.0	0.05
	Unit #4	24.0	
	Unit #5	24.0	
Nuclear	Unit #6	2.4	0.02
	Unit #7	2.4	
Wind	Unit #8	Generation magnitude of each unit are in the ratio 5:4:3	Equivalent-FOR calculated
	Unit #9		
	Unit #10		

The use of a larger number and diverse magnitude of wind generators would lead to a more realistic simulation. However, due to computational limitations, three wind generators are chosen for analysis. In order to simulate a variety of sizes of wind farms in the system, the magnitude of generation of the individual wind generators (Units 8, 9, 10) are divided in to an arbitrary ratio of 5:4:3. The following assumptions have been made while constructing the test case:

- In order to simplify the test case for analysis, only the major energy sources have been accounted for. Such an approximation has very little effect on the accuracy of results since in the above test case around 103.4 GW of generation out of the actual installed 105 GW is already included.
- For all units except for wind generators, derated or partially loaded operation has been neglected. Hence, while serving the power system, Units #1-7 operate either in a state of being fully committed or having a full outage.

Utilizing the actual ERCOT hourly load data of 2008 [45], the load duration curve is constructed for the 8760 hours over the entire year (Figure 3.1). It is observed that the maximum load of Texas in 2008 is 62.1 GW and the minimum is around 20.2 GW.

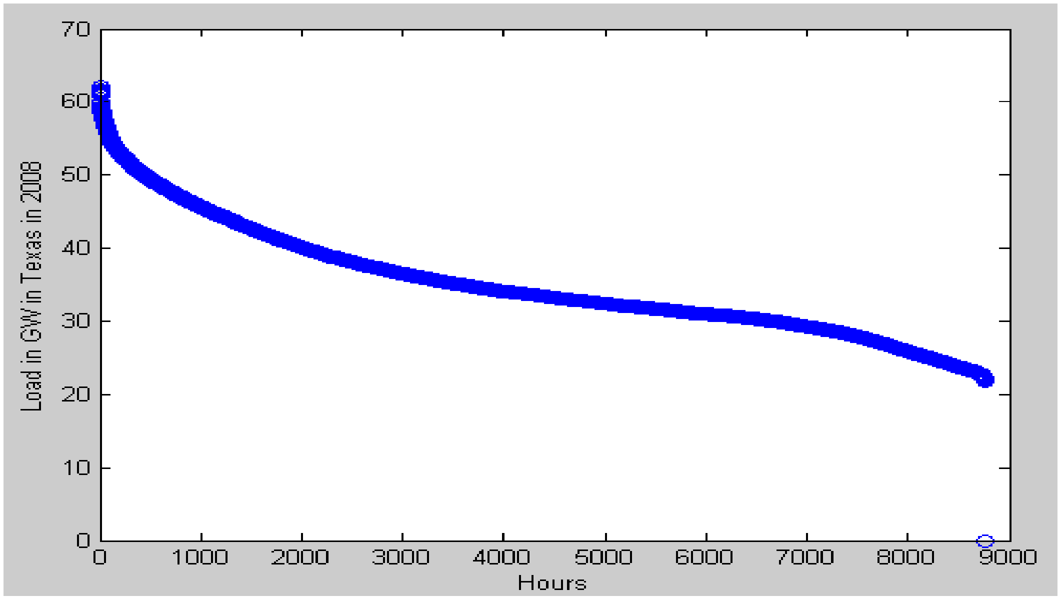


Figure 3.1 Load duration curve for load in Texas in year 2008

3.4 Simulation showing LOLP and EFOR variation for the Texas test case

The highly variable pattern of wind profile necessitates that the proposed methodology be simulated and the reliability index be calculated for the test case for two types of wind generation profiles – one having a wide variation of wind generation output over the entire day and another having a relatively ‘flat’ wind generation profile. Such an approach provides an opportunity to evaluate the performance of the method for varied patterns of wind generation outputs.

3.4.1 Case #1: 9th June 2008

From the available hourly wind generation data [40], the wind generation profile is constructed graphically as shown in Figure 3.2. The wind generation is observed to be swinging from a maximum value of 4.37 GW to a minimum of 0.97 GW during the 24 hour period.

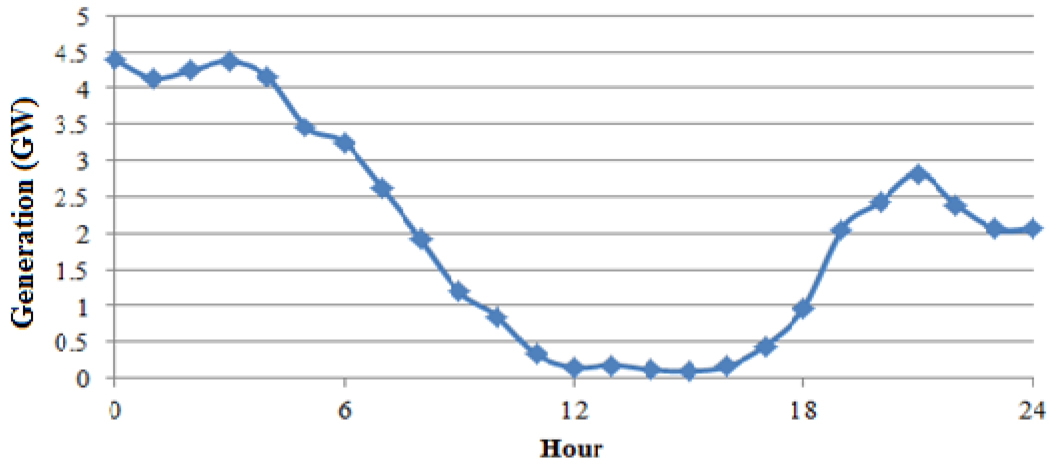


Figure 3.2 Hourly wind generation of Texas on 9th June 2008

For the wind profile shown in Figure 3.2, the individual wind generation output of each of the three wind generator units (Units #8, 9 and 10) are calculated in the ratio 5:4:3 and plotted as shown in Figure 3.3.

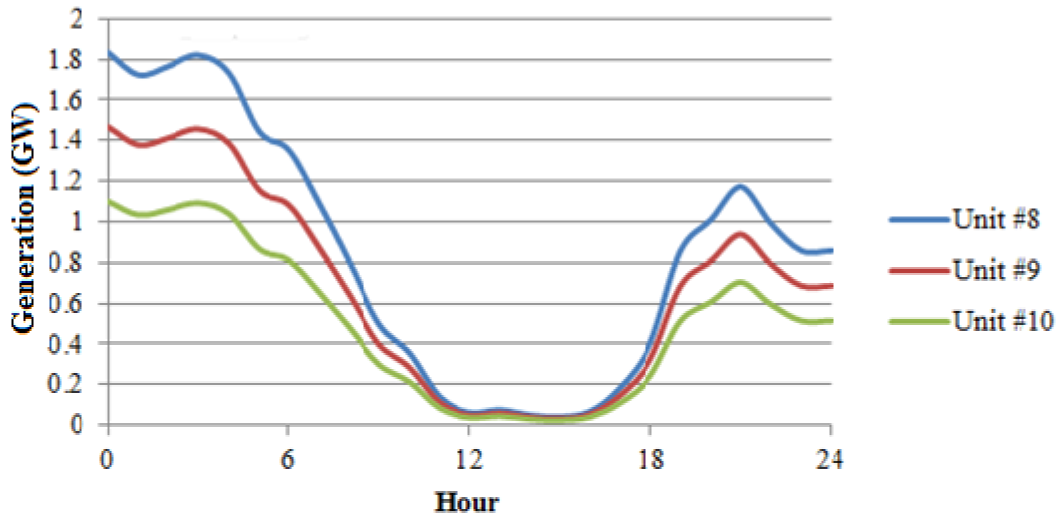


Figure 3.3 Individual generation profile of wind generators in test case

As discussed in Chapter 2, the process of calculating LOLP requires the selection of a definite set of intervals into which the entire hourly 24-hour generation data is divided into. For this, cubic splines are used to interpolate in between the known 24 data points and obtain wind generation output for each of the desired intervals. Figure 3.4 shows the result of implementing cubic splines to segment the wind generation profile into 72 intervals. The 'o' shows the known 24 values of known generation at each hour while '+' shows the 72 values obtained from cubic spline interpolation.

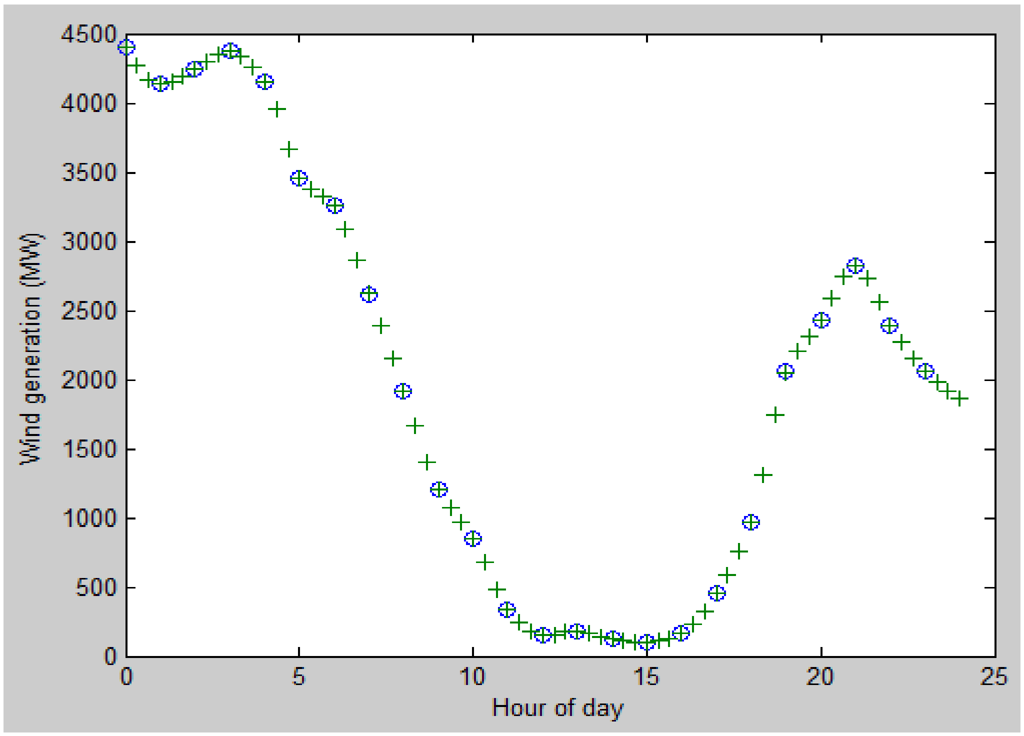


Figure 3.4 Derivation of additional data points by implementing cubic spline for 72 intervals

In order to calculate the Equivalent FOR (as described in Section 2.8) for each wind generator, the exact installed wind capacity must be known. From historical data available, the installed wind generation capacity was around 7.5% of the total installed generation in Texas in 2008. Knowing that the exact installed capacity of the other sources is 103.4 GW (Table 3.1) in the chosen test case, the installed capacity of wind is determined as follows,

(100 - 7.5) % of (Total installed generation) = 103.4 GW

Total installed generation = 111.8 GW

Hence, installed wind generation = 111.8 – 103.4 = 8.38 GW

Next, for each of the 72 intervals (for example), the DF and the EFOR is calculated using (3.1) and (3.2),

$$DF = \frac{Actual\_generation}{Installed\_capacity} \tag{3.1}$$

$$EFOR = f_0 + \sum \frac{(t_i.DF)}{T} \tag{3.2}$$

where, t_i is the duration of the derated hours. For 72 intervals, the value of t_i is = (24/72) hours. The forced outage rate f_0 is zero since for the wind generation profile under study, the wind generators are continuously operating and never have a complete outage.

On calculating for the case of 72 intervals, the EFOR for the wind generator Unit #8 is obtained as 0.253708. It must be noted that this value is very high as compared to the FOR of conventional generation units which typically ranges around 0.02-0.07. Such a high outage probability for wind generator clearly indicates that calculating LOLP (for a wind generation integrated system) through conventional methods would result in extremely high error in reliability studies and incorrectly yield an ‘optimistic’ picture of power system performance.

The data derived up to this point are sufficient to construct the COT for the 10 generators under study and subsequently calculate the LOLP. The above procedure is repeated for a varied number of intervals (4, 6, 12, 24, 32, 48, 72 and 96), and the following variation of LOLP and EFOR is observed as depicted in Figure 3.5 and 3.6.

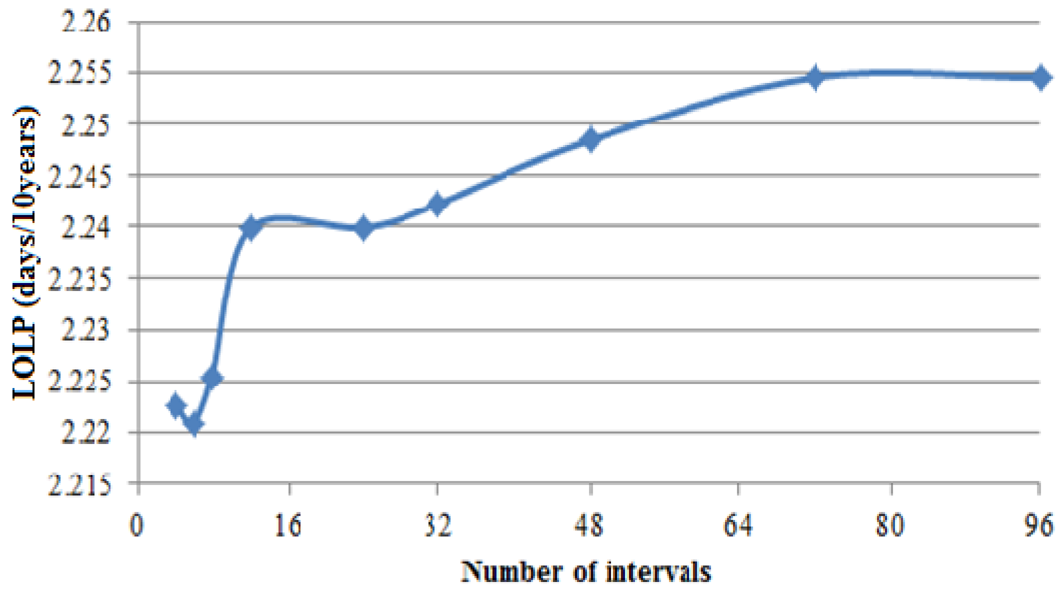


Figure 3.5 Variation of LOLP with change in number of intervals

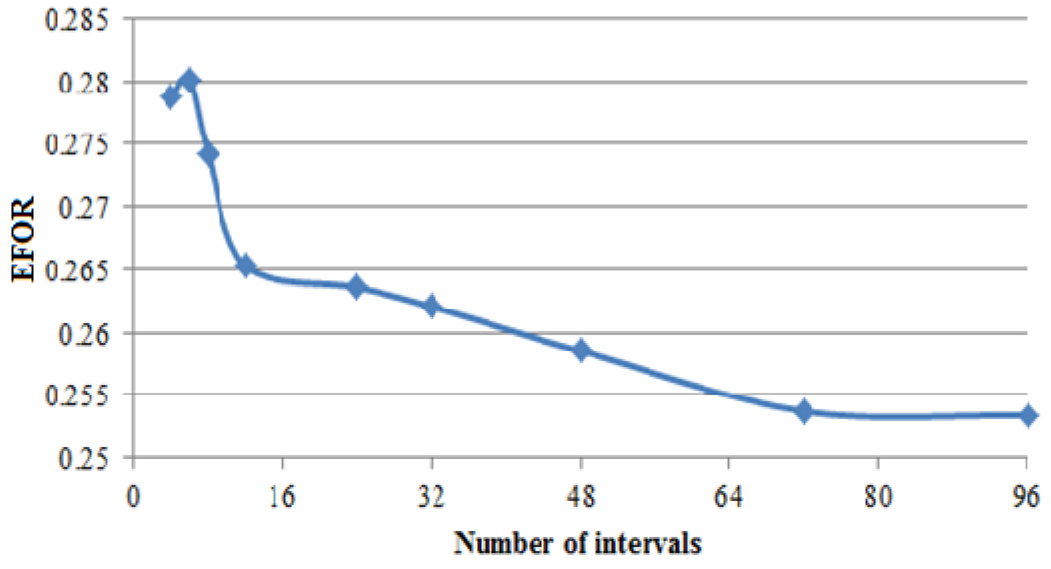


Figure 3.6 Variation of EFOR with change in number of intervals

The results depicted in Figures 3.5 and 3.6 are for a fixed penetration level of 7.5%. The following points must be noted:

- The EFOR values are much higher than the typical values of FOR of conventional generators.
- The LOLP value for this test case is observed to be around 2.25 days/10yr which is indeed quite high compared to typical values of LOLP for a power system in US. The reason may be attributed to a lesser number of generators used in the test case.
- For a given penetration level, the LOLP increases and EFOR decreases as number of intervals is increased. This may be seen as an indication that the accuracy of calculation improves with an increase in the number of intervals and leads to a higher LOLP (hence more unreliable) due to addition of the variable wind energy.
- After 72 intervals, the values of LOLP and EFOR are observed to stabilize and seem to be the 'optimal' number of intervals for this case.

3.4.2 Case #2: 23rd December 2008

Unlike the highly fluctuating wind generation profile used for analysis in Case #1, this section demonstrates the LOLP calculation methodology for a relatively 'flat' profile in which the wind generation output varies very little throughout the day. Figure 3.7 shows the wind generation profile on 23rd December 2008 [40]. The wind generation varies from a maximum value of 4.52 GW to a minimum of 2.65 GW during a 24 hour period.

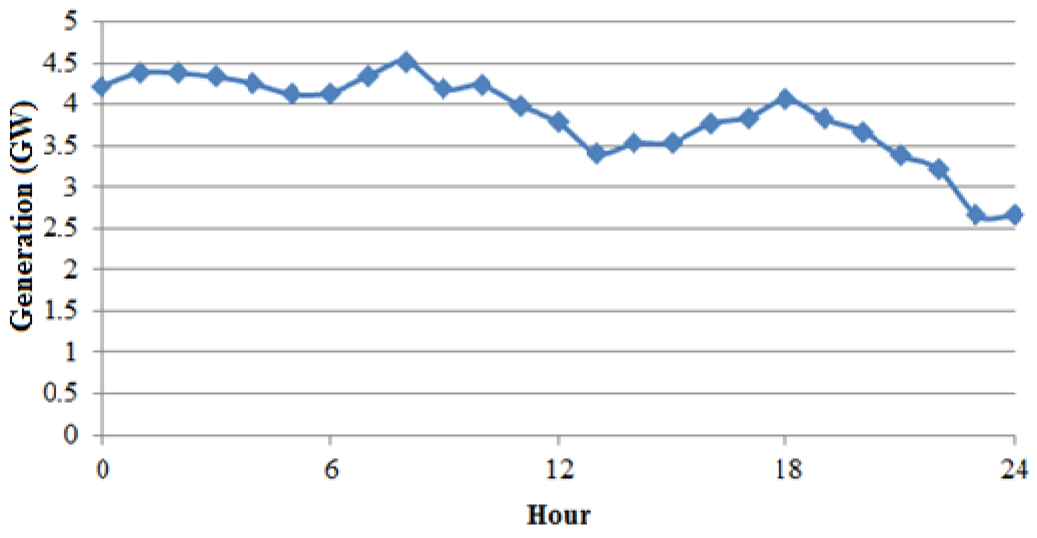


Figure 3.7 Hourly wind generation of Texas on 23rd December 2008

For the wind profile, the individual wind generation output of each of the three wind generator units (Units #8, 9 and 10) are calculated in the ratio 5:4:3 and plotted as shown in Figure 3.8.

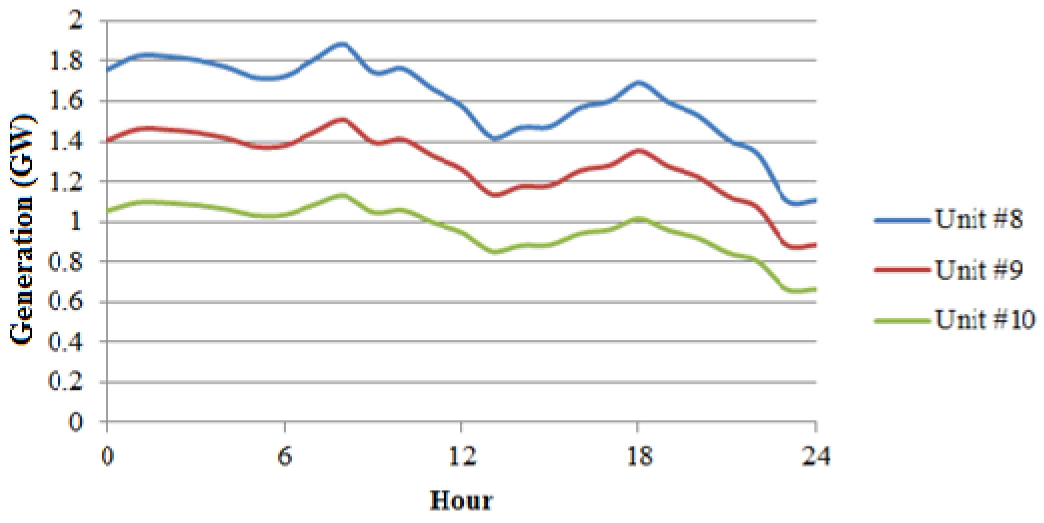


Figure 3.8 Individual generation profile of wind generators in test case #2

As a next step, the desired number of intervals is selected for analysis and subsequently cubic splines are used to segment the wind generation profile into desired number of intervals. Figure 3.9 shows the result of implementing cubic splines for 72 intervals. In the figure, the ‘o’ shows the known 24 values of generation at each hour while ‘+’ shows the 72 values obtained from cubic spline interpolation.

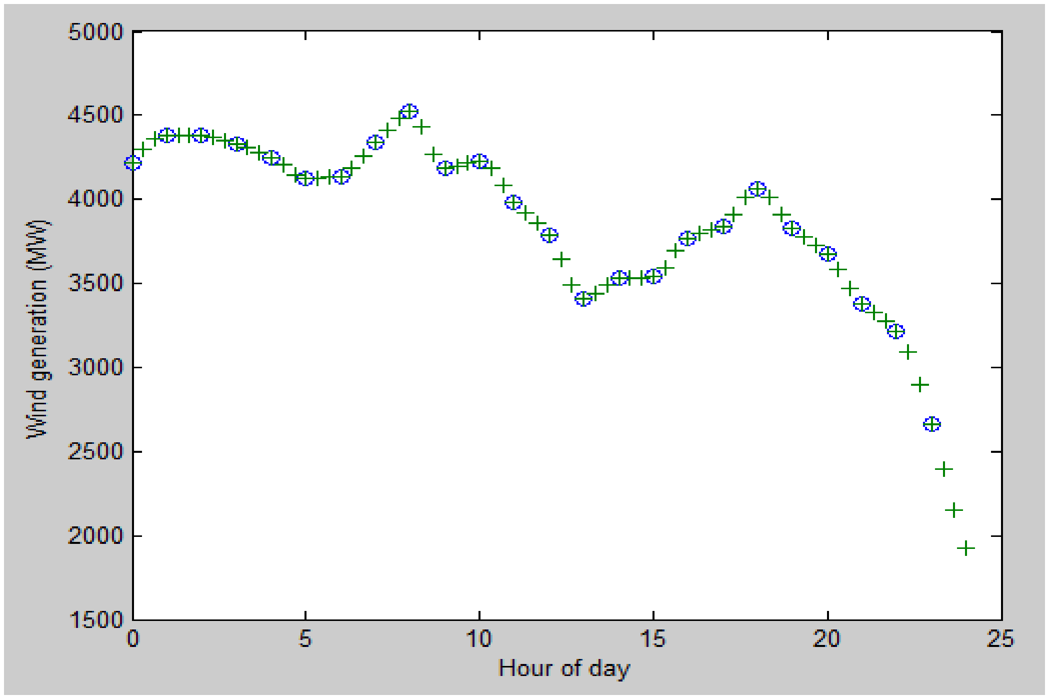


Figure 3.9 Derivation of additional data points by implementing cubic spline for 72 intervals

As explained in the previous section, the installed wind capacity is calculated on the basis of the known total installed generation in Texas in 2008 and the selected level of penetration. Choosing 7.5% as penetration level, the installed wind generation capacity is found as:

(100 - 7.5) % of (Total installed generation) = 103.4 GW

Total installed generation = 111.8 GW

Hence, installed wind generation = 111.8 – 103.4 = 8.38 GW

Next, knowing the installed wind generation, the DF is calculated using (3.1) for each of the 72 intervals (say). Subsequently the EFOR is evaluated using (3.2). For the case of 72 intervals, the EFOR for wind generator Unit #8 is obtained as 0.246. Similar to Case #1, the EFOR value is found to be much higher than the FOR of conventional generation units which typically ranges around 0.02-0.07.

From the data derived up to this point, the COT is constructed for the 10 generator test system and the LOLP is subsequently calculated. Repeating the above procedure for a varied number of intervals (4, 6, 12, 24, 32, 48, 72 and 96), the following variation of LOLP and EFOR is observed as depicted in Figures 3.10 and 3.11 respectively.

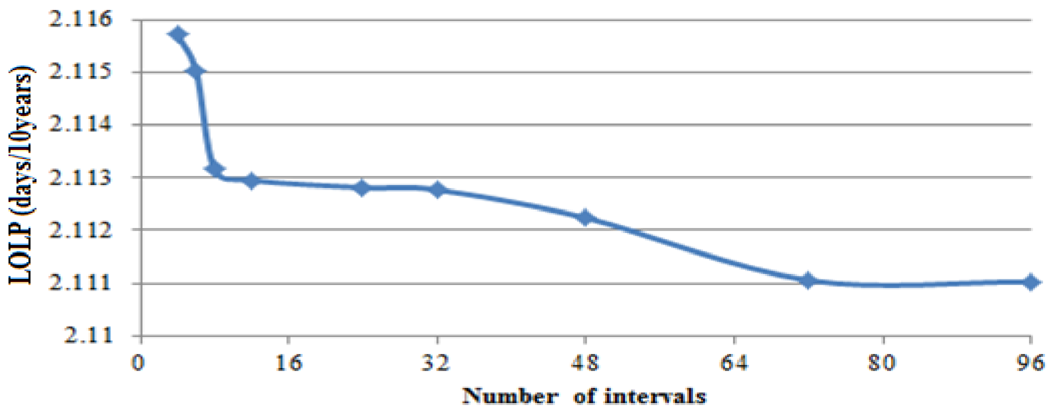


Figure 3.10 Variation of LOLP with change in number of intervals for case #2

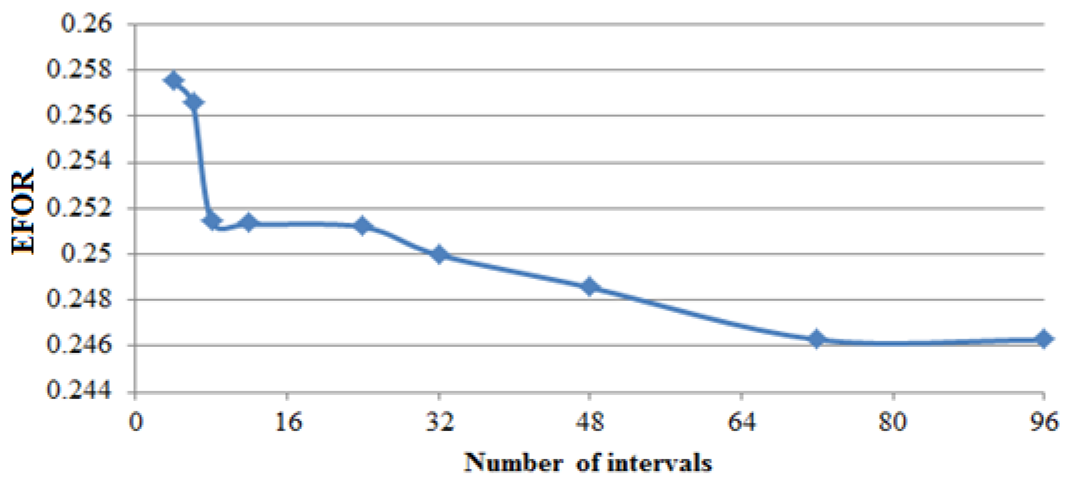


Figure 3.11 Variation of EFOR with change in number of intervals for case #2

For a fixed penetration level (7.5% in this case) for case #2, the following points must be noted:

- As found in case #1, the EFOR values are much higher than the typical values of FOR of conventional generators. Also, the LOLP value is found to be higher (around 2.11 days /10 year) due to the test case comprising of small number of generators.
- Contrary to case #1, the LOLP is observed to be decreasing with an increase in the number of intervals. It may be deduced that as a flat generation profile represents a more stable system, the LOLP decreases owing to improvement in accuracy due to increase in the number of intervals used for analysis.
- Similar to case #1, the EFOR decreases with an increased number of intervals.

- Like case #1, the values of LOLP and EFOR are observed to stabilize after 72 intervals and thus seem to be the ‘optimal’ number of intervals for this test case.

3.5 Results depicting the effect of increased wind penetration

The penetration of wind is expected to increases aggressively in Texas in the coming years. In the event of such an expansion, it is necessary to evaluate the generation adequacy of the existing power system infrastructure. This section presents the results of the pattern of change in LOLP with an increase in wind capacity penetration from 5% to 10% for different wind generation profiles.

3.5.1 Case #1: 9th June 2008

As shown in Figure 3.2, the wind generation profile on this day varies over a very wide range. Figures 3.12 and 3.13 respectively demonstrate the variation of LOLP and EFOR for such a generation pattern.

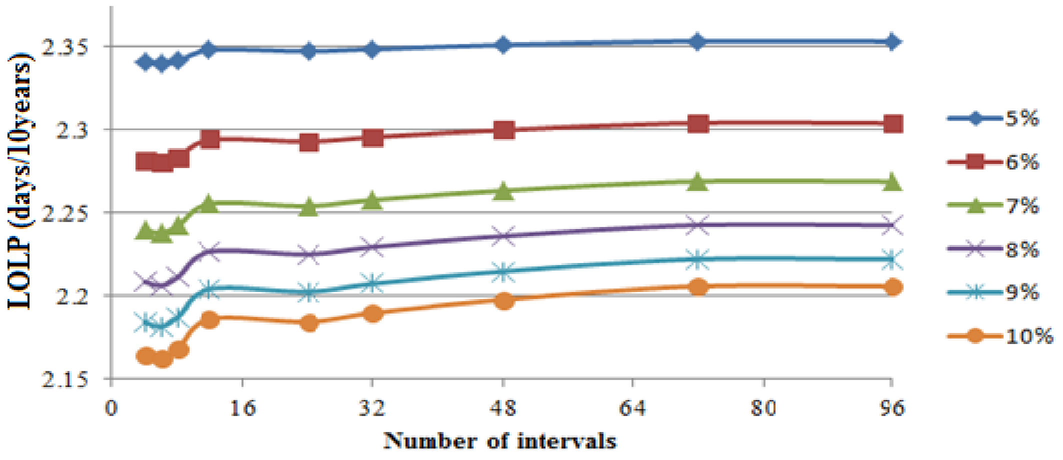


Figure 3.12 LOLP variation with change in wind penetration level for case #1

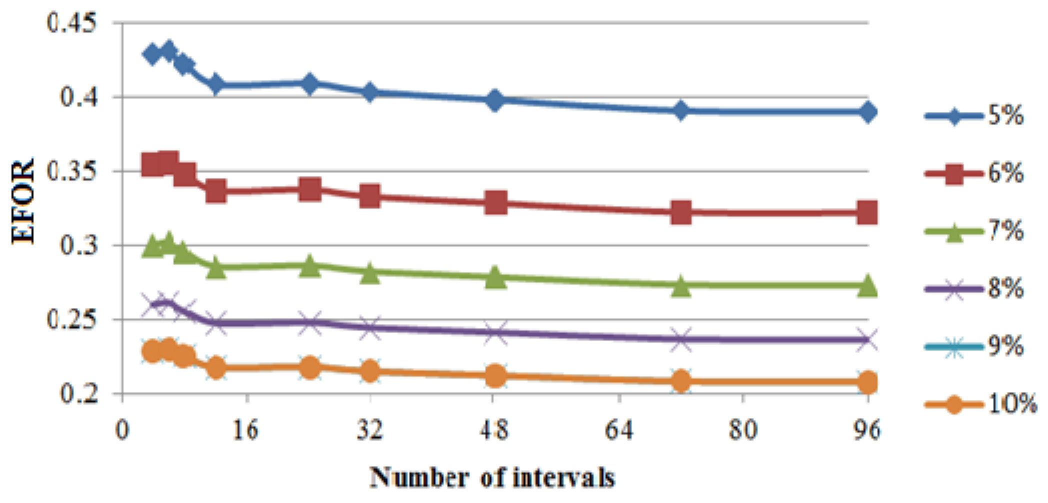


Figure 3.13 EFOR variation with change in wind penetration level for case #1

3.5.2 Case #2: 23rd December 2008

Case #2 is based on the wind generation profile shown in Figure 3.7 which is a relatively flat profile over the entire day. Figures 3.14 and 3.15 respectively demonstrate the variation of LOLP and EFOR for such a generation pattern.

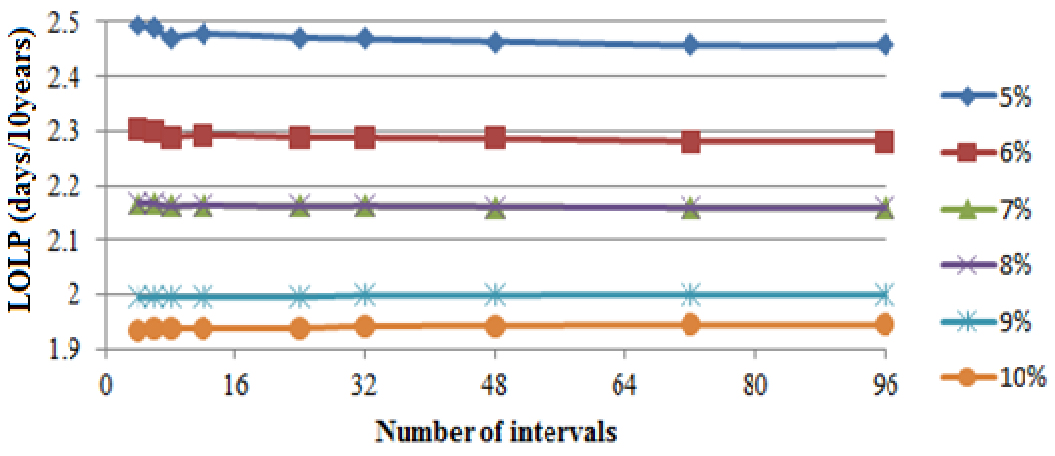


Figure 3.14 LOLP variation with change in wind penetration level for case #2

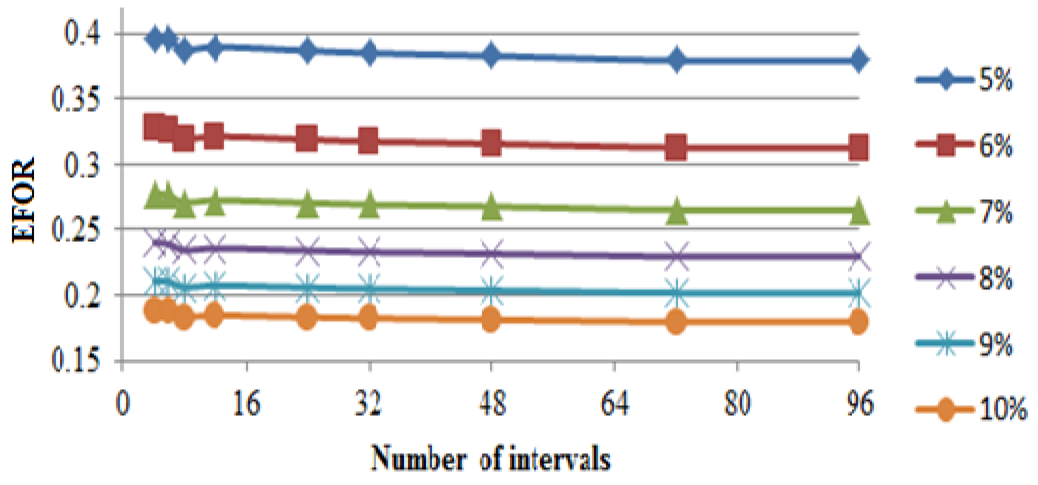


Figure 3.15 EFOR variation with change in wind penetration level for case #2

Observing the patterns of LOLP and EFOR for different penetration levels the following observations can be made:

- For case #1, as wind penetration changes from 5% to 10%, the LOLP decreases from 2.35 days/10years to 2.2 days/10years (a 6.4% decrease) while it decreases from 2.45 days/10years to 1.94 days/10years (a 20.8% decrease) for case #2. Hence, for any kind of wind generation profile (highly variable or flat through the day) the LOLP decreases with an increase in the penetration level. The reason may be attributed to an increase in overall installed capacity resulting in a more reliable system.
- The EFOR is always decreasing with an increase in the penetration level.
- Irrespective of the level of wind penetration, the values of LOLP and EFOR seem to stabilize after 72 intervals. Perhaps it is the most optimum number of intervals for the present test case and computational space can be saved by not analyzing for any intervals beyond this number.

CHAPTER 4

THEORY OF WIND GENERATION TECHNOLOGIES AND THE DFIG POWER CONVERTER TOPOLOGY

4.1 Overview: wind turbine configurations

A wind generator may be broadly classified as a fixed speed or a variable speed type. A fixed speed turbine is simple in construction and does not have a power electronics converter for its control [29]. This design makes a cheaper configuration than the variable speed systems. The fixed speed may also have some advantages in lower losses. However, fixed speed machines extract the maximum power only at a particular wind speed [23]. Hence, for a site where wind speeds are highly variable, such a configuration does not deliver the optimal performance. On the other hand, variable speed turbines use power electronics converters to control the electrical energy injected into the grid. Unlike the fixed speed topologies, these systems can specifically control the voltage, frequency, active power and reactive power output and easily enable smooth integration of even large sized wind farms into the grid. Such turbine systems are costlier and inject high harmonics into the power system. Broadly, wind turbine configurations [48], [49] can be categorized as:

a) Type 1 turbine configuration

This topology typically consists of an asynchronous squirrel cage induction generator (SCIG) connected to a fixed speed wind turbine. With an active stall control, these turbines have the ability to stop and start faster than the other configurations. The major drawback of Type 1 turbines is that they operate at a fixed speed, cannot generate reactive power and requires a stiff grid to enable stable operation. Further, the induction generators themselves demand reactive power for operation. Figure 4.1 depicts the above mentioned topology.

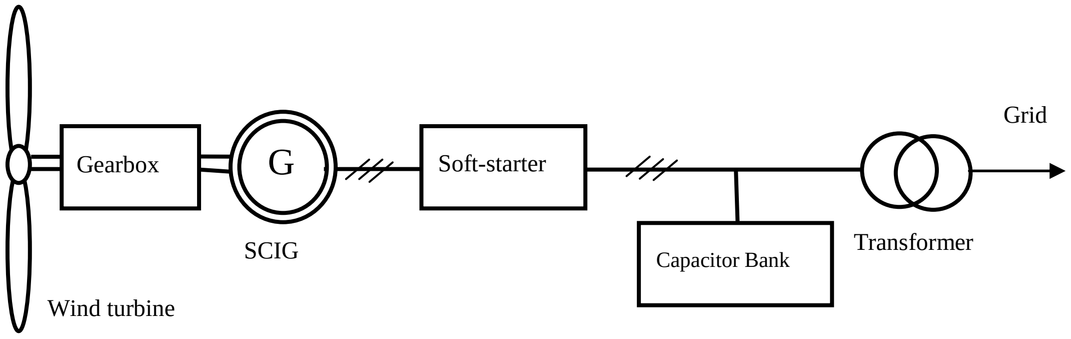


Figure 4.1 Type 1 wind turbine configuration

b) Type 2 turbine configuration

Type 2 is a variable speed wind turbine coupled with a wound rotor induction generator (WRIG) to obtain the energy conversion. This topology allows variation of the rotor resistance to achieve a speed variation and is called *dynamic slip control* [21]. A speed variation of as much as 10% above the synchronous speed is possible which makes the power output of the turbine controllable. To enable a smoother startup, soft starters are used. Figure 4.2 shows a typical Type 2 turbine configuration.

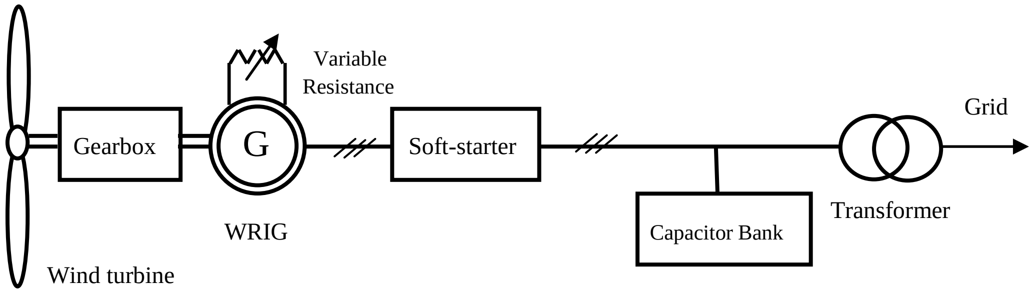


Figure 4.2 Type 2 wind turbine configuration

c) Type 3 turbine configuration

This topology is commonly referred to as the DFIG and consists of a WRIG coupled with a variable speed turbine. A power electronic converter is used to control the reactive power flow through the turbine.

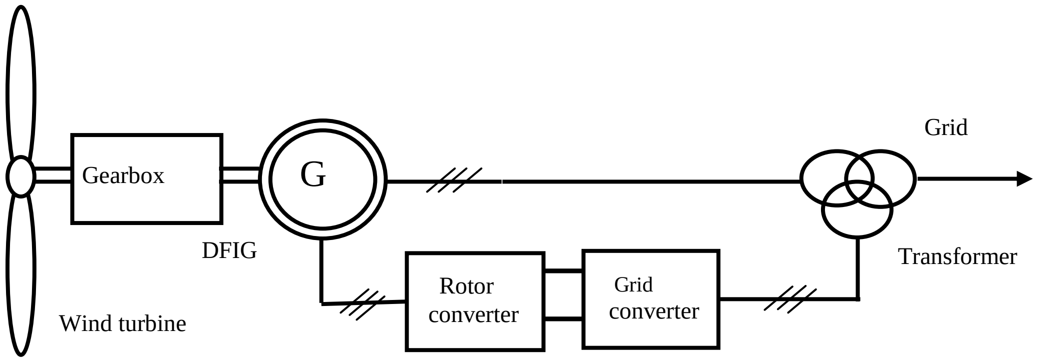


Figure 4.3 Type 3 wind turbine configuration

d) Type 4 turbine configuration

The topology has a variable speed turbine connected to the grid through a power electronic converter capable of controlling the full range of active and reactive power (Figure 4.4). Type 4 designs may not have a gearbox. However, with the entire generated power passing through the converter, the overall efficiency of the configuration is decreased.

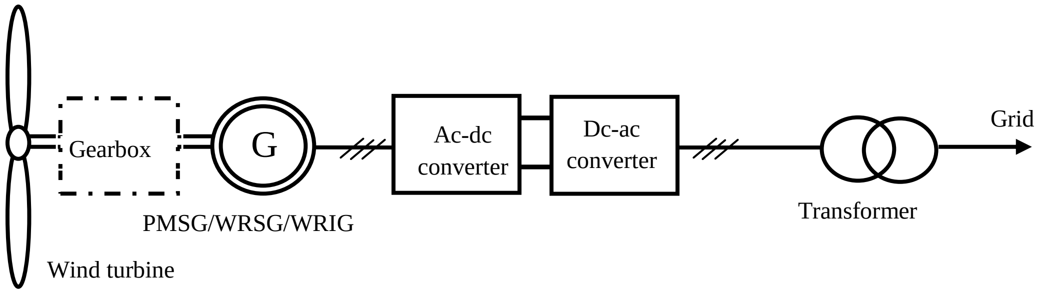


Figure 4.4 Type 4 wind turbine configuration

4.2 The doubly fed induction generators

The DFIG based configuration (Type 3) enables an active tracking of the wind speed to operate the rotor near its optimum tip speed ratio (TSR) and thereby extract the maximum power. Depending on the site location and turbine aerodynamics, such a configuration can, on an average, collect around 10% more annual energy [23]. Hence, of all the wind turbine configurations discussed in Section 4.1, the Type 3 turbines (Figure 4.3) are the most economical and popular form of topology in use [48] and are discussed in detail in this section.

4.2.1 Power flow in a DFIG machine

Figure 4.5 shows the back-to-back converter system utilized in a DFIG [33]. Power flow directions are also indicated.

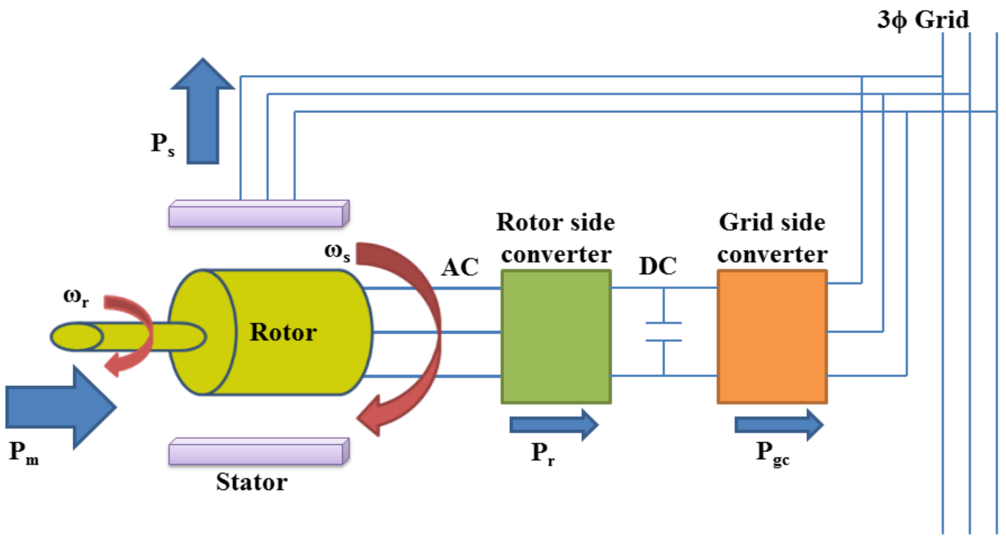


Figure 4.5 Power flow in a DFIG based configuration (Type 3)

For operation in steady state, the stator power P_s is expressed as [50],

$$P_s = P_{gap} - P_{loss\_stator} \tag{4.1}$$

where, P_{gap} is the power transferred through the air gap and P_{loss_stator} is the copper losses in the rotor circuit. The air gap power is defined in terms of the mechanical power input from the wind turbine (P_m) and the power through the rotor (P_r) as,

$$P_{gap} = P_m - P_r \tag{4.2}$$

From (4.1) and (4.2) for negligible rotor losses the stator power is defined as,

$$P_s = P_m - P_r \tag{4.3}$$

Defining the quantities in terms of the generator torque T, P_s and P_m are expressed as,

$$P_s = T\omega_s \tag{4.4}$$

$$P_m = T\omega_r \tag{4.5}$$

where, ω_s is the stator electrical frequency and ω_r is the rotor electrical frequency. Subtracting (4.4) and (4.5) and rearranging,

$$P_r = -T(\omega_s - \omega_r) = -sT\omega_s \tag{4.6}$$

where, s is the slip and is defined as,

$$s = \frac{(\omega_s - \omega_r)}{\omega_s} \tag{4.7}$$

From (4.3) and (4.6), (4.8) is obtained,

$$P_r = -sP_s \tag{4.8}$$

Combining (4.3) and (4.8), P_m can be expressed as,

$$P_m = P_s + P_r = (1-s)P_s \tag{4.9}$$

As illustrated by (4.9), in a DFIG the electrical power output can be varied by the control of the slip. Using (4.7), theoretically a rotor speed up to twice the synchronous speed can be obtained by varying the slip from -1 to +1 (i.e., 7,200 rpm for 60 Hz electrical for one pole-pair). Such operation enables the rotor to absorb as well as deliver power. On the basis of rotational speed of generator relative to the synchronous speed, the DFIG operation can be generalized as [51]:

- At synchronous speed, the rotor current is dc as in a synchronous machine. If losses are neglected, all of the mechanical power inputted by the turbine to the rotor gets transferred to the grid via the stator. No power is exchanged directly between the rotor and the grid through the back-to-back converters.
- If the machine operates below the synchronous speed, it is known as the subsynchronous operation. The stator generates power to feed the grid but part of it is fed back to the rotor through the converters.
- In the supersynchronous mode of operation (operating above synchronous speed), both the rotor and the stator feed power to the grid.

Due to mechanical and economic reasons, there are restrictions on the maximum slip achievable and the practical speed range of a DFIG varies typically between -40% to 30% of the synchronous speed [48]. On the basis of (4.1)-(4.9), Figures 4.6 and 4.7 depict the power flow in a DFIG for the subsynchronous and supersynchronous operations.

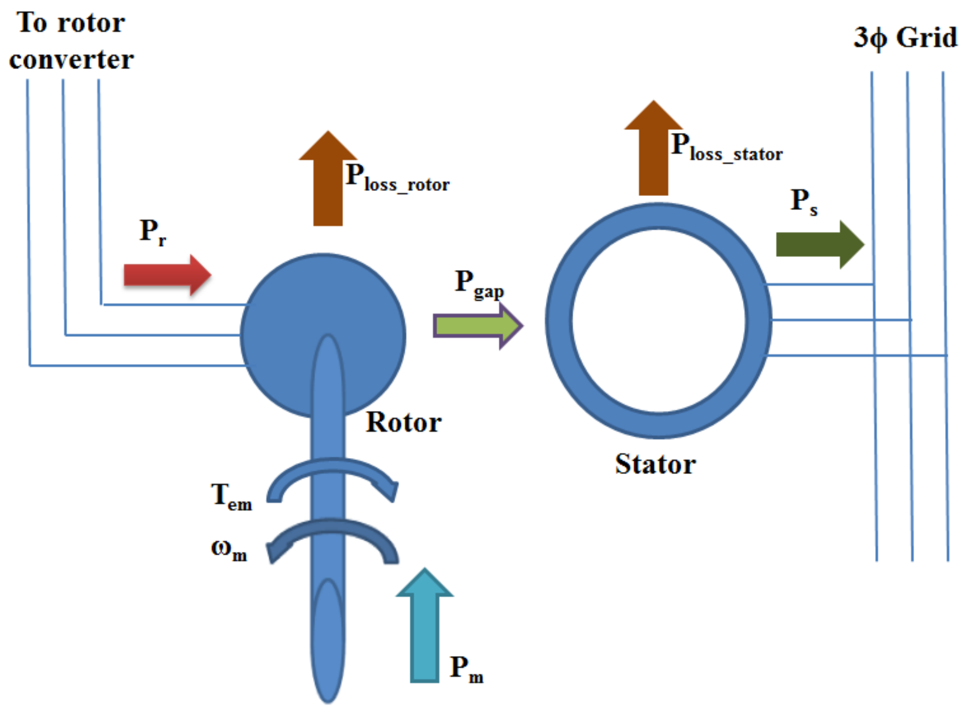


Figure 4.6 Power flow in a DFIG machine in the subsynchronous mode

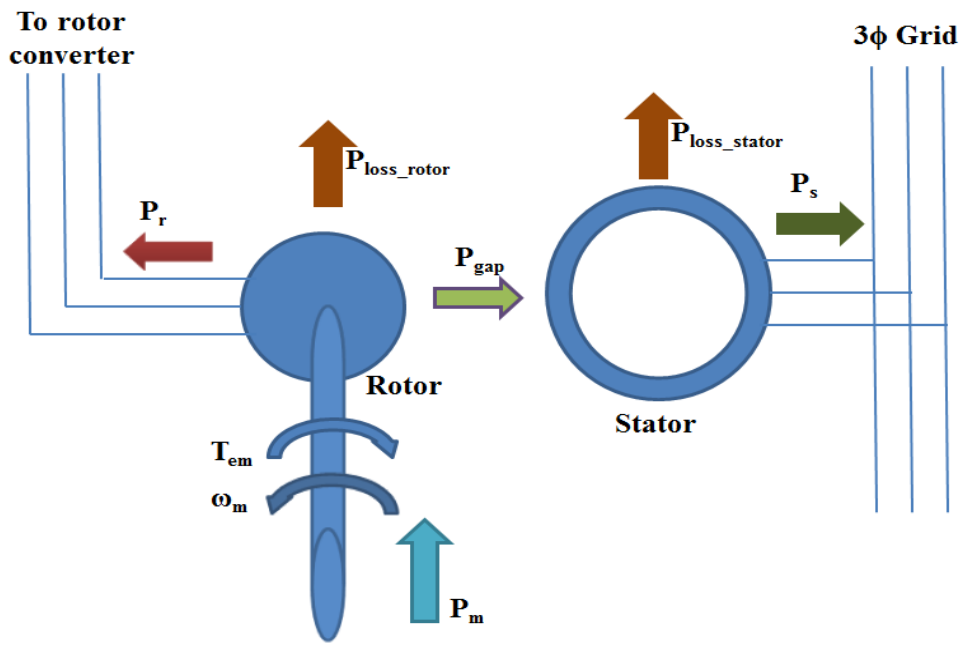


Figure 4.7 Power flow in a DFIG machine in the supersynchronous mode

It must be noted that as derived in (4.9), P_r is dependent on the slip. Thus, for subsynchronous speeds when the slip is positive, P_r is taken out of the rotor-side converter and fed to the rotor. For supersynchronous speeds, P_r is transmitted from the rotor to the dc bus.

4.2.2 The rotor side converter

The rotor side converter utilizes pre-defined power speed characteristics (tracking characteristics) to derive the maximum power at any wind speed within the operation range. For a wind turbine, the power output is related to the wind speed as [52],

$$P_{mech} = \frac{1}{2}\rho A v^3 C_P(\lambda, \theta) \tag{4.10}$$

where, P_{mech} is the turbine output power, ρ is the density of air, A area covered by the span of the turbine blades, v is the speed of the wind, C_P is the power coefficient, λ is the tip speed ratio and θ is the pitch angle of the blades.

It must be noted that while P_{mech} is the turbine power output, P_m is the net power inputted into the generator rotor. For a lossless mechanical power transmission between the turbine and the generator rotor, P_{mech} is equal to P_m.

The power coefficient is expressed as [52],

$$C_P(\lambda, \theta) = c_1\left(\frac{c_2}{\lambda_i} - c_3\theta - c_4\right)e^{-\frac{c_5}{\lambda_i}} \tag{4.11}$$

where, the constants c_1 =0.22, c_2 =116, c_3 =0.4, c_4 =5 and c_5 =12.5 and λ_i is defined as,

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\theta} - \frac{0.035}{\theta^3 + 1} \tag{4.12}$$

The parameters for a General Electric (GE) 1.5MW wind turbine are available from [53]. The values are listed in Table 4.1.

Table 4.1 Parameters for a 1.5 MW General Electric wind turbine

Parameter	Value
$0.5\rho A$	0.00159 kg/m
λ	56.6 ω_t/v $(m/s)^{-1}$

where, ω_t is the angular turbine speed in per unit

On basis of above details, the turbine tracking characteristics the wind turbine is constructed and is shown in Figure 4.8. Its operation is illustrated by defining four points A, B, C and D. The actual speed of rotor (ω_r) is measured and the corresponding optimal mechanical power from the tracking characteristics is used as the reference power. When the power level is above 75% of the rated turbine power, the speed reference is kept at 1.2 p.u. (region C to D). For operation in between 15% to 75%, the speed reference (region B to C) is [53],

$$\omega_{ref} = -0.67P_{m\_pu}^2 + 1.42P_{m\_pu} + 0.51 \tag{4.13}$$

where, P_{m_pu} is the p.u. mechanical power inputted from the turbine into the rotor and ω_{ref} is the generator speed reference in per unit.

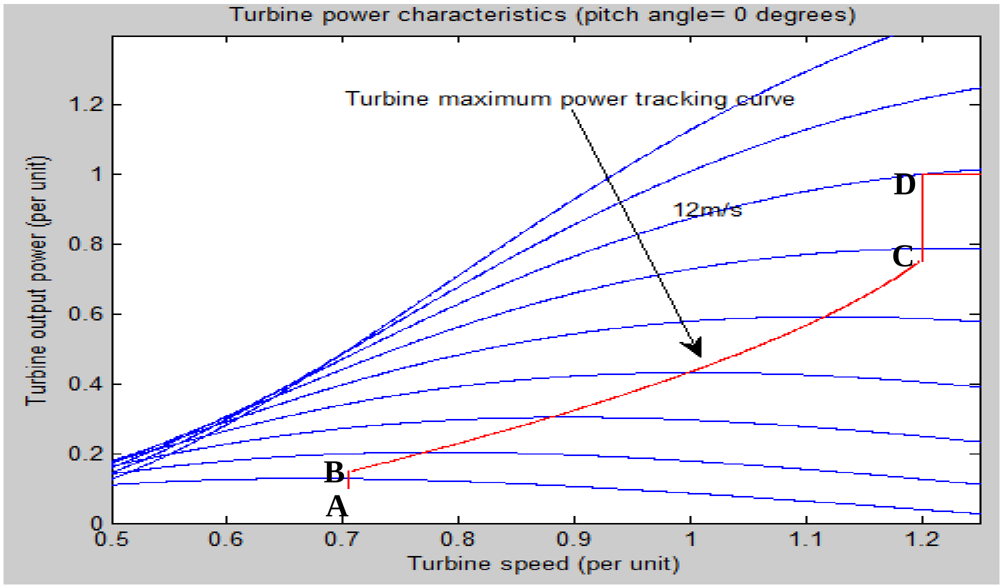


Figure 4.8 Turbine tracking characteristics

4.2.3 The grid side converter

The grid side converter regulates the voltage of the DC bus capacitor and provides a path for rotor power flow to and from the AC system at unity power factor. For a lossless converter system, the power through the grid converter is same as the power through the rotor converter.

4.2.4 Equivalent circuit for a DFIG

An equivalent circuit is a theoretical circuit that represents an electrical system while retaining all of the electrical characteristics. By providing a reduction of complex system in terms of a simpler representation, an equivalent circuit aids in easier performance analysis of the system. Figure 4.9 shows the equivalent circuit of a DFIG machine [53]. The figure represents the stator and the rotor circuits and combines them by referring the rotor circuit to the stator side. The meaning of the symbols is listed in Table 4.2.

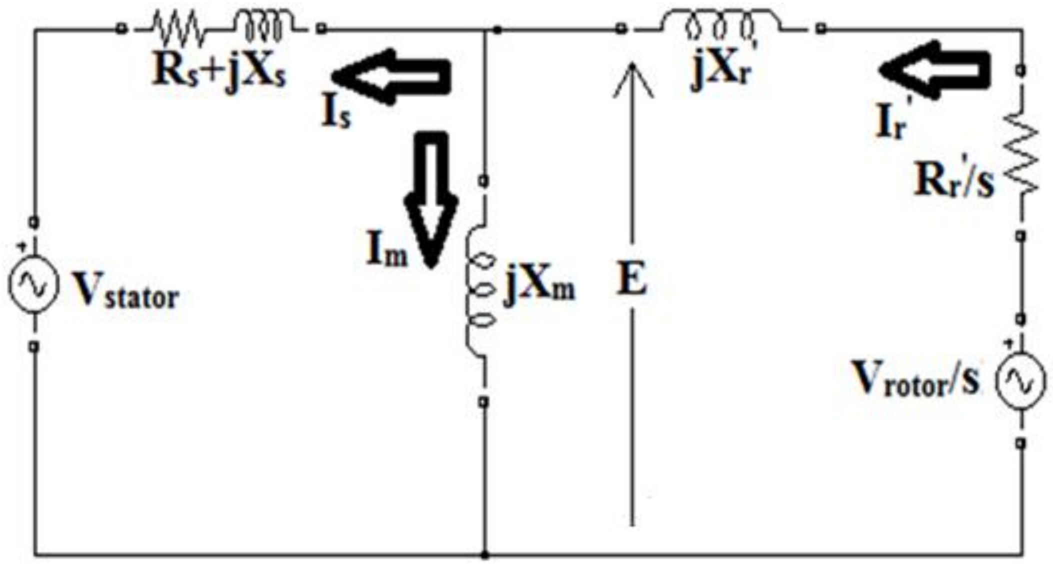


Figure 4.9 Equivalent circuit of a DFIG machine

Table 4.2 List of abbreviations used in Figure 4.9

Symbols	**Meaning**
I_r'	Rotor current referred to stator side
I_m	Magnetizing current
I_s	Stator current
R_r'/s	Rotor resistance referred to stator side
R_s	Stator resistance
s	Value of operating slip
V_{rotor}/s	Equivalent rotor voltage
V_{stator}	Per phase stator voltage
X_r'	Rotor reactance referred to stator side
X_s	Stator reactance

For unity power factor operation, the air gap power can be expressed as,

$$P_{gap} = P_s + P_{loss\_stator} = \left(3V_{stator}I_s\right) + \left(3I_s^2R_s\right) \quad (4.14)$$

The value of I_s can be determined by solving the quadratic equation (4.14). The voltage across the rotor circuit can be calculated as in (4.15),

$$E = V_{stator} + (R_s + jX_s)I_s \tag{4.15}$$

The magnetizing current I_m is calculated as,

$$I_m = \frac{E}{jX_m} \tag{4.16}$$

As seen in Figure 4.9, for the chosen direction of power flow, the rotor current is the addition of the magnetizing and the stator current,

$$I_r^{'} = I_s + I_m \tag{4.17}$$

The slip dependent rotor voltage of the DFIG machine is calculated as,

$$V_{rotor} / s = E + (\frac{R_r^{'}}{s} + jX_r^{'})I_r^{'} \tag{4.18}$$

4.2.5 Phasor diagram of a DFIG machine

The phasor diagram for a DFIG machine can be constructed by utilizing the derived equations in Section 4.2.4. For a DFIG delivering power to grid at unity power factor, the stator current, I_s, is aligned in the direction of the stator voltage V_{stator} (which is the grid voltage). Using (4.15), the voltage drop across stator impedance is added to V_{stator} to obtain the phasor corresponding to internal electro motive force (EMF). The magnetizing current (I_m) is calculated by using (4.16) and its phasor is drawn 90^0 lagging to the magnetizing EMF (E). The rotor current is found using (4.17). Lastly, as defined by (4.18), by incorporating the voltage drops across the rotor impedances, the phasor corresponding to rotor voltage drop may be drawn. Figure 4.10 shows the phasor diagram of DFIG for unity power factor operation.

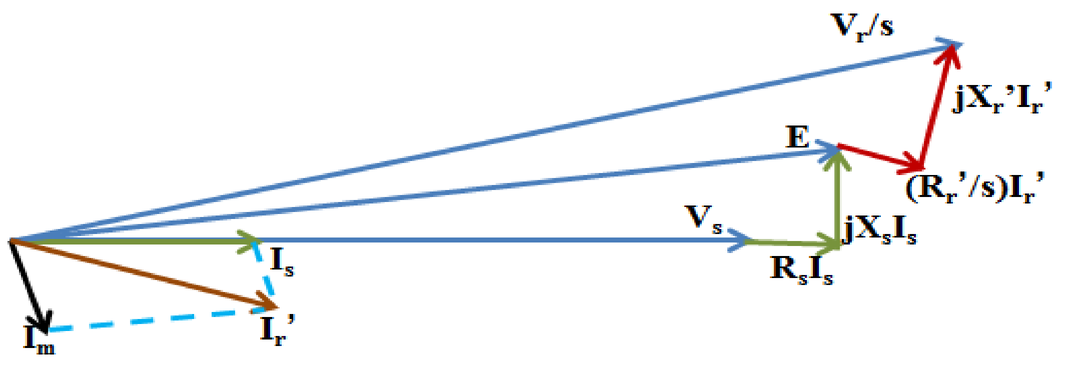


Figure 4.10 Phasor diagram of a DFIG machine for a unity power factor

Following a similar procedure, the phasor diagram for operation at a non-unity power factor operation may be constructed by using (4.14) – (4.18). Figure 4.11 shows the phasor diagram of DFIG for a lagging power factor operation.

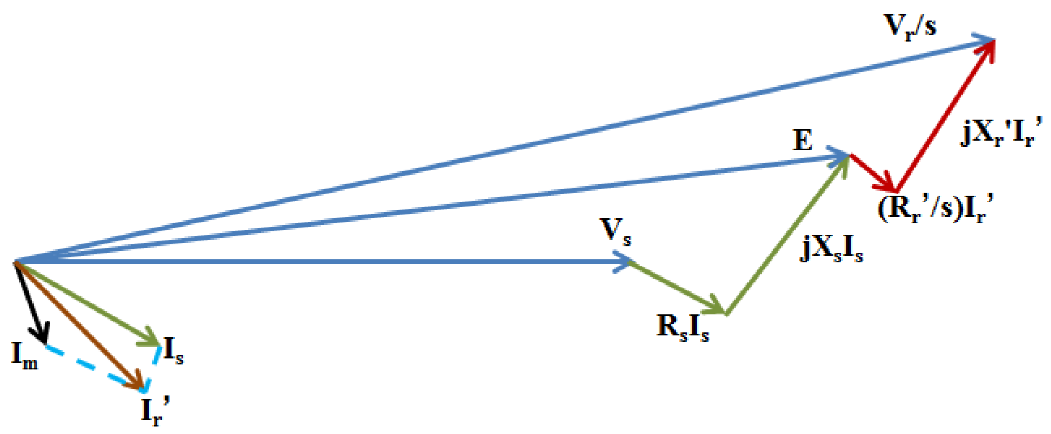


Figure 4.11 Phasor diagram of a DFIG machine for a lagging power factor

It must be observed that similar to Figure 4.10, the phasor diagram shown in Figure 4.11 is drawn with I_m lagging E by 90^0. Further the phasors corresponding to the resistive voltage drop across R_s and (R'_r/s) are always parallel to the respective currents through them.

CHAPTER 5

CONSTRUCTION OF A GUI FOR THE DFIG GENERATION SYSTEM

5.1 Choice of MATLAB for GUI construction

This chapter explains the construction of a GUI to demonstrate the working of the DFIG machine, display its power flow and depict its maximum power point tracking mechanism.

For developing a GUI, numerous programming languages are available. Microsoft Visual Basic is the most preferred choice by advanced programmers. Being a Microsoft product, Visual Basic is easily compatible with the Windows operating system. Similarly JAVA based GUI are inherently implementable on any operating system. However, both of these languages require an advanced skill level to understand, develop or edit programs.

Focusing on choosing a simpler language to demonstrate engineering systems, this thesis uses the dedicated GUI toolbox of MATLAB for illustrating the DFIG system. Due to the nature of the technical content desired to be simulated in this thesis and the kind of end users expected to benefit from it, MATLAB offers the following advantages:

- MATLAB is easily available in universities and electrical engineering students learn it as part of their course work. Hence, the drag-and-drop feature of the MATLAB GUI construction tool eliminates the need to learn any new GUI language to understand or edit the program.

- By using its powerful mathematical and engineering toolbox, MATLAB offers scope for extending this GUI to simulate more complicated aspects of the DFIG in the future.
- MATLAB has the functionality of converting its GUI into standalone executable files. This eliminates the necessity to install MATLAB on user computer and makes the GUI accessible to users belonging to non-engineering background also.

5.2 Features of the GUI for simulation of a DFIG system

The GUI is intended to aid the end user to visualize the electrical working of a DFIG machine and understand its change in operational behavior for a variable range of wind speed inputs. Thus, the GUI has been constructed with four interconnected program interfaces which dynamically modify their display for the entered wind speeds. The GUI is constructed by choosing a wind turbine similar to the GE wind turbine model 1.5sle. The specifications of the turbine are listed in Table 5.1 [54].

Table 5.1 Specification of wind turbine used as test case for GUI design

Specifications	**Detail**
Rated capacity	1.5 MW
Rated wind speed	12 m/s

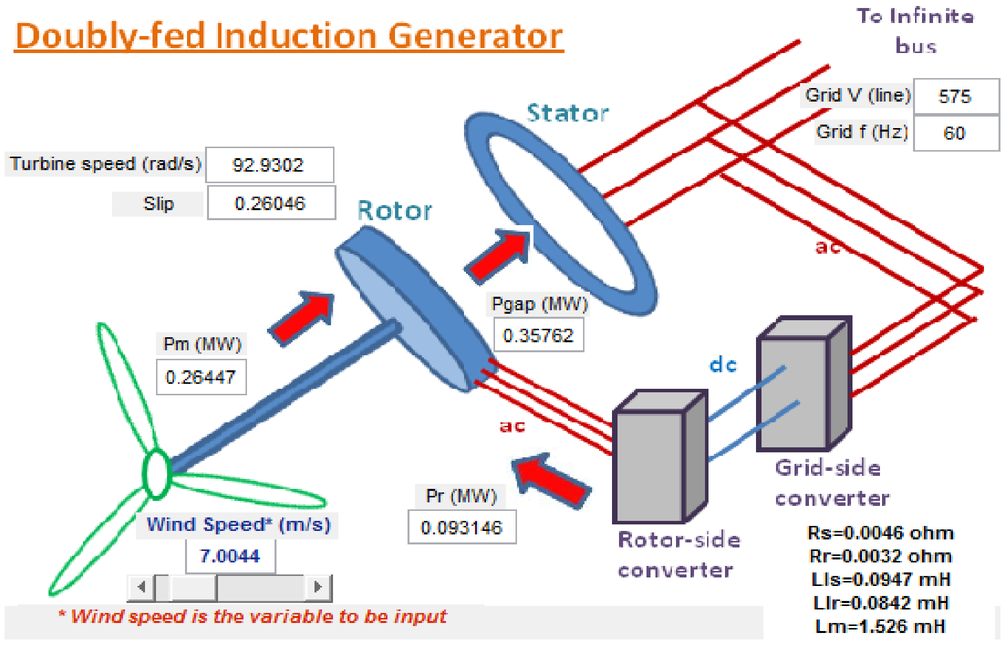
5.2.1 The power flow interface

The interface shows the change in power transfer within the wind turbine for a change in wind speed. The interface allows the user to vary the wind speed from 6 to 14 m/s with the aid of a slider interface. Accordingly, the program calculates the optimum slip to extract maximum power from the turbine by using the theory explained in Section 4.2. The interface displays the following parameters on the screen:

- The optimum slip
- The corresponding turbine speed in rad/s
- The mechanical power inputted into generator rotor (P_m) for a given wind speed (calculated using (4.10))
- The air gap power (P_{gap}) as per the maximum power point tracking
- The magnitude and direction of power transferred between the rotor and the rotor converter (P_r)

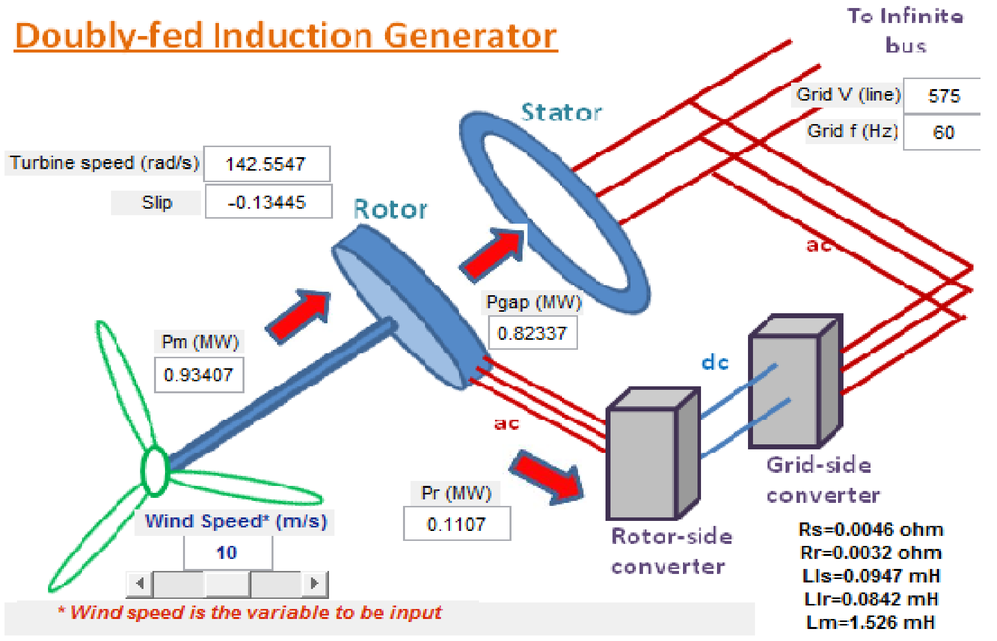
Figures 5.1 and 5.2 show the snapshot of the constructed GUI and depict the change in the direction of the P_r as the wind speed changes from 7 m/s to 10 m/s. The directions of the power flow are programmed to change as per the wind speed variation. It must be noted that in Figure 5.1, the DFIG is operating in sub-subsynchronous operation and power is directed from rotor converter to the rotor. However, in Figure 5.2 when the machine is operating in a supersynchronous operation, the rotor supplies power to the rotor converter. Consequently, in both the

GUI interface snapshots, the arrow indicating the direction of power is also different.



Grid V (line) 575
Grid f (Hz) 60
Turbine speed (rad/s) 92.9302
Slip 0.26046
Pgap (MW) 0.35762
Pm (MW) 0.26447
Pr (MW) 0.093146
Wind Speed* (m/s) 7.0044
* Wind speed is the variable to be input
Rs=0.0046 ohm
Rr=0.0032 ohm
Lls=0.0947 mH
Llr=0.0842 mH
Lm=1.526 mH

Figure 5.1 Power flow GUI showing the subsynchronous operation



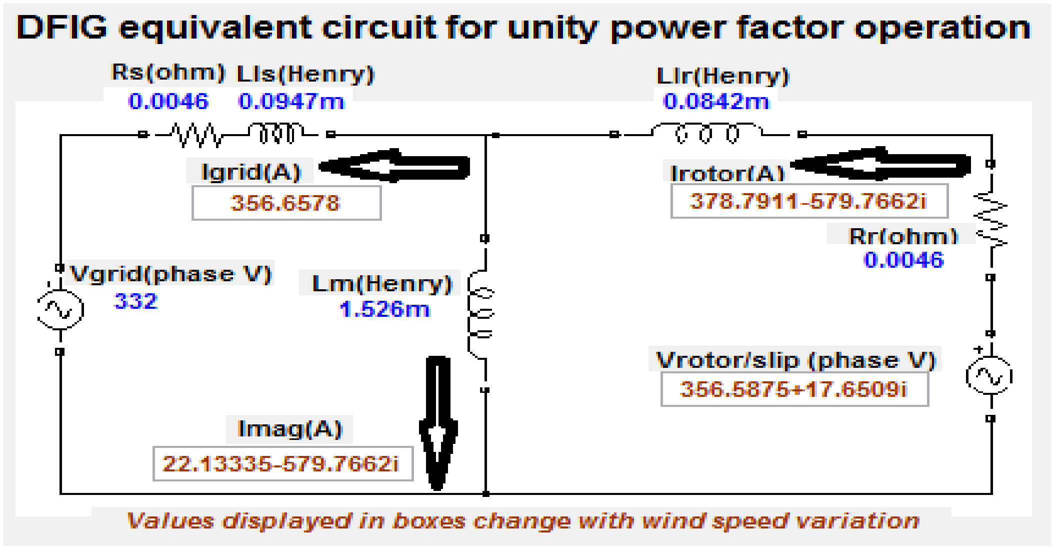
Grid V (line) 575
Grid f (Hz) 60
Turbine speed (rad/s) 142.5547
Slip -0.13445
Pgap (MW) 0.82337
Pm (MW) 0.93407
Pr (MW) 0.1107
Wind Speed* (m/s) 10
* Wind speed is the variable to be input
Rs=0.0046 ohm
Rr=0.0032 ohm
Lls=0.0947 mH
Llr=0.0842 mH
Lm=1.526 mH

Figure 5.2 Power flow GUI showing the supersynchronous operation

The GUI has been designed for fixed values of generator resistances, inductances, grid voltage and frequency values and these fixed parameters have been indicated on the GUI.

5.2.2 The equivalent circuit interface

As the wind speed is varied by the user, another interface also pops up simultaneously and displays the equivalent circuit of the DFIG machine and the change in the values of the current and voltage within the circuit. The values are calculated for the wind turbine delivering power to grid at unity power factor. Figures 5.3 and 5.4 show the snapshots of the GUI at wind speeds corresponding to the subsynchronous (7 m/s) and supersynchronous operation (10 m/s).


DFIG equivalent circuit for unity power factor operation

Rs(ohm) 0.0046

Lls(Henry) 0.0947m

Llr(Henry) 0.0842m

Igrid(A) 356.6578

Irotor(A) 378.7911-579.7662i

Rr(ohm) 0.0046

Vgrid(phase V) 332

Lm(Henry) 1.526m

Vrotor/slip (phase V) 356.5875+17.6509i

Imag(A) 22.13335-579.7662i

Values displayed in boxes change with wind speed variation

Figure 5.3 DFIG equivalent circuit GUI interface for unity power factor operation at wind speed 7 m/s

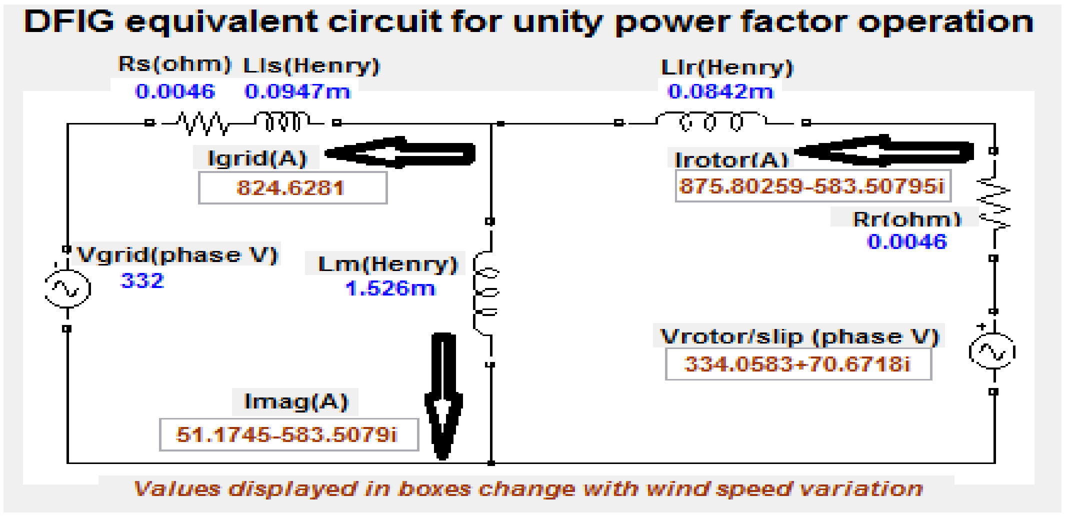


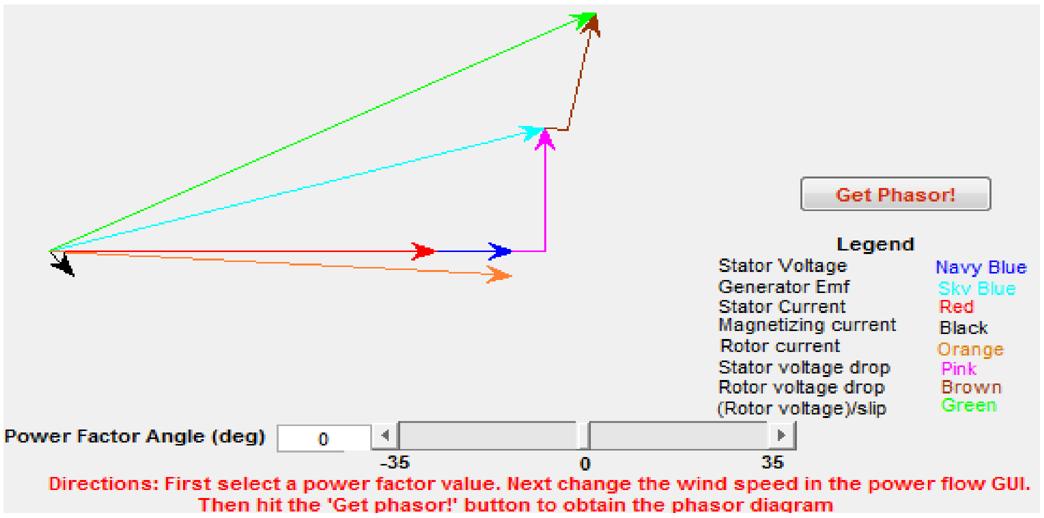
Figure 5.4 DFIG equivalent circuit GUI interface for unity power factor operation at wind speed 10 m/s

In Figures 5.3 and 5.4, the values displayed in blue color are constant values of machine parameters and grid voltage chosen for the implementation. With the variation of wind speed in the power flow GUI (Figure 5.1, 5.2), the individual current and voltages of the equivalent circuit are calculated using the theory described in Section 4.2. The values calculated are displayed in brown on the GUI.

5.2.3 The phasor diagram interface

Based on the theory of phasor diagram for a DFIG machine described in section 4.2.5, a GUI interface is constructed that displays variation of the phasor values as the wind speed and power factor angle is varied. While the user can change the power level by varying the wind speed from the power flow GUI, the interface allows an additional user input of varying the power factor angle too.

Figures 5.5, 5.6 and 5.7 show the phasor diagram GUI interface for operation at unity, lagging and leading power factors for a wind speed of 14 m/s.



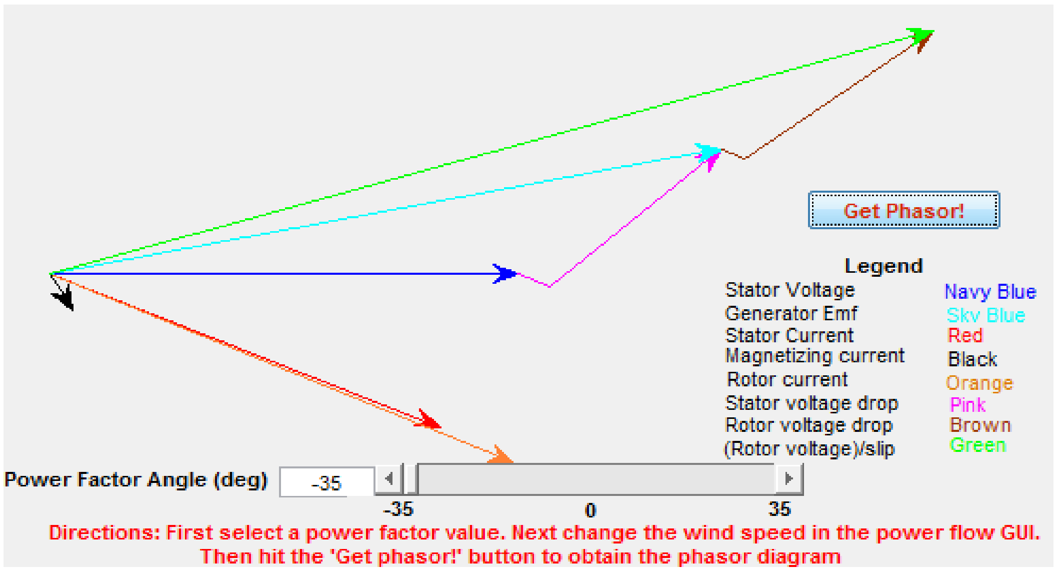
Legend

Stator Voltage	Navy Blue
Generator Emf	Sky Blue
Stator Current	Red
Magnetizing current	Black
Rotor current	Orange
Stator voltage drop	Pink
Rotor voltage drop	Brown
(Rotor voltage)/slip	Green

Power Factor Angle (deg) 0

Directions: First select a power factor value. Next change the wind speed in the power flow GUI. Then hit the 'Get phasor!' button to obtain the phasor diagram

Figure 5.5 Wind speed 14 m/s and unity power factor



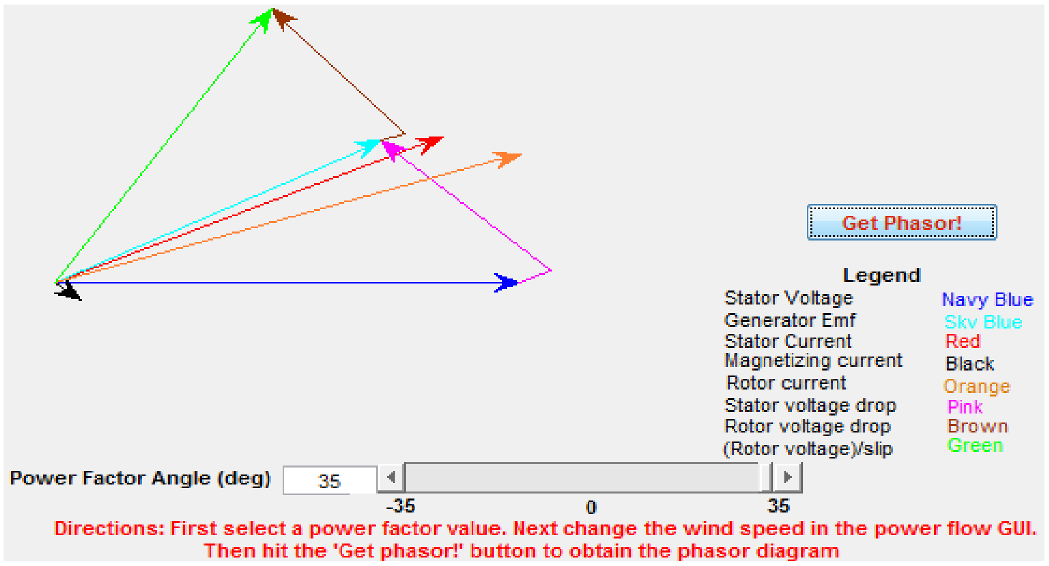
Legend

Stator Voltage	Navy Blue
Generator Emf	Sky Blue
Stator Current	Red
Magnetizing current	Black
Rotor current	Orange
Stator voltage drop	Pink
Rotor voltage drop	Brown
(Rotor voltage)/slip	Green

Power Factor Angle (deg) -35

Directions: First select a power factor value. Next change the wind speed in the power flow GUI. Then hit the 'Get phasor!' button to obtain the phasor diagram

Figure 5.6 Wind speed 14 m/s and power factor angle -35 degrees



Legend

Stator Voltage	Navy Blue
Generator Emf	Sky Blue
Stator Current	Red
Magnetizing current	Black
Rotor current	Orange
Stator voltage drop	Pink
Rotor voltage drop	Brown
(Rotor voltage)/slip	Green

Directions: First select a power factor value. Next change the wind speed in the power flow GUI. Then hit the 'Get phasor!' button to obtain the phasor diagram

Figure 5.7 Wind speed 14 m/s and power factor angle 35 degrees

Due to space constraint and emphasis on showing the behavioral dynamics of phasor diagrams, a power factor angle variation of only -35 to 35 degrees has been allowed in the GUI.

It must be noted that the numerical values of currents are much larger than the voltage values. Hence, to appropriately adjust the phasors within the same GUI screens, the currents have been scaled down by a factor of 8.8.

5.2.4 Maximum power point tracking interface

Theory describing the DFIG rotor converter is discussed in Section 4.2.3. Based on it, a GUI is constructed to track the maximum power point on the turbine curve. For very low wind speeds when the turbine power output is less than

0.15 p.u. of the rated power, the DFIG operates at a constant slip of 0.3. In between 15% to 75% of turbine power level, the optimum operating point it obtained by using (4.13). For wind speeds above the rated speed of 12 m/s, the turbine is made to operate at slip of -0.2. Figures 5.8, 5.9 and 5.10 show the maximum power point GUI operation at wind speeds of 6, 10 and 12 m/s respectively.

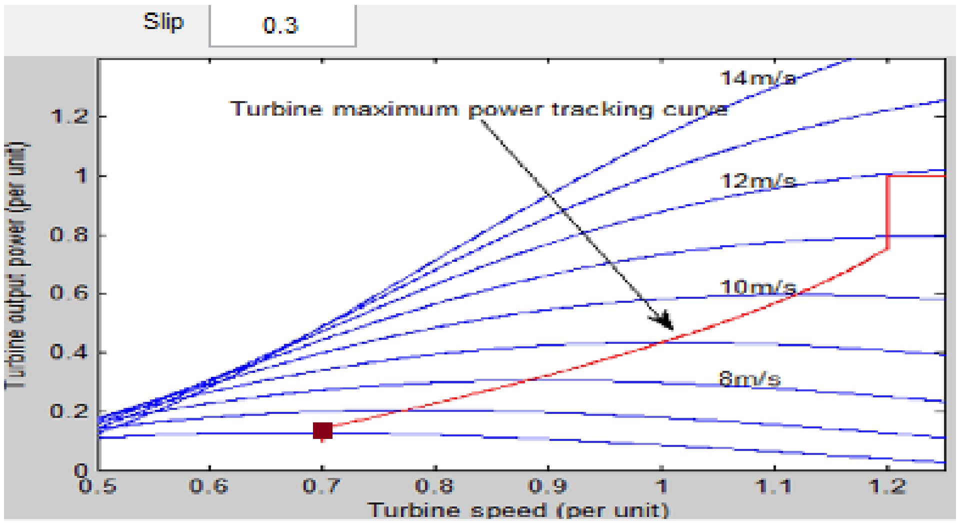


Figure 5.8 Maximum power point tracking GUI at wind speed 6 m/s

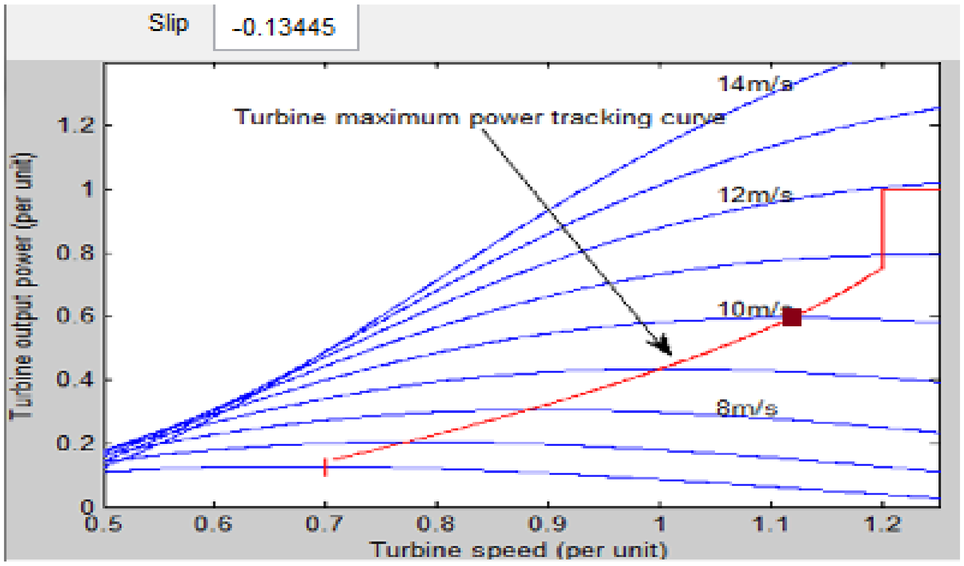


Figure 5.9 Maximum power point tracking GUI at wind speed 10 m/s

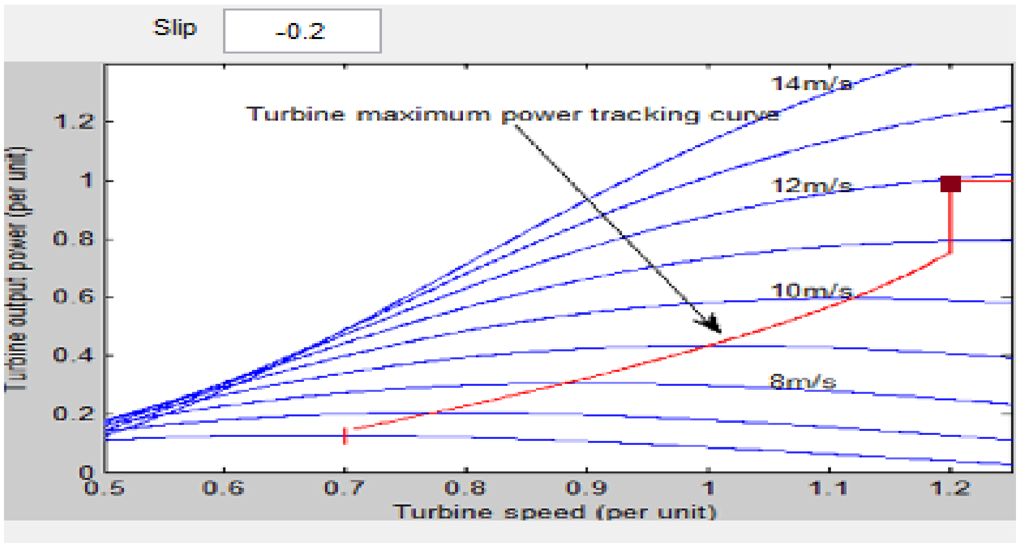


Figure 5.10 Maximum power point tracking GUI at wind speed 12 m/s

CHAPTER 6
CONCLUSIONS AND RECOMMENDATIONS

6.1 Reliability assessment technique

This thesis proposed an accurate reliability evaluation technique for wind energy integrated power system by formulating accurate models of generation availability and outage probability of wind generators. The technique was simulated on a Texas power system of 2008. Following observations are made from the implementation:

- The outage probability of wind generators, which is measured in terms of EFOR in this thesis, was found to be immensely high (0.4) in comparison to the typical values of FOR of conventional generators (0.03 - 0.08). This indicates that approximating the outage probability of wind generators to be same as that of conventional generation system may lead to large error in reliability calculations.
- Accuracy of the LOLP calculation method is increased by choosing an increased number of intervals for the analysis.
- With an increase in the level of wind generation installed capacity, overall LOLP of the entire power system was observed to reduce, thus, indicating towards a more reliable power system.
- The method was found to be independent of the wind generation pattern and offered improvement in precision for largely varying and fairly constant wind generation profiles.

It is recommended that while using the technique for a larger system, the ‘optimum’ number of intervals must be determined by iteration beyond which the proposed LOLP calculation methodology offers no appreciable accuracy benefit. Thus, computational space may be saved and system be simulated faster.

Lastly, with appropriate modifications, the method can be extended to conduct reliability analysis of power system having a large amount of generation contributed by varying sources of energy such as the solar generation.

6.2 GUI construction for a DFIG system

A GUI has been constructed to animatedly depict the operation of the DFIG based wind generation system. The interface shows the behavior of power flow, equivalent circuit, phasor diagram and maximum power point tracking mechanism of the DFIG for the wind speed inputted by the user. The module has been designed to work as a stand-alone software program without dependency on MATLAB.

In addition to being accessible on any Windows based computer, the GUI is a simplified representation of an extremely complicated wind generation technology. The tool could be used to educate as well as invoke interest among science students about the promising potential of renewable power engineering.

In the future, the GUI may be made more versatile by adding features to simulate the dynamic response of the machine and display the change in the electrical waveforms with variation in operation conditions.

REFERENCES

[1] Ernest Orlando Lawrence Berkley National Laboratory, document available on the topic "Understanding the cost of power interruptions to U.S. electricity consumers," available at:
http://certs.lbl.gov/pdf/55718.pdf

[2] S. Panya, T. Detmote, "Economic impact of power outage in Thailand: industry perspectives," International Conference on Energy and Sustainable Development: Issues and Strategies, June 2010, pp. 1-7

[3] U.S. Energy Information Administration, document available on the topic "U.S. electric net summer capacity, 2004 – 2008," available at:
http://205.254.135.7/cneaf/solar.renewables/page/trends/table1_12.pdf

[4] American Wind Energy Association, article appearing on the topic "Industrial statistics," available at:
http://www.awea.org/learnabout/industry_stats/index.cfm

[5] U.S. Energy Information Administration, document available on the topic "State electricity profiles," available at:
http://205.254.135.7/electricity/

[6] U.S. Environmental Protection Agency, article appearing on the topic "Renewable portfolio standards fact sheet," available at:
http://www.epa.gov/chp/state-policy/renewable_fs.html

[7] G.T. Heydt, V. Vittal, R. Ayyanar, "Power system operation and planning for enhanced wind generation penetration – collaborative work force development," US Department of Energy grant award number: DE-EE0000535, October 2011

[8] R. Billinton, A.V. Jain, "Unit derating levels in spinning reserve studies," IEEE Transactions on Power Apparatus and Systems, July 1971, vol. PAS-90, No. 4, pp. 1677-1687

[9] R. Billinton, A.V. Jain, C. MacGowan, "Effect of partial outage representation in generation system planning studies," IEEE Transactions on Power Apparatus and Systems, September 1974, vol. PAS-93, No. 5, pp. 1252-1259

[10] R. Billinton, Y. Li, "Incorporating multi-state unit models in composite system adequacy assessment," International Conference on Probabilistic Methods Applied to Power Systems, September 2004, pp. 70-75

[11] K.F. Schenk, R.B. Misra, S. Vassos, W. Wen, "A new method for the evaluation of expected energy generation and loss of load probability," IEEE Transac-

tions on Power Apparatus and Systems, February 1984, vol. PAS-103, No. 2, pp. 294-303
[12] G. Calabrese, “Generating reserve capacity determined by probability method,” Transactions of the American Institute of Electrical Engineers, January 1947, vol. 66, No. 1, pp. 1439-1450

[13] A.K. Ayoub, J.D. Guy, A.D. Patton, “Evaluation and comparison of some methods for calculating generating system reliability,” IEEE Transactions on Power Apparatus and Systems, April 1970, vol. PAS-89, No. 4, pp. 537-544

[14] R. Karki, R. Billinton, “Cost-effective wind energy utilization for reliable power supply,” IEEE Transactions on Energy Conversion, June 2004, vol. 19, No. 2, pp. 435-440

[15] R. Billinton and R. Karki, “Cost effective wind energy utilization for reliable power supply,” IEEE Transactions on Energy Conversion, June 2004, vol. 19, No. 2, pp. 435–440

[16] R. Billinton, Y.C. Bagen, Y. Cui, “Reliability evaluation of small stand-alone wind energy conversion systems using a time series simulation model,” IEEE Proceedings on Generation, Transmission and Distribution, January 2003, vol.150, No. 1, pp. 96-100

[17] P. Giorsetto, K.F. Utsurogi, “Development of a new procedure for reliability modeling of wind turbine generators,” IEEE Transactions on Power Apparatus and Systems, January 1983, vol. PAS-102, No. 1, pp. 134-143

[18] J.N. Jiang, C. Lin, T. Runolfsson, “A study of short-term impact of wind generation on LOLP,” IEEE PES Conference on Transmission and Distribution, April 2010, pp. 1-10

[19] ISO New England, article available on the topic “GADS/GADS equivalent data,” available at:
http://www.iso-ne.com/genrtion_resrcs/gads/index.html

[20] A. Dimitrovski, K. Tomsovic, “Impact of wind generation uncertainty on generating capacity adequacy,” International Conference on Probabilistic Methods Applied to Power Systems, June 2006, pp. 1-6

[21] Frede Blaabjerg, Zhe Chen, “*Power electronics for modern wind turbines*,” First Edition, United States, Morgan and Claypool Publishers, 2007

[22] D. McSwiggan, T. Littler, D.J. Morrow, J. Kennedy, “A study of tower shadow effect on fixed-speed wind turbines,” 43rd International Universities Power Engineering Conference, September 2008, pp. 1-5

[23] National Renewable Energy Laboratory, document available on the topic "The history and state of the art of variable-speed wind turbine technology," available at:

www.nrel.gov/docs/fy01osti/28607.pdf

[24] L. Dusonchet, F. Massaro, E. Telaretti, "Wind turbine mechanical characteristics and grid parameters influence on the transient voltage stability of a fixed speed wind turbine," 43rd International Universities Power Engineering Conference, September 2008, pp. 1-5

[25] Y. Ashkhane, "A new approach to improve voltage stability in a network with fixed speed wind turbines," 19th Iranian Conference on Electrical Engineering, May 2011, pp. 1-6

[26] G. Jinxia, X. Da, Z. Yanchi, "A new excitation regulating and harmonic eliminating equipment for fixed speed fixed pitch wind turbines," International Conference on Electrical Machines and Systems, October 2008, pp. 2556 – 2560

[27] A. Sinha, D. Kumar, D. Kumar, P. Samuel, R. Gupta, "A two-stage converter based controller for a stand alone wind energy system used for remote applications," 30th IEEE International Conference on Telecommunication Energy, September 2008, pp. 1-5

[28] D. Fujin, C. Zhe, "A new structure based on cascaded multilevel converter for variable speed wind turbine," 36th Annual Conference on IEEE Industrial Electronics Society, November 2010, pp. 3167 - 3172

[29] H. Nikkhajoei, R.H. Lasseter, "Power quality enhancement of a wind-turbine generator under variable wind speeds using matrix converter," Power Electronics Specialist Conference, June 2008, pp. 1755 - 1761

[30] H. Karimi-Davijani, A. Sheikholeslami, R. Ahmadi, H. Livani, "Active and reactive power control of DFIG using SVPWM converter," 43rd International Universities Power Engineering Conference, September 2008, pp. 1-5

[31] O. Duan, L. Zhang, L. Zhang, "A fault detection and tolerant scheme for back-to-back converters in DFIG-based wind power generation systems," 3rd International Conference on Advanced Computer Theory and Engineering, August 2010, vol. 3, pp. 95 - 99

[32] Wikipedia, article appearing on the topic "Reliability engineering," available at:

http://en.wikipedia.org/wiki/Reliability_engineering

[33] Virginia Polytechnic Institute, document available on the topic “Power system reliability analysis with distributed generators,” available at:
http://scholar.lib.vt.edu/theses/available/etd-05162003-090532/unrestricted/Power_System.pdf

[34] Massachusetts Institute of Technology, document available on the topic “The value of reliability on power systems- pricing operating reserves,” available at:
http://web.mit.edu/energylab/www/pubs/el99-005wp.pdf

[35] G. T. Heydt, “Lecture notes on Power Systems Operation and Planning,” Arizona State University, Fall 2010

[36] K. Malmedal, P.K. Sen, “A better understanding of load and loss factors,” Industry Applications Society Annual Meeting, October 2008, pp. 1-6

[37] M. O. M Mahmoud, M. Jaidane-Saidane, J. Souissi, N. Hizaoui, “Modeling of the load duration curve using the asymmetric generalized Gaussian distribution: case of the Tunisian power system,” Power and Energy Society General Meeting on Conversion and Delivery of Electrical Energy in the 21st century, July 2008, pp.1-7

[38] M. O. M Mahmoud, M. Jaidane-Saidane, J. Souissi, N. Hizaoui, “The mixture of generalized Gaussian model for modeling of the load duration curve: case of the Tunisian power system,” 14th IEEE Mediterranean Electrotechnical Conference (MELECON), May 2008, pp. 774 – 779

[39] National Climatic Data Center, document available on the topic “Wind-average wind speed (MPH)” available at:
http://lwf.ncdc.noaa.gov/oa/climate/online/ccd/avgwind.html

[40] Dr. Yih-huei Wan, National Renewable Electric Laboratory, private communication, April 27, 2011

[41] S. Tehrani, T. E. Weymouth, B. Schunck, “Interpolating cubic spline contours by minimizing second derivative discontinuity,” 3rd International Conference on Computer Vision, December 1990, pp. 713 – 716

[42] National Oceanic and Atmospheric Association, article available on the topic “NOAA recorded average wind speed data through 2001,” available at:
http://www.berner.com/sales/energy_windspeed.html

[43] U.S Energy Information Administration, article available on the topic “Electricity generating capacity,” available at:
http://www.eia.gov/electricity/capacity

[44] Wikipedia, article available on the topic "Renewable portfolio standard," available at:
http://en.wikipedia.org/wiki/Renewable_portfolio_standard
[45] Electric Reliability Council of Texas, document available on topic "Load," available at:
http://www.ercot.com/gridinfo/load/

[46] U.S. Energy Information Administration, document available on topic "State total electric power industry net summer capacity, by Energy Source, 2004 – 2008," available at:
http://www.google.com/url?sa=t&rct=j&q=rspt02tx&source=web&cd=1&ved=0CCAQFjAA&url=http%3A%2F%2Fwww.eia.gov%2Fcneaf%2Fsolar.renewables%2Fpage%2Fstate_profiles%2Frspt02tx.xls&ei=kyQST9vCNemriQLV4vm_DQ&usg=AFQjCNFriHZhlbA8k9flIPDg_kqUGSDwgA

[47] ISO New England, article available on the topic "ISO New England EFORd class averages from NERC brochure," available at:
http://www.iso-ne.com/genrtion_resrcs/gads/class_avg_2009.pdf

[48] Thomas Ackerman, "*Wind power in power systems*," First Edition, Sweden, John Wiley and Sons Limited, 2005

[49] Siemens Corporation, article available on the topic "Introduction to generic wind turbine generator models," available at:
https://www.pti-us.com/pti/company/enewsletter/2011may/pdfs/Introduction%20to%20Generic%20Wind%20Models.pdf

[50] Brendan Fox, Damian Flynn, et al., "*Wind power integration connection and system operational aspects*," First Edition, United Kingdom, The Institution of Engineering and Technology, 2007

[51] Wikipedia, article appearing on the topic "Doubly fed electric machine," available at:
http://en.wikipedia.org/wiki/Doubly_fed_electric_machine

[52] User-Defined Model Manual for DSA Tools available at the Electrical Power Engineering Department at Arizona State University

[53] R. Ayyanar, "Lecture notes on Electrical Machines," Arizona State University, Fall 2011

[54] eWashtenaw, document available on the topic "Wind turbine brochures," available at:
http://www.ewashtenaw.org/government/departments/planning_environment/planning/wind_power/Monthly%20Data_Reports/Attachment_1.pdf

APPENDIX A

MATLAB CODE FOR RELIABILITY STUDY IMPLEMENTATION ON TEXAS POWER SYSTEM

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%Author: Anubhav Sinha, Arizona State University

%Faculty Advisor: Dr. Gerald T. Heydt, Dr. Vijay Vittal, Dr. Raja
Ayyanar, Arizona State University

%2011-2012

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

Master_Dec23_08.m

```
% This is the central file that loads the LDC data and calls the
COT function

total_rows=8760;


global Load L1
```

L1=< 8760x1 matrix of actual hourly load data of Texas in 2008>’

```
global Marker
Marker(1,1)=0;
Marker(1,2)=0;
cou=2;
cou_2=1;
watch_1=0;
for(i=1:1:10)
    i;
    G=i*(max(L)/10);
    watch_1=0;
    cou=2;
    while (watch_1==0)
            e1=G-L(cou);
            e2=G-(L(cou-1));
            cou=cou+1;
            if (((e1>0)&&(e2<=0))||((e1>=0)&&(e2<0)))
                watch_1=1;
            end
    end
Marker(i,1)=G;
Marker(i,2)=cou-1;
end
Marker; %Complete Marker matrix

COT_Dec23_08()  %Calling function to generate COT
```

COT_Dec23_08.m

```
% This is the function that constructs the COT for the test case
10-generator system


function COT_Dec23_08()
states=12;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

x=10;   % x indicates the total number of MW entries allowed in
the input
Coal1=[5.19 0.0718]; % Two Coal generators.
Coal2=[15 0.0621];
NG1=[15.86  0.0747]; % Three NG generators
NG2=[25 0.0633];
NG3=[30 0.0548];
Nuclear1=[2.36 0.0273]; % Two Nuclear-reactor based generation
Nuclear2=[2.5 0.0273];
Total_load = [4217.3 4383.3 4377.9 4333.2 4251.1 4122.9 4139.7
4340.5 4520.3 4185.7 4232.3 3986.1 3783 3407.2 3527.6 3538.9
3767.5 3841.4 4062 3825.4 3672.2 3378.9 3216 2656.5];
test_case=[4 6 8 12 24 32 48 72 96];
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

if(states==4) %Number of states
dataspaces = linspace(0,23,24);
```

```
samples = 0:6:23;
p_4 = pchip(dataspaces,Total_load,samples);

G(1).Hours=[6 6 6 6];
G(2).Hours=[6 6 6 6];
G(3).Hours=[6 6 6 6];

G(1).Ld=(5/12)*p_4;
G(2).Ld=(4/12)*p_4;
G(3).Ld=(3/12)*p_4;

G(1).FOR=p_4/7.43/1000;
G(2).FOR=p_4/7.43/1000;
G(3).FOR=p_4/7.43/1000;
end
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
if(states==6) %Number of states EQUAL SPACED
dataspaces = linspace(0,23,24);
samples = 0:4:23;
p_6 = pchip(dataspaces,Total_load,samples);

G(1).Hours=[4 4 4 4 4 4];
G(2).Hours=[4 4 4 4 4 4];
G(3).Hours=[4 4 4 4 4 4];

G(1).Ld=(5/12)*p_6;
G(2).Ld=(4/12)*p_6;
G(3).Ld=(3/12)*p_6;

G(1).FOR=p_6/7.43/1000;
G(2).FOR=p_6/7.43/1000;
G(3).FOR=p_6/7.43/1000;
end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

```
if(states==8) %Number of states
dataspaces = linspace(0,23,24);
samples = 0:3:24;
p_8 = pchip(dataspaces,Total_load,samples);
plot(dataspaces,Total_load,'o ',samples,p_8,'+')

G(1).Hours=[3  3  3  3  3  3  3  3];
G(2).Hours=[3  3  3  3  3  3  3  3];
G(3).Hours=[3  3  3  3  3  3  3  3];

G(1).Ld=(5/12)*p_8;
G(2).Ld=(4/12)*p_8;
G(3).Ld=(3/12)*p_8;

G(1).FOR=p_8/7.43/1000;
G(2).FOR=p_8/7.43/1000;
G(3).FOR=p_8/7.43/1000;
end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
if(states==12) %Number of states
dataspaces = linspace(0,23,24);
samples = 0:2:24;
p_12 = pchip(dataspaces,Total_load,samples);
plot(dataspaces,Total_load,'o ',samples,p_12,'+')
G(1).Hours=[2  2  2  2  2  2  2  2  2  2  2  2];
G(2).Hours=[2  2  2  2  2  2  2  2  2  2  2  2];
G(3).Hours=[2  2  2  2  2  2  2  2  2  2  2  2];

G(1).Ld=(5/12)*p_12;
G(2).Ld=(4/12)*p_12;
G(3).Ld=(3/12)*p_12;

G(1).FOR=p_12/7.43/1000;
G(2).FOR=p_12/7.43/1000;
```

```
G(3).FOR=p_12/7.43/1000;
end
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

if(states==18) %Number of states
G(1).Hours=[1 1 1 1 1 1 1 1 1 1 1 1 1 1 6 1 1 1];
G(2).Hours=[1 1 1 1 1 1 1 1 1 1 1 1 1 1 6 1 1 1];
G(3).Hours=[1 1 1 1 1 1 1 1 1 1 1 1 1 1 6 1 1 1];

G(1).Ld=[1.145 1.167 1.146 1.146 1.125 1.104 1.0833 1.042 0.9375
0.833 0.833 0.667 0.521 0.375 0.7083 1.0833 1.0833 0.9167];
G(2).Ld=[0.9167 0.933 0.9166 0.9166 0.9 0.8833 0.866 0.833 0.75
0.667 0.667 0.533 0.4167 0.3 0.5667 0.866 0.866 0.733];
G(3).Ld=[0.6875 0.7 0.6875 0.6875 0.675 0.6625 0.65 0.625 0.5625
0.5 0.5 0.4 0.3125 0.225 0.425 0.65 0.65 0.55];

G(1).FOR=[0.6395 0.6512 0.6395 0.6395 0.6279 0.6163 0.6046 0.5814
0.5233 0.4651 0.4651 0.3721 0.2907 0.2093 0.3953 0.6046 0.6046
0.5116];
G(2).FOR=[0.6395 0.6512 0.6395 0.6395 0.6279 0.6163 0.6046 0.5814
0.5233 0.4651 0.4651 0.3721 0.2907 0.2093 0.3953 0.6046 0.6046
0.5116];
G(3).FOR=[0.6395 0.6512 0.6395 0.6395 0.6279 0.6163 0.6046 0.5814
0.5233 0.4651 0.4651 0.3721 0.2907 0.2093 0.3953 0.6046 0.6046
0.5116];
end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

if(states==24) %Number of states
dataspaces = linspace(0,23,24);
samples = 0:1:24;
p_24 = pchip(dataspaces,Total_load,samples);
p_24(24)=0.5*(p_24(23)+p_24(1));
```

```
G(1).Hours=[1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1];
G(2).Hours=[1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1];
G(3).Hours=[1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1];

G(1).Ld=(5/12)*p_24;
G(2).Ld=(4/12)*p_24;
G(3).Ld=(3/12)*p_24;

G(1).FOR=p_24/7.43/1000;
G(2).FOR=p_24/7.43/1000;
G(3).FOR=p_24/7.43/1000;
end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
if(states==32) %Number of states
dataspaces = linspace(0,23,24);
samples = 0:.75:23.25;
p_32 = pchip(dataspaces,Total_load,samples);
p_32(32)=0.5*(p_32(31)+p_32(1));

G(1).Hours=[0.75 0.75 0.75 0.75 0.75 0.75 0.75 0.75 0.75 0.75
0.75 0.75 0.75 0.75 0.75 0.75 0.75 0.75 0.75 0.75 0.75 0.75 0.75
0.75 0.75 0.75 0.75 0.75 0.75 0.75 0.75 0.75];
G(2).Hours=[0.75 0.75 0.75 0.75 0.75 0.75 0.75 0.75 0.75 0.75
0.75 0.75 0.75 0.75 0.75 0.75 0.75 0.75 0.75 0.75 0.75 0.75 0.75
0.75 0.75 0.75 0.75 0.75 0.75 0.75 0.75 0.75];
G(3).Hours=[0.75 0.75 0.75 0.75 0.75 0.75 0.75 0.75 0.75 0.75
0.75 0.75 0.75 0.75 0.75 0.75 0.75 0.75 0.75 0.75 0.75 0.75 0.75
0.75 0.75 0.75 0.75 0.75 0.75 0.75 0.75 0.75];

G(1).Ld=(5/12)*p_32;
G(2).Ld=(4/12)*p_32;
G(3).Ld=(3/12)*p_32;

G(1).FOR=p_32/7.43/1000;
```

```
G(2).FOR=p_32/7.43/1000;
G(3).FOR=p_32/7.43/1000;
end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

if(states==48) %Number of states
dataspaces = linspace(0,23,24);
samples = 0:.5:23.5;
p_48 = pchip(dataspaces,Total_load,samples);
p_48(48)=0.5*(p_48(47)+p_48(1));
%s = spline(x,y,t);
%plot(dataspaces,Total_load,'o ',samples,p_48,'+')
%legend('data','pchip','spline',4)

G(1).Hours=[0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5
0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5
0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5
0.5 0.5 0.5];
G(2).Hours=[0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5
0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5
0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5
0.5 0.5 0.5];
G(3).Hours=[0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5
0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5
0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5
0.5 0.5 0.5];

G(1).Ld=(5/12)*p_48;
G(2).Ld=(4/12)*p_48;
G(3).Ld=(3/12)*p_48;

G(1).FOR=p_48/7.43/1000;
G(2).FOR=p_48/7.43/1000;
G(3).FOR=p_48/7.43/1000;
```

```
end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
if(states==72) %Number of states
dataspaces = linspace(0,23,24);
samples = 0:0.3333:23.999;
p_72 = pchip(dataspaces,Total_load,samples);
%p_72(72)=0.5*(p_72(71)+p_72(1));
%s = spline(x,y,t);
%plot(dataspaces,Total_load,'o ',samples,p_72,'+')
%legend('data','pchip','spline',4)

G(1).Hours=[0.333 0.333 0.333 0.333 0.333 0.333 0.333 0.333 0.333
0.333 0.333 0.333 0.333 0.333 0.333 0.333 0.333 0.333 0.333 0.333
0.333 0.333 0.333 0.333 0.333 0.333 0.333 0.333 0.333 0.333 0.333
0.333 0.333 0.333 0.333 0.333 0.333 0.333 0.333 0.333 0.333 0.333
0.333 0.333 0.333 0.333 0.333 0.333 0.333 0.333 0.333 0.333 0.333
0.333 0.333 0.333 0.333 0.333 0.333 0.333 0.333 0.333 0.333 0.333
0.333 0.333 0.333 0.333 0.333 0.333 0.333 0.333];
G(2).Hours=G(1).Hours;
G(3).Hours=G(2).Hours;

G(1).Ld=(5/12)*p_72;
G(2).Ld=(4/12)*p_72;
G(3).Ld=(3/12)*p_72;

G(1).FOR=p_72/7.43/1000;
G(2).FOR=p_72/7.43/1000;
G(3).FOR=p_72/7.43/1000;
end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
if(states==96) %Number of states
dataspaces = linspace(0,23,24);
samples = 0:0.25:23.999;
p_96 = pchip(dataspaces,Total_load,samples);
```

```
plot(dataspaces,Total_load,'o ',samples,p_96,'+')

G(1).Hours=[0.25 0.25 0.25 0.25 0.25 0.25 0.25 0.25 0.25 0.25
0.25 0.25 0.25 0.25 0.25 0.25 0.25 0.25 0.25 0.25 0.25 0.25 0.25
0.25 0.25 0.25 0.25 0.25 0.25 0.25 0.25 0.25 0.25 0.25 0.25 0.25
0.25 0.25 0.25 0.25 0.25 0.25 0.25 0.25 0.25 0.25 0.25 0.25 0.25
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0.25 0.25 0.25 0.25 0.25 0.25 0.25 0.25 0.25 0.25 0.25 0.25 0.25
0.25 0.25 0.25 0.25 0.25 0.25 0.25 0.25 0.25 0.25 0.25 0.25 0.25
0.25 0.25 0.25 0.25 0.25 0.25 0.25 0.25];
G(2).Hours=G(1).Hours;
G(3).Hours=G(2).Hours;

G(1).Ld=(5/12)*p_96;
G(2).Ld=(4/12)*p_96;
G(3).Ld=(3/12)*p_96;

G(1).FOR=p_96/7.43/1000;
G(2).FOR=p_96/7.43/1000;
G(3).FOR=p_96/7.43/1000;
end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

if(states==144) %Number of states
dataspaces = linspace(0,23,24);
samples = 0:0.16667:23.999;
p_144 = pchip(dataspaces,Total_load,samples);

G(1).Hours=[0.16667 0.16667 0.16667 0.16667 0.16667 0.16667
0.16667 0.16667 0.16667 0.16667 0.16667 0.16667 0.16667 0.16667
0.16667 0.16667 0.16667 0.16667 0.16667 0.16667 0.16667 0.16667
0.16667 0.16667 0.16667 0.16667 0.16667 0.16667 0.16667 0.16667
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0.16667 0.16667 0.16667 0.16667 0.16667 0.16667 0.16667 0.16667
0.16667 0.16667];
G(2).Hours=G(1).Hours;
G(3).Hours=G(2).Hours;

G(1).Ld=(5/12)*p_144;
G(2).Ld=(4/12)*p_144;
G(3).Ld=(3/12)*p_144;

G(1).FOR=p_144/7.43/1000;
G(2).FOR=p_144/7.43/1000;
G(3).FOR=p_144/7.43/1000;
end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

G4=Coal1;

G5=Coal2;
%%%%%%%%%%%%%%%%%%
G6=NG1;

G7=NG2;
```

```
G8=NG3;

%%%%%%%%%%%%%%%%%%
G9=Nuclear1;

G10=Nuclear2;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%

for (d=1:1:3) %Calculating Equivalent load
    Sum=0;
    for(c=1:1:states)
        Sum=Sum+(G(d).Hours(c))*(G(d).Ld(c));
    end
    M(d)= Sum/24*0.001;
end

for (d=1:1:3)  %Calculating Equivalent load
Sum=0;
    for(c=1:1:states)
        Sum=Sum+(G(d).Hours(c))*(G(d).FOR(c));
    end
    P(d)= Sum/24;
end
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
M(4)=G4(1,1); %Tabulating generation data
M(5)=G5(1,1);
M(6)=G6(1,1);
M(7)=G7(1,1);
M(8)=G8(1,1);
M(9)=G9(1,1);
M(10)=G10(1,1);
M;
```

```
P(4)=G4(1,2); % Tabulating the outage probability
P(5)=G5(1,2);
P(6)=G6(1,2);
P(7)=G7(1,2);
P(8)=G8(1,2);
P(9)=G9(1,2);
P(10)=G10(1,2);
P;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Eliminating zero values in 'm' array
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%


c=1;
 for i=1:1:x
     if (M(i)~=0)
         m(c)=M(i); %Transfer the non-zero entries to 'm' array
         p(c)=P(i); %Save the corresponding FOR in 'p' array
         c=c+1;  %c calculates the number of non-zero MW values
     end
 end
c=c-1;
m;
p;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Generating Binary Table g
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
i=0;
j=c;
for i=0:1:((2^c)-1)
    for k=1:1:c
    g((i+1),k)=bitget(i,j);
    j=j-1;
end
i=i+1;
j=c;
```

```
end
g;




%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Bitwise multipication of m and g
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%



for j=1:1:(2^c)
    for i=1:1:c
        k(j,i)=m(i)*g(j,i);
    end
end
k;



%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Obtain 'Load' column of COT
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
for i=1:1:(2^c)
    r(i,1)=0;
end

for j=1:1:(2^c)
    for i=1:1:c
        r(j,1)=k(j,i)+r(j,1);
    end
end
r;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Generate table of FOR multiplication
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

```
for j=1:1:(2^c)
    for i=1:1:c
        if g(j,i)==0
            a(j,i)=p(i);
        else
            p(i);
            a(j,i)=1-p(i);
    end
    end
end
a;

for i=1:1:(2^c)
    s(i,1)=1;
end

for j=1:1:(2^c)
    for i=1:1:c
        s(j,1)=a(j,i)*s(j,1);
    end
end
s;




%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Complete COT
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
b=[r,s];
b=sortrows(b);  %COT obtained in ascendening order of
load(However, FORs are not added for same load).

%fprintf('%13.9f\t\t%13.15f\n', b')

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

```
%Program to combine FOR of same loads
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%


j=1;
i=j+1;
n=(2^c)-1;
for j=1:1:n
     while (b(j,1)==b(i,1)) && (b(i,1)~=0) && (b(j,1)~=0)
        b(j,2)=b(i,2)+b(j,2);
        z=i;
        for k=1:1:((2^c)-j)
            if ((z<(2^c)) && (z~=(2^c)))
            b(z,1)=b(z+1,1);
            b(z,2)=b(z+1,2);
              z=z+1;
              end


        end
        b(n+1,1)=0; %making last row zero
        b(n+1,2)=0; %making last row zero
        n=n-1; %decreasing number of iterations since now one row
is reduced
    end
    if i<(2^c)
        i=i+1;
    end
end
b ;             %Final COT obtained

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%


for j=1:1:n
    GW_Req=b(j,1);
    t_Req=LDC_Dec23_08(GW_Req); %send b(j,1) value to LDC_Final
and store there in MW_Requested
     b(j,3)=t_Req; %b(j,3)= time %output of the LDC_Final time
     WG=M(1)+M(2)+M(3);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Calculating LOLP
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
LOLP=0;
for j=1:1:(n)
    LOLP=b(j,4)+LOLP;
end
disp('states')
fprintf('%3.6f\n', states')
disp('LOLP')
fprintf('%3.6f\n', LOLP');
EFOR=P(1);
disp('EFOR')
fprintf('%3.6f\n', EFOR');
disp('Wind Generation')
fprintf('%3.6f\n\n\n', WG')
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
M
P
disp('Capacity Outage Table')
fprintf('%13.9f\t\t%13.15f\t\t%13.20f\t\t%13.20f\n', b');
end
```

LDC_Dec23_08.m

```
% This function refers to the LDC and outputs the 'time' corre-
sponding to a requested generation

function t_Req=LDC_Dec23_08(GW_Requested)
global L
global H
global Marker


if (GW_Requested>=55.7 && GW_Requested<=55.9 )
    GW_Requested=55.9;
end
```

```
if (GW_Requested>=43.46845873 && GW_Requested<=43.468458739 )
    GW_Requested=43.44;
end

if (GW_Requested>=43.46849638 && GW_Requested<=43.46849639 )
    GW_Requested=43.44;
end

if (GW_Requested>=49.67704236 && GW_Requested<=49.67704237 )
    GW_Requested=49.66;
end

    watch_2=0; %variable to enable exit from while loop

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Checking that GW_Requested exactly within which band of Marker
matrix
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
    if((GW_Requested>=min(L))&&(GW_Requested<(max(L)/10)))
        Tcount=Marker(1,2);
    elseif
((GW_Requested>=(max(L)/10))&&(GW_Requested<2*(max(L)/10)))
        Tcount=Marker(2,2);
    elseif
((GW_Requested>=2*(max(L)/10))&&(GW_Requested<3*(max(L)/10)))
        Tcount=Marker(3,2);
    elseif
((GW_Requested>=3*(max(L)/10))&&(GW_Requested<4*(max(L)/10)))
        Tcount=Marker(4,2);
    elseif
((GW_Requested>=4*(max(L)/10))&&(GW_Requested<5*(max(L)/10)))
        Tcount=Marker(5,2);
    elseif
((GW_Requested>=5*(max(L)/10))&&(GW_Requested<6*(max(L)/10)))
        Tcount=Marker(6,2);
    elseif
((GW_Requested>=6*(max(L)/10))&&(GW_Requested<7*(max(L)/10)))
        Tcount=Marker(7,2);
    elseif
((GW_Requested>=7*(max(L)/10))&&(GW_Requested<8*(max(L)/10)))
        Tcount=Marker(8,2);
    elseif
((GW_Requested>=8*(max(L)/10))&&(GW_Requested<9*(max(L)/10)))
        Tcount=Marker(9,2);
    elseif ((GW_Requested>=9*(max(L)/10))&&(GW_Requested<max(L)))
        Tcount=1;
    elseif (GW_Requested>(max(L)))
        Tcount=0; %Taking care of case when GW_Requested exceeds
maximum L
    end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
bias1=0; %Both variables initialized to take care of special cas-
es
bias2=0;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
    while (watch_2==0)
        if(Tcount==8760) %Case if GW_Requested is too low
            watch_2=1;
            bias1=1;
        end
        if(Tcount==0)%Case if GW_Requested is beyond maximum Load
            watch_2=1;
            bias2=1;
        end
        if(watch_2~=1)
            e1=(GW_Requested)-L(Tcount);
            e2=(GW_Requested)-L(Tcount+1);
            if ((e1<0)&&(e2>=0))
                watch_2=1;
            end
            Tcount=Tcount+1;
            GW_Requested;
        end
    end

 N=Tcount-1; %N is value of the element number corresponding to
the lower value of the two number between which M lies
 count_3=0;
 watch_3=0;
 count_4=0;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
if((bias1~=1)&&(bias2~=1))
    while (watch_3~=1)
     if (N~=1)  %Taking care that M doesnt lies beyond the LDC
curve maximum GW. If so then t=0
            if(L(N)==L(N-1))
                count_3=(count_3)+ 1;
                N=N-1;
            else
                watch_3=1; %exit out of loop if no equal terms
                            found anymore in the GW data
            end
     else
         time=0; %Taking care that M doesnt lies beyond the LDC
                  curve maximum GW. If so then t=0
         watch_3=1; %exit out of loop if M lies beyond mximum GW
     end
    end
end
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
if((bias1~=1)&&(bias2~=1))
    time=H(N+(count_3)) +  e2*((count_3)+1); %Determine t value
by approximately linearizing assuming it as straight line
elseif(bias1==1)
    time=8760;
elseif(bias2==1)
```

```
    time=0;
end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
if(time>=8760)
    time=8760;
end
t_Req=time; %Sending time data back to the calling function

end
```

APPENDIX B

MATLAB CODE FOR THE DFIG GUI

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%Author: Anubhav Sinha, Arizona State University

%Faculty Advisor: Dr. Gerald T. Heydt, Dr. Vijay Vittal, Dr. Raja
Ayyanar, Arizona State University

%2011-2012

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

Total_model.m

```
function varargout = Total_model(varargin)
% TOTAL_MODEL MATLAB code for Total_model.fig
%      TOTAL_MODEL, by itself, creates a new TOTAL_MODEL or rais-
es the existing
%      singleton*.
%
%      H = TOTAL_MODEL returns the handle to a new TOTAL_MODEL or
the handle to
%      the existing singleton*.
%
%      TOTAL_MODEL('CALLBACK',hObject,eventData,handles,...)
calls the local
%      function named CALLBACK in TOTAL_MODEL.M with the given
input arguments.
%
%      TOTAL_MODEL('Property','Value',...) creates a new TO-
TAL_MODEL or raises the
%      existing singleton*.  Starting from the left, property
value pairs are
%      applied to the GUI before Total_model_OpeningFcn gets
called.  An
%      unrecognized property name or invalid value makes property
application
%      stop.  All inputs are passed to Total_model_OpeningFcn via
varargin.
%
%      *See GUI Options on GUIDE's Tools menu.  Choose "GUI al-
lows only one
%      instance to run (singleton)".
%
% See also: GUIDE, GUIDATA, GUIHANDLES

% Edit the above text to modify the response to help Total_model

% Last Modified by GUIDE v2.5 29-Jan-2012 15:19:02

% Begin initialization code - DO NOT EDIT
gui_Singleton = 1;
gui_State = struct('gui_Name',       mfilename, ...
                   'gui_Singleton',  gui_Singleton, ...
                   'gui_OpeningFcn', @Total_model_OpeningFcn, ...
                   'gui_OutputFcn',  @Total_model_OutputFcn, ...
                   'gui_LayoutFcn',  [] , ...
                   'gui_Callback',   []);
if nargin && ischar(varargin{1})
    gui_State.gui_Callback = str2func(varargin{1});
end

if nargout
    [varargout{1:nargout}] = gui_mainfcn(gui_State, varargin{:});
else
    gui_mainfcn(gui_State, varargin{:});
end
% End initialization code - DO NOT EDIT

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% --- Executes just before Total_model is made visible.
function Total_model_OpeningFcn(hObject, eventdata, handles,
varargin)
% This function has no output args, see OutputFcn.
% hObject    handle to figure
% eventdata  reserved - to be defined in a future version of
MATLAB
% handles    structure with handles and user data (see GUIDATA)
% varargin   command line arguments to Total_model (see VARARGIN)

% Choose default command line output for Total_model
axes(handles.Background_photo);
load('DFIG_Background');
imshow(myimage3);
handles.output = hObject;

global arrow_fixer
if arrow_fixer==45
 axes(handles.axes_Pr);
 load('Left_Arrow');
 imshow(myimage2);
 handles.output = hObject;
elseif arrow_fixer==46
 axes(handles.axes_Pr);
 load('Right_Arrow');
 imshow(myimage4);
 handles.output = hObject;

    else
        axes(handles.axes_Pr);
        load('Right_Arrow');
        imshow(myimage4);
        handles.output = hObject;
end


axes(handles.axes_Pm);
load('Up_Arrow');
```

```
imshow(myimage5);
handles.output = hObject;

axes(handles.axes_Pgap);
load('Up_Arrow');
imshow(myimage5);
handles.output = hObject;


global wmref_pu

    wmref_pu=1;

guidata(hObject, handles);

% UIWAIT makes Total_model wait for user response (see UIRESUME)
% uiwait(handles.figure1);


% --- Outputs from this function are returned to the command
line.
function varargout = Total_model_OutputFcn(hObject, eventdata,
handles)
% varargout  cell array for returning output args (see
VARARGOUT);
% hObject    handle to figure
% eventdata  reserved - to be defined in a future version of
MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Get default command line output from handles structure
varargout{1} = handles.output;



function eWind_speed_Callback(hObject, eventdata, handles)
% hObject    handle to eWind_speed (see GCBO)
% eventdata  reserved - to be defined in a future version of
MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of eWind_speed as
text
%        str2double(get(hObject,'String')) returns contents of
eWind_speed as a double

%get the string for the editText component
SliderWindValue = get(handles.eWind_speed,'String');

%convert from string to number if possible, otherwise returns
empty
```

```
set(handles.Slider_wind,'Value', str2num(SliderWindValue));


% --- Executes during object creation, after setting all proper-
ties.
function eWind_speed_CreateFcn(hObject, eventdata, handles)
% hObject    handle to eWind_speed (see GCBO)
% eventdata  reserved - to be defined in a future version of
MATLAB
% handles    empty - handles not created until after all Cre-
ateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end



function ePm_MW_Callback(hObject, eventdata, handles)
% hObject    handle to ePm_MW (see GCBO)
% eventdata  reserved - to be defined in a future version of
MATLAB
% handles    structure with handles and user data (see GUIDATA)


guidata(hObject, handles);

% --- Executes during object creation, after setting all proper-
ties.
function ePm_MW_CreateFcn(hObject, eventdata, handles)
% hObject    handle to ePm_MW (see GCBO)
% eventdata  reserved - to be defined in a future version of
MATLAB
% handles    empty - handles not created until after all Cre-
ateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end



function ePr_Callback(hObject, eventdata, handles)
% hObject    handle to ePr (see GCBO)
% eventdata  reserved - to be defined in a future version of
MATLAB
```

```
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of ePr as text
%        str2double(get(hObject,'String')) returns contents of
ePr as a double


% --- Executes during object creation, after setting all proper-
ties.
function ePr_CreateFcn(hObject, eventdata, handles)
% hObject    handle to ePr (see GCBO)
% eventdata  reserved - to be defined in a future version of
MATLAB
% handles    empty - handles not created until after all Cre-
ateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end



function ePgap_Callback(hObject, eventdata, handles)
% hObject    handle to ePgap (see GCBO)
% eventdata  reserved - to be defined in a future version of
MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of ePgap as text
%        str2double(get(hObject,'String')) returns contents of
ePgap as a double


% --- Executes during object creation, after setting all proper-
ties.
function ePgap_CreateFcn(hObject, eventdata, handles)
% hObject    handle to ePgap (see GCBO)
% eventdata  reserved - to be defined in a future version of
MATLAB
% handles    empty - handles not created until after all Cre-
ateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end
```

```
function ePs_Callback(hObject, eventdata, handles)
% hObject    handle to ePs (see GCBO)
% eventdata  reserved - to be defined in a future version of
MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of ePs as text
%        str2double(get(hObject,'String')) returns contents of
ePs as a double


% --- Executes during object creation, after setting all proper-
ties.
function ePs_CreateFcn(hObject, eventdata, handles)
% hObject    handle to ePs (see GCBO)
% eventdata  reserved - to be defined in a future version of
MATLAB
% handles    empty - handles not created until after all Cre-
ateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end



function eSlip_Callback(hObject, eventdata, handles)
% hObject    handle to eSlip (see GCBO)
% eventdata  reserved - to be defined in a future version of
MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of eSlip as text
%        str2double(get(hObject,'String')) returns contents of
eSlip as a double


% --- Executes during object creation, after setting all proper-
ties.
function eSlip_CreateFcn(hObject, eventdata, handles)
% hObject    handle to eSlip (see GCBO)
% eventdata  reserved - to be defined in a future version of
MATLAB
% handles    empty - handles not created until after all Cre-
ateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end





function ePm_pu_Callback(hObject, eventdata, handles)
% hObject    handle to ePm_pu (see GCBO)
% eventdata  reserved - to be defined in a future version of
MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of ePm_pu as text
%        str2double(get(hObject,'String')) returns contents of
ePm_pu as a double


% --- Executes during object creation, after setting all proper-
ties.
function ePm_pu_CreateFcn(hObject, eventdata, handles)
% hObject    handle to ePm_pu (see GCBO)
% eventdata  reserved - to be defined in a future version of
MATLAB
% handles    empty - handles not created until after all Cre-
ateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end



function ewref_Callback(hObject, eventdata, handles)
% hObject    handle to ewref (see GCBO)
% eventdata  reserved - to be defined in a future version of
MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of ewref as text
%        str2double(get(hObject,'String')) returns contents of
ewref as a double
```

```
% --- Executes during object creation, after setting all proper-
ties.
function ewref_CreateFcn(hObject, eventdata, handles)
% hObject    handle to ewref (see GCBO)
% eventdata  reserved - to be defined in a future version of
MATLAB
% handles    empty - handles not created until after all Cre-
ateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end



function ePloss_Callback(hObject, eventdata, handles)
% hObject    handle to ePloss (see GCBO)
% eventdata  reserved - to be defined in a future version of
MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of ePloss as text
%        str2double(get(hObject,'String')) returns contents of
ePloss as a double


% --- Executes during object creation, after setting all proper-
ties.
function ePloss_CreateFcn(hObject, eventdata, handles)
% hObject    handle to ePloss (see GCBO)
% eventdata  reserved - to be defined in a future version of
MATLAB
% handles    empty - handles not created until after all Cre-
ateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end


% --- Executes on slider movement.
function Slider_wind_Callback(hObject, eventdata, handles)
% hObject    handle to Slider_wind (see GCBO)
% eventdata  reserved - to be defined in a future version of
MATLAB
% handles    structure with handles and user data (see GUIDATA)
SliderWindValue = get(handles.Slider_wind,'Value');
Wind_speed = SliderWindValue
```

```
set(handles.eWind_speed,'String', num2str(SliderWindValue));
% Hints: get(hObject,'Value') returns position of slider
%        get(hObject,'Min') and get(hObject,'Max') to determine
range of slider

global wmref_pu;
global wmref_pu_send;
global fixer

% if fixer==51
%     wmref_pu=wmref_pu_send
% end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Maximum Power Point Tracking

[Pm_pu, Tem_pu]=Turbine_Power(Wind_speed,wmref_pu)

wmref_pu=-0.67*(Pm_pu)^2+1.42*(Pm_pu)+0.51;
    if(Pm_pu>0.75 && Pm_pu<2)
        wmref_pu=1.2;
    end
    if(Pm_pu<0.15)
            wmref_pu=0.7;
    end

wmref_pu_send=wmref_pu
wmref_pu;
wm=(wmref_pu)*125.66;
slip=(125.66-wm)/125.66;
Pm_actual=Pm_pu*1.5;
Pgap=(Pm_pu*1)*1.5/(1-slip); %Pgap in MW
Protor=(-slip)*Pgap; %In MW

set(handles.ePm_MW,'String',num2str(Pm_actual));
set(handles.ePm_pu,'String',num2str(Pm_pu));
set(handles.ePr,'String',num2str(abs(Protor)));
set(handles.ePgap,'String',num2str(Pgap));
set(handles.ewref,'String',num2str(wm));
set(handles.eSlip,'String',num2str(slip));
%set(handles.ePloss,'String',num2str(Ploss))
global arrow_fixer
if(slip<0)
    axes(handles.axes_Pr);
    load('Right_Arrow');
    imshow(myimage4);
    arrow_fixer=46;
    handles.output = hObject;
% else if (slip==0)
%         axes(handles.axes_Pr);
```

```
%
imshow('C:\Users\asinha14\Documents\MATLAB\DFIG\Cross.PNG')
%          handles.output = hObject;
    else
    axes(handles.axes_Pr);
    load('Left_Arrow');
    imshow(myimage2);
    arrow_fixer=45;
    handles.output = hObject;
end


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Equivalent circuit  calculation
Va=331.9;%Grid voltage rms per phase (575V l-l)
Rs=0.0046;
Rr=0.0032;
Lls=0.0947e-3;
Llr=0.0842e-3;
Lm=1.526e-3;

pol=[Rs Va -(Pgap*1e6)/3];
roots(pol);
Ia_complex=max(roots(pol));
E_complex=Va+(Rs+i*(377*Lls))*Ia_complex;
Ima_complex=E_complex/(i*(377*Lm));
Ira_complex=Ia_complex+Ima_complex;
Vr_slip_complex=(E_complex+Ira_complex*((Rr/slip)+(i*377*Llr)));


Vr_slip=abs(Vr_slip_complex)*slip;
powerfactoran-
gle=(180/pi)*atan(imag(Ira_complex)/real(Ira_complex));


set(handles.eIa,'String',num2str(Ia_complex))
set(handles.eIra,'String',num2str((Ira_complex)))
set(handles.eIma,'String',num2str((Ima_complex)))
set(handles.eVrotor_s,'String',num2str(Vr_slip))
set(handles.ePF_angle,'String',num2str(powerfactorangle))
Phasor_Diagram()
Equivalent_circuit()
Curve_tracking()




guidata(hObject, handles);

% --- Executes during object creation, after setting all proper-
ties.
function Slider_wind_CreateFcn(hObject, eventdata, handles)
```

```
% hObject    handle to Slider_wind (see GCBO)
% eventdata  reserved - to be defined in a future version of
MATLAB
% handles    empty - handles not created until after all Cre-
ateFcns called

% Hint: slider controls usually have a light gray background.
if isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor',[.9 .9 .9]);
end



function eIa_Callback(hObject, eventdata, handles)
% hObject    handle to eIa (see GCBO)
% eventdata  reserved - to be defined in a future version of
MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of eIa as text
%        str2double(get(hObject,'String')) returns contents of
eIa as a double


% --- Executes during object creation, after setting all proper-
ties.
function eIa_CreateFcn(hObject, eventdata, handles)
% hObject    handle to eIa (see GCBO)
% eventdata  reserved - to be defined in a future version of
MATLAB
% handles    empty - handles not created until after all Cre-
ateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end



function eIma_Callback(hObject, eventdata, handles)
% hObject    handle to eIma (see GCBO)
% eventdata  reserved - to be defined in a future version of
MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of eIma as text
%        str2double(get(hObject,'String')) returns contents of
eIma as a double
```

```
% --- Executes during object creation, after setting all proper-
ties.
function eIma_CreateFcn(hObject, eventdata, handles)
% hObject    handle to eIma (see GCBO)
% eventdata  reserved - to be defined in a future version of
MATLAB
% handles    empty - handles not created until after all Cre-
ateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end



function eIra_Callback(hObject, eventdata, handles)
% hObject    handle to eIra (see GCBO)
% eventdata  reserved - to be defined in a future version of
MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of eIra as text
%        str2double(get(hObject,'String')) returns contents of
eIra as a double


% --- Executes during object creation, after setting all proper-
ties.
function eIra_CreateFcn(hObject, eventdata, handles)
% hObject    handle to eIra (see GCBO)
% eventdata  reserved - to be defined in a future version of
MATLAB
% handles    empty - handles not created until after all Cre-
ateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end



function eVrotor_s_Callback(hObject, eventdata, handles)
% hObject    handle to eVrotor_s (see GCBO)
% eventdata  reserved - to be defined in a future version of
MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of eVrotor_s as
text
%        str2double(get(hObject,'String')) returns contents of
eVrotor_s as a double


% --- Executes during object creation, after setting all proper-
ties.
function eVrotor_s_CreateFcn(hObject, eventdata, handles)
% hObject    handle to eVrotor_s (see GCBO)
% eventdata  reserved - to be defined in a future version of
MATLAB
% handles    empty - handles not created until after all Cre-
ateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end



function ePF_angle_Callback(hObject, eventdata, handles)
% hObject    handle to ePF_angle (see GCBO)
% eventdata  reserved - to be defined in a future version of
MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of ePF_angle as
text
%        str2double(get(hObject,'String')) returns contents of
ePF_angle as a double


% --- Executes during object creation, after setting all proper-
ties.
function ePF_angle_CreateFcn(hObject, eventdata, handles)
% hObject    handle to ePF_angle (see GCBO)
% eventdata  reserved - to be defined in a future version of
MATLAB
% handles    empty - handles not created until after all Cre-
ateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
```

```
if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end



function edit18_Callback(hObject, eventdata, handles)
% hObject    handle to edit18 (see GCBO)
% eventdata  reserved - to be defined in a future version of
MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of edit18 as text
%        str2double(get(hObject,'String')) returns contents of
edit18 as a double


% --- Executes during object creation, after setting all proper-
ties.
function edit18_CreateFcn(hObject, eventdata, handles)
% hObject    handle to edit18 (see GCBO)
% eventdata  reserved - to be defined in a future version of
MATLAB
% handles    empty - handles not created until after all Cre-
ateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end



function edit19_Callback(hObject, eventdata, handles)
% hObject    handle to edit19 (see GCBO)
% eventdata  reserved - to be defined in a future version of
MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of edit19 as text
%        str2double(get(hObject,'String')) returns contents of
edit19 as a double


% --- Executes during object creation, after setting all proper-
ties.
function edit19_CreateFcn(hObject, eventdata, handles)
% hObject    handle to edit19 (see GCBO)
% eventdata  reserved - to be defined in a future version of
MATLAB
% handles    empty - handles not created until after all Cre-
ateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end


% --- Executes on selection change in listbox1.
function listbox1_Callback(hObject, eventdata, handles)
% hObject    handle to listbox1 (see GCBO)
% eventdata  reserved - to be defined in a future version of
MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: contents = cellstr(get(hObject,'String')) returns
listbox1 contents as cell array
%        contents{get(hObject,'Value')} returns selected item
from listbox1


% --- Executes during object creation, after setting all proper-
ties.
function listbox1_CreateFcn(hObject, eventdata, handles)
% hObject    handle to listbox1 (see GCBO)
% eventdata  reserved - to be defined in a future version of
MATLAB
% handles    empty - handles not created until after all Cre-
ateFcns called

% Hint: listbox controls usually have a white background on Win-
dows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end
```

Equivalent_circuit.m

```
function varargout = Equivalent_circuit(varargin)
% EQUIVALENT_CIRCUIT MATLAB code for Equivalent_circuit.fig
%      EQUIVALENT_CIRCUIT, by itself, creates a new EQUIVA-
LENT_CIRCUIT or raises the existing
%      singleton*.
```

```
%
%      H = EQUIVALENT_CIRCUIT returns the handle to a new EQUIVA-
LENT_CIRCUIT or the handle to
%      the existing singleton*.
%
%      EQUIVA-
LENT_CIRCUIT('CALLBACK',hObject,eventData,handles,...) calls the
local
%      function named CALLBACK in EQUIVALENT_CIRCUIT.M with the
given input arguments.
%
%      EQUIVALENT_CIRCUIT('Property','Value',...) creates a new
EQUIVALENT_CIRCUIT or raises the
%      existing singleton*.  Starting from the left, property
value pairs are
%      applied to the GUI before Equivalent_circuit_OpeningFcn
gets called.  An
%      unrecognized property name or invalid value makes property
application
%      stop.  All inputs are passed to Equiva-
lent_circuit_OpeningFcn via varargin.
%
%      *See GUI Options on GUIDE's Tools menu.  Choose "GUI al-
lows only one
%      instance to run (singleton)".
%
% See also: GUIDE, GUIDATA, GUIHANDLES

% Edit the above text to modify the response to help Equiva-
lent_circuit

% Last Modified by GUIDE v2.5 27-Nov-2011 18:16:41

% Begin initialization code - DO NOT EDIT
gui_Singleton = 1;
gui_State = struct('gui_Name',       mfilename, ...
                   'gui_Singleton',  gui_Singleton, ...
                   'gui_OpeningFcn',
@Equivalent_circuit_OpeningFcn, ...
                   'gui_OutputFcn',
@Equivalent_circuit_OutputFcn, ...
                   'gui_LayoutFcn',  [] , ...
                   'gui_Callback',   []);
if nargin && ischar(varargin{1})
    gui_State.gui_Callback = str2func(varargin{1});
end

if nargout
    [varargout{1:nargout}] = gui_mainfcn(gui_State, varargin{:});
else
    gui_mainfcn(gui_State, varargin{:});
end
% End initialization code - DO NOT EDIT
% --- Executes just before Equivalent_circuit is made visible.
function Equivalent_circuit_OpeningFcn(hObject, eventdata, han-
dles, varargin)
% This function has no output args, see OutputFcn.
% hObject    handle to figure
% eventdata  reserved - to be defined in a future version of
MATLAB
% handles    structure with handles and user data (see GUIDATA)
% varargin   command line arguments to Equivalent_circuit (see
VARARGIN)

% Choose default command line output for Equivalent_circuit
handles.output = hObject;

axes(handles.axes1);
load('Equivalent_circuit');
imshow(myimage6);
handles.output = hObject;



Total_modelFigureHandle  = Total_model; %stores the figure handle
of Daniel's GUI here

%stores the GUI data from Daniel's GUI here
%now we can access any of the data from Daniel's GUI!!!!
EqData = guidata(Total_modelFigureHandle);

%store the input text from Daniel's GUI
%into the variable daniel_input
RotorV_slip = get(EqData.eVrotor_s,'String');
Ia = get(EqData.eIa,'String');
Im = get(EqData.eIma,'String');
Ir = get(EqData.eIra,'String');

%set the static text on Quan's GUI to match the
%input text from Daniel's GUI
set(handles.eVrotor,'String',num2str(RotorV_slip));
set(handles.eIgrid,'String',num2str(Ia));
set(handles.eIm,'String',num2str(Im));
set(handles.eIrotor,'String',num2str(Ir));






% Update handles structure
guidata(hObject, handles);
```

```
% UIWAIT makes Equivalent_circuit wait for user response (see
UIRESUME)
% uiwait(handles.figure1);


% --- Outputs from this function are returned to the command
line.
function varargout = Equivalent_circuit_OutputFcn(hObject, event-
data, handles)
% varargout  cell array for returning output args (see
VARARGOUT);
% hObject    handle to figure
% eventdata  reserved - to be defined in a future version of
MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Get default command line output from handles structure
varargout{1} = handles.output;



function edit3_Callback(hObject, eventdata, handles)
% hObject    handle to edit3 (see GCBO)
% eventdata  reserved - to be defined in a future version of
MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of edit3 as text
%        str2double(get(hObject,'String')) returns contents of
edit3 as a double


% --- Executes during object creation, after setting all proper-
ties.
function edit3_CreateFcn(hObject, eventdata, handles)
% hObject    handle to edit3 (see GCBO)
% eventdata  reserved - to be defined in a future version of
MATLAB
% handles    empty - handles not created until after all Cre-
ateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end



function eIgrid_Callback(hObject, eventdata, handles)
% hObject    handle to eIgrid (see GCBO)
% eventdata  reserved - to be defined in a future version of
MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of eIgrid as text
%        str2double(get(hObject,'String')) returns contents of
eIgrid as a double


% --- Executes during object creation, after setting all proper-
ties.
function eIgrid_CreateFcn(hObject, eventdata, handles)
% hObject    handle to eIgrid (see GCBO)
% eventdata  reserved - to be defined in a future version of
MATLAB
% handles    empty - handles not created until after all Cre-
ateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end



function edit6_Callback(hObject, eventdata, handles)
% hObject    handle to edit6 (see GCBO)
% eventdata  reserved - to be defined in a future version of
MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of edit6 as text
%        str2double(get(hObject,'String')) returns contents of
edit6 as a double


% --- Executes during object creation, after setting all proper-
ties.
function edit6_CreateFcn(hObject, eventdata, handles)
% hObject    handle to edit6 (see GCBO)
% eventdata  reserved - to be defined in a future version of
MATLAB
% handles    empty - handles not created until after all Cre-
ateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
```

```
end



function edit7_Callback(hObject, eventdata, handles)
% hObject    handle to edit7 (see GCBO)
% eventdata  reserved - to be defined in a future version of
MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of edit7 as text
%        str2double(get(hObject,'String')) returns contents of
edit7 as a double


% --- Executes during object creation, after setting all proper-
ties.
function edit7_CreateFcn(hObject, eventdata, handles)
% hObject    handle to edit7 (see GCBO)
% eventdata  reserved - to be defined in a future version of
MATLAB
% handles    empty - handles not created until after all Cre-
ateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end



function edit8_Callback(hObject, eventdata, handles)
% hObject    handle to edit8 (see GCBO)
% eventdata  reserved - to be defined in a future version of
MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of edit8 as text
%        str2double(get(hObject,'String')) returns contents of
edit8 as a double


% --- Executes during object creation, after setting all proper-
ties.
function edit8_CreateFcn(hObject, eventdata, handles)
% hObject    handle to edit8 (see GCBO)
% eventdata  reserved - to be defined in a future version of
MATLAB
% handles    empty - handles not created until after all Cre-
ateFcns called
```

```
% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end



function edit9_Callback(hObject, eventdata, handles)
% hObject    handle to edit9 (see GCBO)
% eventdata  reserved - to be defined in a future version of
MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of edit9 as text
%        str2double(get(hObject,'String')) returns contents of
edit9 as a double


% --- Executes during object creation, after setting all proper-
ties.
function edit9_CreateFcn(hObject, eventdata, handles)
% hObject    handle to edit9 (see GCBO)
% eventdata  reserved - to be defined in a future version of
MATLAB
% handles    empty - handles not created until after all Cre-
ateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end



function edit10_Callback(hObject, eventdata, handles)
% hObject    handle to edit10 (see GCBO)
% eventdata  reserved - to be defined in a future version of
MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of edit10 as text
%        str2double(get(hObject,'String')) returns contents of
edit10 as a double


% --- Executes during object creation, after setting all proper-
ties.
```

```
function edit10_CreateFcn(hObject, eventdata, handles)
% hObject    handle to edit10 (see GCBO)
% eventdata  reserved - to be defined in a future version of
MATLAB
% handles    empty - handles not created until after all Cre-
ateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end



function eVrotor_Callback(hObject, eventdata, handles)
% hObject    handle to eVrotor (see GCBO)
% eventdata  reserved - to be defined in a future version of
MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of eVrotor as
text
%        str2double(get(hObject,'String')) returns contents of
eVrotor as a double


% --- Executes during object creation, after setting all proper-
ties.
function eVrotor_CreateFcn(hObject, eventdata, handles)
% hObject    handle to eVrotor (see GCBO)
% eventdata  reserved - to be defined in a future version of
MATLAB
% handles    empty - handles not created until after all Cre-
ateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end



function eIm_Callback(hObject, eventdata, handles)
% hObject    handle to eIm (see GCBO)
% eventdata  reserved - to be defined in a future version of
MATLAB
% handles    structure with handles and user data (see GUIDATA)
% Hints: get(hObject,'String') returns contents of eIm as text
%        str2double(get(hObject,'String')) returns contents of
eIm as a double


% --- Executes during object creation, after setting all proper-
ties.
function eIm_CreateFcn(hObject, eventdata, handles)
% hObject    handle to eIm (see GCBO)
% eventdata  reserved - to be defined in a future version of
MATLAB
% handles    empty - handles not created until after all Cre-
ateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end



function eIrotor_Callback(hObject, eventdata, handles)
% hObject    handle to Irotor (see GCBO)
% eventdata  reserved - to be defined in a future version of
MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of Irotor as text
%        str2double(get(hObject,'String')) returns contents of
Irotor as a double


% --- Executes during object creation, after setting all proper-
ties.
function Irotor_CreateFcn(hObject, eventdata, handles)
% hObject    handle to Irotor (see GCBO)
% eventdata  reserved - to be defined in a future version of
MATLAB
% handles    empty - handles not created until after all Cre-
ateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end
```

Phasor_Diagram.m

```
function varargout = Phasor_Diagram(varargin)
% PHASOR_DIAGRAM MATLAB code for Phasor_Diagram.fig
%      PHASOR_DIAGRAM, by itself, creates a new PHASOR_DIAGRAM or 
raises the existing
%      singleton*.
%
%      H = PHASOR_DIAGRAM returns the handle to a new PHAS-
OR_DIAGRAM or the handle to
%      the existing singleton*.
%
%      PHASOR_DIAGRAM('CALLBACK',hObject,eventData,handles,...) 
calls the local
%      function named CALLBACK in PHASOR_DIAGRAM.M with the given 
input arguments.
%
%      PHASOR_DIAGRAM('Property','Value',...) creates a new PHAS-
OR_DIAGRAM or raises the
%      existing singleton*.  Starting from the left, property 
value pairs are
%      applied to the GUI before Phasor_Diagram_OpeningFcn gets 
called.  An
%      unrecognized property name or invalid value makes property 
application
%      stop.  All inputs are passed to Phasor_Diagram_OpeningFcn 
via varargin.
%
%      *See GUI Options on GUIDE's Tools menu.  Choose "GUI al-
lows only one
%      instance to run (singleton)".
%
% See also: GUIDE, GUIDATA, GUIHANDLES

% Edit the above text to modify the response to help Phas-
or_Diagram

% Last Modified by GUIDE v2.5 10-Feb-2012 18:33:18

% Begin initialization code - DO NOT EDIT
gui_Singleton = 1;
gui_State = struct('gui_Name',       mfilename, ...
                   'gui_Singleton',  gui_Singleton, ...
                   'gui_OpeningFcn', @Phasor_Diagram_OpeningFcn, 
...
                   'gui_OutputFcn',  @Phasor_Diagram_OutputFcn, 
...
                   'gui_LayoutFcn',  [] , ...
                   'gui_Callback',   []);
if nargin && ischar(varargin{1})
    gui_State.gui_Callback = str2func(varargin{1});
end
```

```
if nargout
    [varargout{1:nargout}] = gui_mainfcn(gui_State, varargin{:});
else
    gui_mainfcn(gui_State, varargin{:});
end
% End initialization code - DO NOT EDIT


% --- Executes just before Phasor_Diagram is made visible.
function Phasor_Diagram_OpeningFcn(hObject, eventdata, handles,
varargin)
% This function has no output args, see OutputFcn.
% hObject    handle to figure
% eventdata  reserved - to be defined in a future version of
MATLAB
% handles    structure with handles and user data (see GUIDATA)
% varargin   command line arguments to Phasor_Diagram (see
VARARGIN)
handles.output = hObject;
Total_modelHandle  = Total_model; %stores the figure handle of
Daniel's GUI here

%stores the GUI data from Daniel's GUI here
%now we can access any of the data from Daniel's GUI!!!!
ArrowData = guidata(Total_modelHandle);

%store the input text from Daniel's GUI
%into the variable daniel_input
global Pgap_color slip_color
Pgap_color = get(ArrowData.ePgap,'String')
slip_color = get(ArrowData.eSlip,'String')


%% User Declaration 1


% End of User Declaration 1


%% --- Outputs from this function are returned to the command
line.
function varargout = Phasor_Diagram_OutputFcn(hObject, eventdata,
handles)
% varargout  cell array for returning output args (see
VARARGOUT);
% hObject    handle to figure
% eventdata  reserved - to be defined in a future version of
MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Get default command line output from handles structure
varargout{1} = handles.output;
```

```
% --- Executes on slider movement.
function slider1_Callback(hObject, eventdata, handles)


handles.output = hObject;

%% --- Executes during object creation, after setting all proper-
ties.
function slider1_CreateFcn(hObject, eventdata, handles)
% hObject    handle to slider1 (see GCBO)
% eventdata  reserved - to be defined in a future version of
MATLAB
% handles    empty - handles not created until after all Cre-
ateFcns called

% Hint: slider controls usually have a light gray background.
if isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor',[.9 .9 .9]);
end



function edit1_Callback(hObject, eventdata, handles)
% hObject    handle to edit1 (see GCBO)
% eventdata  reserved - to be defined in a future version of
MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of edit1 as text
%        str2double(get(hObject,'String')) returns contents of
edit1 as a double


% --- Executes during object creation, after setting all proper-
ties.
function edit1_CreateFcn(hObject, eventdata, handles)
% hObject    handle to edit1 (see GCBO)
% eventdata  reserved - to be defined in a future version of
MATLAB
% handles    empty - handles not created until after all Cre-
ateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end
```

```
% --- Executes on button press in pushbutton1.
function pushbutton1_Callback(hObject, eventdata, handles)
% hObject    handle to pushbutton1 (see GCBO)
% eventdata  reserved - to be defined in a future version of
MATLAB
% handles    structure with handles and user data (see GUIDATA)
global handle_Va x_init_Va y_init_Va handle_Ia x_init_Ia
y_init_Ia handle_IRs x_init_IRs y_init_IRs handle_IXs x_init_IXs
y_init_IXs...
    handle_E x_init_E y_init_E handle_Imag x_init_Imag
y_init_Imag handle_Ira x_init_Ira y_init_Ira handle_IRr
x_init_IRr y_init_IRr ...
    handle_IXr x_init_IXr y_init_IXr handle_Vr_s x_init_Vr_s
y_init_Vr_s scaling_Ia scaling_Va scaling_IRs scaling_IXs scal-
ing_Imag ...
    scaling_Ira scaling_IRr scaling_IXr scaling_Vr_s
k1=2
scaling_Va=1.5*1000/k1;
scaling_IRs=1.5*1000/k1;
scaling_IXs=1.5*1000/k1;
scaling_IRr=1.5*1000/k1;
scaling_IXr=1.5*1000/k1;

k2=3;
scaling_Ia=(1.5*1000)*8.792; % 100/4/3
scaling_Imag=(1.5*1000)*8.792;%2*10/k2); % 2*10/3
scaling_Ira=(1.5*1000)*8.792; % 2*100/3



clf
%SliderValue = get(handles.PowerFactorSlider,'Value')
global Pgap_color slip_color
%Pgap_color=1.5/3; %MW
%slip_color=-0.2;

Va=332;
Rs=0.0046;
Rr=0.0032;
Lls=0.0947e-3;
Xs=377*Lls;
Llr=0.0842e-3;
Xr=377*Llr;
Lm=1.526e-3;
Xm=377*Lm;

global SliderValue
SliderValue = get(handles.slider1,'Value')
pf_angle=SliderValue
set(handles.edit1,'String',num2str(pf_angle))

pf=cosd(pf_angle)
```

```
Pgap_color=str2num(Pgap_color)
slip_color=str2num(slip_color)
Va
Iax=(Pgap_color)*1000000/Va
S=Pgap_color/pf
Q=S*sind(pf_angle)
Iay=Q*1e6/Va
Ia=Iax+j*Iay
abs(Ia)
angle_Ia=angle(Ia)*180/pi

E=Va+(Rs+j*(377*Lls))*Ia;
angle_E=angle(E)*180/pi;

Ima=E/(i*(377*Lm))
abs(Ima)
angle_Ima=angle(Ima)*180/pi

Ira=Ia+Ima
abs(Ira)
angle_Ira=angle(Ira)*180/pi

Vr_s=E+Ira*((Rr/slip_color)+1j*(377*Llr));
angle_Vr_s=angle(Vr_s)*180/pi;

x_init_Va = [0.05 0.4];
x_init_Va(2)=x_init_Va(1)+(Va/scaling_Va);
y_init_Va = [0.5 0.5];
handle_Va = annotation('textarrow',x_init_Va,y_init_Va);


x_init_Ia = [0.05 0.4];
x_init_Ia(2)=x_init_Ia(1)+(abs(Ia)*abs(cosd(angle_Ia))/scaling_Ia
);
y_init_Ia = [0.5 0.5];
y_init_Ia(2)=y_init_Ia(1)+(abs(Ia)*sind(angle_Ia)/scaling_Ia);
handle_Ia = annotation('arrow',x_init_Ia,y_init_Ia);


x_init_IRs = [x_init_Va(2) 0.4];
x_init_IRs(2)=x_init_IRs(1)+(Rs*abs(Ia)*abs(cosd(angle_Ia))/scali
ng_IRs);
y_init_IRs = [y_init_Va(2) 0.4];
y_init_IRs(2)=y_init_IRs(1)+(Rs*abs(Ia)*sind(angle_Ia)/scaling_IR
s);
handle_IRs = annota-
tion('line',x_init_IRs,y_init_IRs)%,'String','Va','FontSize',14);


x_init_IXs = [x_init_IRs(2) 0.4];
```

```
x_init_IXs(2)=x_init_IXs(1)-
(Xs*abs(Ia)*(sind(angle_Ia))/scaling_IXs);
y_init_IXs = [y_init_IRs(2) 0.4];
y_init_IXs(2)=y_init_IXs(1)+(Xs*abs(Ia)*abs(cosd(angle_Ia))/scali
ng_IXs);
handle_IXs = annotation('arrow',x_init_IXs,y_init_IXs);


x_init_E = [x_init_Va(1) 0.4];
x_init_E(2)=x_init_IXs(2);
y_init_E = [y_init_Va(2) 0.4];
y_init_E(2)=y_init_IXs(2);
handle_E = annotation('arrow',x_init_E,y_init_E);


x_init_Imag = [x_init_Va(1) 0.4];
x_init_Imag(2)=x_init_E(1)+(abs(E/Xm)*abs(cosd(angle_Ima))/scalin
g_Imag);
y_init_Imag = [y_init_Va(2) 0.4];
y_init_Imag(2)=y_init_E(1)-
(abs(E/Xm)*abs(sind(angle_Ima))/scaling_Imag);
handle_Imag = annotation('arrow',x_init_Imag,y_init_Imag);

% x_init_Ira = [x_init_Va(1) 0.4];
%
x_init_Ira(2)=x_init_Ira(1)+(abs(Ira)*abs(cosd(angle_Ira))/scalin
g_Ira);
% y_init_Ira = [y_init_Va(2) 0.4];
%
y_init_Ira(2)=y_init_Ira(1)+(abs(Ira)*sind(angle_Ira)/scaling_Ira
);
% handle_Ira = annotation('arrow',x_init_Ira,y_init_Ira);
y_init_Va(1)
y_init_Ia(2)
Fixer_y_a=y_init_Ia(2)-y_init_Va(1)
y_init_Imag(2)
Fixer_y_b=y_init_Imag(2)-y_init_Va(1)

x_init_Ira =[x_init_Va(1) 0.4]
x_init_Ira(2)=x_init_Ia(2)+x_init_Imag(2)
y_init_Ira = [y_init_Va(2) 0.4];
y_init_Ira(2)=y_init_Va(1)+Fixer_y_a+Fixer_y_b %-
y_init_Ia(2)+y_init_Imag(2)%     (y_init_Va(1)-)+(y_init_Va(1)-
y_init_Imag(2))
handle_Ira = annotation('arrow',x_init_Ira,y_init_Ira);

angle_Ira;
x_init_IRr = [x_init_E(2) 0.4];
x_init_IRr(2)=x_init_IRr(1)+(Rr*abs(Ira)*abs(cosd(angle_Ira))/sca
ling_IRr);
y_init_IRr = [y_init_E(2) 0.4];
y_init_IRr(2)=y_init_IRr(1)+(Rr*abs(Ira)*sind(angle_Ira)/scaling_
IRr);
```

```
handle_IRr = annotation('line',x_init_IRr,y_init_IRr);

x_init_IXr = [x_init_IRr(2) 0.4];
x_init_IXr(2)=x_init_IXr(1)-
(Xr*abs(Ira)*(sind(angle_Ira))/scaling_IXr);
y_init_IXr = [y_init_IRr(2) 0.4];
y_init_IXr(2)=y_init_IXr(1)+(Xr*abs(Ira)*abs(cosd(angle_Ira))/sca
ling_IXr);
handle_IXr = annotation('arrow',x_init_IXr,y_init_IXr);

x_init_Vr_s = [x_init_Va(1) 0.4];
x_init_Vr_s(2)=x_init_IXr(2);
y_init_Vr_s = [y_init_Va(2) 0.4];
y_init_Vr_s(2)=y_init_IXr(2);
handle_Vr_s = annotation('arrow',x_init_Vr_s,y_init_Vr_s);
set(handle_IRs,'Color',[1,0,1]);
set(handle_IXs,'Color',[1,0,1]);
set(handle_IRr,'Color',[0.6,0.2,0]);
set(handle_IXr,'Color',[0.6,0.2,0]);
set(handle_Vr_s,'Color',[0,1,0]);
set(handle_Ia,'Color',[1,0,0]);
set(handle_Va,'Color',[0,0,1]);
set(handle_E,'Color',[0,1,1]);
set(handle_Ira,'Color',[1,0.5,0.2]);
```

Curve_tracking.m

```
function varargout = Curve_tracking(varargin)
% CURVE_TRACKING MATLAB code for Curve_tracking.fig
%      CURVE_TRACKING, by itself, creates a new CURVE_TRACKING or
raises the existing
%      singleton*.
%
%      H = CURVE_TRACKING returns the handle to a new
CURVE_TRACKING or the handle to
%      the existing singleton*.
%
%      CURVE_TRACKING('CALLBACK',hObject,eventData,handles,...)
calls the local
%      function named CALLBACK in CURVE_TRACKING.M with the given
input arguments.
%
%      CURVE_TRACKING('Property','Value',...) creates a new
CURVE_TRACKING or raises the
%      existing singleton*.  Starting from the left, property
value pairs are
%      applied to the GUI before Curve_tracking_OpeningFcn gets
called.  An
%      unrecognized property name or invalid value makes property
application
```

```
%       stop.  All inputs are passed to Curve_tracking_OpeningFcn
via varargin.
%
%       *See GUI Options on GUIDE's Tools menu.  Choose "GUI al-
lows only one
%       instance to run (singleton)".
%
% See also: GUIDE, GUIDATA, GUIHANDLES

% Edit the above text to modify the response to help
Curve_tracking

% Last Modified by GUIDE v2.5 31-Jan-2012 19:45:36

% Begin initialization code - DO NOT EDIT
gui_Singleton = 1;
gui_State = struct('gui_Name',       mfilename, ...
                   'gui_Singleton',  gui_Singleton, ...
                   'gui_OpeningFcn', @Curve_tracking_OpeningFcn,
...
                   'gui_OutputFcn',  @Curve_tracking_OutputFcn,
...
                   'gui_LayoutFcn',  [] , ...
                   'gui_Callback',   []);
if nargin && ischar(varargin{1})
    gui_State.gui_Callback = str2func(varargin{1});
end

if nargout
    [varargout{1:nargout}] = gui_mainfcn(gui_State, varargin{:});
else
    gui_mainfcn(gui_State, varargin{:});
end
% End initialization code - DO NOT EDIT


% --- Executes just before Curve_tracking is made visible.
function Curve_tracking_OpeningFcn(hObject, eventdata, handles,
varargin)
% This function has no output args, see OutputFcn.
% hObject    handle to figure
% eventdata  reserved - to be defined in a future version of
MATLAB
% handles    structure with handles and user data (see GUIDATA)
% varargin   command line arguments to Curve_tracking (see
VARARGIN)

axes(handles.MPPT_Background);

load('MPPT_VVHigh');
imshow(myimage777);

handles.output = hObject;
```

```
Total_Handle  = Total_model; %stores the figure handle of Dan-
iel's GUI here

%stores the GUI data from Daniel's GUI here
%now we can access any of the data from Daniel's GUI!!!!
Tracking = guidata(Total_Handle);

%store the input text from Daniel's GUI
%into the variable daniel_input

Slip_tracking = get(Tracking.eSlip,'String');
Pm_tracking = get(Tracking.ePm_pu,'String');
% Choose default command line output for Curve_tracking

set(handles.edit_slip,'String',num2str(Slip_tracking));
set(handles.edit_Pm,'String',num2str(Pm_tracking));

axes(handles.Dot)
load('Dot_Brown');
imshow(myimage300);

set(handles.Dot,'Position',[46.8, 12, 1.6, 0.615])

if(str2num(Slip_tracking)==0.3)
    set(handles.Dot,'Position',[25.8, 5.623, 1.6, 0.615])

end
if(str2num(Slip_tracking)<0.3 && str2num(Slip_tracking)>0.275)
    set(handles.Dot,'Position',[28, 5.931, 1.6, 0.615])
end
if(str2num(Slip_tracking)<=0.275 && str2num(Slip_tracking)>0.25)
    set(handles.Dot,'Position',[30.2, 6.231, 1.6, 0.615])
end
if(str2num(Slip_tracking)<=0.25 && str2num(Slip_tracking)>0.225)
    set(handles.Dot,'Position',[32.4, 6.438, 1.6, 0.615])
end
if(str2num(Slip_tracking)<=0.225 && str2num(Slip_tracking)>0.2)
    set(handles.Dot,'Position',[34.8, 6.623, 1.6, 0.615])
end
if(str2num(Slip_tracking)<=0.2 && str2num(Slip_tracking)>0.175)
    set(handles.Dot,'Position',[37.2, 6.854, 1.6, 0.615])
end
if(str2num(Slip_tracking)<=0.175 && str2num(Slip_tracking)>0.15)
    set(handles.Dot,'Position',[39.8, 7.185, 1.6, 0.615])
end
if(str2num(Slip_tracking)<=0.15 && str2num(Slip_tracking)>0.125)
    set(handles.Dot,'Position',[41.4, 7.3, 1.6, 0.615])
end
if(str2num(Slip_tracking)<=0.125 && str2num(Slip_tracking)>0.1)
    set(handles.Dot,'Position',[43.8, 7.7, 1.6, 0.615])
end
if(str2num(Slip_tracking)<=0.1 && str2num(Slip_tracking)>0.075)
```

```
    set(handles.Dot,'Position',[46, 8, 1.6, 0.615])
end
if(str2num(Slip_tracking)<=0.075 && str2num(Slip_tracking)>0.05)
    set(handles.Dot,'Position',[48.2, 8.2, 1.6, 0.615])
end
if(str2num(Slip_tracking)<=0.05 && str2num(Slip_tracking)>0.025)
    set(handles.Dot,'Position',[50.6, 8.5, 1.6, 0.615])
end
if(str2num(Slip_tracking)<=0.025 && str2num(Slip_tracking)>0)
    set(handles.Dot,'Position',[53.1, 8.9, 1.6, 0.615])
end
if(str2num(Slip_tracking)<=0 && str2num(Slip_tracking)>-0.025)
    set(handles.Dot,'Position',[55.3, 9.2, 1.6, 0.615])
end
if(str2num(Slip_tracking)<=-0.025 && str2num(Slip_tracking)>-
0.05)
    set(handles.Dot,'Position',[57.6, 9.6, 1.6, 0.615])
end
if(str2num(Slip_tracking)<=-0.05 && str2num(Slip_tracking)>-
0.075)
    set(handles.Dot,'Position',[60, 9.9, 1.6, 0.615])
end
if(str2num(Slip_tracking)<=-0.075 && str2num(Slip_tracking)>-0.1)
    set(handles.Dot,'Position',[62.7, 10.3, 1.6, 0.615])
end
if(str2num(Slip_tracking)<=-0.1 && str2num(Slip_tracking)>-0.125)
    set(handles.Dot,'Position',[62.8, 10.3, 1.6, 0.615])
end
if(str2num(Slip_tracking)<=-0.125 && str2num(Slip_tracking)>-
0.15)
    set(handles.Dot,'Position',[64.6, 10.7, 1.6, 0.615])
end
if(str2num(Slip_tracking)<=-0.15 && str2num(Slip_tracking)>-
0.175)
    set(handles.Dot,'Position',[66.9, 11.2, 1.6, 0.615])
end
if(str2num(Slip_tracking)<=-0.175 && str2num(Slip_tracking)>-0.2)
    set(handles.Dot,'Position',[69.9, 11.8, 1.6, 0.615])
end
if(str2num(Slip_tracking)==(-0.2))
    set(handles.Dot,'Position',[72.1, 12.5, 1.6, 0.615])
end
if(str2num(Pm_tracking)<0.765 && str2num(Pm_tracking)>0.75)
    set(handles.Dot,'Position',[72.1, 12.7, 1.6, 0.615])
end
% if(str2num(Pm_tracking)<0.77 && str2num(Pm_tracking)>0.75)
%     set(handles.Dot,'Position',[48.4, 13.25, 1.6, 0.615])
% end
if(str2num(Pm_tracking)<=0.84 && str2num(Pm_tracking)>0.765)
    set(handles.Dot,'Position',[72.1, 12.9, 1.6, 0.615])
end

if(str2num(Pm_tracking)<=0.88 && str2num(Pm_tracking)>0.84)
    set(handles.Dot,'Position',[72.1, 13.3, 1.6, 0.615])
```

```
end
if(str2num(Pm_tracking)<=0.92 && str2num(Pm_tracking)>0.88)
    set(handles.Dot,'Position',[72.1, 13.9, 1.6, 0.615])
end
if(str2num(Pm_tracking)<=0.96 && str2num(Pm_tracking)>0.92)
    set(handles.Dot,'Position',[72.1, 14.4, 1.6, 0.615])
end
if(str2num(Pm_tracking)<=1&& str2num(Pm_tracking)>0.96)
    set(handles.Dot,'Position',[72.1, 15, 1.6, 0.615])
end
if(str2num(Pm_tracking)>1)
     set(handles.Dot,'Position',[72.1, 15, 1.6, 0.615])
end


% Update handles structure
guidata(hObject, handles);

% UIWAIT makes Curve_tracking wait for user response (see
UIRESUME)
% uiwait(handles.figure1);


% --- Outputs from this function are returned to the command
line.
function varargout = Curve_tracking_OutputFcn(hObject, eventdata,
handles)
% varargout  cell array for returning output args (see
VARARGOUT);
% hObject    handle to figure
% eventdata  reserved - to be defined in a future version of
MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Get default command line output from handles structure
varargout{1} = handles.output;



function edit_slip_Callback(hObject, eventdata, handles)
% hObject    handle to edit_slip (see GCBO)
% eventdata  reserved - to be defined in a future version of
MATLAB
% handles    structure with handles and user data (see GUIDATA)


% Hints: get(hObject,'String') returns contents of edit_slip as
text
%        str2double(get(hObject,'String')) returns contents of
edit_slip as a double
```

```
% --- Executes during object creation, after setting all proper-
ties.
function edit_slip_CreateFcn(hObject, eventdata, handles)
% hObject    handle to edit_slip (see GCBO)
% eventdata  reserved - to be defined in a future version of
MATLAB
% handles    empty - handles not created until after all Cre-
ateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end



function edit_Pm_Callback(hObject, eventdata, handles)
% hObject    handle to edit_Pm (see GCBO)
% eventdata  reserved - to be defined in a future version of
MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of edit_Pm as
text
%        str2double(get(hObject,'String')) returns contents of
edit_Pm as a double


% --- Executes during object creation, after setting all proper-
ties.
function edit_Pm_CreateFcn(hObject, eventdata, handles)
% hObject    handle to edit_Pm (see GCBO)
% eventdata  reserved - to be defined in a future version of
MATLAB
% handles    empty - handles not created until after all Cre-
ateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end
```

APPENDIX C

INSTALLATION INSTRUCTIONS FOR STAND ALONE GUI

File: ‘Installation instructions.txt’

This file is provided to the user along with the stand alone executable file of the DFIG GUI. It enlists the step by step procedure to install the software and use the interface on any Windows based operating system without the need of MATLAB. Its content is quoted as follows:

Please follow steps 1 and 2 to access the GUI on Windows based computer systems. For systems having MATLAB and its toolbox 'MATLAB Compiler' installed on them, skip directly to step 5 after step 2. Else follow all the steps:

Step 1:
Download the file 'DFIG_GUI' in a new folder.

Step 2:
Double click on the file and click 'Run'.
The file would get decompressed and following files get extracted:
- DFIG_GUI_pkg.exe
- MCRInstaller.exe
- Windows batch file 'install.bat' (Do not worry if this file is not visible. This may happen if computer settings are in hidden view mode.)
- A 'readme' file. (User is requested to ignore the file at this moment.)

Step 3:
After the extraction of the files (listed in step 2) is over, MCRInstaller execution would automatically commence. Else, double click on 'MCRInstaller.exe'. Window screen pops up to select language. Next click 'Install'. Next allow the permission to install.

Step 4:
a) 'MATLAB Compiler Runtime 7.15- InstallShield Wizard' screen appears. Click Next.
b) 'Customer Information' screen appears. Enter user information and click Next.
c) 'Destination Folder' screen appears. Choose any desired folder location and click Next. It is recommended to let MATLAB choose and install at the location of its choice.

d) Click 'Install'. Installation of MATLAB MCR begins. Allow permission to install. The installation would take some time.
e) When MATLAB MCR installs, click 'Finish'.
If the error "This installation package is not supported by this processor type. Contact product vendor." appears, the GUI cannot be accessed on the computer.

Step 5:
Double click on the file 'DFIG_GUI_pkg.exe' that was extracted in step 2. If any error related to some missing '.dll' file is displayed, refer to step 6. Else the GUI screen titled 'Total_model' must appear. For best screen alignment, set the screen display to 100% and screen resolution to the maximum value.

Step 6:
If the error similar to "mclcmcr.dll not found" appears, follow the steps 6(a)-6(e):
6(a): Right click on 'Computer'. Go to 'Properties'>>Advanced system settings>>Environment variables
6(b): Scroll on 'System variables' and look for 'path'
6(c): Select 'path' and click 'edit'. 'Edit system variable' dialogue box appears
6(d): In the 'Variable value field', scroll towards the end. Place a semicolon and paste the folder path (example... 'C:\Users\Computer_name\Desktop') of the folder into which the original file was downloaded in step 1.
6(e): Press OK.

Repeat step 5. The file 'DFIG_GUI_pkg.exe' must run and the screen titled 'Total_model' would appear.