CHAPTER 1

INTRODUCTION

1.1 GENERAL

Renewable energy sources play a pivotal role in the improvement of the country. Renewable energy sources are important alternative energy sources. Rapid industrialization and application of technology in the industrial and agricultural sector has prompted the demand for power. Renewable energy sources are very useful to manage the power in the demand side. In the modern electrical generation systems, renewable energy sources are getting importance to produce high quality green electricity and the technology development to produce power from renewable energy sources are increasing very quickly. Wind energy is the one of the prominent renewable energy source.

Wind is a freely available resource for power generation. Conversion of power from wind is a rapidly developing area. The running cost for converting renewable energy into power is negligible, compared to conventional power plant and the value of fuel saving is very high. Also extraction of power from wind is cheaper than solar energy system, in the large wind farms.

As far as wind power is concerned and when production curtailment is foreseen, it will be necessary to develop combined generation/storage solutions, where the electrical wind power production curtailed for the network could be stored (producing for instance hydrogen or
pumping water to upper level reservoirs) and later injected in the system during periods of low wind speeds. Naturally, such capabilities need to be remunerated as reserve services (Pecas Lopes et al. 2007).

Due to the variable wind speed, the generated power of the wind turbine is fluctuated. The power fluctuations are occurred for the interaction of wind turbulence with the complex turbine dynamics. In case of the low wind fluctuations, the wind turbine regulation accomplishes its target and the wind turbine dynamics are negligible. Besides, for the high wind fluctuations, the wind turbine interrelates with the structural and drive train vibrations. The complexities of the wind turbine control, drive-train vibrations, and nonlinearities of the generator power converters influence the output power fluctuations significantly (Howlader et al. 2013).

Among the several renewable sources, wind energy conversion system (WECS) is the rapidly growing source of the energy, which is considered as the backbone of renewable energy and the smart grid. Wind velocity is a fluctuating resource and the generated power of wind turbine is cubic proportional to the wind speed. Therefore, output power of the wind turbine is fluctuated. In this paper, an Electric Double Layer Capacitor (EDLC) energy storage is applied to generate a smooth line power for the smart grid system. The line power can be smoothed by the EDLC system extensively. In addition, a stable operation can be performed at the fault condition through the chopper circuit approaches. From the simulation results, Howlader et al. (2014) verifies the effectiveness of this method.

Mansour Mohseni et al. (2011) presents a new analysis into the impacts of various symmetrical and asymmetrical voltage sags on doubly fed induction generator (DFIG)-based wind turbines. Fault ride through requirements are usually defined by the grid codes at the point of common coupling (PCC) of wind farms to the power network. However, depending on
the network characteristics and constraints, the voltage sag conditions
tolerated at the wind generator terminals can be significantly different
from the conditions at the PCC. Therefore, it is very important to identify the
voltage sags that can practically affect the operation of wind generators.

The wind farms consist of the doubly fed induction generators
(DFIGs) are very sensitive to the fault condition since DFIGs are directly
connected to the power grid. Therefore, the wind farms are required to the
LVRT capability. There are several approaches to apply for the LVRT
capability of the DFIG wind turbine. A bypass resister has been used to
enhance the LVRT capability (Rahimi & Parniani 2010).

Chandrasekaran (2014) described the Vector Proportional Integral
(VPI) Controller for the DFIG wind turbine and of its power converter and to
the ability to protect itself without disconnection during grid faults. It
provides also an overview on the interaction between variable speed
DFIG wind turbines and the power system subjected to disturbances, such as
short circuit faults. The dynamic model of DFIG wind turbine includes
models for both mechanical components as well as for all electrical
components, controllers and for the protection device of DFIG necessary
during grid faults. The dynamic behavior of DFIG wind turbines during
grid faults is simulated and assessed by using a transmission power
system generic model developed and delivered by Transmission System
Operator in the power system simulation toolbox Digsilent, Matlab/Simulink.

Induction machines are mass-produced and they have a proven
track record of robust performance in a wide range of industrial applications,
though outside of the renewable energy industry it is not usual to use them as
generators. One drawback to using induction machines as generators is that,
because they rely on the grid to provide their field excitation, they tend to
weaken the grid. Unfortunately, the best wind resources are often in more
remote locations, which have weak grids and this has led to grid compliance issues. In the early days of the wind industry, this was of little importance, but as wind turbines start to achieve significant penetration in the electricity generation market, their influence on power quality is becoming greater and operators have started to require wind farms to meet stringent grid compliance criteria. Consequently low voltage ride through (LVRT) and high voltage ride through (HVRT) have posed challenging control problems for the wind industry, and this is an area where there has been considerable research effort over the last decade (Matthew W. G. Whittle 2013).

1.2 POTENTIAL OF WIND ENERGY IN INDIA

Wind energy is the key development area to meet the power demand of the country. India is one of the leading countries in the world for natural resource availability. The high-speed wind is one among them. Rural electrification is one of the key issues associated with the Indian wind energy development. Many researches are still going on to improve the generation of power from wind. Commercialization of wind energy depends mainly on technological development and making it economically viable. It is specially to be noted that in all wind speeds, wind turbine will not work. Hence, it is required to do the feasibility study about the particular place to install the wind turbine. Depending on the wind speed, the power generation capacity also varies in a particular place.

In India, Tamil Nadu, Gujarat, Karnataka, Andhra Pradesh, Rajasthan and a few other places are identified as suitable for wind power generation. Energy Alternatives India given the details of wind projects installed in India as on 31.03.2013, it is cited in Table 1.1 (http://www.eai.in/ref/ae/win/policies.html). In Tamil Nadu, Muppandal is identified as a highly windy area. The Muppandal region in Tamil Nadu has the distinction of having one of the largest concentrations of wind turbines at
a single location with installed capacity of more than 1000 MW. Wind farms are spread along the national highway from Muppandal to Kanyakumari, at the confluence of the Bay of Bengal, Arabian Sea and the Indian Ocean. The Aralvaimozhi mountain pass intensifies the winds of South-West monsoon, which blows from May to September and reaches an average speed of 12–13 m/s. The annual average wind speed in this area is 5–6 m/s (Carolin Mabel & Fernandez 2008).

<table>
<thead>
<tr>
<th>Name of State</th>
<th>Gross potential in MW</th>
<th>Installed capacity in MW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Andra Pradesh</td>
<td>8968</td>
<td>200.2</td>
</tr>
<tr>
<td>Gujarat</td>
<td>10645</td>
<td>2175.6</td>
</tr>
<tr>
<td>Karnataka</td>
<td>11531</td>
<td>1730.1</td>
</tr>
<tr>
<td>Kerala</td>
<td>1171</td>
<td>32.8</td>
</tr>
<tr>
<td>Madhya Pradesh</td>
<td>1019</td>
<td>275.5</td>
</tr>
<tr>
<td>Maharashtra</td>
<td>4584</td>
<td>2310.7</td>
</tr>
<tr>
<td>Orissa</td>
<td>255</td>
<td>-</td>
</tr>
<tr>
<td>Rajasthan</td>
<td>4858</td>
<td>1524.7</td>
</tr>
<tr>
<td>Tamil Nadu</td>
<td>5530</td>
<td>5904.4</td>
</tr>
<tr>
<td>Others</td>
<td>-</td>
<td>1.60</td>
</tr>
<tr>
<td>Total</td>
<td>48561</td>
<td>14158</td>
</tr>
</tbody>
</table>

The Government of India is encouraging the applications of wind energy in India by giving subsidies. The Ministry of New and Renewable Energy (MNRE) has proposed to reintroduce tax depreciation benefits for wind farm owners and increase an alternate generation based subsidy
The harnessing of wind energy is the highest in Tamil Nadu with an installed capacity of 7055.475 MW, contributing 40% of the country’s total installed capacity as on 30.06.2012 (Energy department 2012). Table 1.2 shows the favorable wind flow locations in Tamil Nadu (Comprehensive Tariff Order on Wind Energy 2012).

Table 1.2 Favorable wind flow locations in Tamil Nadu

<table>
<thead>
<tr>
<th>Name of the Places/Districts</th>
<th>Areas</th>
</tr>
</thead>
<tbody>
<tr>
<td>Palghat</td>
<td>Coimbatore, Erode and Dindigul</td>
</tr>
<tr>
<td>Shencottah</td>
<td>Tirunelveli and Tuticorin</td>
</tr>
<tr>
<td>Aralvoimozhi</td>
<td>Kanyakumari, Radhapuram and Muppadal</td>
</tr>
<tr>
<td>Theni Districts</td>
<td>Theni, Cumbum and Andippatty</td>
</tr>
<tr>
<td>Sea coast</td>
<td>Uvari, Tuticorin, Rameshwaram, Poompuhar and Ennore</td>
</tr>
</tbody>
</table>

1.3 PROBLEMS ASSOCIATED WITH TRANSMISSION OF WIND POWER

The grid integration of wind farms has several problems. One of the main problems is fault ride through and the fluctuation. Voltage Sag Ride Through (VSRT) is a critical phenomenon in wind power generation system. The main causes for the voltage sag are error in system configuration, problems in grid connections, failure in protective devices, lightning and different types of faults.

According to the present requirements, wind turbines should remain connected and actively support the grid during faults. This
requirement became essential because the contribution of power generated by a wind farm can be significant and it was at risk of being lost as in the past practices. Earlier, wind turbines were simply disconnected from the grid during faulty condition and reconnected when the fault is cleared and the voltage returned to normal. This method causes financial losses and more manpower requirement.

With the increase in power transmission distance, long AC cables will produce large amount of capacitive reactive power. It will reduce the cable transmission capacity accordingly. The capacitive power of the cable needs to be balanced by inductive reactive power in order to avoid creating problems with regard to high voltage and cable derating. Therefore, large reactive power compensation is required (Lie Xu et al 2006). Mohammadi et al (2014) says that during the grid faults, by injecting the rotor currents against the negative sequence and natural components of the stator flux, rotor over voltages are decreased and stator flux damping is increased.

1.4 REVIEW OF DFIG

The first wind turbine was developed using squirrel cage machine in the late 1980s with a rated power of less than 100kW. The modern wind turbines with DFIG have a rated power up to 5.0MW. These turbines are constructed for very high efficiency, performance and very low maintenance. Also it is suitable for next generation offshore application. As a variable speed generator, it is one-step ahead to increase the efficiency of wind energy conversion. Normally, induction generators are very sensitive to sudden changes in voltage. The DFIG became more and more common in wind power generation.

Now a days more than 70% of the wind turbines produced are equipped with this type of induction machine. Usually the voltage source
converter is connected with the machine side to the wound rotor via collector rings. The grid side converter and the stator of the induction machine are directly connected to the grid. A few years ago, a transformer was to be placed between converter and the grid to adapt the voltages. It is not necessary anymore, because it is possible to increase the dimension of the rotor windings even in the area of low rotor frequencies (synchronous operating point). It is high enough to feed into the grid only by using an inductance.

The voltage source converter, which deals with approximately 30% of the whole generator power, is divided into two separate structures, which are controlling the machine side and the grid side independently. The grid side of the converter is responsible for the inter circuit voltage and has to control the power flow from or to the grid. This is done by controlling the active power axis of the grid converter in either direction dependent of the DC inter circuit voltage (Stefan Soter & Ralf Wegener 2007).

1.4.1 Configuration for shunt connected DFIG

Static Schribious Drive Structure (SSDS) is commonly used in DFIG windmill applications. Such a configuration is attractive in large power applications with limited speed range of operation. The rotor currents are controlled at any desired phase, frequency and magnitude to control the active and reactive powers of the machine independently. The system under consideration is shunt connected, the stator is directly connected to the constant frequency three-phase grid and the rotor is supplied by two back-to-back three-phase voltage source converters and inverters with a common DC link, as shown in the Figure 1.1.
Figure 1.1 General configuration for shunt connected DFIG wind turbine system

Performance of DFIG depends on the factors like wound rotor, two converters (including passive components), control strategy and scheme of the implementation specifically for Fault Ride Through (FRT). However, the DFIG is inherently more controllable than a synchronous generator. DFIG wind farms are very popular due to its separate controllability in rotor side and grid side. DFIG offers a vast reduction in converter size.

DFIG is the most employed generator for wind turbines due to advantages given below (Jamal A. Baroudi et al 2007).

Advantages

1. Reduced converter cost. Converter rating is typically 25% of total system power.
2. Improved efficiency due to reduced losses in the power electronic converter.

3. Suitable for high power applications including recent advances in offshore installation.

4. Allows converter to generate or absorb reactive power.

5. Control may be applied at a lower cost due to reduced converter power rating and it is rated for only 30% of the total power of the generator.

6. The EMC filters are cheaper because of the lower power-rating converter.

7. Reduced volt-ampere rating of the power converter is used to control the rotor current.

8. Robustness and stable response of this machine face external disturbance.

Disadvantages

1. Increased control complexity due to increased number of switches in converter.

2. Stator winding is directly connected to the grid and susceptible to grid disturbances, especially grid faults. The voltage sag at the stator terminals due to the grid faults cause the rotor over currents, DC-link over voltage, and torque oscillations that could lead to destruction of the rotor side converter (RSC), DC-link capacitor and mechanical parts.

3. The wound rotor induction machine is not as rugged as the squirrel cage machine. The necessity of collector rings
increases the capital cost and the need for periodic slip ring maintenance. It is also slightly heavier than the squirrel cage induction generator of same rating.

4. Increased slip ring sensitivity and maintenance in offshore installations.

5. It is not a direct drive and therefore requires a maintenance intensive gearbox for connecting it to wind turbine.

1.5 OBJECTIVE OF THE RESEARCH

The present work aims at the development of rotor side current control strategies using adaptive internal model controllers for grid connected DFIG, with particular reference to wind power generation. The general objective of this research is to investigate the improvements required in the Indian grid code, performance of the adaptive internal model controller with adjustment mechanisms used to support the generator and to minimize the VSRT problems.

1.6 BASIC CONCEPT OF ROTOR CURRENT CONTROL

Rotor current control is mostly employed in DFIG wind farms because it is more efficient to improve the performance during fault (Boldea 2006). The main task of the machine side converter is to control the rotor current. This is done by having an inner current control loop that controls the rotor current. The field orientation could, for example, be aligned either with the stator flux of the DFIG or with the grid flux. In both reference frames, the ‘q’ component of the rotor current largely determines the produced torque while the ‘d’ component can be used to control, for instance, the reactive power at the stator terminals. It is common to control the rotor current with either stator-flux orientation or grid-flux orientation. The choice
of current control method is of greater importance if the bandwidth of the current control loop is low (Andreas Peterson 2005).

The current is kept within limit by limiting the rate of change of control voltage with time. The rotor current variations reflect the stator current variation. Hence, it is possible to control stator active and reactive power using rotor current control. The active power supplied to the grid by the rotor is 25% approximately. Further small error in fast current dynamics causes instability in the system. Rajib Datta (2000) had given remarkable explanation about rotor side control and concluded that rotor side control is economically competitive. The shaft and gear are connected at one end of the rotor and are used to produce torque and to do the useful work. The schematic block diagram of rotor side controller structure is shown in Figure 1.2.

![Figure 1.2 Schematic of rotor side controller structure](image-url)
The WECS’ electric power generation depends on wind speed, the turbine’s aerodynamics, and the machine’s operating point. Slip power flows from and into the rotor circuit through a back-to-back converter, which comprises a rotor side converter (RSC) that controls the machine and a grid side converter (GSC) for dc-link regulation and power factor control at the point of common coupling (PCC)(Etienne Tremblay et al 2011).

1.7 PERFORMANCE IMPROVEMENTS

Normally, FACTS devices like SVC, STATCOM, Storage devices and superconducting technology are used to improve the performance of the VSRT. In this thesis, much emphasis is given to the performance of the adaptive internal model controller with model free and model reference approach. Further, the influence of adjustment mechanism used in the adaptive internal model controller is studied for VSRT Problem. Fixed gain adjustment mechanism with MIT Rule is simulated and the problems associated with the fixed gain adjustment mechanism are rectified with variable gain adjustment mechanism using FUZZY and ANFIS.

1.8 SURVEY OF RELATED LITERATURE AND REVIEW

Marcio Magalhães de Oliveira (2000) says that for small type of disturbance, controller is the main part to handle the problem quickly. Even for 1 min duration over 0.5 cycle, decrease of rms voltage between 0.1 and 0.9 p.u. is commonly known as voltage sag and it is associated with fault.

Controller is another main part of the wind farms to improve the state of art performance (Mai Tuan Dat et al 2007, Poitiers et al 2001). Wind energy conversion is normally nonlinear in nature (Boukhezzar & Siguerdidjane 2005). Mullane Alan et al (2005) says that nonlinear controller design results in considerable improvement in the ‘ride-through
faults capability’ of wind turbines. Boukhezzar & Siguerdidjane (2010) have also confirmed that nonlinear control strategies bring more performance improvements in the exploitation of wind energy conversion systems.

When the parameter variation of controlled plant is small, good control effort can be obtained. On the other hand, as the plant model and actual plant mismatch seriously, control quality of system gets poor. So adaptive control is added to reduce mismatch of plant model and actual plant and improve the adaptability of system (Xuejuan Shao et al 2005). A celebrated property is the fact that the adaptive algorithm does not formally require ‘any prior assumption on the plant’ and the plant can be of any order, stable or unstable, non-minimum phase, linear or nonlinear (Brian D.O. Anderson & Arvin Dehghani 2006).

Many control techniques are followed to overcome VSRT problem. Some of the control technique available in literature is summarized below.

1.8.1 PI Controller based VSRT


PI Control used for rotor voltage control is given by Baike Shen & Boon Teck Ooi 2007, Gabriele Michalke et al 2007 and Rahim & Habiballah 2011. PI Controller used for grid side control is given by Anca D. Hansen & Gabriele Michalke 2007c and Hee-Sang Ko 2008.


1.8.2 Vector control based VSRT


1.8.3 Internal Model Controller based VSRT

Internal Model Controller (IMC), a robust controller was proposed in 1982. Internal model controller is mostly used in current control; papers by Andreas Peterson 2005, Johan Morren & Sjoerd WH de Haan 2005, HU Jia-bing et al 2006, Yuan Xufeng et al 2010, Al-Chalabi et al 2009 and David Campos-Gaona et al 2013 describe the internal model controller for voltage sag ride through.

1.8.4 Neural Network Controller based VSRT


1.8.5 Sliding Mode Control based VSRT

Sliding Mode Control by Orlando Soares et al 2010 and Galindo et al 2006, sliding mode controller for the active and reactive power of a grid-connected variable-speed WECS is based on a DFIG has been designed in this work given by Evangelista et al 2012 and Youcef Bekakra & Djilani Ben attous 2011, sliding mode controller used for direct power control is presented by Mohammad Verij Kazem et al (2012).
1.8.6 Other controllers in VSRT


1.8.7 Adaptive controllers based VSRT

Hee-Sang Ko et al (2008) says that adaptive controller allows fast convergence to a simple linear dynamic behavior, even in the presence of parameter changes and model uncertainties. The resulting adaptive controller is simple enough to be synthesized using fixed point signal processors, by Miguel Angel Mayosky et al (1999). Song & Dhinakaran (2000) used adaptive algorithm in variable speed generator. Mullane et al (2001) use adaptive controller in wind turbines. In this paper field oriented controller for the induction machine is described, and an adaptation law is chosen to provide an estimate of the uncertain and time varying turbine torque.

Zhanfeng Song et al (2012) present an adaptive disturbance rejection controller using current control method. A novel adaptive current controller for DFIG-based wind turbines is introduced in this paper. The attractiveness of the proposed strategy results from its ability to actively estimate and actively compensate for the plant dynamics and external disturbances in real time. Thus, the control strategy can successfully drive the rotor current to track the reference value, ensuring that the performance degradation caused by grid disturbances, cross-coupling terms and parameter uncertainties can be successfully suppressed. Besides, the two-parameter
tuning feature makes the control strategy practical and easy to implement in commercial wind turbines.

1.8.8 Converters in VSRT

Performance improvement of wind energy conversion system using matrix converter is described by Ghedami & Aouzellag (2010). Impact of FACTS controllers on the stability of power systems connected with wind is presented by Senthil Kumar & Gokulakrishnan (2011).

1.9 STRUCTURE OF THE THESIS

This thesis has been organized into six chapters. The present chapter introduces very briefly, the basics of rotor current controller, review of doubly fed induction generator, and some of the technical challenges in the interconnection of grid. It presents the relevant state of art survey and sets the aim of the work carried out in the thesis.

In Chapter 2 the Indian and International grid code requirements are reviewed. The improvements required in the Indian grid codes are also presented. In addition, some of the possible solutions are mentioned and power quality issues are discussed.

In Chapter 3 the modeling of the doubly fed induction generator is dealt with. Review of wind speed and system Configurations are also given.

In Chapter 4 the internal model controller and adaptive internal model controllers for voltage sag ride through and grid fault response of the conventional DFIG system have been presented through simulations.
In Chapter 5 the performance of direct model reference adaptive internal model controllers for voltage sag ride through during grid fault response of DFIG system has been presented through simulations.

In Chapter 6 conclusion of the thesis with suggestions for further works are given.