A DOUBLY-FED INDUCTION GENERATOR AND ENERGY STORAGE SYSTEM FOR WIND POWER APPLICATIONS

by

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Abstract

Wind generation has become the most important alternate energy source and has experienced increased growth in Europe during the past decade while more recently, the same trends have been exhibited in North America. Although it has great potential as an alternative to less environmentally friendly energy sources, there are various technical challenges that cause wind to be regarded negatively by many utilities. Others are hesitant to accept its widespread implementation, particularly when the penetration of wind in a given area is high.

The problems of wind are associated with dependence on the local environmental conditions. Variability of the wind speed causes oscillations in the output power of the wind generators, resulting in a variety of consequences within the power system and in its operation. Although some power control can be enacted using mechanical means, this usually implies a decrease in overall power capture and during calm conditions, these solutions can no longer offer any improvement over the situation. For these reasons, added to the fact that reactive power and weak system interconnection are often relevant concerns, wind parks are often susceptible to voltage and transient instability problems.

This work presents the addition of an energy storage system to a wind turbine design. The control philosophy of the conventional generator and its representation are discussed initially, followed by a modification of the turbine design to incorporate the storage system. The conventional and energy storage designs are compared on a single machine basis as well as on the system level.

Various advantages are exhibited for the wind turbine with energy storage. Firstly, the generator is capable of accurately controlling the output power of the generator and inevitably of the wind park. Reactive power requirements are also reduced as a result of a more stable voltage at the point of interconnection. In addition, improved transient performance is exhibited for various local disturbances.

Résumé

Au cours des dix dernières années, les éoliennes sont devenues la méthode la plus importante de génération d'énergie électrique alternative en Europe et, plus récemment, en Amérique du Nord. Bien que la production d'électricité par le vent ait beaucoup d'avantages au niveau de l'impact sur l'environnement, il existe plusieurs inconvénients techniques à considérer. Plusieurs compagnies d'électricité hésitent donc à intégrer cette forme d'électricité, surtout dans certaines régions où il y a une forte concentration d'éoliennes.

Les problèmes associés avec la production d'électricité utilisant le vent sont reliés aux conditions environnementales, notamment la vitesse du vent. Les fluctuations de la vitesse du vent causent des oscillations dans l'énergie produite par les génératrices, ce qui peut avoir des impacts négatifs sur le réseau électrique. Bien qu'il existe des méthodes mécaniques pour limiter l'impact de cette variation, leur utilisation entraîne une réduction de l'énergie totale fournie. De plus, pendant les périodes généralement calmes, ces solutions ne s'avèrent pas efficaces. Ajoutés aux demandes de puissance réactives et au fait que souvent l'interconnexion est faite à un système faible, les parcs d'éoliennes ont souvent des problèmes d'instabilité transitoire et de contrôle de tension.

Ce mémoire présente l'addition d'un système de stockage d'énergie à une éolienne. La théorie du contrôle d'une génératrice conventionnelle et sa représentation sont discutées, suivie par la modification pour l'incorporation du système de stockage d'énergie. Basés sur les deux topologies, les performances des deux systèmes sont comparées au niveau d'une seule machine et au niveau de parc d'éoliennes.

Les caractéristiques et avantages de l'éolienne associée à un stockage d'énergie sont présentes. La génératrice peut précisément contrôler sa puissance réelle et les demandes de puissance réactive sont réduites grâce à un contrôle de la tension au point de raccordement. De plus, le comportement performance transitoire suite à des défauts sur le réseau est nettement améliorée.

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List of Symbols

C : Capacitance
C_{SC} : Supercapacitor capacitance
E : Stored energy
E_{ESS} : Energy storage system stored energy
E_{max} : Maximum storage capability of energy storage system
E_{min} : Minimum storage capability of energy storage system
i_{band} : Hysteresis band for hysteresis current control
I_{conv} : Supply side current vector for DFIG system
$i_{conv,q}$: Reactive component of supply side converter
I_r : Rotor side current vector for DFIG system
i_{ref} : Reference current waveform
i_{rq} : Reactive component of rotor current
I_s : Stator side current vector for DFIG system
I_{SMES} : SMES dc current
J : Moment of inertia of machine
K : Reactive compensation constant
L_{SMES} : SMES equivalent inductance
m_a : Modulation index
n : Transformer turns ratio
n_{max} : Maximum transformer turns ratio
n_{min} : Minimum transformer turns ratio
P_{conv} : Supply side converter power delivered to system
$P_{conv,ref}$: Reference supply side converter power delivered to system
P_e : Electromechanical power of machine
pf : Power factor
P_{grid} : Power delivered to the grid from the DFIG
P_m : Mechanical input power to the machine
P_{rated} : Rated power of the machine
P_s : Stator power delivered to the grid
$P_{s,ref}$: Reference stator power delivered to the grid
Q_{conv} : Reactive power delivered by the supply side converter
$Q_{conv,ref}$: Reference reactive power delivered by the supply side converter
Q_{grid} : Reactive power delivered to the grid from the DFIG
$Q_{grid,ref}$: Reference reactive power delivered to the grid from the DFIG
Q_s : Reactive power delivered to the grid
$Q_{s,ref}$: Reference reactive power delivered to the grid
R_r : Rotor resistance of DFIG as seen from the stator side
R_s : Stator resistance of DFIG as seen from the stator side
S_{conv} : Reactive power supplied from supply side converter
s_{max} : Magnitude of maximum slip
S_r : Reactive power supplied from rotor side converter
S_{rating} : Converter kVA rating
T_e : Electromagnetic torque

T_m : Mechanical input torque
V_{dc} : Dc voltage
V_{ess} : Energy storage system voltage
$V_{ess,max}$: Maximum energy storage system voltage
$V_{ess,min}$: Minimum energy storage system voltage
V_{LL} : Line-to-line voltage
V_m : Voltage vector across DFIG magnetizing branch
$V_{r,ind}$: Induced voltage from rotor side
V_{SC} : Supercapacitor dc voltage
v_{wind} : Wind velocity
X_m : Magnetizing reactance of DFIG
X_r : Rotor reactance of DFIG as seen from the stator side
X_s : Stator reactance of DFIG as seen from the stator side
β : Wind turbine blade pitch angle
δ_r : Angle of rotor side voltage vector relative to stator side voltage vector, both expressed on the synchronously rotating frame
θ_m : Mechanical rotor angle
θ_r : Electrical rotor angle
μ : Angle of stator voltage vector as obtained from PLL
ρ : air density
ω_m : Mechanical rotor angular velocity
$\omega_{m,ref}$: Reference mechanical rotor angular velocity
ω_r : Electrical rotor angular velocity
ω_s : Angular velocity of grid voltage vector
ω_{syn} : Synchronous angular velocity

List of Abbreviations

Ac	Alternating current
BESS	Battery energy storage system
CHP	Combined heat and power
Dc	Direct current
DFIG	Doubly-fed induction generator
DFIG-ESS	Doubly-fed induction generator and energy storage system
DG	Distributed generation
EMPT-RV	Electromagnetic Transient Program – Restructured Version
ESS	Energy storage system
FACTS	Flexible AC transmission systems
HV	High voltage
HVDC	High voltage DC transmission
IG	Induction generator
IPP	Independent power producer
KVA	Kilo volt ampere
MV	Medium voltage
PCC	Point of common coupling
PI	Proportional integral
PLL	Phase locked loop
PMSM	Permanent magnet synchronous machine
PWM	Pulse width modulation
PV	Photovoltaic
SMES	Superconducting magnetic energy storage system
STATCOM	Static synchronous compensator
SVC	Static Var compensator
UPS	Uninterruptible power supply
WECS	Wind energy conversion system
VSC	Voltage source converter

Chapter 1: Wind Energy Systems

1.1 Introduction

During the past decade and a half, wind power has received enormous attention and has been identified as the most promising of alternative energy sources. Fueled by the search for environmentally friendly sources of electrical power and the need for reliable and large capacity forms of renewable energy, wind energy has doubled in global capacity every three years since 1990 [1]. The financial gains associated with the low price of coal as a means of cheap generation to supplement either hydro or nuclear has been overshadowed by public pressure to limit greenhouse gas production. Wind installations have not only become more competitive with new coal plants in terms of cost but now also promise similar reliability and ancillary services which until recently was not possible.

However, there still exist various shortcomings associated with wind energy which makes energy producers hesitate to invest, despite its merits. Not only does it fail to offer the efficiency of more conventional forms of generation but its energy production is still closely coupled to the environmental conditions, thereby making it inherently stochastic by nature. This becomes one of the greatest barriers to its high penetration in the conventional power system wherein the generation must always meet the demand, and thus strictly requires predictable, dispatchable forms of generation.

Wind and most other renewables are for the most part considered to be non-dispatchable [2]. Particularly when the wind generator is a distributed generator (DG), i.e. a single wind generator connected to the grid and usually operated by an independent power producer (IPP), the dependence of the output power on the wind speed is high. In the case of a wind park, the net output power tends to have smaller oscillations as a result of the averaging effect across all of the generators. As well, supervisory controls and wind forecasting can help to reduce the power fluctuations [3], [4]. Therefore, the issue of power regulation is of even greater importance in small wind parks and for DGs.

The introduction of DGs into the power system, which at the moment is still relatively limited, has given way to a new form of grid, where the power consumed at the loads may be produced from a number of different sources, power producers, and at various locations. This sets the framework for a possible grid of the future with a more elaborate and variable structure and which will require the corresponding standards for interconnection, protection, and controls in order to ensure its smooth and stable operation.

The recent changes in the structure of the grid have been facilitated by deregulation of the power system, the focus on these new forms of generation, and the interconnection of previously isolated power systems. Although ratifications to the traditional structure and ideology of the power system are underway, new generation must still adhere to constraints set by the operators of the transmission and power delivery systems. Therefore, in order to continue to experience its rapid growth worldwide, wind energy conversion systems must strive to increase their dispatchability and their ability to provide ancillary services.

1.2 Wind Power

Wind power is perhaps the field that has experienced the most attention within the power industry during the past five years. The prime factor that has influenced its growth is public pressure to reduce the harmful emissions, which are typically associated with generators utilizing coal as their fuel source. Secondly, the availability of other forms of generation, namely hydro and nuclear has determined the extent to which wind and other alternative energy sources have been exercised. This perhaps explains the relative lack of interest in wind in Québec, other Canadian provinces, and the United States where hydro and nuclear are abundant. However, the growth of wind reflects the public opinion, the resulting political movements and government incentives to support its development and this has begun to push its growth in North America as well.

1.2.1 Growth of Wind Power

European countries have led the way in wind power utilization and the majority of the expertise in this field has been developed through experience in wind parks in the Scandinavian countries, the UK, France, Spain, and Greece [5]-[12]. Only recently has wind power been developed substantially in North America and in other parts of the world. However, this trend is likely to increase as political reform takes into account greenhouse gases and technologies improve. Wind turbines presently have capacities of up to 3 MW (with experimental versions up to 4.5 MW) and this could reach upwards of 5 MW in the next couple of years, while turbines rated at 10 MW are expected by 2020 [2].

Various sites have been identified as having good wind energy potential including both on- and off-shore locations and the wind installations can be subjected to very different system characteristics. Previously, wind energy has been considered only for distributed generators, meant only to operate in isolated systems or to supplement the demands of a specific load. Distributed generators for the most part are assumed to have little effect on the system as a whole and in North America, *IEEE* standards are usually followed for their interconnection and protection practices [13]. However, with the development of large capacity machines and a better understanding of high penetration of wind on system dynamics [14],[15],[16], wind parks can now offer similar capacities as some conventional generation plants. The consequence is that their effect on the grid is greater and as a result they must aid in support and control of the system.

1.2.2 Wind Energy as an Alternate Energy Source

The greatest advantage of wind is that it is an environmentally friendly form of energy production. Without this characteristic, its growth would be significantly hindered since government incentives have helped to make it competitive in Europe and in North America [1],[2]. Compared with other alternate energy sources such as photovoltaics (PV), and combined heat and power (CHP) units, wind is also non-dispatchable, however it has the advantage of high capacity and is more well suited for large installations.

In addition, wind may serve as one of the larger capacity forms of DG while it may be supplemented by more controllable forms of DG either in the form of PV or diesel.

Modeling issues for wind and other forms of DG have been addressed [16], [17] and attempts are now being made to look at the potential of DG to benefit the system. Photovoltaics and small CHP will likely required wind and other larger capacity forms of DG like small hydropower (which are also currently more cost effective) in order to make the case for DG as a means of replacing transmission upgrades a realistic solution.

1.2.3 Technical Challenges

As the penetration of wind increases, the way in which it interacts with the power system becomes increasingly important. DGs are typically required to trip during undervoltages and other system disturbances and are not required to aid in voltage or frequency regulation [13]. However, for high penetrations of DG, these requirements are likely unreasonable and in some cases may even be detrimental to the stability of the system. For instance, without voltage regulation controls, the voltage may often fluctuate outside the acceptable operating range [2], and fast tripping of wind generators following undervoltages have been shown to lead to voltage collapse [16], suggesting the need for low-voltage ride through capability.

The problem of voltage regulation and reactive power control is even greater in the case of a weak connection. The large source impedance results in significant fluctuations in the voltage at the point of common coupling (PCC) due to changes in power flows and in this case reactive compensation has been shown to be crucial [18]. Propagation of harmonics in the system is relatively unimportant compared with voltage stability issues. The ability to smooth the power oscillations will result in a more stable terminal voltage, however, reactive compensation would still be a strict requirement, in steady-state but even more importantly during transients.

The response of systems with increased levels of wind energy to various transients has been investigated [15], [16], [19]. Unlike conventional systems, the loss of synchronism is not a concern since the generators are typically all asynchronous, however overspeed and undervoltage protection causes tripping of the turbines, which can often lead to voltage instability or collapse. From these studies, it was shown that wind parks composed of DFIGs typically demonstrate a higher level of stability due to the ability for reactive power compensation and a greater control of the generator speed. The effect of additional energy storage may further improve the DFIGs tolerance to power system disturbances. However, definition of the various protections for this system and an assessment of the system performance under transients are required.

1.2.4 Wind Turbine Technologies

The main types of wind turbines are presented in Fig. 1.1. As mentioned, wind generators differ from conventional generators in that variable speed generators are more commonly used, due to the fact that optimum power capture is obtained at different rotor speeds for different wind speeds. In addition, variable speed operation limits the mechanical stresses on the blades resulting from wind gusts. Thus, the synchronous generator is rarely used when directly coupled since it requires a mechanical means of regulating the speed and lacks the benefits associated with a variable speed wind generator.

Synchronous generators are, however, sometimes implemented and variable speed operation is possible when the generator is connected to the system using a back-to-back voltage source converter (VSC). Permanent magnet synchronous machines (PMSM) are the most common choice and are typically implemented in stand-alone systems. PMSM are often used since no field winding control is necessary and the gear-box can be eliminated, making it low maintenance and therefore ideal for operation in remote locations.

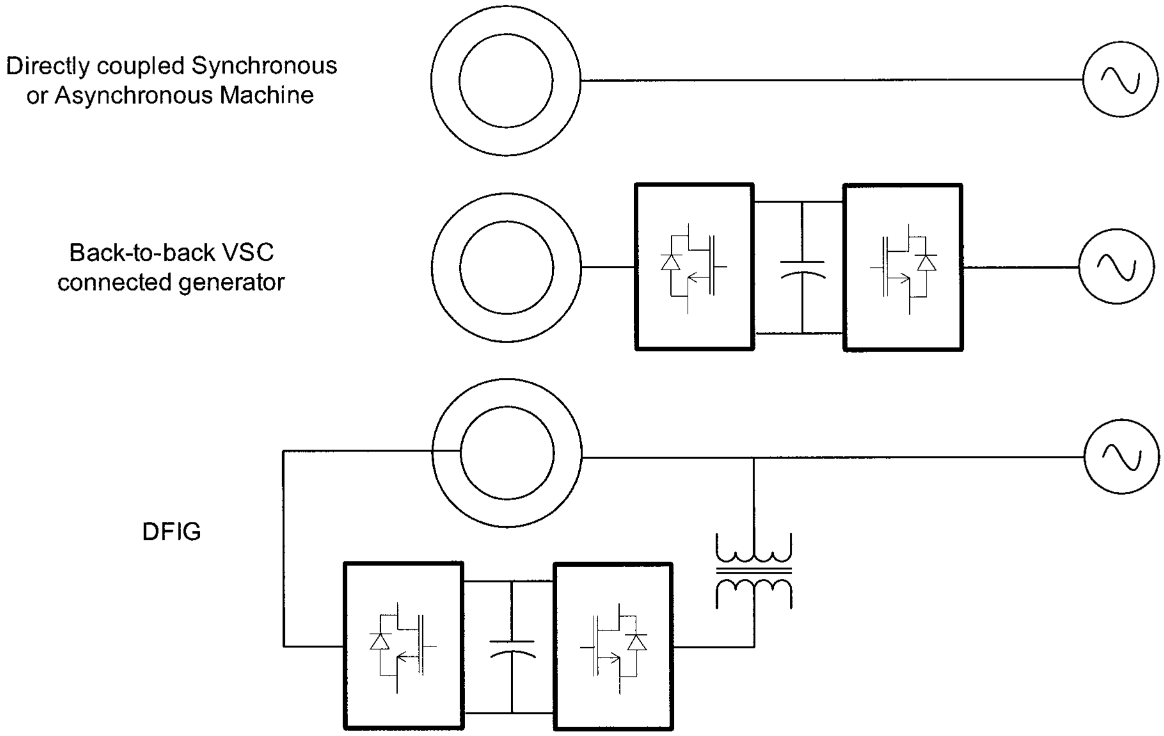


Fig. 1.1 Different wind generator topologies

The advantage with the back-to-back VSC topology is that the generator side converter can control the speed of the generator while the line side converter can adjust the reactive power delivered to the system. Thereby the wind generator system emulates a synchronous machine at the PCC, with the exception that the output power is not completely controllable.

When the wind generator is directly coupled, it is typically a squirrel cage induction machine because it does not need to be synchronized with the system. However, addition of reactive power sources is usually required since the generators consume VArs under all modes of operation, and hence impact the voltage at the PCC, especially during transients.

Finally, the generator may be of the doubly-fed induction machine type, also known as a wound-rotor induction machine, where a back-to-back VSC is connected between the rotor and stator windings. This allows control of the reactive power from both the rotor and supply side converters, with a reduced converter rating. Again the machine speed can be controlled as well which enables peak power tracking or adjustment of the real power output. However, the cost of the machine is greater than the case of a squirrel cage induction machine and therefore, the additional controls come with an additional price.

1.3 Doubly-Fed Induction Generator

The DFIG is currently the most popular machine topology for wind power applications. The majority of large capacity machines (>1 MW) available from manufacturers such as *Vestas* and *General Electric-Wind* are all DFIGs (although some producers such as *Entercon* are favoring PMSM). The power electronic converters enable control over the generator operating characteristics such as speed and reactive power, features which are lacking or limited in squirrel cage induction machine. This allows for variable speed operation for peak power point tracking or output power regulation. In addition, the converter rating is significantly reduced compared with the stator connected converter system.

1.3.1 Advantages of DFIGs

The main reasons that make the DFIG a popular choice for wind power applications include its ability for variable speed operation, reactive power control, and reduced converter ratings. Due to the fact that the rotor side presents voltages, which are at most 20% of the stator side voltage, the minimum kVA rating of the converter is approximately 20% that of the case of a back-to-back converter connected machine. Table 1.1 summarizes the differences between the three main wind generator topologies.

Table 1.1: Comparison of wind generator design characteristics and costs

WECS	*Converter*	*Var control*	*Speed control*	*Overall Cost*
Directly connected	None	None	None/ limited control using pitch angle	Inexpensive
DFIG	30-50% machine rating	Two reactive power sources	Pitch control and converter control	Low converter cost, machine expensive
VSC connected	Full machine rating	Reactive power control	Pitch control and converter control	Machine inexpensive, converter cost high

1.3.2 Power Electronic Converters

The converters that are connected between the rotor and the stator of the machine are typically back-to-back VSC, however a matrix converter could be used alternatively. The advantages compared with the VSC connected machine is that the converter rating is reduced by about factor of between 2 and 5, since the rating is now based upon rotor voltages which are related to the speed range of the machine. The rotor voltages are related to the stator voltages by:

$$|v_r| = s|v_s| \tag{1.1}$$

where the machine slip, s is a measure of the rotor speed relative to synchronous speed, which is given by:

$$s = \frac{n_{syn} - n_r}{n_{syn}} \tag{1.2}$$

The converter rating is then defined by the maximum speed and the maximum stator current and voltage at that speed. The turns ratio which exists across the machine has been assumed to be 1 for simplicity and therefore, the rotor current magnitude is equal to the stator current magnitude. If the upper speed limit is taken to be 1.2 of synchronous speed then the minimum converter rating will be 20% that of the machine's rating. However, for practical purposes a rating of 30-50% might be used taking into account transient operation and the ability to deliver reactive power from the stator.

1.3.3 Power System Interconnection

The DFIG is connected to the medium voltage (MV) level of the power system by a step-up transformer. Since the line side converter typically requires an additional transformer to match the converter output voltage to the line voltage, either two, 2-winding transformers or one, 3-winding transformer may be used Fig. 1.2.

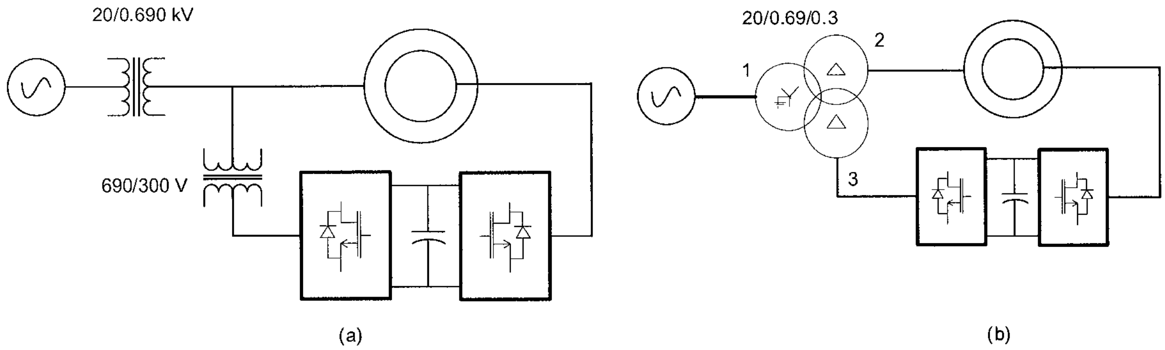


Fig. 1.2 Connection of the DFIG to the MV network using (a) 2-winding transformers (b) 3-winding transformer

Typically in a wind park, numerous wind generators would be connected to the MV bus which would then be connected to the high voltage feeder via another transformer. High voltage dc (HVDC) transmission systems have been considered for integration of wind with the ac system, however, it seems to be only economically feasible for very large installations, located far offshore [8],[9]. Recently low voltage dc transmission (LVDC) has received interest as a possible compromise between HVDC and ac interconnection, with the advantages of HVDC at a reduced cost [20]. However, in most cases an ac intertie is the preferred method of interconnection. These wind park arrangements are presented in Fig. 1.3.

Wind parks are typically only connected at a single point although reliability could be improved if connection to multiple feeders was done. Particularly in the case of offshore installations, the cost associated with multiple interties compounded with the strict environmental regulations make the connection of a radial wind farm at a single point to the transmission system the norm.

The interconnection of the wind farm is often to a weak system, which amplifies many of the technical difficulties associated with wind generators [18]. In this case, fluctuating output power results in a highly variable voltage at the PCC and therefore, reactive power control is required to help regulate the system voltage. The response of the system following faults in this case is also of great concern and the undervoltage and overspeed protections must be carefully chosen [21].

Future wind park projects have been limited by a number of factors, most importantly, issues related to transmission [1]. Since new installations are usually located away from central generation and load centers, transmission problems have slowed their progress. Although many sites have access to rural distribution networks, the transmission system is usually very weak or inadequate to support large amounts of generation. The problem is complicated further when the generation is unpredictable, resulting in similar changes in the bus voltage. This emphasizes the need for reactive power control but also the ability to smooth the power fluctuations due to the wind dynamics.

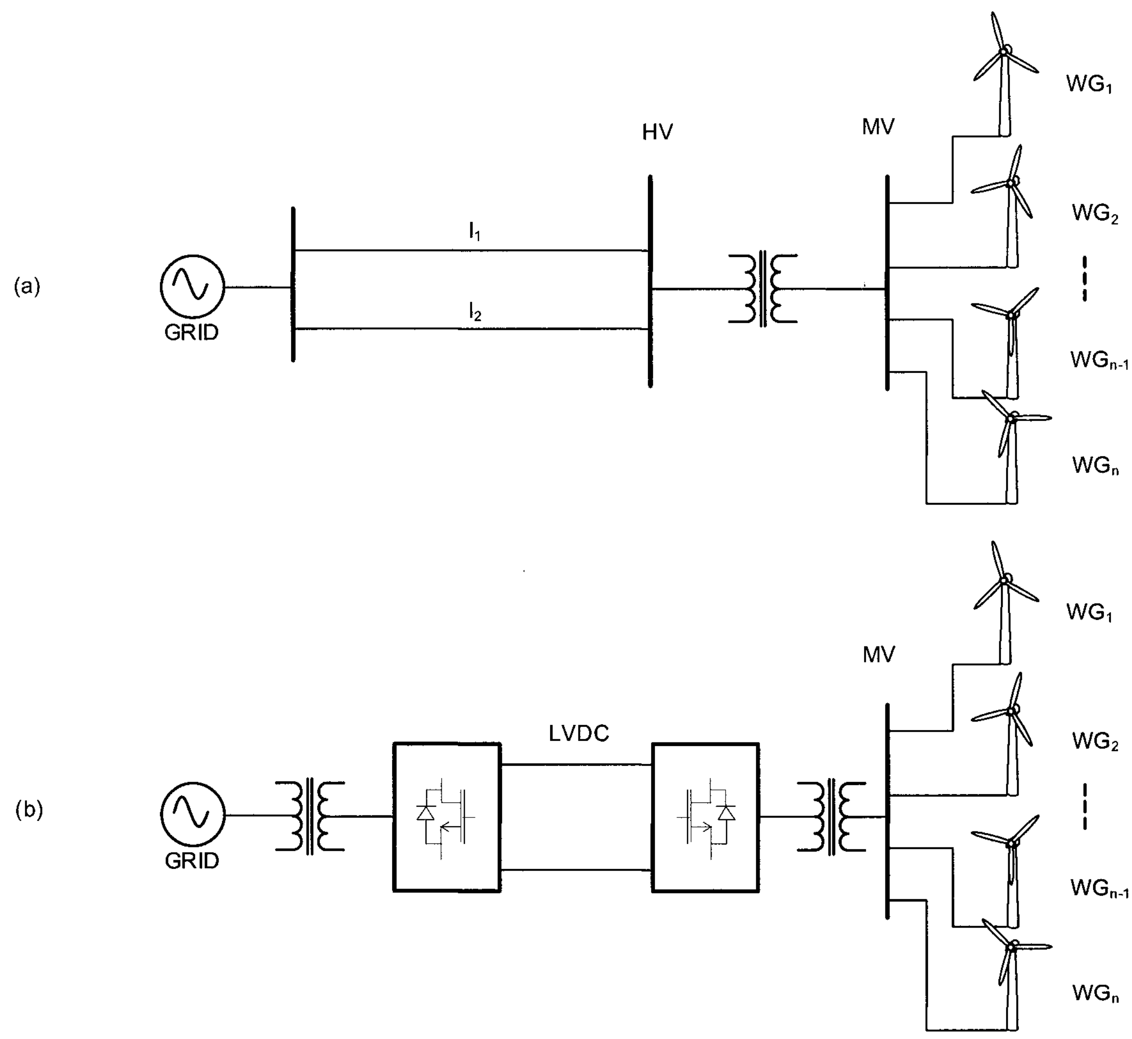


Fig. 1.3 Wind farm interconnections (a) ac interconnect (b) LVDC interconnect

1.3.4 Wind Power Challenges

The challenges associated with operation of a wind farm lead to a greater concern for the operation under disturbances within the nearby power system. Asymmetric and symmetric faults can lead to voltage instabilities and loss of synchronism in traditional power systems. Since wind farms are typically composed of only induction machines, loss of stability is no longer a concern. However, tripping of the generators due to undervoltage and overspeed of the generators can result in voltage stability problems and even small disturbances may lead to widespread tripping and associated instabilities. Reactive power compensation can help to improve transient stability and the integration of energy storage into variable reactive power sources has shown to provide a further increase in the transient stability of the system [22].

1.4 Energy Storage Systems

Although storage of energy is used extensively in low power applications, viable, low-cost energy storage devices still do not exist presently. In the conventional utility, power is produced at one location in the system and consumed at another, connection between the two points being accomplished by the transmission network. However, many benefits can be realized through application of a short term energy storage device and energy storage systems (ESS) have been utilized in various applications, despite their consistently elevated costs [19],[23],[24],[25].

1.4.1 Benefits of ESS

Energy storage has been used for various applications including transportation, flexible ac transmission systems (FACTS), and uninterruptible power supplies (UPS). The main benefits can be summarized by:

(i) Instantaneous exchange of real power with the system using power electronic interface.
(ii) Enables both storage and supply of energy
(iii) Short term supply prevents multiple switching of back-up generators

(iv) Integration of ESS with FACTS has been shown to further improve the transient stability

(v) Smoothing of the output power from non-dispatchable energy sources

The final two points can be taken advantage of for wind power applications. Integration of energy storage into the wind energy conversion system (WECS) can improve the ability to dispatch the wind generator. Also the transient stability of the wind park is improved while the associated transmission system benefits from this design choice.

1.4.2 Types of ESS

There exist numerous types of ESS, and each is modeled somewhat differently. Fig. 1.4 presents the four most common systems which are available today. Each of the systems realizes the same goal, however, the manner in which they store energy is quite different and consequently, their modeling and control differs significantly as well.

Various factors need to be considered when choosing the type of energy storage system including: size, rating, speed, and cost. Some storage devices are better suited for larger ratings and the speed of exchange of energy also typically differs. As is expected the cost differs greatly between the various elements and for this reason, flywheels are commonly used in higher power applications since it is the most competitive in this respect. Table 1.2 summarizes the characteristics of the different technologies.

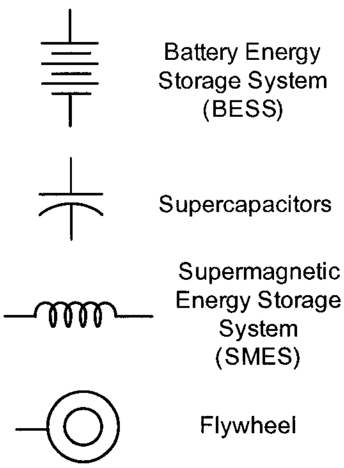


Fig. 1.4 Energy storage system technologies

Table 1.2 Summary of energy storage system characteristics

	Energy Function	*Power Range*	*Energy Range*	*Charge Time*	*Power Density (W/kg)*	*Cost (US$/kJ)*
BESS[1]	$E(t) = E_o + \int v(t)i(t)$	5 kW – 10 MW	0.1 – 600 MJ	Hours	10 - 300	0.2 - 1.5
Super-Capacitors[1]	$E(t) = \frac{1}{2} C V_{sc}^2$	5 – 100 kW	1 kJ – 10 MJ	Seconds – minutes	2000 - 10000	5 - 20
SMES[2]	$E(t) = \frac{1}{2} L_{smes} I_{smes}^2$	1 – 50 MW	1 – 100 MJ	Seconds	300 - 1000	30 – 50
Flywheel[1]	$E(t) = \frac{1}{2} J \omega_{fw}^2$	1 kW – 10 MW	1 – 15 MJ	Minutes	1000 - 10000	0.3 - 2

1 – taken from [26], 2 –taken from [27],[28]

1.4.3 Distributed Energy Storage

In wind power applications, the location of the energy storage device may be either in each of the generators or lumped at one point, such as in the dc bus of a static compensator (STATCOM) connected at the PCC. In the case of a DFIG, the dc link is already required, and therefore, it is reasonable to incorporate the ESS in the dc bus. In this way the ESS device, in the form of BESS or supercapacitors is located within each of the DFIGs.

For this arrangement, it could be argued that the system is more reliable compared to the case where the ESS is concentrated at one location. This is due to the fact that if one of the DFIGs is disconnected from the system, only a portion of the energy storage capability of the system is lost. In the case where the STATCOM with ESS is out of service, the wind farm reduces to the conventional case and all of the benefits of energy storage are lost.

1.4.4 Energy Management

The addition of energy storage to a WECS introduces new complexity into the system since now the limits of the storage device must be taken into account. Since the cost of the storage device is a function of its rating, the system should be sized to be as small as possible in order to minimize its price and physical dimensions. This requires that the control system be able to handle extraneous conditions, whereby either the upper or lower limits of the ESS are attained. Not only must the control be able to handle these conditions but it must be able to transfer control back to normal operation to once again reap the benefits of the ESS. Therefore, the advantages associated with energy storage come with an increase in both cost and control complexity.

1.5 Research Objectives

The focus of this research is on the utilization of the doubly-fed induction machine as a wind powered generator. Furthermore, the integration of an energy storage device into the wind generator design is considered. The study is conducted first on a single generator system, followed by addition of the energy storage element and its control, and finally the investigation of the system characteristics when connected to a distribution feeder.

1.5.1 Problem Definition

The problem of this research is to understand and implement the control of a wind powered DFIG. Once the basic generator has been constructed and its control is verified, then the energy storage is added. The secondary problem becomes the control of the ESS itself, under both normal operating conditions and abnormal operation. Finally, the benefits of this type of generator design on a system level needs to be evaluated.

1.5.2 Research Goals

The research should accomplish the following tasks:

1. Investigation of stator and rotor reactive power distribution and overall converter rating minimization.
2. Integration and control of energy storage into the DFIG converter system.
3. Demonstrate that a DFIG and ESS can regulate the output power under normal circumstances and thereby make wind energy dispatchable.
4. Demonstrate proper energy management under normal and abnormal conditions.
5. Investigate the operation of the system and show how energy storage can improve transient stability and power quality.
6. Develop simulation models within EMTP-RV in collaboration with *TransÉnergie Technologie and Hydro-Québec*, including technology transfer of documents and models.

1.5.3 Claim of Originality

This thesis has contributed various original ideas in this field of study. The method of reactive power distribution discussed within Chapter 2 was not looked at before as a means of minimizing the converter ratings. As well, the application of energy storage to the DFIG wind generator has not been looked at previously in the literature. Although the idea of applying energy storage to fluctuating power generators is not unique, the implementation for this topology and the control philosophy, to the best of the author's knowledge is original.

1.6 Thesis Outline

The thesis is organized into a total of six chapters including this introduction. Chapter 2 introduces the details of the DFIG system and discusses the basis for its control. Following this, the transient models are developed in Chapter 3 and the control is verified using two simulation platforms: EMTP-RV and MATLAB SimPowerSystems. Energy storage is discussed in depth in Chapter 4 and its feasibility is demonstrated. Chapter 5 presents the operation of the system in a distribution network and the response following symmetric and asymmetric faults is shown. Finally, Chapter 6 summarizes the benefits of this system and further studies are outlined.

Chapter 2: DFIG Operation and Design

2.1 Introduction

The wound rotor induction machine or doubly-fed induction machine has limited applications in the power industry, however, it has become the most popular choice amongst the various wind generator options, especially for large capacity machines. The ability to control the speed of the generator along with controllable power factor has been shown to improve both the efficiency as well as the stability of this generator [29], [30], [31]. This is accomplished by decoupled control of the stator real and reactive powers while the supply side converter maintains the dc bus voltage. Numerous control methods have been developed which demonstrate these concepts [29] - [44].

This chapter discusses the steady-state operation of the DFIG which serves as the foundation for the control of the real and reactive power. The DFIG system is introduced and the various issues concerning the control are discussed. Reactive power sources are presented and a method for allocation of reactive power between the two converters is given. Steady-state calculations are performed for various operating points and the results are compared to the EMTP-RV transient models operating at these points. This provides the theoretical basis from which the transient models follow.

2.1.1 DFIG Based Wind Generator

The wind energy conversion system (WECS) using a DFIG is shown in Fig. 2.1. Two back-to-back voltage source converters connect the stator windings to the rotor windings and as previously mentioned, a transformer is required between the line side converter and the supply. Control of the dc bus voltage is accomplished by the line side converter while the rotor side converter controls both the speed and the pf of the machine. The line side converter may also deliver reactive power and thus, together with the rotor side converter dictates the generator pf.

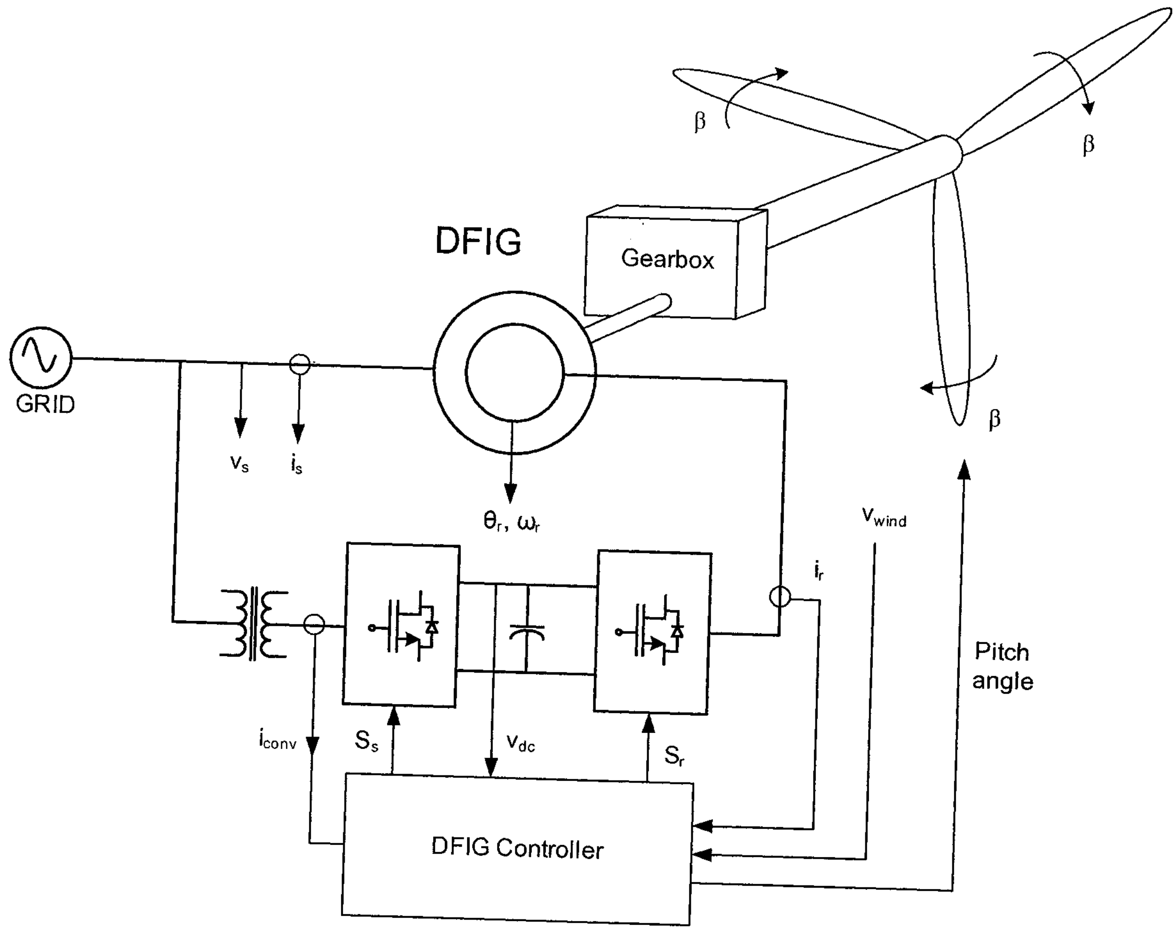


Fig. 2.1 DFIG wind energy conversion system

The ratings of each of the converters as well as of the generator itself must be respected and therefore, current limits must be implemented in each of the two control algorithms as in [29]. The speed is limited as well in order to respect the mechanical limitations of the system. The summary of the control objectives of the two converters as well as the machine are given below in Table 2.1.

Table 2.1 Control objectives for converters and DFIG-WECS

Converter	*Objective*	*V_{ac} regulation*	*Reactive power source*	*Speed control*
Rotor side	P_s, Q_s control	Yes	Yes	Using $P_{s,ref}$
Supply side	Regulate dc bus	Yes	Yes	No

2.1.2 Steady-State Equivalent Circuit

The induction machine can be represented by it steady-state equivalent circuit as is given in all machine theory textbooks, such as [45]. It is presented in Fig. 2.2 in order to develop the basis for decoupled control of P_s and Q_s. From the equivalent circuit one can derive the following equations which relate the steady-state quantities of the rotor and stator sides.

$$\begin{bmatrix} 1 & R_s + jX_s & 0 \\ 1 & 0 & R_r/s + jX_r \\ 1 & jX_m & jX_m \end{bmatrix} \begin{bmatrix} V_m \\ I_s \\ I_r \end{bmatrix} = \begin{bmatrix} V_s\angle 0^\circ \\ V_r/s\ \angle\delta_r \\ 0 \end{bmatrix} \tag{2.1}$$

If the stator side voltage is used as the angle reference then the remainder of the quantities can be defined assuming a fixed stator voltage magnitude and given the required real and reactive power. From P_s and Q_s, one can then define the magnitude and phase of the current, I_s as follows:

$$\mathrm{Re}(i_s) = \frac{P_s}{V_s} \tag{2.2}$$

$$\mathrm{Im}(i_s) = -\frac{Q_s}{V_s} \tag{2.3}$$

Then using (2.1), the first and third row equations are used to find I_r, followed by the second to find the required voltage applied at the rotor terminals. This apparently elementary study forms the basis for transient control of the rotor side converter. Of course there are various technical issues related to synchronization of the various signals and application of the necessary forward and reverse transformations, however, the control algorithm follows from this simple analysis.

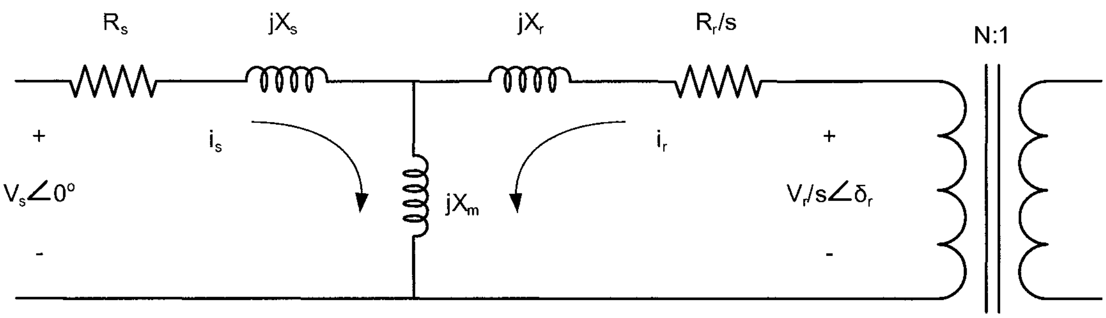


Fig. 2.2 Wound rotor induction machine equivalent circuit

2.1.3 Wind Energy System Models

In order to investigate the operation of a DFIG as a wind generator, all of the necessary models include realistic machine parameters, wind speed, input torque characteristics, and the required protection settings are required. Accurate modeling of the mechanical system is crucial especially in regards to the various time constants associated with the wind turbine itself, the blades, and the pitch control. The modeling of these components is discussed in detail in many of the literature and they will not be revisited here. The machine parameters and basic wind models are included in the Appendix for the interested reader while greater details can be found in references [15].

2.2 Reactive Power Allocation

Reactive power control is an important issue, particularly in WECS which are connected to weak networks. Voltage support capability is often required to maintain the ac voltage within the limits of operation and improve recovery following disturbances and is possible in MV networks when reactive power can be accurately controlled. The DFIG is one type of wind generator which has the ability to at the very least compensate for the reactive power required by the induction machine. Various studies have shown that this and other wind generators capable of reactive power control can improve the stability of the system and its tolerance to disturbances [6], [18], [19].

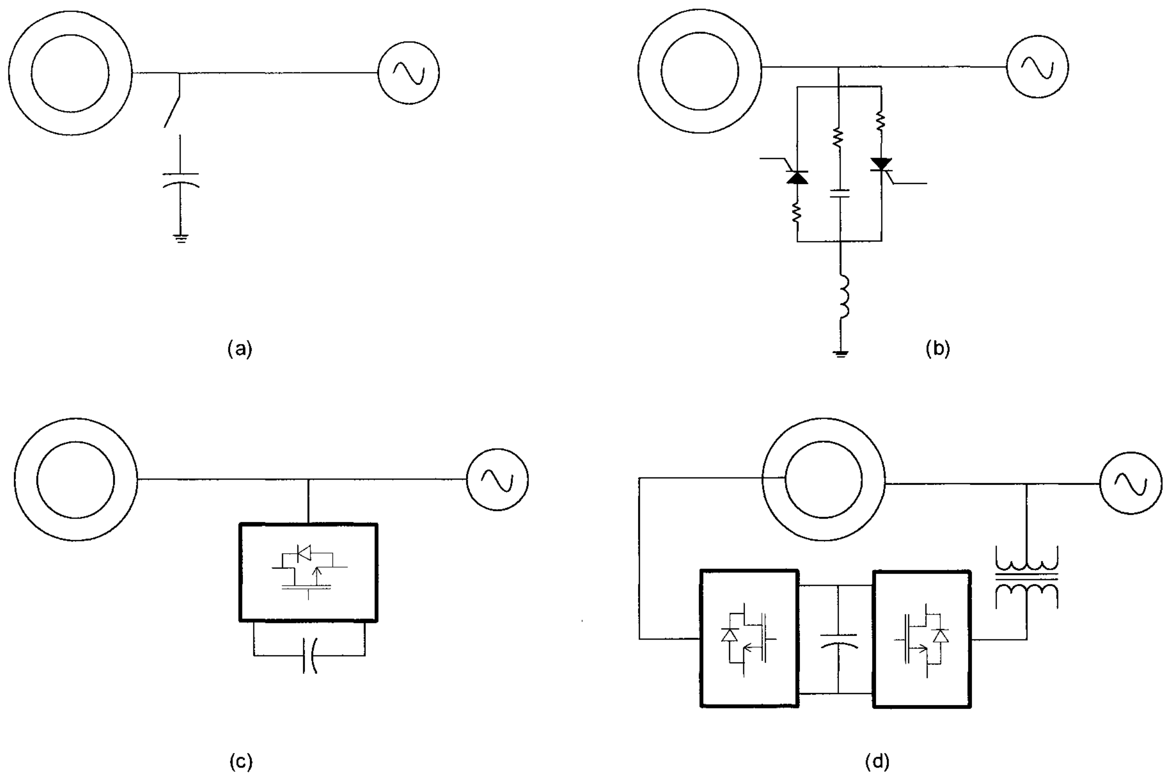


Fig. 2.3 Reactive power options for wind generators (a) switched capacitors (b) SVC (c) STATCOM (d) DFIG

2.2.1 Reactive Power Sources

One of the differences between squirrel cage induction machines and synchronous machines is that induction machines consume reactive power in all modes of operation whereas for synchronous generators, the reactive power can be controlled to be leading or lagging depending on whether the machine is over or under-excited. The DFIG possesses the ability to control its power factor and additionally it is capable of supplying reactive power from two separate sources: from the stator by control of the rotor side converter or from the supply side converter, in a manner analogous to a STATCOM. Since the controls of these two converters are essentially decoupled, the reactive power can be adjusted by independently adjusting the amount supplied from either of the two sources. The combined VAr injection then determines the amount supplied to or absorbed from the grid, Fig. 2.4.

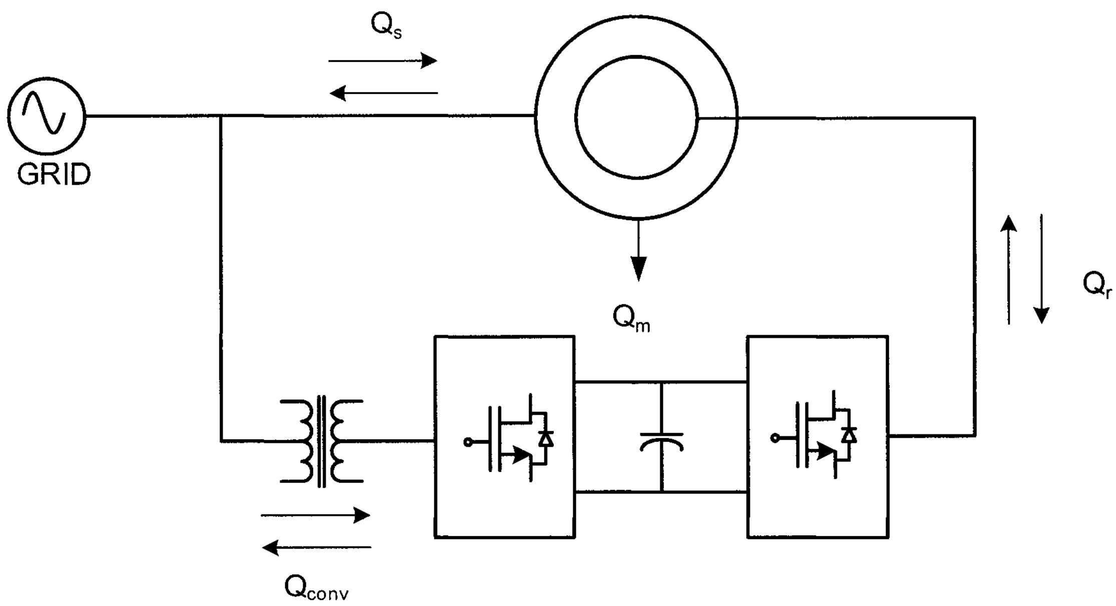


Fig. 2.4 Reactive power sources in the DFIG

2.2.2 Optimum Reactive Power Distribution

The manner in which the reactive power is allocated will result in different current magnitudes in the two converters and consequently, will affect their kVA ratings. Studies performed by the author have shown that in order to minimize the combined current magnitude the majority of the reactive power should be supplied from the rotor side converter, while approximately 20% is supplied from the supply side converter [46]. However, when generation is high and the real component of the machine current is high, the current limits may curtail the reactive power supplied from the stator side and thus the distribution becomes more equal. This allocation method is based on steady-state considerations and therefore, the current limits of two converters may cause discrepancies under these extreme transient cases.

This section focuses on the delegation of the reactive power compensation and demonstrates that through proper division of the reactive power compensation between the two converters, the overall rating of the two converters can be minimized. The parameter, *K* will be referred to as the rotor side converter compensation constant and will be defined as:

$$K = \frac{Q_r}{Q_r + Q_{conv}} \tag{2.4}$$

Where Q_r and Q_{conv} are defined as the reactive power injected into the machine from the rotor side and the reactive power injected by the supply side converter, respectively, Fig. 2.4. Note that the denominator represents the total reactive compensation supplied because of the way Q_{conv} has been defined. If the synchronously rotating frame is considered, the reactive powers in (2.4) will be proportional to the currents i_{rq} and $i_{conv,q}$. The compensation constant will be chosen in order to minimize the combined complex power of the rotor side and grid side converters.

2.2.2.1 Problem Definition

The greater of the two ratings was chosen as the minimizing function, since generally in practice, the kVA ratings of the two converters should be matched. Matched converters are typically standard and thus, a reduction in cost is possible if they are chosen to be equal. Thus, the following function will be minimized:

$$S_{rating} = \left\| S_r \quad S_{conv} \right\|_{\infty} \tag{2.5}$$

Subject to the following constraints:

$$n_{\min} \leq n \leq n_{\max} \tag{2.6}$$

i_s, i_r satisfy (2.1), the steady-state equivalent circuit model (2.7)

Where n is the transformer turns ratio. The dc link voltage is chosen in order to ensure control over the set speed range of 80 to 120% of synchronous speed. This implies that at the maximum magnitude of slip, s_{max}, the machine will present an induced voltage, $V_{r,ind}$ on the rotor side of magnitude given by:

$$\left|V_{r,ind}\right| = \frac{V_s}{s_{\max}} \tag{2.8}$$

The relationship between the line-to-line voltage and the dc voltage is approximately given by:

$$V_{LL} = 0.612 m_a V_{dc} \qquad (m_a \leq 1.0) \tag{2.9}$$

Where, m_a is the modulation index of the rotor side converter. Therefore, in order to ensure control at the maximum magnitude of slip, and assuming the rotor side converter operates in the linear modulation range with $m_a = 1$, the dc voltage, V_{dc} is chosen using:

$$V_{dc} = \frac{s_{\max} V_s}{0.612} \tag{2.10}$$

The values of n_{min} and n_{max} are chosen by assuming that the supply side converter operates with a modulation index between $0.8 \leq m_a \leq 1$. Then, incorporating (2.9) into (2.10) results in:

$$0.8 s_{\max} \leq n \leq s_{\max} \tag{2.11}$$

2.2.2.2 Optimum Allocation

The results of the optimization problem are summarized in Fig. 2.5. The maximum rating of the two converters is plotted over K for different values of the system reactive power, Q_{grid}. This has been done assuming the generator is supplying its rated real power (~ 0.92 pu). Only the case of slip = -20% is shown, the speed at which the maximum converter currents results.

It can be noted that the majority of the compensation is supplied from the rotor side converter (70-85%) however, a small percentage should come from the supply side converter in order to minimize the maximum rating of the two VSCs. Considering only the limiting case, when 0.8 pu is injected into the system (Q_{grid} = -0.8), it can be noted that approximately 20% should be supplied from the line side converter and thus, the rating of the converter should based upon this value. It should also be noted that when comparing the curves of ratings of the individual converters, they do in fact, become equal at the minimum point as should be expected. This explains the discontinuity at this point, as it is the intersection of these two curves.

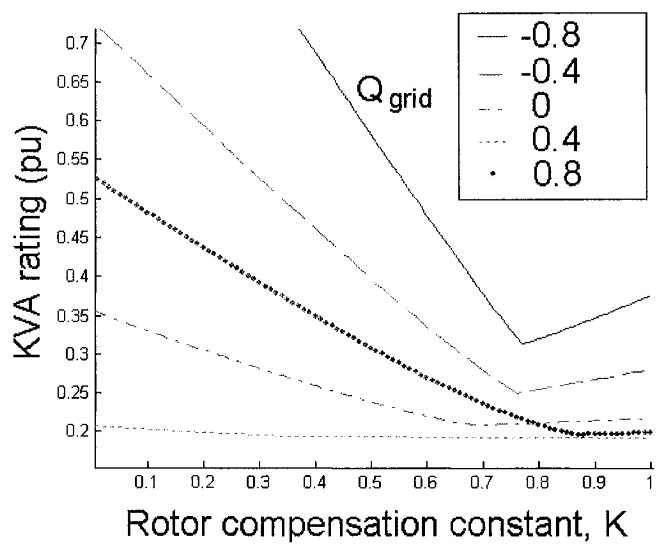
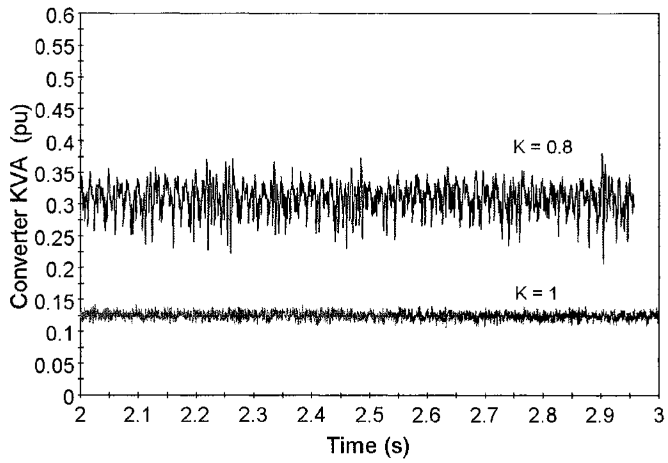


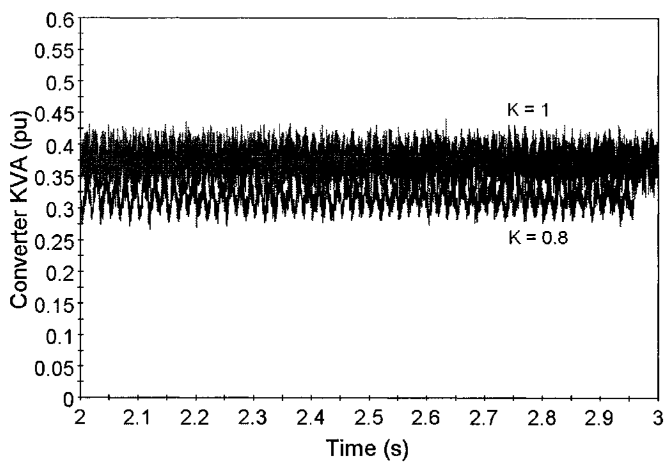
Fig. 2.5 Maximum kVA ratings of converters as a function of the proportion of reactive power supplied from rotor side converter

2.2.2.3 Comparison with Transient Model

Simulations in EMTP-RV were carried out to show that in fact a reduction in the kVA rating is possible by sharing the reactive compensation between the two converters, Fig. 2.6. The kVAs of the two converters were obtained for the limiting case of Q_{grid} = -0.8 while controlling the machine to 1.2 ω_{syn} (slip = -0.2). The complex powers are shown for K = 1 and K = 0.8. In the latter case, it can be noted that the rating of the rotor side converter is decreased while the line side converter is increased such that they are balanced, whereby $S_{line} \approx S_{rotor} \approx 0.3$ pu, approximately the same as predicted using the steady-state model. Thus, since the rating is chosen based upon the maximum of the two converters, a reduction in installed rating and therefore, cost is possible.



(a)



(b)

Fig. 2.6 KVA of (a) supply side and (b) rotor side converters for $\omega_r = 1.2\omega_{syn}$ and Q_{grid} = - 0.8

2.3 Steady-State Calculations

Here various operating points are chosen and the steady-state values are determined for the stator and rotor currents using the steady-state equivalent circuit model. This allows for a greater understanding of the operation of the generator over the entire operating range. In order to perform the calculations, the following quantities are first specified: the rotor speed, ω_r, the power delivered to the grid, P_{grid}, and the reactive power supplied to the grid, Q_{grid}. Then the remaining quantities can be calculated in steady-state assuming the voltage at the PCC is 1 pu. The reactive power is divided between the two sources as previously mentioned.

Using the same machine parameters as in the transient models, the results for operation with leading, lagging, and unity power factor operation at super and subsynchronous speeds are obtained. The results are shown in Table 2.2. The same list of operating characteristics is then obtained using the transient model developed in EMTP-RV (discussed in detail in chapter 3). It can be noted that the transient waveforms roughly match the values obtained using the steady-state calculations, supporting the calculations but also the validity of the transient models.

Table 2.2 Steady-state operating conditions of DFIG

ω_r (pu)	P_{grid} (pu)	Q_{grid} (pu)	$\lvert I_{conv}\rvert$ (pu)	$\angle I_{conv}$ (deg)	$\lvert I_s\rvert$ (pu)	$\angle I_s$ (deg)	$\lvert I_r\rvert$ (pu)	$\angle I_r$ (deg)
0.8	-1.08	0.44	0.20	154.15	0.97	21.18	0.93	2.10
0.8	-1.08	0.00	0.18	180.00	0.90	360.00	0.98	-19.34
0.8	-1.08	-0.44	0.20	-154.15	0.97	-21.18	1.15	-36.47
1.2	-0.72	0.44	0.20	25.85	0.97	21.18	0.93	2.10
1.2	-0.72	0.00	0.18	0.00	0.90	360.00	0.98	-19.34
1.2	-0.72	-0.44	0.20	-25.85	0.97	-21.18	1.15	-36.47

$Q_s = 0.8\ Q_{grid}$ and $Q_{conv} = 0.2\ Q_{grid}$ whereas $P_s = 0.9$ pu

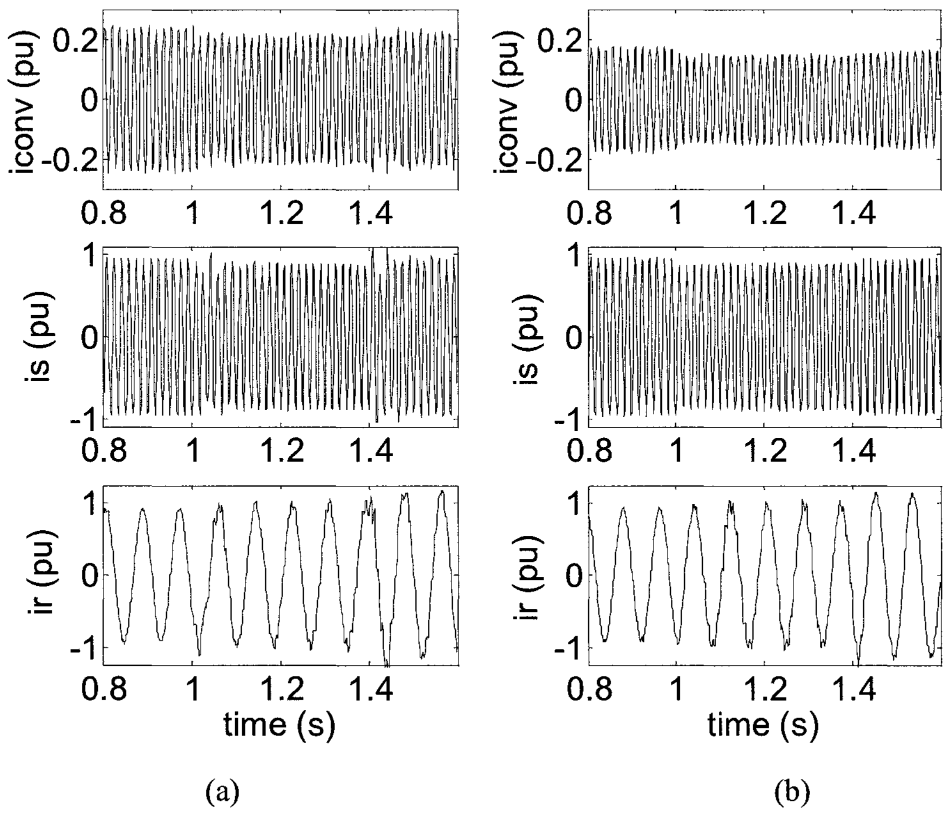


Fig. 2.7 Stator, rotor, and grid converter currents for the conditions in Table 2.2. (a) $0.8\omega_{syn}$ (b) $1.2\ \omega_{syn}$. Obtained using EMTP-RV representation of system, Q_{grid} = -0.44 (t < 1), Q_{grid} = 0 (1 < t < 1.4), Q_{grid} = 0.44 (t >1.4)

2.4 Conclusions

In this chapter the steady-state models of the DFIG – WECS have been introduced. The various sources of real and reactive power were presented and the control goals along with the fundamental basis for development of the algorithm were given. Reactive power is an important issue and the DFIG is able to control the reactive power from two sources. It is shown that the majority of reactive power should be supplied from the rotor side converter in order to reduce the overall kVA rating of the two converters. Comparison of steady-state calculations with the transient models shows good agreement. Small discrepancies result from the simplifications made when using the transformer equivalent circuit while the EMTP-RV model utilizes the full state space representation of the system. The instantaneous control of the DFIG can now be developed following the principles outlined in this chapter.

Chapter 3: Transient Models and Control

3.1 Introduction

The control of the DFIG consists of two separate control algorithms, which together realize the overall function of the system. Through appropriate modulation of the rotor side converter, decoupled control of P_s and Q_s is possible. The supply side control is responsible for regulating the dc bus voltage and thereby facilitates the flow of rotor power either to or from the machine, depending on the sign of the slip. Higher-level controls select the real and reactive power references in order to control the speed of the machine and regulate the ac voltage, respectively. The controls are demonstrated using EMTP-RV. As a means of verifying the representation, a similar representation is built in MATLAB – SimPowerSystems and the results are compared.

3.2 Converter Controls

As mentioned, the two converters are controlled separately using two separate control algorithms. The rotor side control was developed using the steady-state equivalent circuit with PI compensation, however closely resembles the control structures discussed in [30],[39] ,[44]. The line side control follows from STATCOM or rectifier control theory and will not be presented in depth.

3.2.1 Current Control

Current control techniques using an inverter can be grouped into two main classes: (i) pulse-width modulation (PWM) based linear feedback control and (ii) hysteresis control. A third category could include the numerous nonlinear control techniques, however, they were not implemented in this case and thus will not be discussed further.

3.2.1.1 PWM Linear Feedback Control

In this control structure, the three phase currents are decomposed into their *d* and *q* components. These components are compared with the reference signal and the error signal is passed through a proportional integral (PI) or other linear compensator block, whose output generates the *d* and *q* components of the modulating signals. A feedforward signal may be included which can in some cases improve the transient response, Fig. 3.1.

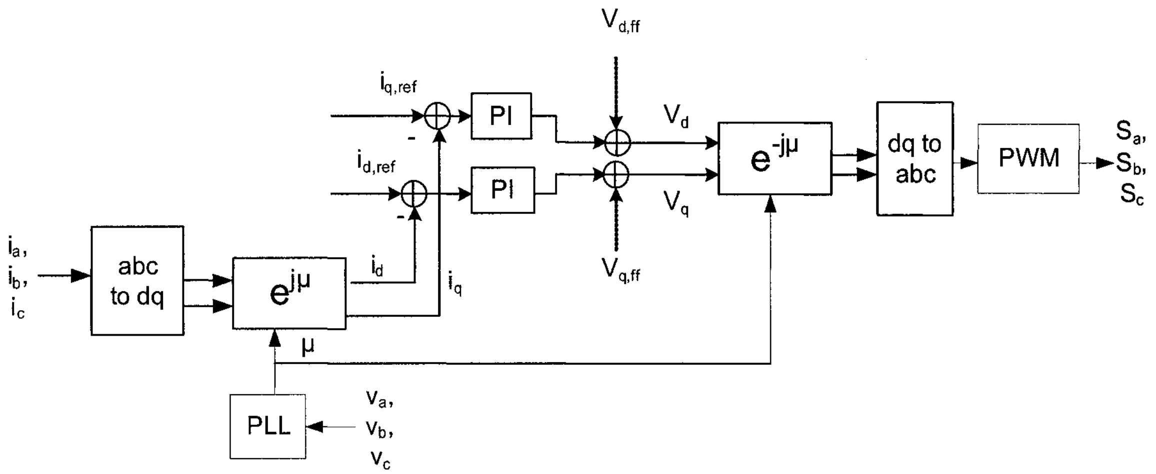


Fig. 3.1 PWM linear feedback current control structure

3.2.1.2 Hysteresis Current Control

In hysteresis current control, a small hysteresis band is added to the reference signal Fig. 3.2. The gating signals are then chosen based upon the required slope of the instantaneous line currents. In this way, the current remains within the band. Drawbacks of this method include unpredictable switching frequency (making tuning of filtering components difficult) and increased switch stresses, however, the control is very precise.

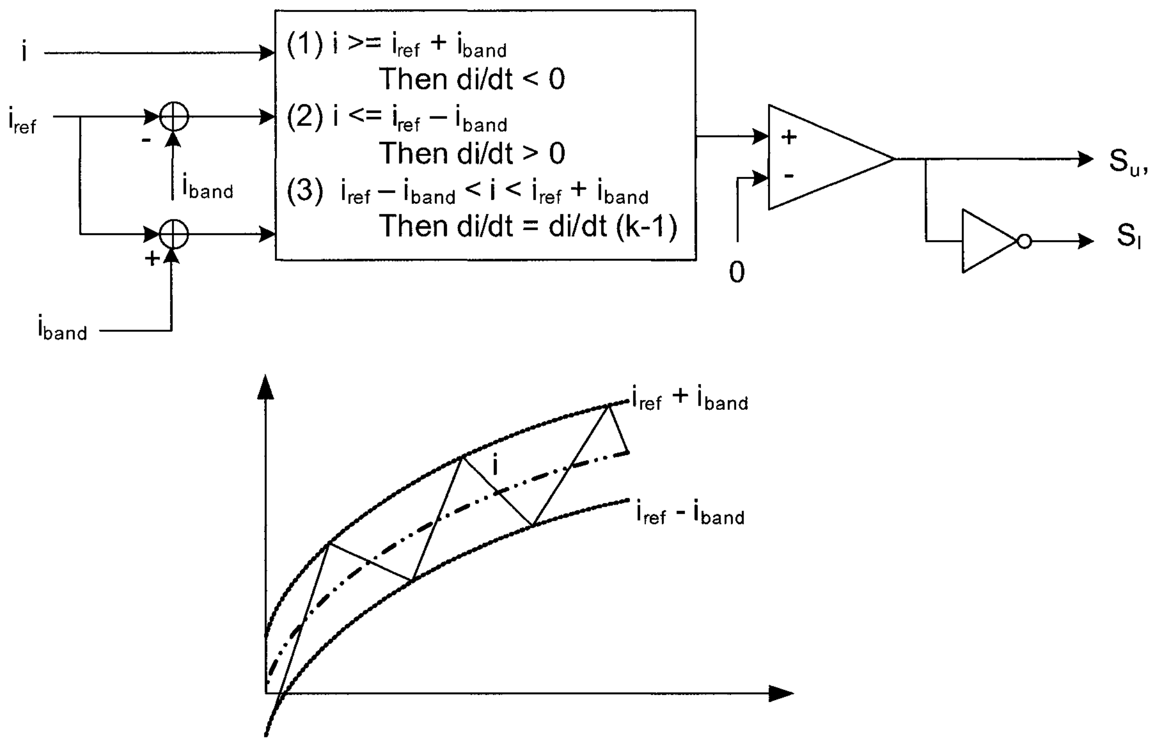


Fig. 3.2 Hysteresis current control structure and principle

3.2.2 Real and Reactive Power Control

The real and reactive power control of the stator is realized by the control of the rotor side currents. In effect, P_s and Q_s are first related to the rotor currents and then the rotor currents are controlled through the appropriate gating of the rotor converter. Since control is accomplished on the synchronously rotating frame, this requires both the rotor angle and supply voltage angle for synchronization.

The sequence of the control is outlined here:

a) Measure all required quantities including stator voltages, rotor and stator currents, rotor angle
b) Extract the voltage angle using a phase-locked loop (PLL)
c) Perform the appropriate transformations to express all voltage and current quantities on the synchronously rotating frame
d) Calculation of P_s and Q_s

e) Generate the rotor current references using the output of the output PI compensator outputs
f) Rotor current control using PI compensators for *d* and *q* components and the feedforward terms based upon the steady-state equivalent circuit.
g) Transform the rotor voltage back to rotor side *abc* quantities
h) Modulation of the rotor voltages for generation of the gating signals

The control algorithm is represented in block diagram form in Fig. 3.3.

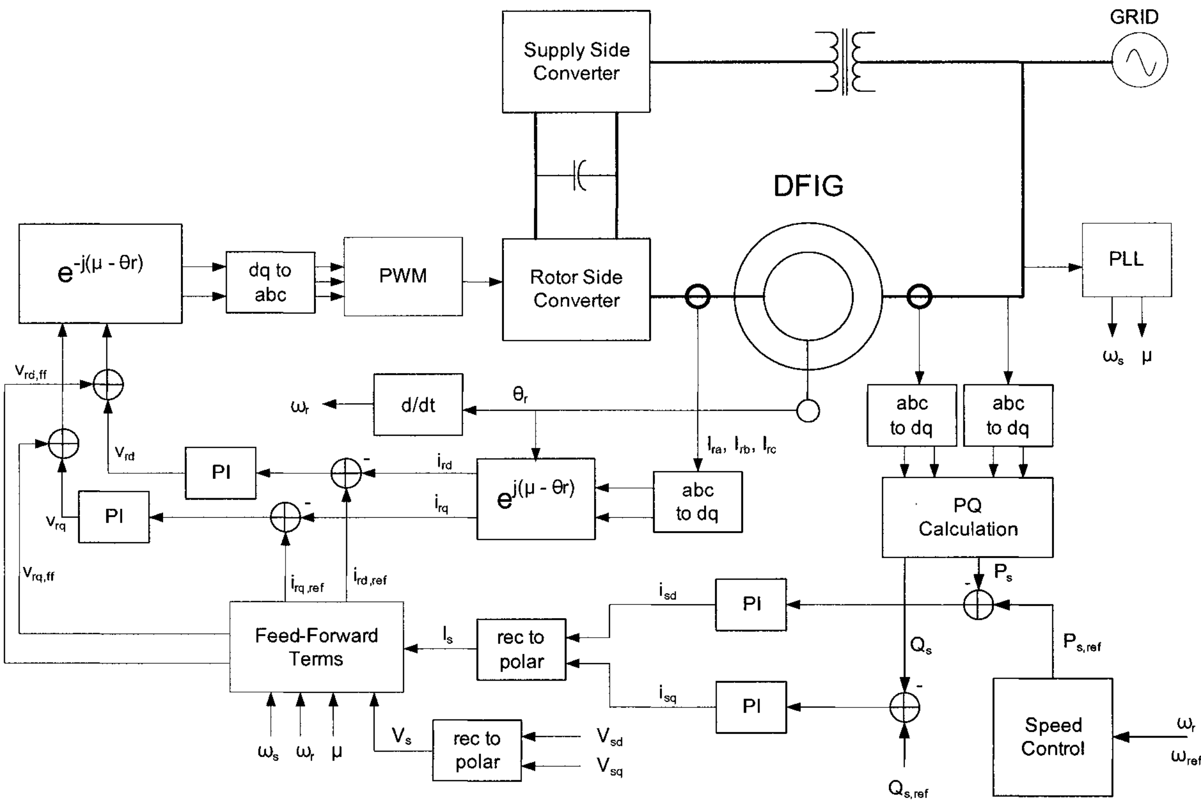


Fig. 3.3 Rotor side converter control algorithm for control of P_s and Q_s

In Fig. 3.3, the rotor angle and speed are shown to be measured using an encoder, however, these quantities can be estimated, thereby making the control sensorless, in that only electrical transducers are required. This type of sensorless control was utilized, following the work done in [39].

3.2.3 Line Side Converter Control

The line side converter control consist of generation of *d* and *q* current references using the dc voltage error and the reactive power references, followed by a hysteresis current control block for generation of the gating signals. Again a PLL is required for synchronization to the grid voltage and proper transformation to *dq* components. The complete block diagram of the control is given in Fig. 3.4.

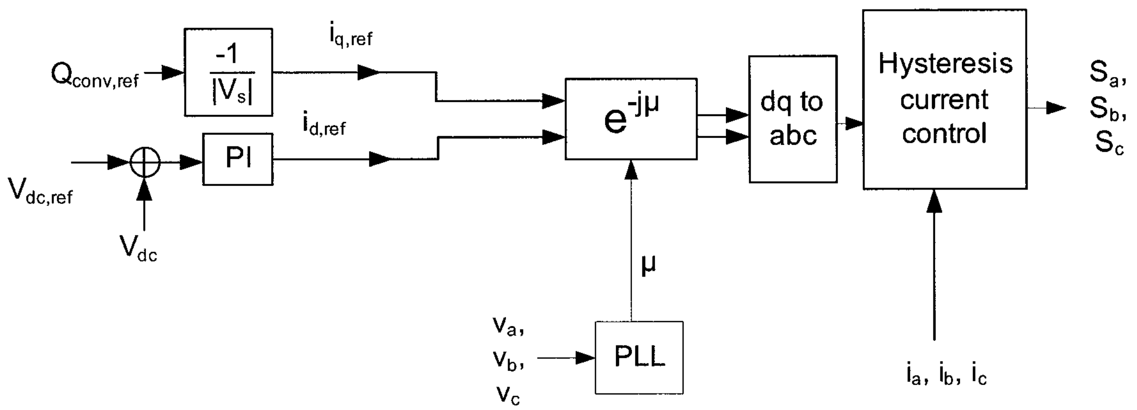


Fig. 3.4 Line side converter control for regulation of dc voltage and supply of reactive power

3.3 Higher Level Control Signals

Once the inner controls have been developed and verified it is then possible to consider higher level controls, allowing a more complete representation of the system. There are essentially two control references that are required: reactive power reference (which is typically divided between the two converters in a 20/80% manner) and the stator real power reference. These two signals are discussed here.

3.3.1 Speed Control

Through control the stator real power, one is able to regulate the speed of the machine. This is most easily explained by considering the equation which describes the mechanical state variables of the system.

$$J\frac{d\omega_m}{dt} = P_m - P_e \tag{3.1}$$

Here, it can be noted that if there is an imbalance between P_m and P_e then the machine will either accelerate or decelerate. Therefore, by setting P_s, the speed of the machine can be regulated. Once the set speed has been reached, P_s automatically adjusts $P_e = P_m$ and the speed remains constant. The block diagram for the speed control is given in Fig. 3.5. The speed reference is typically chosen in order to track the optimum power capture points, which vary as the wind speed changes [30], [43]. Once the rating of the machine has been reached, the pitch control is then used to limit the stator power to this value.

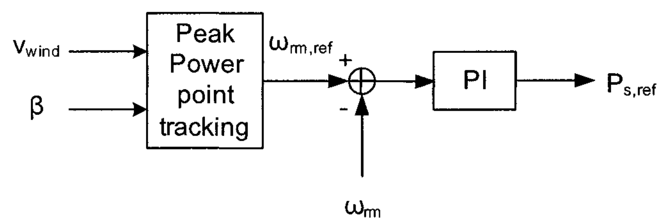


Fig. 3.5 Speed control loop for generation of $P_{s,ref}$

3.3.2 Ac Voltage Regulation

The fluctuations in the ac voltage at the PCC depend upon the flows along the line, which are dependent upon both *P* and *Q*. However, in cases where the *X/R* of the line is large, the terminal voltage can be controlled through management of the reactive power at the terminal bus. The basic concepts of reactive compensation are discussed in [47].

In squirrel cage generators, the machines consume reactive power irregardless of the state of operation. Typically, capacitor compensation is used at the PCC in order to bring up the voltage, however, this solution offers no ability to change the reactive power delivered, with the exception of switching the banks in and out, with limited usefulness under transient conditions.

The DFIG has two sources of reactive power and therefore, not only can the internal reactive power requirement be met but it is also possible to supply reactive power in order to support the voltage at the PCC. Therefore, the reactive power reference is chosen based upon the difference between the ac voltage magnitude and the reference Fig. 3.6. A 1-3% droop has been incorporated in order to promote sharing of the compensation between DFIGs connected in parallel.

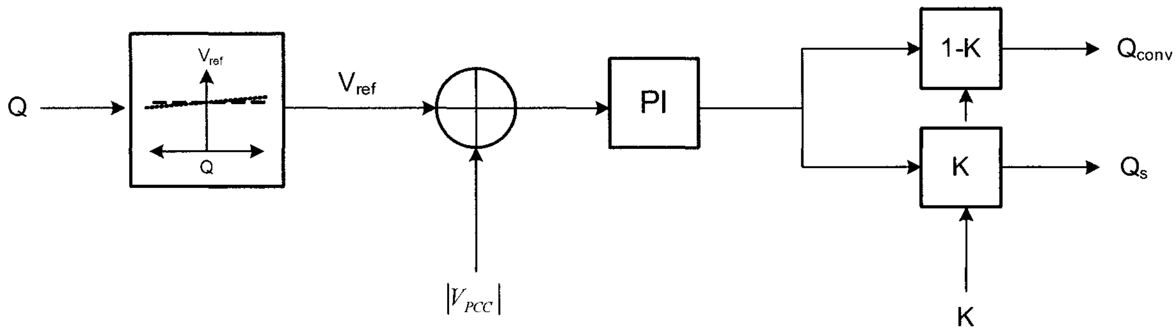


Fig. 3.6 Generation of the reactive power reference for support of ac voltage, (K = 0.8 in most cases)

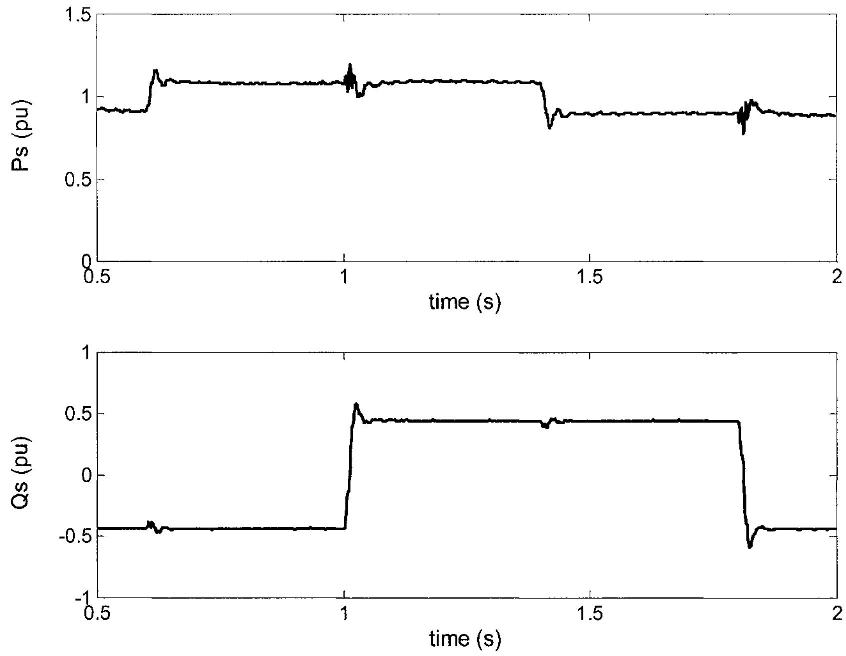
3.4 Control Verification

The DFIG system was developed in EMTP-RV since it enables representation of a system with numerous nodes and therefore, facilitates system level studies while still using the transient model. In order to present a means of verification, the simulation results were compared with an average model representation in MATLAB – SimPowerSystems. This was meant as a comparison only and the intent was only to support the control results since SimPowerSystems is not as well suited for simulation of large systems.

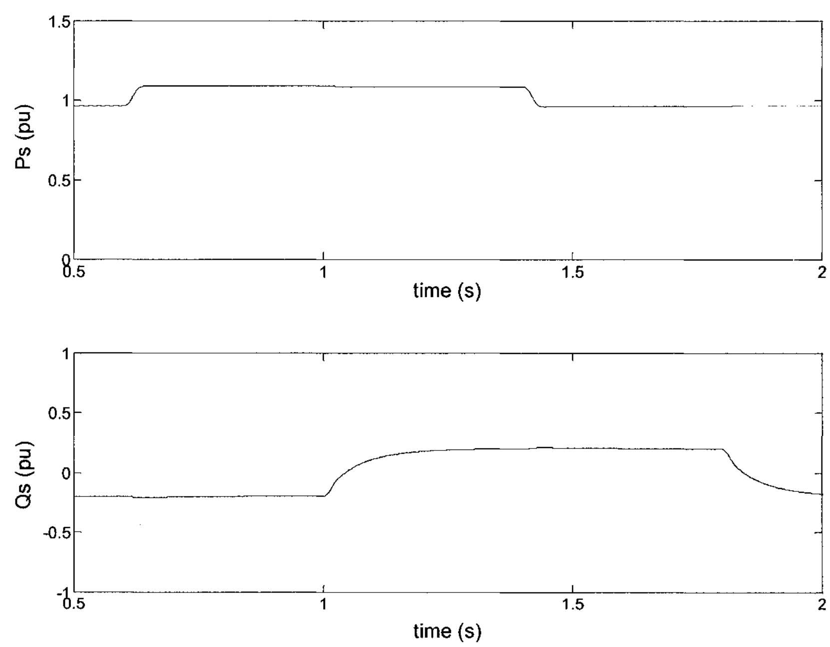
3.4.1 Decoupled Control of Ps and Qs

Here, the rotor side control was tested, subjecting the control to step changes in real and reactive power references. As can be noted the control responds quite well, however, it is not completely decoupled as is to be expected. The existence of losses in the machine and the magnetizing branch account for the resulting change in the real power as the reactive power is changed. The coupling is limited and the control function is satisfactory.

The SimPowerSystem model performs less well and the step change in Q used is smaller, however, exhibits somewhat similar response in terms of a slight coupling between P and Q. Tuning of the control parameters was not possible as the model was an example within the software and access to these variables was limited.



(a)

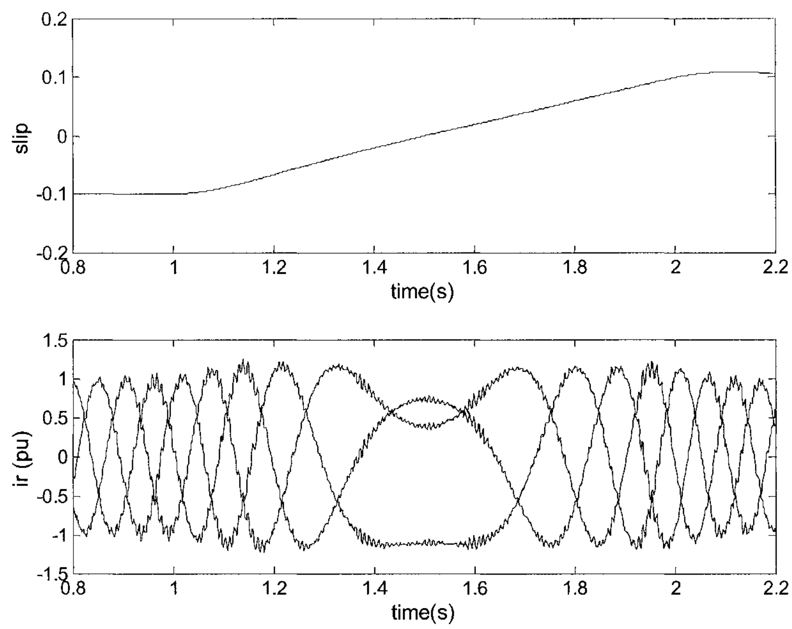


(b)

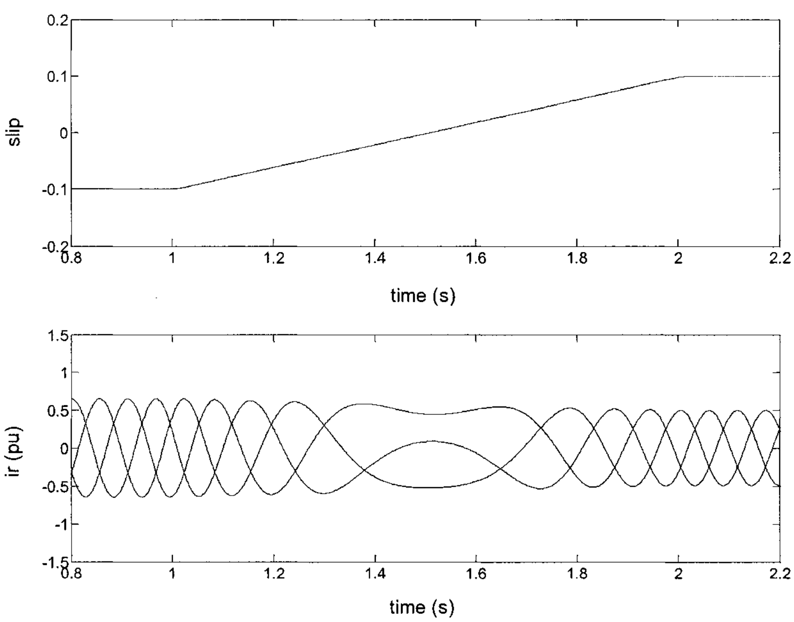
Fig. 3.7 Step response for P_s and Q_s using (a) EMTP-RV (b) MATLAB – SimPowerSystems

3.4.2 Speed Control

The control of the DFIG must be able to change the speed of the machine, in order to track the peak power points but also to limit the output power in some cases. Therefore, the speed control was verified by varying the generator speed over the speed range: $0.9\omega_{syn}$ to $1.1\omega_{syn}$, Fig. 3.8. As can be noted the generator follows well the intended trajectory and the frequency of the rotor currents goes to dc as the generator passes through synchronous speed. The SimPowerSystems model did not possess electrical speed control however upon variation of the input torque the variations in rotor frequency were obtained. Since the model is an average model it lacks the harmonics of the EMTP-RV case but fundamental frequency components are similar.



(a)



(b)

Fig. 3.8 Slip and rotor currents for operation from 1.1 ω_{syn} to 0.9 ω_{syn} using (a) EMTP-RV (b) MATLAB – SimPowerSystems

3.4.3 Dc Voltage Regulation

The dc voltage regulation loop is verified by observing the step response, Fig. 3.9. Again the response is satisfactory for both softwares and confirms that the control responds adequately under transient conditions. Again in the case of the SimPowerSystem model, there is a lack of harmonics due to the use of average modeling which neglects the higher frequency terms in order to speed up the solution time.

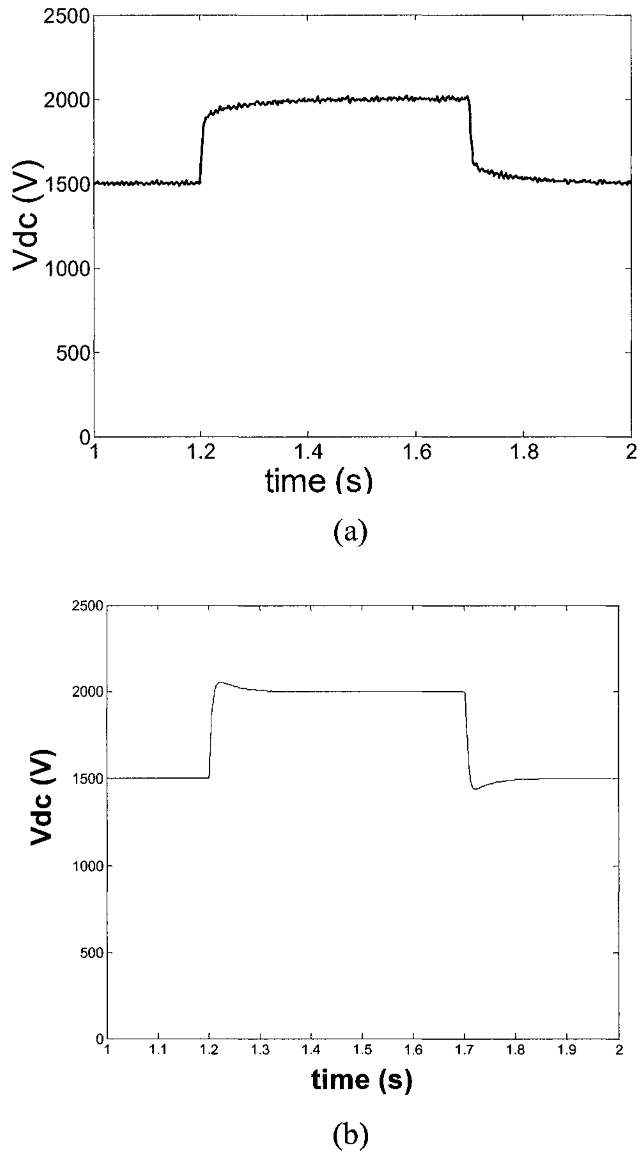


Fig. 3.9 Step response of dc voltage regulator using (a) EMTP-RV (b) MATLAB – SimPowerSystems

3.5 Conclusions

In this chapter, the transient control models have been presented and were verified using numerical simulations. The rotor side and stator side control models, which are both based upon inner current loops with outer loops for generation of the current references, were tested using both EMTP-RV and MATLAB – SimPowerSystems. The control verification shows that the various control algorithms function as they should in all cases. In addition, the SimPowerSystem simulations supported the results obtained in EMTP-RV, with similar results, where the inconsistencies are explained by the model development differences (EMTP-RV being full transient model while SimPowerSystems being an average model).

It should be noted that the cases tested were artificially generated and transients occurring in the power systems may result in different responses due to conditions to which the system has not been subjected here, such as inability to accurately measure the system frequency and voltage or supply unbalances. In summary, the control verification has shown that the control principles are reasonable, however, once connected to a realistic power system, which is subjected to typical disturbances, the performance may differ somewhat.

Chapter 4: Integration of Energy Storage

4.1 Introduction

The main drawback associated with wind energy, other than its relatively high installation cost, is the fluctuation of its output power as a result of variations in the wind speed. The DFIG can be used to smooth the output power by simply varying the torque characteristics, using a combination of pitch control and variation of the generator speed, with the end goal of regulating the supplied power. This is a technique commonly employed by wind turbine manufacturers such as *VESTAS* and *GE-Wind*. However, this requires operation at suboptimal points and therefore, a significant portion of the potential power capture is wasted in order to schedule more accurately the generator output power. Furthermore, it is only applicable at or above rated wind speeds and therefore, cannot help during low wind conditions.

The use of the generator inertia to regulate the output power is relevant at higher wind speeds when the output power approaches the rated value of the machine. In this case, the generator is temporarily storing energy in the inertia of the rotating mass. When the mechanical input power exceeds the required output, the generator speeds up and stores energy, which is later released when the input power falls below the reference. Therefore, the generator functions similar to a flywheel in this respect in order to regulate the output power. This action, combined with pitch control to reduce the input torque at higher wind speeds, allows some amount of power regulation.

The addition of energy storage has been considered for wind energy applications but its implementation has been slowed by the high cost. It has been shown that energy storage is capable of aiding in the regulation of the wind generator output power [50], [52], [53], however, the implications of this design choice have not been investigated in detail. Instead, these studies have focused mainly upon the technical requirements and have failed to address the issues of energy management and the added performance of wind generator. Integration of energy storage to DFIGs and induction generators have been presented in [54] and [55], respectively, however, further studies are still necessary.

In the present work, the basis for incorporation of super-capacitors into a DFIG is considered. A method of rating the energy storage element is provided and the controls for normal operation and operation at the limits are presented. This topology possesses the advantage that each of the wind turbines has its own energy storage, and therefore, it could be argued that the overall reliability of the system is improved compared with centralized energy storage. This is due to the fact that when a single generator is unavailable, the energy storage capability of the system and consequently the ability to dispatch a required amount of power is not lost.

4.2 Energy Storage System

Introduction of energy storage into the design adds another degree of complexity and the control is modified in order to account for the different modes of operation. Under normal operation energy is exchanged with the system based upon the system requirements: energy is stored when there is excess generation and is supplied when the output power drops below the reference level. However, it is necessary to consider the case when the storage element has reached either its upper or lower limit.

The control must be modified once the energy storage has completely supplied all of its energy or it is saturated, i.e. it has stored its total capacity. In this case, the DFIG is controlled as though the energy storage is no longer available and again the output power reflects the variations in the wind. In addition, the control must then detect when to revert back to normal operation in order to once again take advantage of the ESS. Furthermore, the maximum amount of power that the device may store or supply should be considered, however, this can be done indirectly through the current limit of the line side converter. Table 4.1 summarizes the considerations for the ESS control during the different modes of operation.

Table 4.1 Energy storage system control for normal and limiting operation

Energy stored	*Operation*	*Error signal*	*Transfer of control*
$E_{min} < E_{ESS} < E_{max}$	Normal	P_{grid}	$V_{ess} = V_{max}$ or $V_{ess} = V_{min}$
$E_{ESS} = E_{max}$	Upper limit	V_{dc}	$P_{grid} = 0.95\ P_{ref}$
$E_{ESS} = E_{min}$	Lower limit	V_{dc}	$P_{grid} = 1.05\ P_{ref}$

4.2.1 DFIG and ESS System and Rating

Through addition of energy storage in the dc bus, the line side converter can serve as either a source or sink of real power. The ESS may be either directly connected across the dc bus or alternatively it may be interfaced with the bus using a dc/dc converter. Fig. 4.1 shows the block diagram of the case where the ESS (in this case supercapacitors) is connected to the dc bus using a 2-quadrant dc/dc converter as is used in [48]. For this topology, the ESS regulates the dc voltage via the chopper while the line side converter regulates the generator output power.

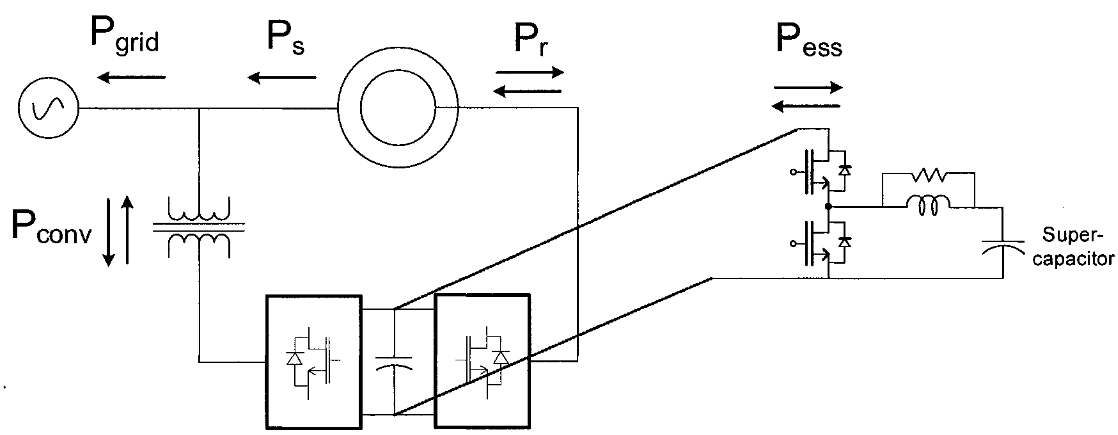


Fig. 4.1 Energy storage interfaced with dc bus using dc/dc converter

In this arrangement, the voltage across the ESS would vary between roughly 0 and 100% of V_{dc}, depending on the amount of energy stored. Once the voltage reaches one of the boundaries, the storage device becomes either saturated or exhausted and the control must be modified.

The design of the ESS must be such that it will be able to supply or absorb a certain amount of energy over a given period of time. For example, consider the requirement that the ESS be able to supply 20% of the rated power of the machine over a 10 min interval. In this way, the generator would still be able to output rated values even while the input torque was only 80% of nominal. In order to represent the rating of the storage system, the size of the supercapacitor is determined as follows:

$$E_{ESS} = 0.2 P_{rated} t \tag{4.1}$$

$$E_{ESS} = \frac{1}{2} C_{SC} \left(V_{\max}{}^2 - V_{\min}{}^2 \right) \tag{4.2}$$

$$C_{SC} = \frac{0.4 P_{rated} t}{\left(V_{\max}{}^2 - V_{\min}{}^2 \right)} \tag{4.3}$$

If an energy storage element other than supercapacitors is used, the modeling will be somewhat different, however, the basic idea is the same. Also, it is worthwhile noting that the rating of the energy storage device can be more or less translated into addition cost and therefore it should be minimized to a certain degree (there is however, a fixed cost associated with the storage system components, e.g. switches, additional controls, minimum storage device rating). Also, the storage requirements on a per machine basis will be reduced as the number of the generators in the wind park is increased. This is due to the fact that in larger wind parks there is an averaging effect over all the generators and therefore, the dispatch to a single generator may be more flexible whereas the combined energy storage will account for fluctuations in the power at the point of common coupling and not the output power of the generator itself. Alternatively, a more reasonable design may be to include ESS in only a few of generators dispersed throughout the wind park.

4.2.2 Energy Storage Control

The addition of energy storage in the dc bus requires some modifications to the controls, which were outlined in the previous chapter and an additional control function for the dc/dc chopper. The control of the rotor side converter remains unchanged since the flow of energy is to or from the grid via the line side converter. The output power of generator system is now regulated using the line side converter while the regulation of the dc bus becomes the responsibility of the dc chopper.

4.2.2.1 Supply Side Converter

The supply side converter is controlled to regulate the generator output power to its reference and to provide reactive power depending on system requirements, Fig. 4.2. The reactive power reference is chosen to control the ac bus voltage to its reference value. Converter limits must be taken into account and the amount of real power supplied by the converter will dictate the maximum available reactive compensation available from the converter.

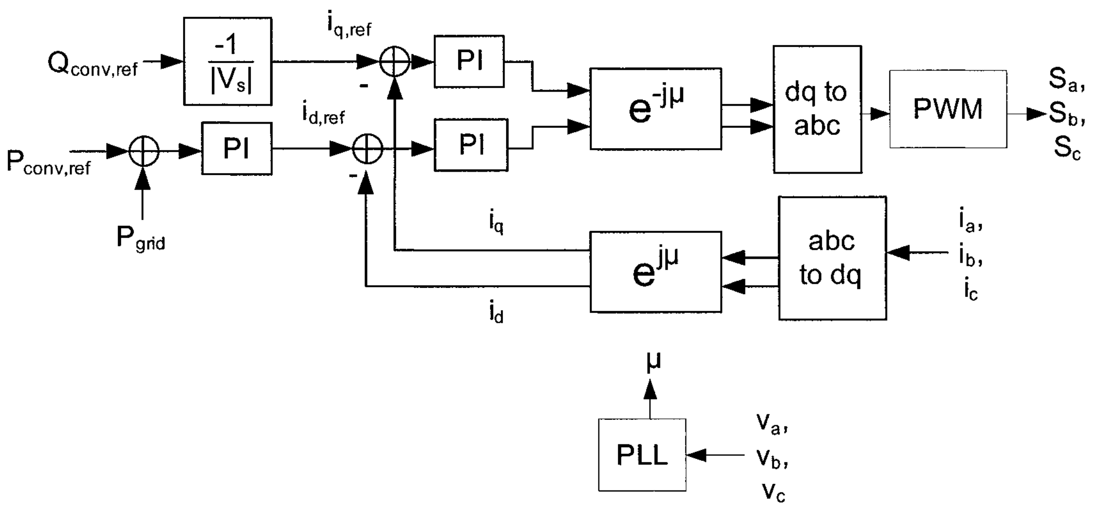


Fig. 4.2 Supply side converter control algorithm for DFIG with ESS

4.2.2.2 Dc/dc Converter Control

Under normal operation, the dc/dc converter is controlled in order to regulate the dc voltage to its reference, Fig. 4.3. In this way, energy is exchanged with the system indirectly through regulation of the dc bus. Although the line side converter sets the power injected to the system, the chopper responds to changes in the dc bus voltage and thereby, facilitates the flow of energy to or from the storage device.

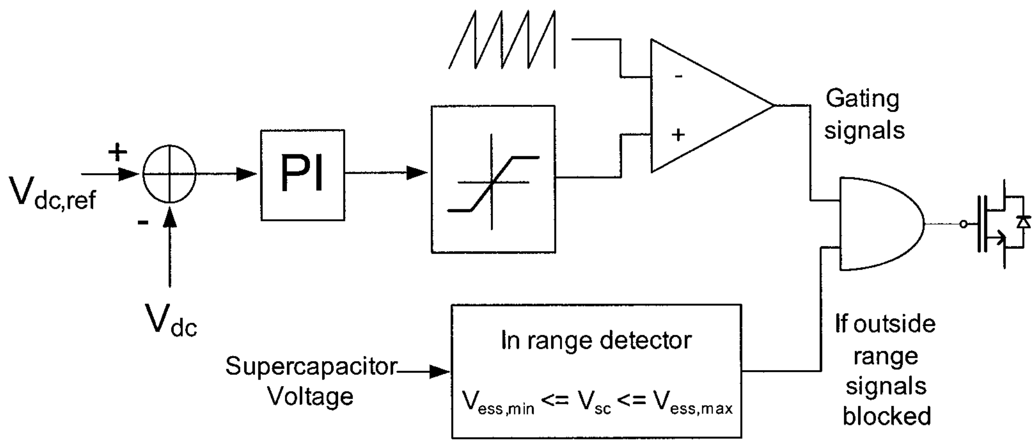


Fig. 4.3 Dc/dc converter control for regulation of dc bus and supplementary control for detection of limits

4.2.3 Energy Storage Limitations

The control of the DFIG system is unchanged with regards to the rotor side converter as a result of the addition of the ESS, whereas the supply side converter control enables the transfer of energy to or from the storage device. The line side converter control is modified in order to regulate the power supplied to the grid, P_{grid}. Then the regulation of the dc bus voltage is accomplished by the dc/dc converter, and in this way energy is exchanged between the grid and the storage device.

However, due to abnormal wind speeds such as particularly stormy or calm conditions, the ESS may reach either its maximum storage capability or become completely discharged. Under these conditions, the control of the line side converter and the dc/dc converter must be modified.

First, the detection of the limiting condition is necessary, which can be accomplished simply by monitoring of the ESS dc voltage. Once either the upper or lower limit is reached the control of the two converters of interest change. The line side converter becomes the dc-voltage regulator, the feedback signal and reference switching from the generator powers to the dc voltage. The gating signals to the dc/dc converter are then blocked and the ESS is essentially disconnected from the system.

The condition to change back to the normal control algorithms is detected using the voltage across the ESS and by monitoring the signal:

$$P_{grid} - P_{grid,ref} \tag{4.4}$$

If the expression in (4.4) is > 0 it suggests that energy could be stored and therefore if $V_{ESS} = V_{ess,min}$ then the ESS control should be reactivated. On the other hand if (4.4) is < 0 and $V_{ESS} = V_{ess,max}$ then the ESS control should be enabled such that energy is injected into the system. In this way, the state of the ESS is constantly monitored and transfer between normal and contingency operation is possible. In order to prevent oscillations between the two states of operation, a small hysteresis band is introduced such that the conditions to switch back to ESS control become the following:

$$V_{ess} = V_{ess,\min} \quad and \quad P_{grid} \geq 1.05 P_{grid,ref} \tag{4.5}$$

$$V_{ess} = V_{ess,\max} \quad and \quad P_{grid} \leq 0.95 P_{grid,ref} \tag{4.6}$$

The actual size of the bands could be adjusted based upon specific requirements, they have been chosen arbitrarily as 5% above only to convey the concept. The block diagram representation of the energy management is shown in Fig. 4.4.

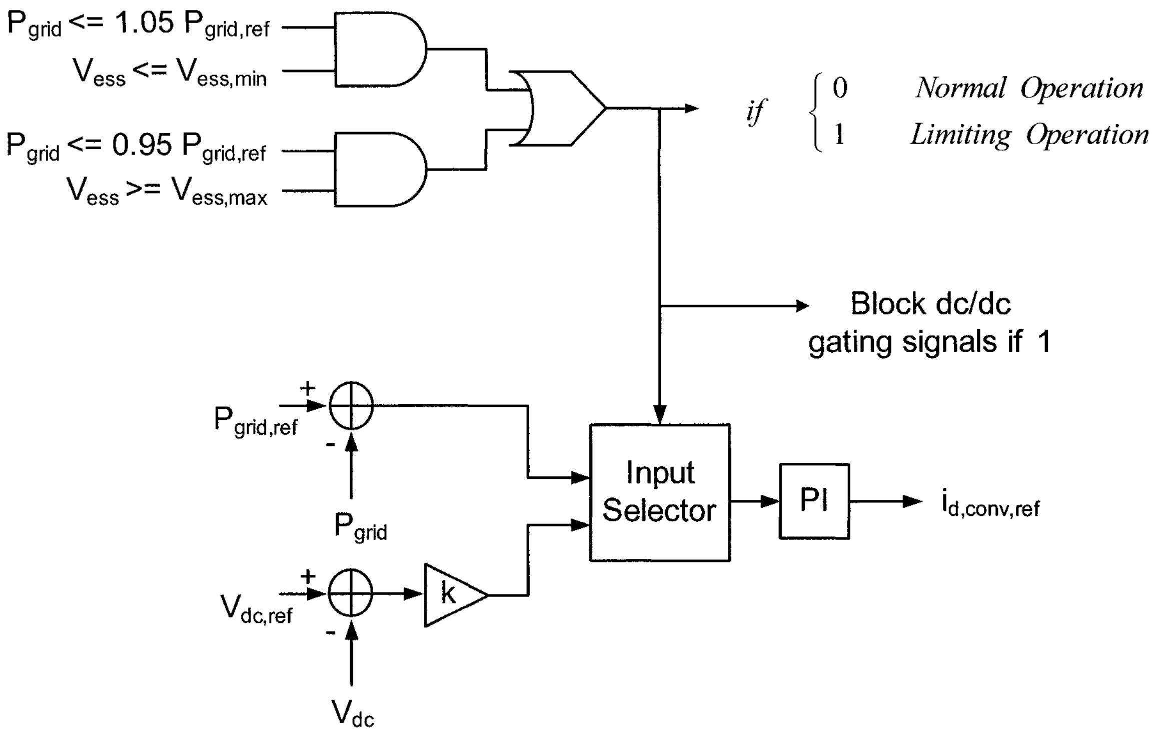


Fig. 4.4 Control algorithm to transfer control between different states of operation

4.3 System Characteristics

The benefits of energy storage are demonstrated in the following section. Here the DFIG and DFIG and ESS systems are compared to show how energy storage enables a much greater control over the output power profile compared with the more conventional case. The DFIG system is simulated using two control schemes: (i) tracking of the peak power points and (ii) limited output power regulation using combined inertia and pitch control. Here, the results are shown for a single generator only whereas the multiple machine case is considered in Chapter 5.

The test system used in this study consists of a single machine connected to the Thevenin equivalent representation of the grid. In order to highlight the need for reactive power, the short circuit ratio (SCR) of the system is set to 6, characteristic of a weak system. The reactive power reference is set in order to regulate the grid voltage using a 3% droop characteristic.

4.3.1 Normal Operating Characteristics

During normal operation, the line side converter functions as the power regulator and helps the DFIG to supply the required amount of power. In this way, the wind generator is able to capture the maximum amount of power and at the same time deliver the dispatched power to the grid. In addition, this is no way interferes with the reactive power control of the generator, which continues to be decoupled from the real component and can be used to help support the grid voltage.

Fig. 4.5 and Fig. 4.6 show the real and reactive power flows for the cases of the DFIG with and without energy storage, respectively. As can be noted the DFIG is able to supply 0.9 pu of real power over the entire 50 second interval in the case where energy storage is used. In the case without energy storage the output power fluctuates with the changes in the wind. The reactive power flows are decoupled from the real power, however, slight discrepancies between the reactive power flows can be noted in the two cases. This can be explained by the fact that the real power flows play a role in the change in the terminal voltage. As the reactive power reference is chosen in order to regulate the ac bus voltage it is no surprise that Q is highly variable in the case without energy storage whereas it is fairly constant in the case with ESS.

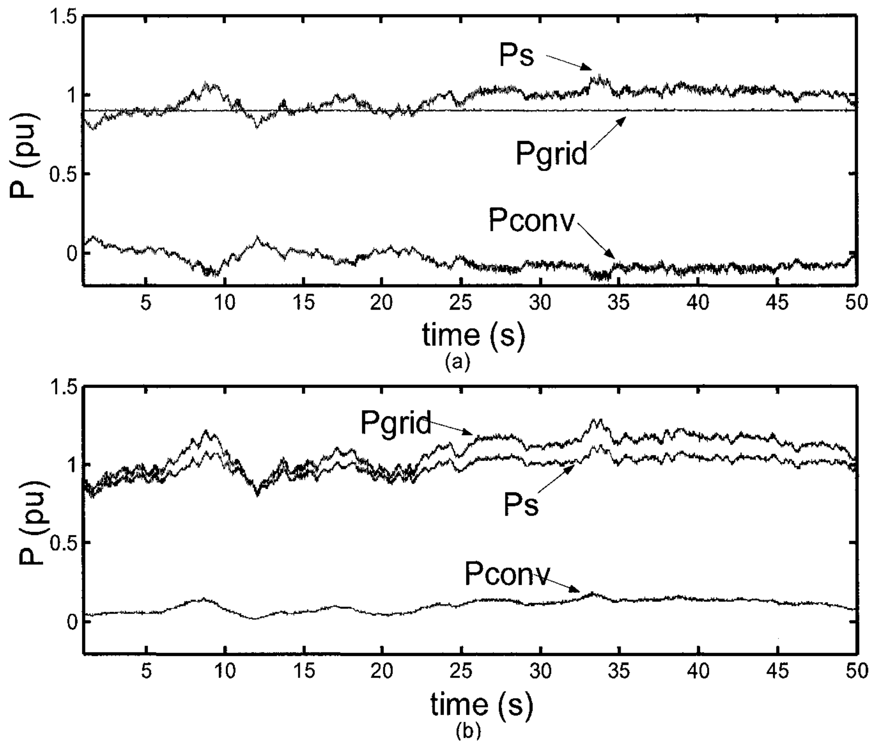


Fig. 4.5 Power flows for DFIG (a) with and (b) without energy storage

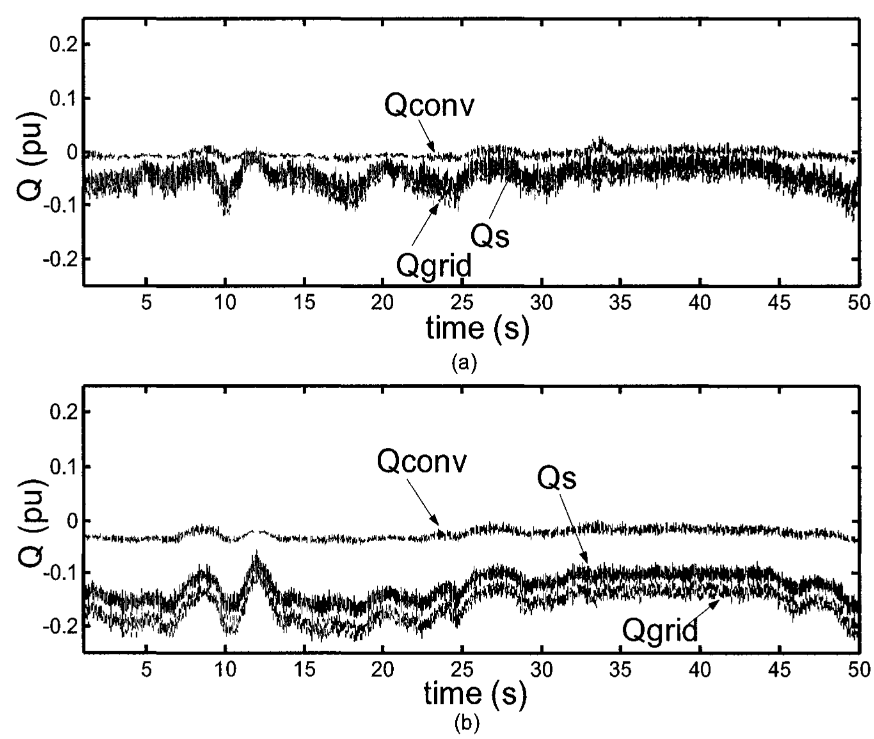


Fig. 4.6 Reactive power flows for DFIG (a) with and (b) without energy storage

Finally, the alternate power control scheme can be considered where the generator speed and torque characteristics are controlled in order to regulate the stator power during high wind speeds. Fig. 4.7 presents the real power flows in this case along with the case where the peak power points are followed and energy storage is used. It can be noted that although the output power reference (P_s for case *a* and P_{grid} for case *b*) is regulated in both cases, the case with ESS is able to capture a greater amount of power over the entire period since it tracks the peak power points. Also, when the wind speed drops below a certain level, the pitch control of the generator is unable to help boost the generation. Although the two cases perform similarly during high wind speeds, energy storage possesses the clear advantage that it can not only provide continuous regulation but it is also able to capture a greater amount of wind over the entire time interval, assuming of course that it does not exceed it storage limitations.

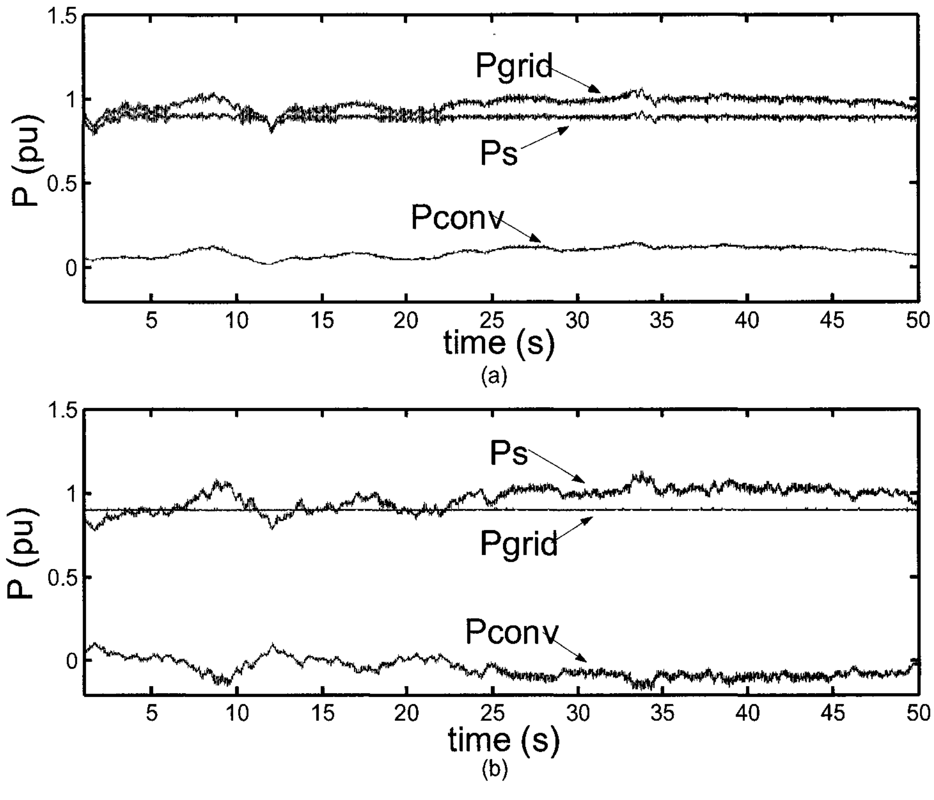


Fig. 4.7 Real power flows for output power regulation using (a) suboptimum power points (b) energy storage

4.3.2 Contingency Operating Characteristics

Although energy storage improves the ability to dispatch the wind generator, it cannot realistically accomplish this feat at all times, due to the fact that the ESS has a finite limit to both store and provide power. Therefore, the ability of the control to handle these conditions as well as to be able to transfer control back to normal operation must be verified. To accomplish this, the rating of the energy storage is reduced, thus causing it to reach its limits with greater frequency. Alternatively, the system could be tested using long periods of low wind speeds followed by long periods of high wind speed, however, it was deemed preferable to demonstrate both cases together and therefore, the former of the two procedures was chosen.

Following reduction of the supercapacitor rating to 5%, the simulation was repeated to verify that energy management control could successfully handle the limiting conditions. Fig. 4.8 shows the response of the system when the energy storage rating has been reduced. Here both the ESS voltage and grid power have been normalized in order to present the results on the same axis.

As can be noted, the system fails to achieve the reference output of 0.9 pu when either the upper or lower limitation of ESS is reached. At this point, dc regulation control is transferred to the line side converter and the power exported to the grid then fluctuates with the wind speed. Once the condition to reactivate the ESS is received, the line side converter again regulates the output power to the specified reference. This confirms that the system is not only able to handle these extraneous conditions but is also able to transfer back to normal operation.

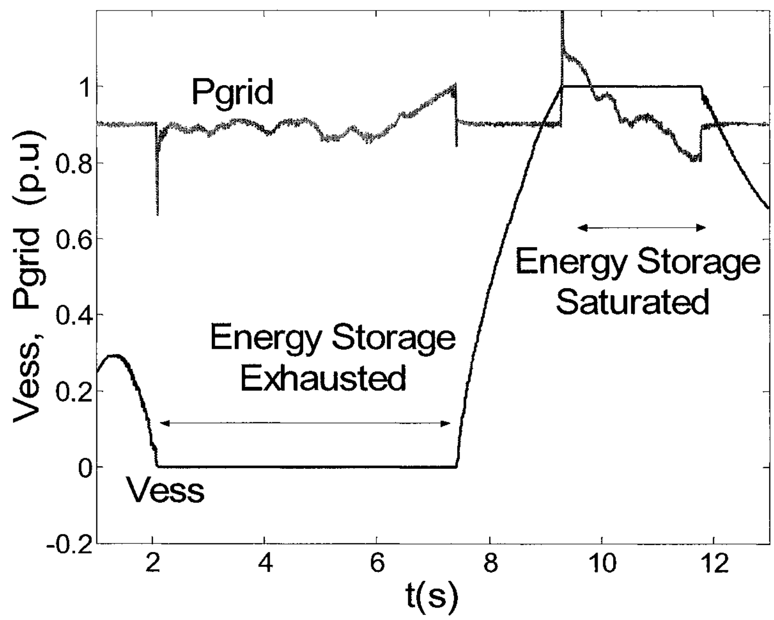


Fig. 4.8 Grid power and supercapacitor voltage. Peak power point tracking algorithm enabled

4.4 Conclusions

Wind energy conversion systems suffer from the fact that their real power generation is closely dependent on the local environmental conditions, namely wind speed and air density. This chapter has shown that through integration of supercapacitors in the dc link of the DFIG, full control over both real and reactive power becomes possible. This enables not only dispatching of the generator but also decreases the variability in the reactive power requirements as well, particularly in the case of a weak system.

The control modifications brought about by the addition of the energy storage system were presented as well as a method for handling the limitations of the energy storage device. The benefits of the ESS were highlighted by comparison with the more conventional DFIG systems using a single generator system. Finally, the ability of the control algorithm to handle the contingencies was confirmed. This provides the basis for larger system studies which will be treated in the following chapter where the behavior of the DFIG and DFIG-ESS will be contrasted in a multi-machine network, with operation in both an intact and faulted system.

Chapter 5: Grid Interconnection of DFIGs

5.1 Introduction

The impact of the interconnection of wind generation on the power system is of the greatest interest from a utility perspective but also for the advocates of wind energy. Transient simulations of high penetration wind energy systems can be used to propose and test new technologies and methods that limit the disadvantages of wind, thereby indirectly promoting its growth. The limiting factors to the increased growth of wind energy technologies are technical as well as economic and political, and an improvement in any of these areas will aid in the acceptance and further development of wind power.

Here the proposed DFIG-ESS system is compared on a system level with the conventional DFIG topology. Transient models of the two wind parks with identical ratings are compared for a power system interconnection representative of a weak system. The performance under normal operation as well as in response to a variety of potential contingencies is considered.

5.2 Wind Park Interconnection

The wind park is connected to a 50 km, MV feeder that is in turn fed from a high voltage (HV) transmission system via a 69/230 kV transformer, Fig. 5.1. The dual transmission line also serves a local PQ load. The total installed capacity of the wind park is 40 MW while its reactive power capability is rated at 0.5 pu or ±20 MVAr.

The wind farm itself is composed of four turbines, each represented using the transient models developed in the previous chapters. Aggregated models were used assuming that each grouping of 10 turbines is subjected to identical wind conditions, whereas the wind speed experienced by the neighboring aggregated turbines uses the same wind data only delayed by 5 seconds. In this way, the averaging effect can be observed while maintaining a reasonable length of simulation time.

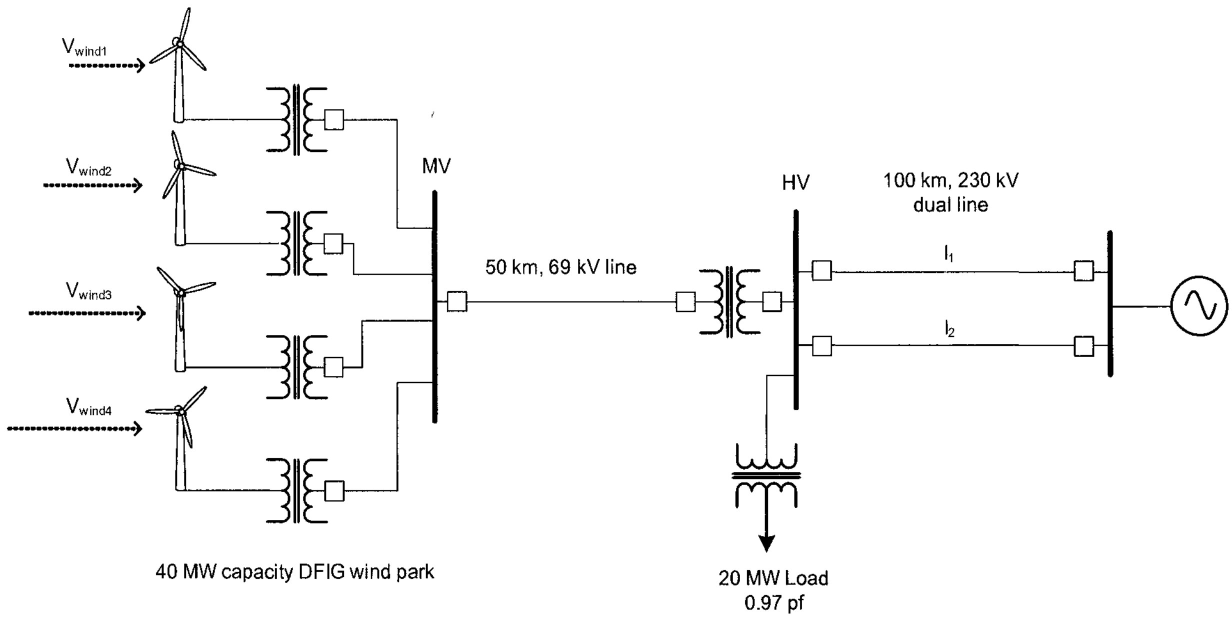


Fig. 5.1 Interconnection of small wind farm with power system for transient system level studies

The wind park is subjected to numerous tests in order to compare the steady-state nature of the systems as well as its response to various disturbances. Each of the turbines is equipped with protection settings and as mentioned, each of the aggregated models experiences different wind conditions. Details regarding the generator parameters and network data can be found in Appendix B.

5.3 Normal Wind Farm Operation

The operation of the two systems under typical conditions was considered first. Here, the behavior of the wind parks over a 20 second window was simulated. The generators actively participate in the support of the local MV bus and therefore, the response of the real and reactive power flows are presented and analyzed.

5.3.1 Real Power Production

The power flows are shown in the case of the conventional wind farm composed of DFIGs, Fig. 5.2. Each of the generators supplies a different amount of power, as the individual output power is proportional to the local wind conditions. The combined output power is much more constant as the output powers are averaged. This demonstrates that in larger wind farms, the different wind conditions contribute to the smoothing of the output power. Fig. 5.3 presents the differences between wind parks composed of DFIG versus those made up of DFIG-ESS. In addition, the averaging effect is demonstrated by including the case where each generator sees identical wind speeds.

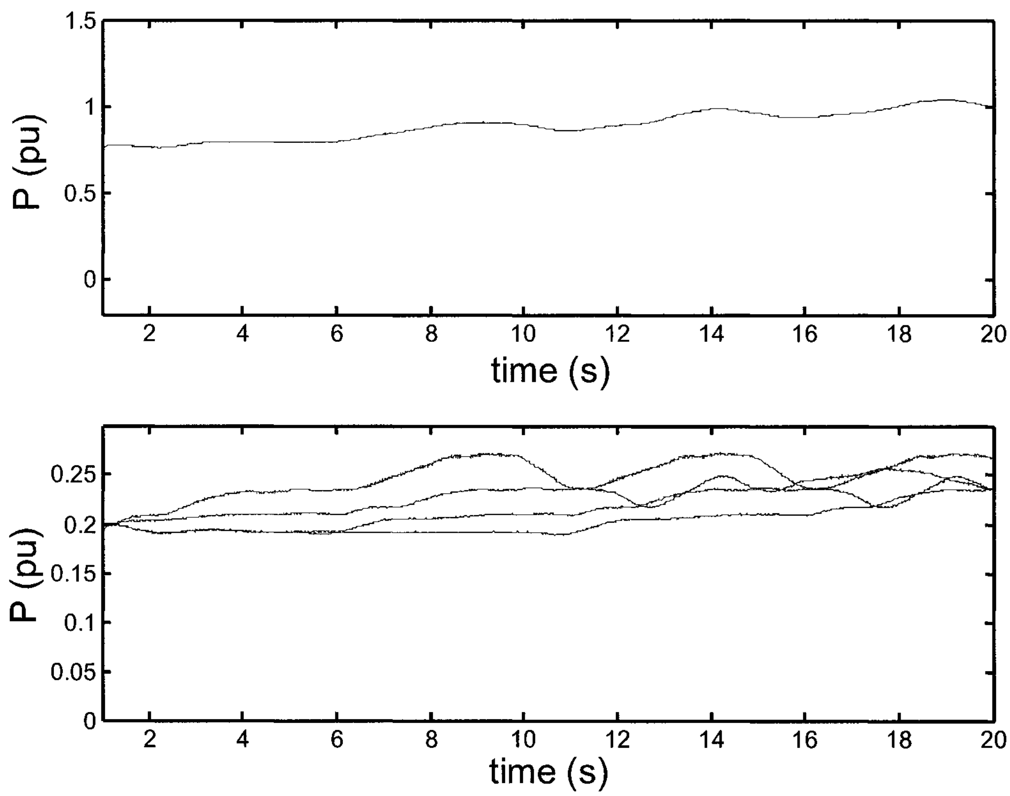


Fig. 5.2 Power flows of individual generators and combined power supplied to the system

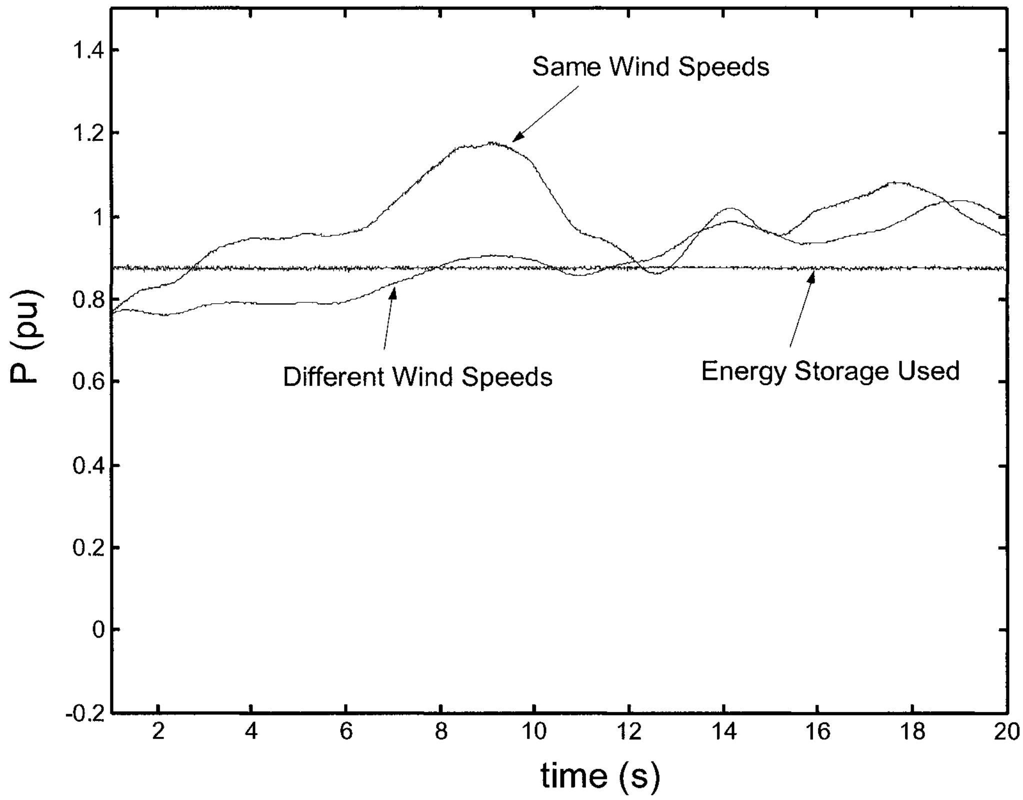


Fig. 5.3 Power supplied to the system for the cases of identical wind conditions, different wind conditions, and DFIGs with energy storage

5.3.2 Voltage Regulation

Although the reactive power ratings of the two different wind generator topologies are identical, the reactive power requirements depend closely on the output power of the generators. In the above cases, the reactive power reference is chosen to regulate the voltage at the point of connection of the wind turbine to 1 pu, with a 3% droop. Due to the fluctuating output power in the case of the DFIG alone, the reactive power also fluctuates in order to regulate the terminal voltage to the required reference. In the case of the DFIG-ESS, the output power is held constant and with all other things being equal, the reactive power supplied by the generator remains constant as well, Fig. 5.4. In addition, the reactive power supplied is fairly small, since the real power is regulated close to the rating of the machine, which allows a given margin for reactive power capability under transient conditions.

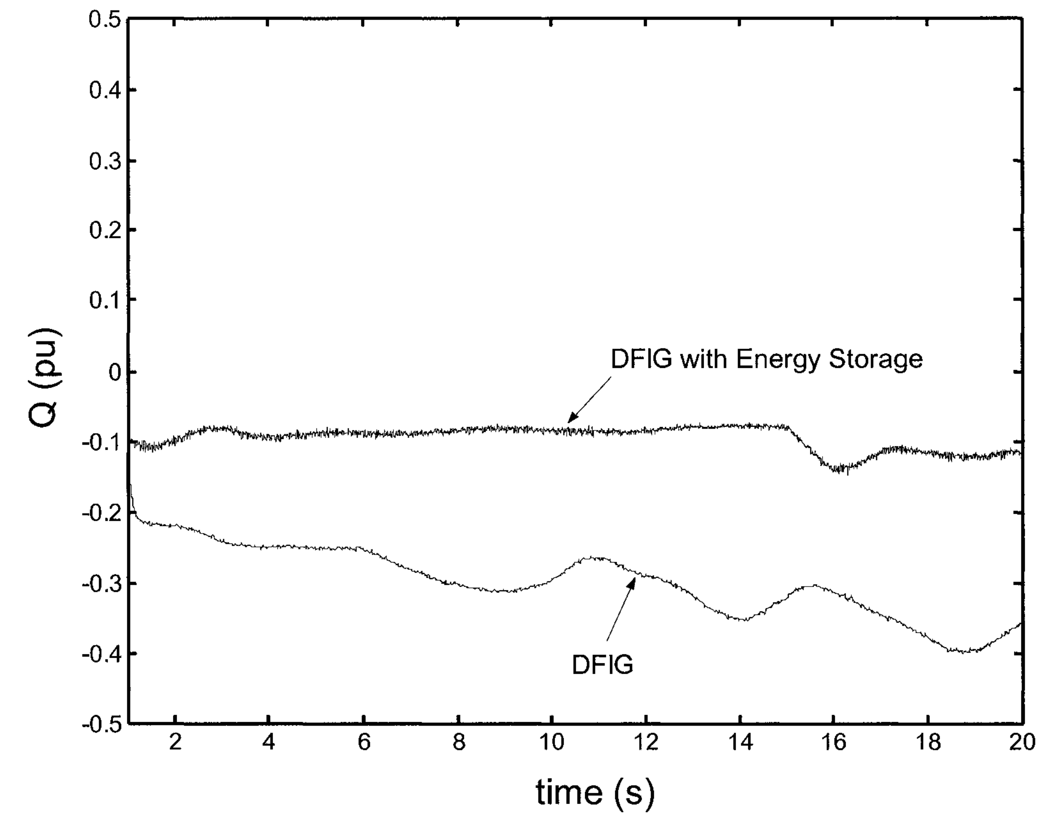


Fig. 5.4 Reactive power supplied by wind farm with and without energy storage

5.4 Power System Disturbances

The performance of the system in response to various disturbances was investigated since the transient stability of the system depends on its ability to handle various contingencies that can occur within the system. The various types of faults that can arise are treated, including both permanent and temporary faults. The disturbances tested follow in order of decreasing frequency and increasing severity. A summary of the faults tested is included in Table 5.1 and the fault locations are presented in Fig. 5.5.

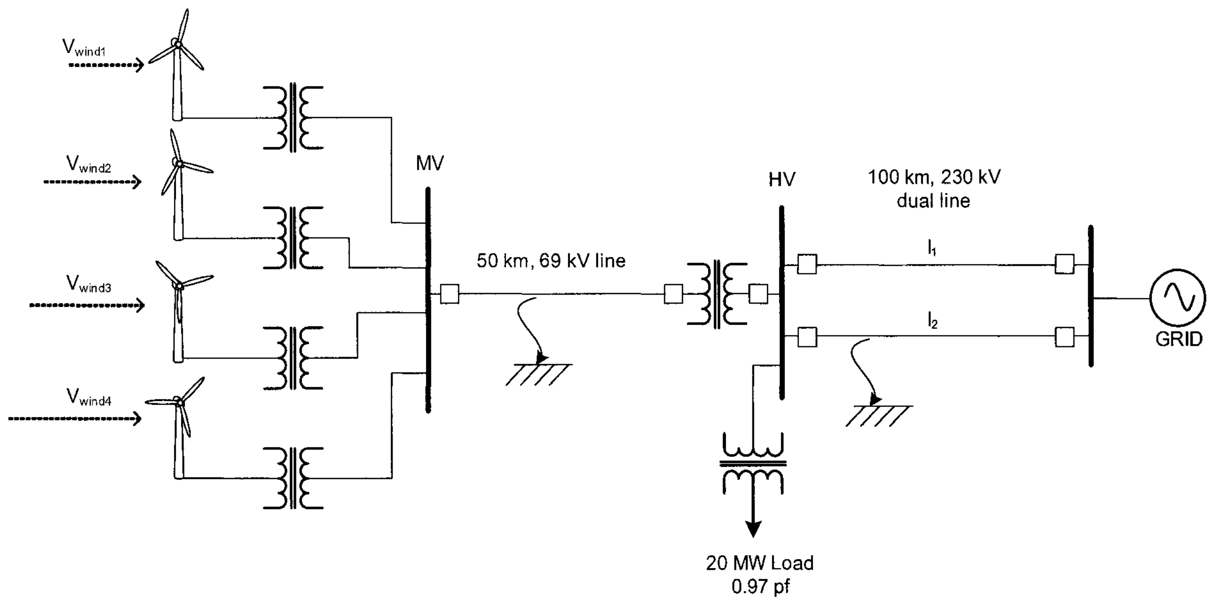


Fig. 5.5 Network representation showing locations of various faults for transient response studies

Table 5.1 Fault information for system transient response studies

Case[1,2]	*Fault Type*	*Fault Length*	*Fault Location*
1	P-G	Temporary	HV line
2	P-G	Temporary	MV line
3	P-P-G	Temporary	HV line
4	P-P-P-G	Permanent	HV line

1 - Fault clearing time of 9 cycles, 2 – Reclosing time of 30 cycles

5.4.1 Asymmetrical Faults

Asymmetric faults are the most common type of faults occurring in the power system, most often resulting from lightning strikes hitting overhead lines. Here both single-phase to ground and phase-phase-ground faults are considered. Typically, they are nonpermanent faults and therefore, following reclosing it has been assumed that the fault has been cleared. It has been assumed that the circuit breakers clear the fault 9 cycles after its occurrence and that a 30 cycle reclosing is used, both typical values [59].

5.4.1.1 Single-Phase to Ground

Single-phase to ground faults were considered on the HV transmission line as well as on the MV distribution feeder. The case of the HV line is the least serious of all of the faults considered since it is a dual transmission line, and the generators recover following a short acceleration. Upon reclosing, there is a very small transient, so small it is hardly noticeable, since the generators have already decelerated and the voltage has assumed its normal operating value, Fig. 5.6. The conventional DFIGs performance resembles very closely that of the DFIG with energy storage and no important differences can be noted.

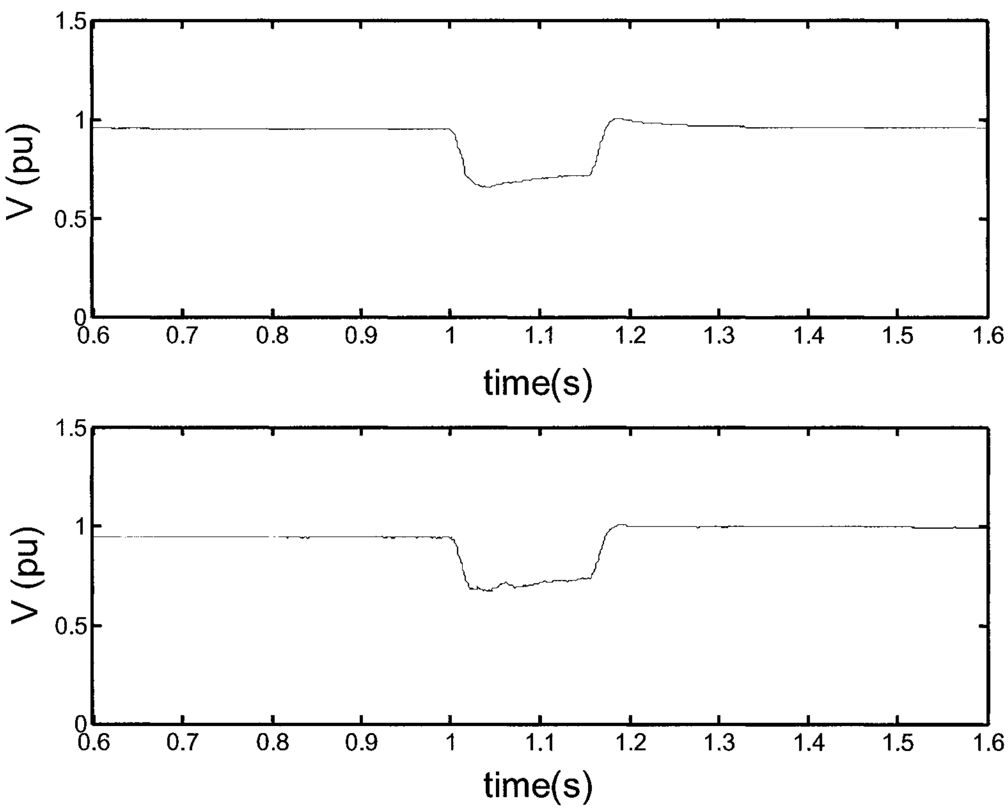


Fig. 5.6 Single phase fault on transmission line for DFIG (upper) and DFIG-ESS (lower) systems

The single phase fault on the MV line is a much more serious fault since it is located much closer to the wind park itself and is the only connection between the park and the rest of the system. As is sometimes done in protection systems, only the faulted phase is opened, allowing continued connection of the two unfaulted phases and transmission of power [59]. However, this implies unbalance operation of generators from the time of fault to reclosing. In this case, the DFIG-ESS clearly outperforms the DFIG. This is due to the fact that the dc bus is held more constant whereas, in the case of the DFIG, the dc voltage becomes unstable and the generator is never able to regain control. In addition, since the power transmitted by the DFIG-ESS is set by the magnitude of the system voltage, the generator curtains its output during this period and thereby limits its acceleration. Clearly the DFIG-ESS dominates in this case and the system voltage re-stabilizing following the fault, Fig. 5.7.

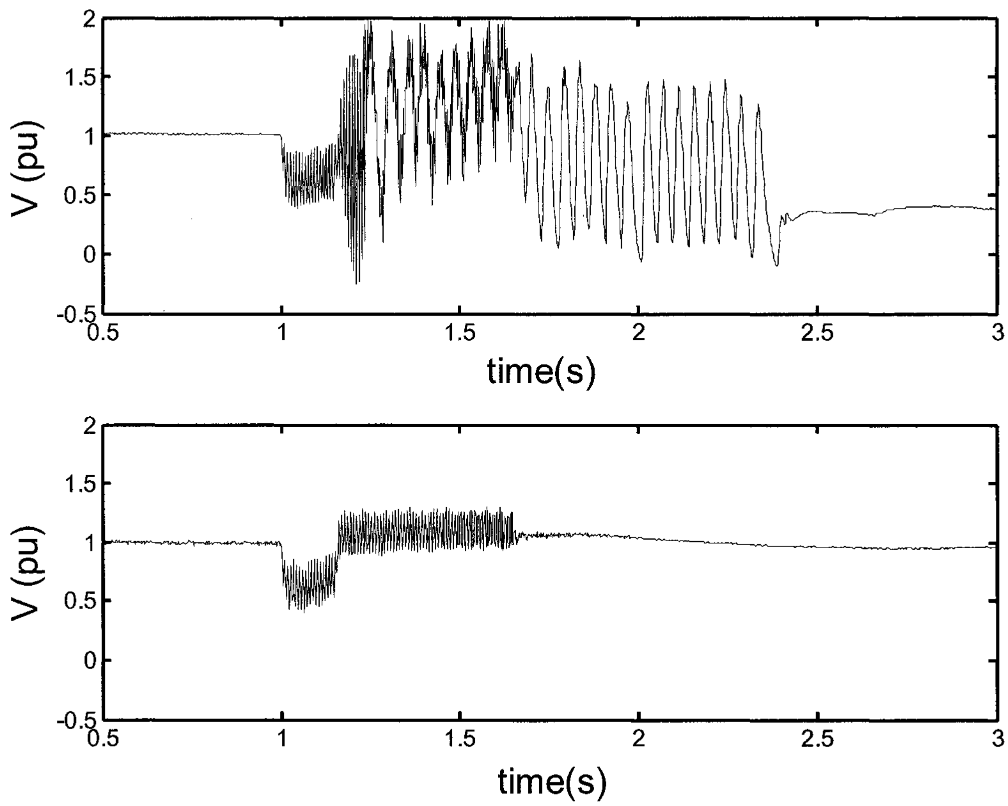


Fig. 5.7 Single-phase to ground fault on 50 km, MV line for DFIG (upper) and DFIG-ESS (lower) systems

5.4.1.2 Phase-Phase-Ground

Here the phase-phase-ground fault is considered only at the transmission level. Compared with the single phase fault, it is much more serious causing the voltage magnitude to dip considerably. The DFIG-ESS performs much better as it is able to re-stabilize the system voltage a short time following the fault clearing, prior to reclosing.

Again the ability to maintain a constant dc voltage immediately following the fault enables the generators to aid in voltage recovery. It appears that the voltage in the DFIG case may eventually recover but the recovery time is significantly longer and likely overvoltage or other protections would cause the generator to trip before the voltage stabilizes.

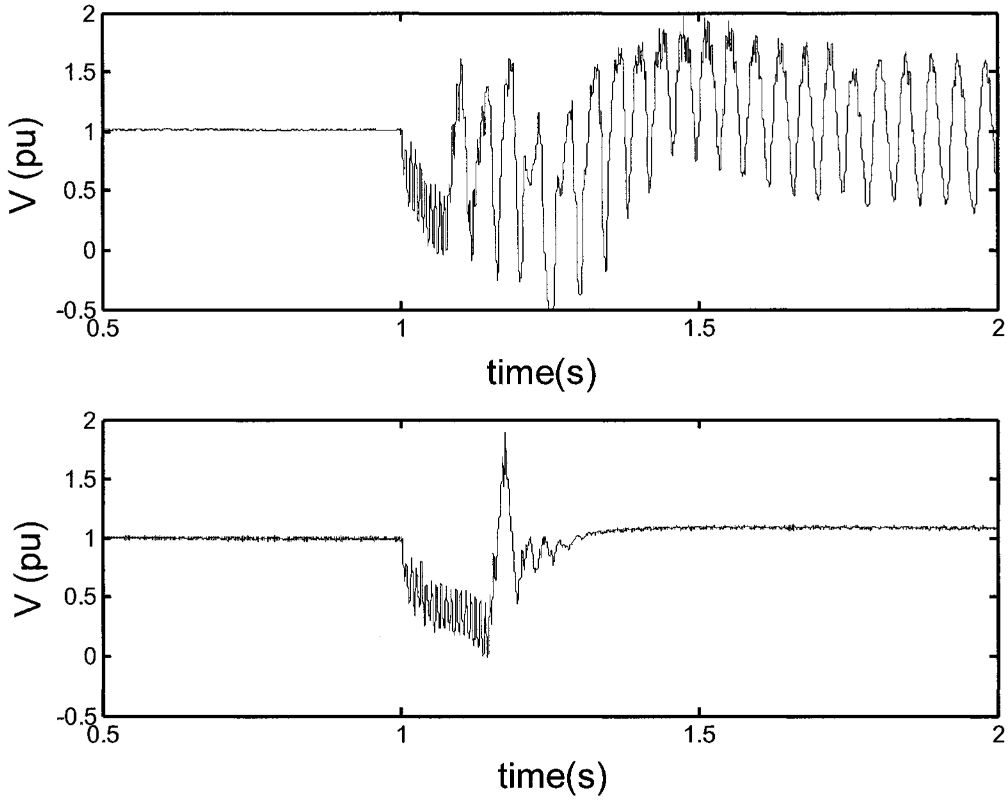


Fig. 5.8 Phase-phase-ground faults at high voltage level for DFIG (upper) and DFIG-ESS (lower) systems

5.4.2 Three-Phase to Ground Faults

Three-phase to ground faults are the most uncommon faults and most of the time they are permanent faults, likely the result of broken conductors or a fallen tower and therefore require the services of the utility workers. Thus, only a three phase fault on the HV transmission line was considered since in the case of the MV line, a permanent three phase faults will invariably lead to tripping of all generators.

As in the previous two cases the DFIG-ESS system dominates and the system is stablizes following the fault and the upon reclosing onto the fault. In the case of the DFIG, voltage stability is lost and it never regains normal operation which would eventually lead to tripping of the wind generators. Once again the loss of the dc voltage is likely the root cause of the instability since the voltage stability is lost long before the generator overspeed protection is activated.

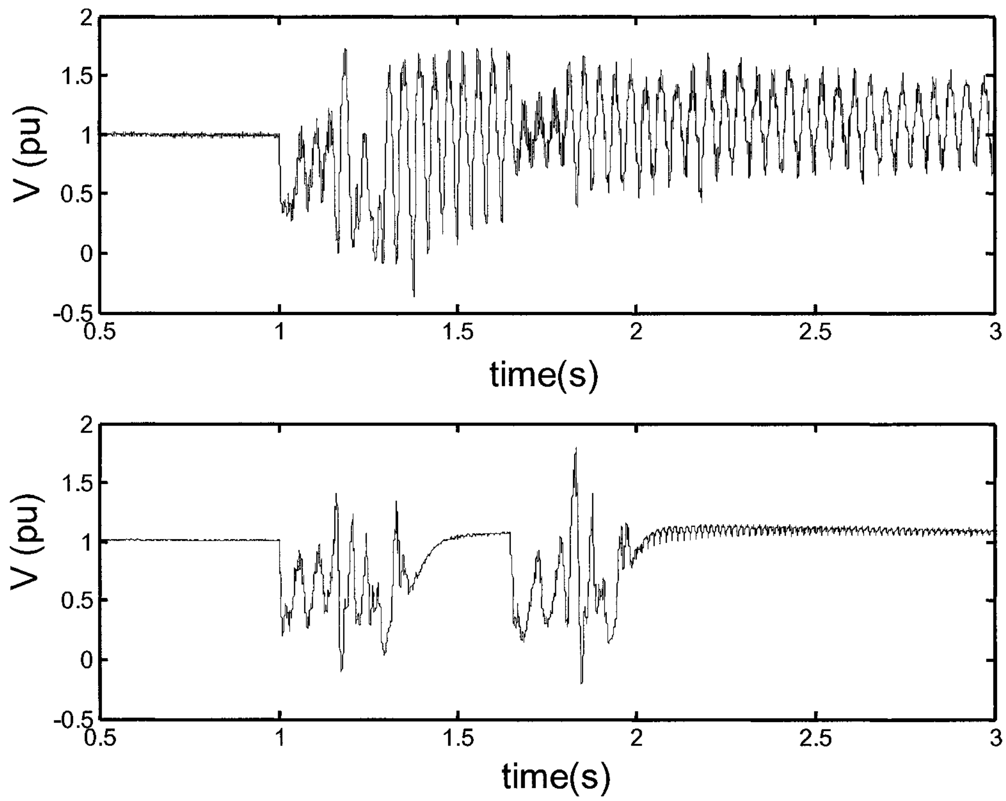


Fig. 5.9 Three phase permanent line to ground fault on dual transmission line

5.5 Conclusions

This chapter has highlighted the advantages of including energy storage in the design of a DFIG based wind generator by considering the system level performance of a wind park based on this technology. The performance of the wind generator is improved both the areas of steady-state operating characteristics as well as the response to faults on the system. The improvement of the transient performance appears to be due to the ability of the DFIG-ESS to hold the dc bus voltage during faults and thereby continue to aid in voltage support. The ability of the DFIG-ESS to curtail its output power during voltage dips also helps to limit the acceleration of the machine and prevent the tripping of the generator by the overspeed protection. However, the primary problem seems to be voltage stability and not overspeed tripping. Also, the study reveals that asymmetrical faults appear to be particularly problematic for the DFIG, perhaps as a result of unbalanced operation.

This study is particularly interesting as is enables the study of a fairly large system composed of DFIG generators and demonstrates the transient characteristics, offering insight into the behaviour of unbalanced operation and the ability of the generator to improve transient stability. It sets the framework for future studies to compare not only the implementation of energy storage but perhaps more importantly the performance of different wind generator topologies.

Chapter 6: Conclusions and Future Work

6.1 Summary

This work has contributed to the research on wind energy by examining the advantages associated with the addition of an energy storage device to the DFIG design. This was done first from the standpoint of a single machine and then was considered for the case of a wind park. The research revealed benefits in terms of improved controllability of output power and also improved response following local disturbances, namely symmetrical and asymmetrical faults. Although the work has given some insight into what can be gained through the use of energy storage devices, there is still much to be done in the areas of energy storage applications and wind energy.

6.2 Conclusions

Energy storage has long been considered for its use in conjunction with wind energy conversion systems and in this work it has been studied using the DFIG topology. Just as the DFIG is not always the chosen technology among wind turbine options, the type of energy storage presented here will likely not be suitable in all cases either. The technical requirements associated with the integration of energy storage have been presented, from the power electronics and control perspective.

Controllable output power is the main benefit to using an energy storage device. Particularly in the case of a weak system, where the terminal voltage depends strongly on the power flows, limiting the fluctuations in the output power can contribute to a more stable voltage at the PCC and consequently to a reduction in fast reactive power requirements. Furthermore, the ESS enables the maintenance of a firm dc bus voltage, even during faults when short circuit current contributions from the machine and the inverter can cause steep drops or rises in the dc voltage.

Although mentioned briefly, the feasibility of this design was not examined in full, something that would require extra attention in order for the DFIG-ESS hybrid to achieve the same level of acceptance from the wind power industry that the conventional DFIG has attained.

6.2.1 Doubly-Fed Induction Generator

The DFIG is one of the most popular choices for wind turbines due to the favorable characteristics of variable speed operation, decoupled control of the real and reactive power, speed control, and limited control over the output power. Therefore, the DFIG became the logical choice for the study of integration of energy storage. In addition, it requires a dc bus making the integration of energy storage easier since almost all ESS require some kind of dc interconnection. A DFIG model was developed using both EMTP-RV and MATLAB-SimPowerSystems and the control strategy was verified. The allocation of reactive power was studied in detail and it was shown that the majority should be delivered from the rotor side converter in or to minimize current flows and consequently kVA ratings.

6.2.2 Energy Storage

Energy storage systems of large ratings are still relatively expensive, a characteristic which slows their implementation in power system applications. There exist many different technologies and here supercapacitors were applied in order to smooth the fluctuations in the wind generator output power.

Following cross validation of the developed DFIG wind turbine model, supercapacitors were added to the design, interfaced with the dc bus using a two-quadrant dc/dc chopper. This design enabled the turbine to schedule the output power accurately, while tracking the peak power points. In addition, the constant output power reduced the fluctuations in reactive power requirements.

The benefits of energy storage were further demonstrated when comparing the system level characteristics of the two generator designs. The DFIG-ESS showed more desirable performance in terms of both steady-state operation and transient response. The energy storage element enables the generator to maintain a more stable dc bus voltage even under severe faults in the local power system. In addition, the DFIG-ESS can store some excess power during local faults limiting the acceleration of the generator, and thereby maintaining operation within the normal limits. Although voltage instability was observed prior to over acceleration in the cases considered for the DFIG, overspeed tripping could be greater factor for fault conditions not considered here or in the case of smaller machines where the inertia of the machine is greatly reduced.

6.2.3 Alternate Topologies

Although the DFIG is one of the most promising technologies for wind power, especially in the area of off-shore wind farms, it will still have to compete with the other forms available, the direction in which industry seems to be headed. Investors may prefer simpler technologies such as the squirrel cage induction machine or else the DFIG may simply not be practical in some applications like distributed generation, where the size of the turbine may be less than 1 MW. Furthermore the PMSM has been shown to be a potential competitor in high power designs. However, in all these cases, energy storage can still improve the system performance, although the integration of the device may be completely different from that presented.

The concept of distributed versus centralized energy storage can be illustrated by comparing two different wind farms: one composed of DFIG-ESS and another made up of induction generators and a SMES. The two systems have similar characteristics from the point of common coupling (PCC), however, they have very different structures, controls, and protection. These concepts can be contrasted to learn more about not only the operation of systems utilizing energy storage but also regarding the benefits of various arrangements compared with their alternatives.

The application of energy storage and reactive power sources is becoming a subject which is not only relevant to wind power but also to distributed generation and the architecture of the future distribution networks. Before the implementation of energy storage to even small wind power systems becomes a reality, reactive power and voltage stability concerns will be increasingly investigated. The control of capacitor bank switching and tap changing transformers as well as the use of STATCOM and SVCs will likely become very important issues in the near future whereas energy storage will follow as a logical progression.

6.3 Future Work

The work presented here has only moderately investigated the application of energy storage to wind power, with wind power being only one of a wide variety of possible applications. Although the implementation of ESS to the DFIG has been outlined, the same principles and modeling are required for other energy storage devices but also for other wind energy technologies. Following the development of the different systems, a thorough comparison could be performed, looking at everything from performance characteristics, to installation and operational costs, to the availability and practicality of the various technologies.

6.3.1 Energy Management

The comparison of these different technologies invariably leads to issues regarding control and management at a higher level. The problem of how to coordinate the flow of energy as well as the dispatch of the various generators in a larger wind farm becomes a complicated but interesting debate. Certainly there are optimal means of scheduling the individual generators and the energy storage devices in order to achieve the desired characteristics, while taking into account system losses, costs, and other limiting factors. As well, due to the averaging effect in larger wind farms the energy storage requirements on a per machine basis are reduced. A systematic method for the rating of the storage device from the single machine level to a large wind park needs to be developed. The method used in the present work needs to be evaluated in terms of its relevance and the resulting additional costs accrued.

As wind energy continues to grow worldwide, the effect of high penetration of wind energy at the local level needs to be addressed further. Whether or not energy storage can be used in order to limit the impact of high penetration of wind and also the spinning reserve requirements needs to be determined. Moreover, the level at which wind energy becomes important needs to be identified. How far this level can be extended by incorporation of energy storage should be answered in order to have a method for evaluation of its value and need.

6.3.2 Storage Device Energy Management

Additional work is required in the area of energy management for the storage device itself, in particular how the energy flow is controlled. This is most evident when the storage element reaches either the upper or lower limit. Likely the most favorable characteristic will be obtained by curtailing the reference power once the storage device approaches the lower limit. Likewise once the maximum storage capacity is neared the output power reference should be increased. In this way, the time that the system remains in normal operation can be extended using these slight variations on the general control scheme. The transition between the states of operation will likely be smoothed as well thereby contributing to an overall improvement in the performance of the system. These studies could first be accomplished for the single machine and then extended to the more complicated case of a wind park where other methods may be required in order to optimize all of the benefits of energy storage.

6.3.3 Distributed Generation and MicroGrids

The case of a single machine is most relevant for distributed generation and this presents a wide range of possibilities in the area of energy storage applications. As the penetration of distributed generators increases in the power system, the energy storage requirements will undoubtedly increase in a similar fashion. Particularly in the area of MicroGrids, where a section of the power system may be required to support itself while temporarily disconnected from the grid, the need for energy storage devices is imperative when the generation is based on intermittent power supply technologies, in order to avoid any type of load shedding.

The growth of distributed or embedded generation will most likely be accompanied by a growth in the energy storage industry or at least a renewed focus on the management of energy. The interface of these technologies may not be limited DG alone, as the dc link of variable speed drives or other self-commutated rectifiers may be utilized to integrate either ESS or dc generation systems such as photovoltaics (PV). The move towards more intelligent buildings and the use of various hybrid systems will also drive the restructuring of the grid, at least at the distribution level. Maximization of the benefits of ESS and other new technologies will require an increased focus on the way these devices are operated and controlled, at both the micro and macro-levels.

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Appendix A: Wind Models

This section presents the various models required for representation of a wind turbine. For more detailed treatment of this topic, readers are referred to [15] - [17].

A.1 Wind Speed

The wind speed is typically composed of four different components and can be represented using a mathematical representation or by using typical wind speed measurements as taken from [60]. Fig. A1.1 shows a typical plot of data obtained from the website.

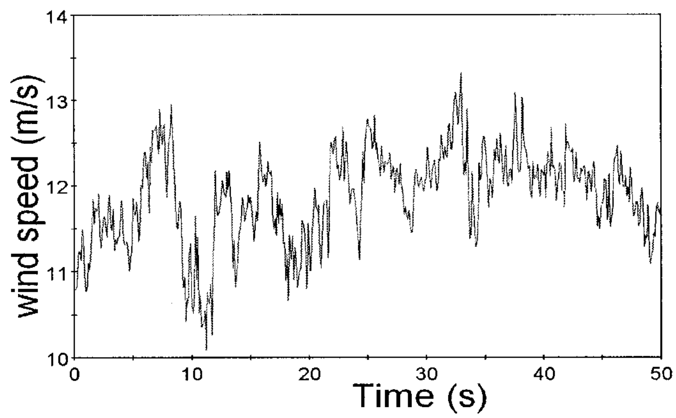

Fig. A.1 Typical wind speed measurements

A.2 Torque Model

The wind speed is translated into input torque using the basic wind function which depends on local environmental conditions (air density and wind speed), the size of the blades, the speed of the machine, as well as a characteristic torque coefficient which depends on the nature of the machine and is related to aerodynamics, machine rating and mechanical factors.

$$T_m = \frac{1}{2}\pi\rho C_t(\lambda, \beta)R^3 v_w^2 \qquad \text{(A.1)}$$

where

ρ : The air density

R : The wind turbine radius

$\lambda = \dfrac{\omega_m R}{v_w}$: The ratio of blade tip speed to wind speed.

ω_m : The wind turbine rotational speed (rad /sec.)

β : Blade pitch angle

The wind turbine blade aerodynamics is characterized by non-dimensional curve of torque coefficient, C_p, which is a function of tip-speed ratio, λ, and blade pitch angles, β.

$$C_t(\lambda, \beta) = \frac{C_p(\lambda, \beta)}{\lambda} \tag{A.2}$$

$$C_p(\lambda, \beta) = c_1(c_2 - c_3\beta - c_4\beta^x - c_5)e^{-c_6} \tag{A.3}$$

Literature [19] gives the parameters of MOD 2 turbine, where

$$c_1 = 0.5 \quad c_2 = 116/\lambda_1 \quad c_3 = 0.4$$

$$c_4 = 0 \quad c_5 = 5 \quad c_6 = 21/\lambda_1 \quad \textit{and} \quad \frac{1}{\lambda_1} = \frac{1}{\lambda + 0.08\theta} - \frac{0.035}{\theta^3 + 1}$$

The torque coefficient for various blade angles is plotted below for the range of tip-speed ratios.

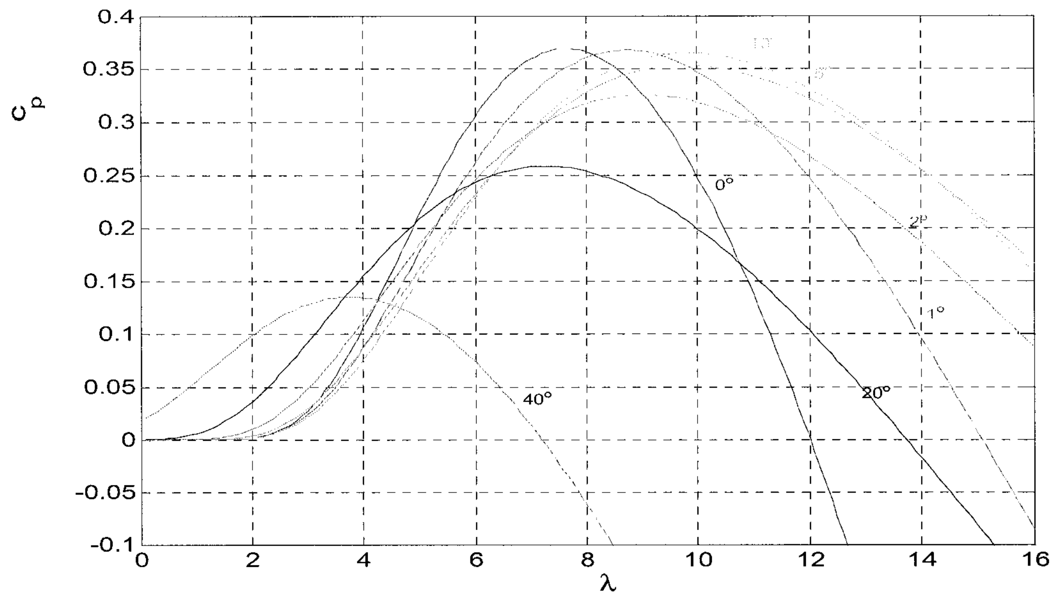

Fig. A.2 Torque coefficient curves as a function of tip-speed ratio

A.3 Wind Power Characteristic

Upon plotting of the torque speed curve, a similar curve can be obtained which describes the output power of a wind turbine which is a function of the input torque and the operating rotor speed. Typically, the wind generator speed range is limited to near synchronous speed (± 20 %) as given in Fig. A1.3, which illustrates the power characteristic for a 2 MW machine.

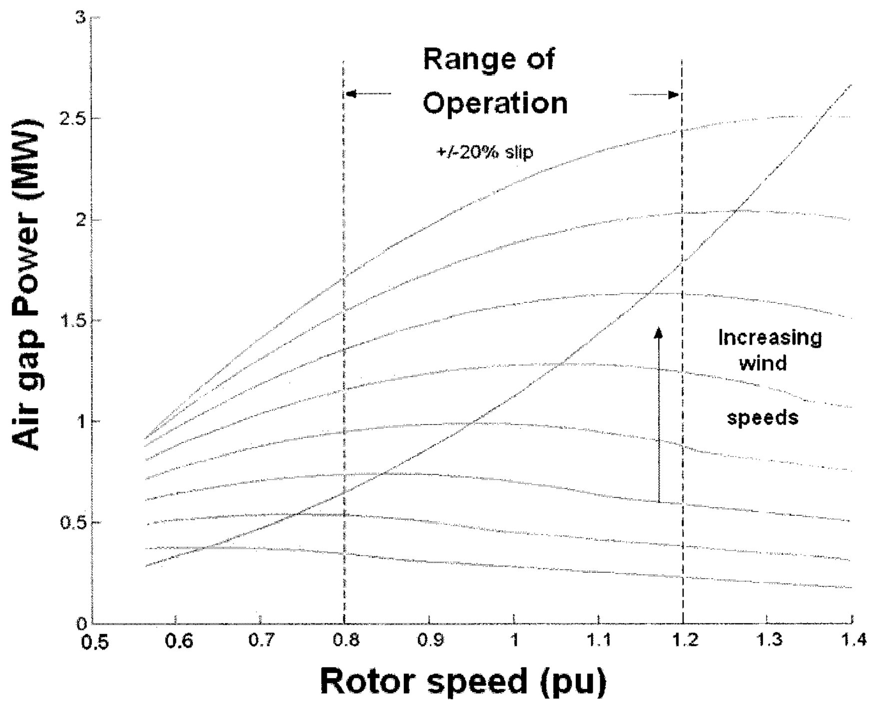

Fig. A.3 Wind power characteristic curves (red) and optimum power points (blue)

Appendix B: Model Parameters

Wound rotor induction machine parameters

Rated Voltage (kV)	4
Rated Power (MVA)	7.46
R_1 (pu)	0.00621
R_2' (pu)	0.00627
X_1 (pu)	0.117
X_2' (pu)	0.1136
X_m (pu)	3.28
u_s (turns ratio)	1.547
pole pairs	3
Machine Type	Wound-rotor
Inertia Constant, H (s)	1
Voltage trip	Set to permit low voltage ride-through

Network data

	MV		HV		
V (kV)	69	69	230	230	230
mode	0	1	0	1	2
R' (ohm/km)	0.53	0.053	0.5306	0.0117	0.0304
X' (ohm/km)	1.59	0.53	1.521	0.327	0.656
C' (uS/km)	5.21	5.21	3.239	4.92	3.239
Line type	single - three phase		dual - three phase		
Line length (km)	50		100		

Appendix C: Wind Park SCC

The network can for most purposes be represented by its Thevenin equivalent at the point of connection. The type of connection can then be modeled by simply adjusting the short circuit ratio (SCR), given by:

$$SCR = \frac{SCC}{S_{base}} \tag{C.1}$$

Where SCC is the short circuit capacity of the grid defined by

$$SCC = \frac{V_e^2}{Z_e} \tag{C.2}$$

Where V_e is the RMS of line-to-line voltage and Z_e is the Thevenin impedance, which represents the combined impedances of transmission lines, transformer leakage reactances, and internal generator impedances. The SCR can be adjusted by increasing or decreasing the Thevenin impedance.

In the case of a wind farm, S_{base} is defined by the total installed capacity of the wind farm. Lengthening the transmission lines or changing the line parameters (related to the types of conductors), or voltage levels can all contribute to a weak system.

Appendix D: Droop Characteristic

The steady-state operation of the DFIG can be represented by a PQ bus with a variable P which is dependent on the wind variation and whose reactive injections are a function of the reference voltage at the PCC. The reference voltage depends on the percentage of rated reactive power supplied, known as the droop characteristic, whereby the reference voltage is slightly less at maximum leading reactive current and slightly greater at maximum lagging reactive current. Typically, the variation in the reference voltage is 3% and this characteristic results in the following benefits [47]:

(i) The linear operating region of the compensator can be extended

(ii) Strictly defined voltage reference can result in a poorly defined operating point and resulting oscillations.

(iii) The slope can lead to favorable compensation sharing by numerous regulation devices which are connected at various points in the system.

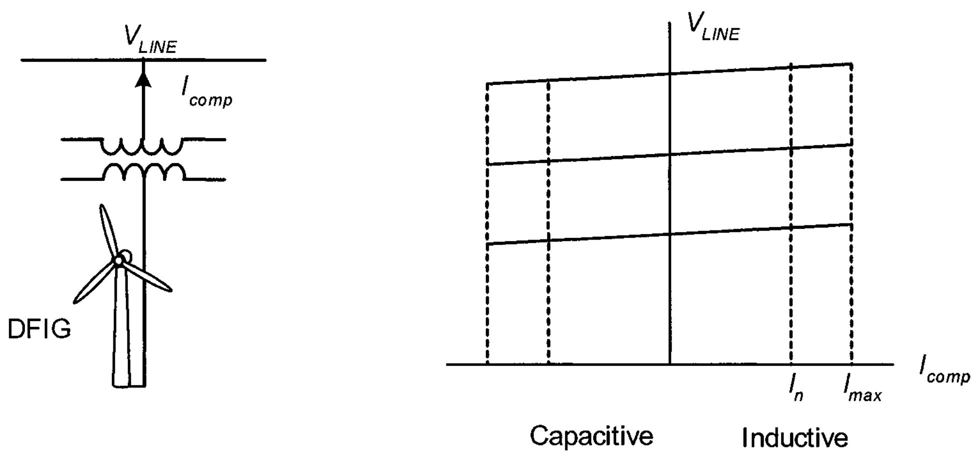

Fig. D.1 Droop characteristic for determination of DFIG reference voltage

The reactive power for the DFIG is divided between the supply side and rotor side converters in the 20 / 80 % manner, as explained in detail in [46].

Appendix E: EMTP-RV Models

This section provides the EMTP-RV representation of the most important components required for modeling of the DFIG wind generator system. The figures which follow correspond, in whole or in part, to those from Chapter 3: Fig 3.3, Fig. 3.4, Fig. 3.5, Fig. 3.6, as well as the test system utilized in the system level studies in Chapter 6. For sake of space not all of the details are shown.

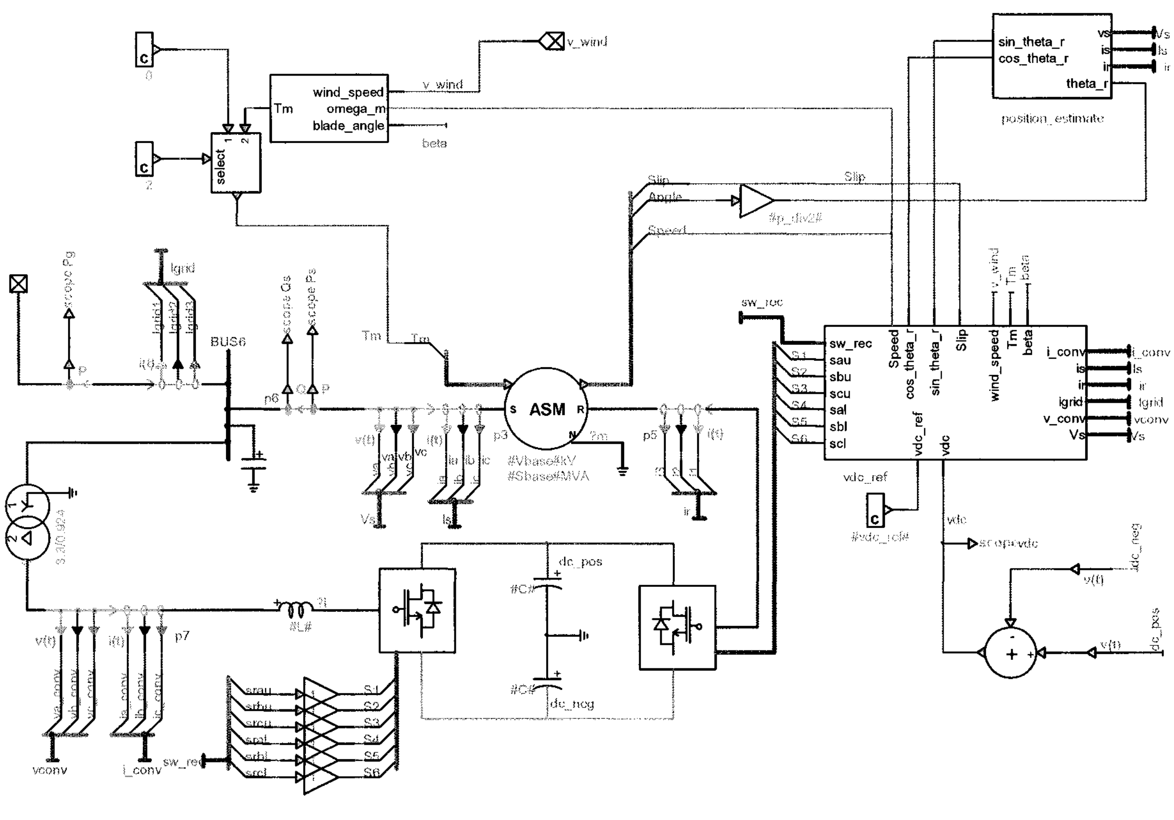

Fig. E.1 EMTP-RV representation of DFIG wind turbine system

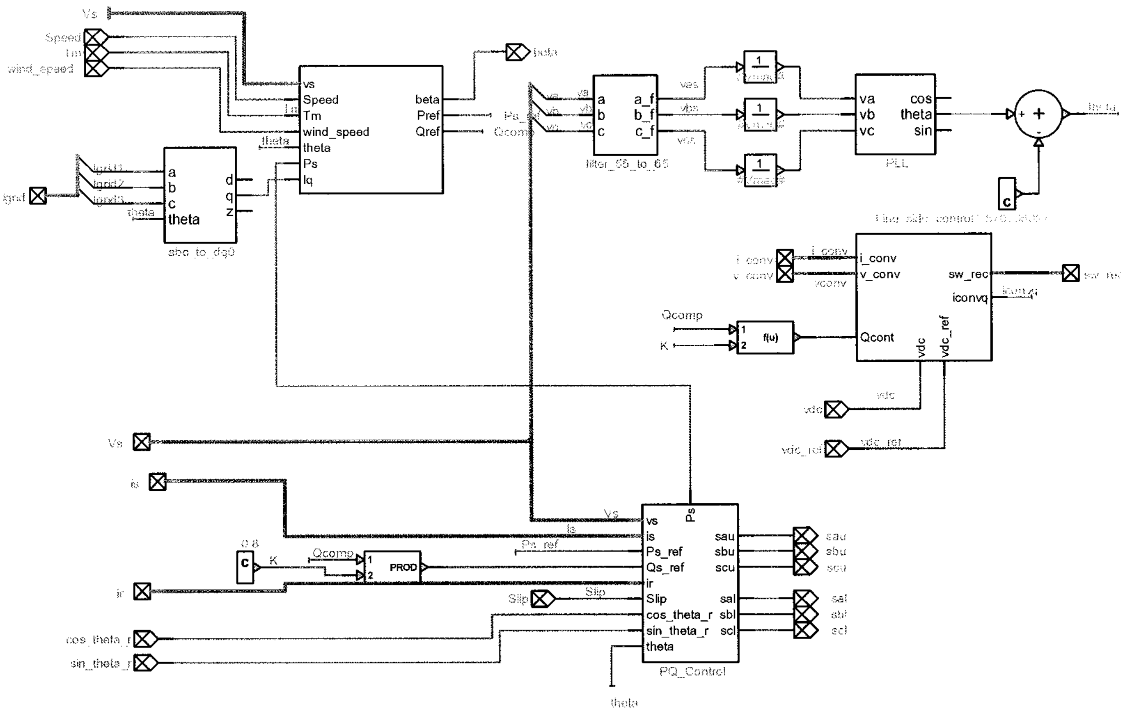

Fig. E.2 EMTP-RV representation of overall control structure

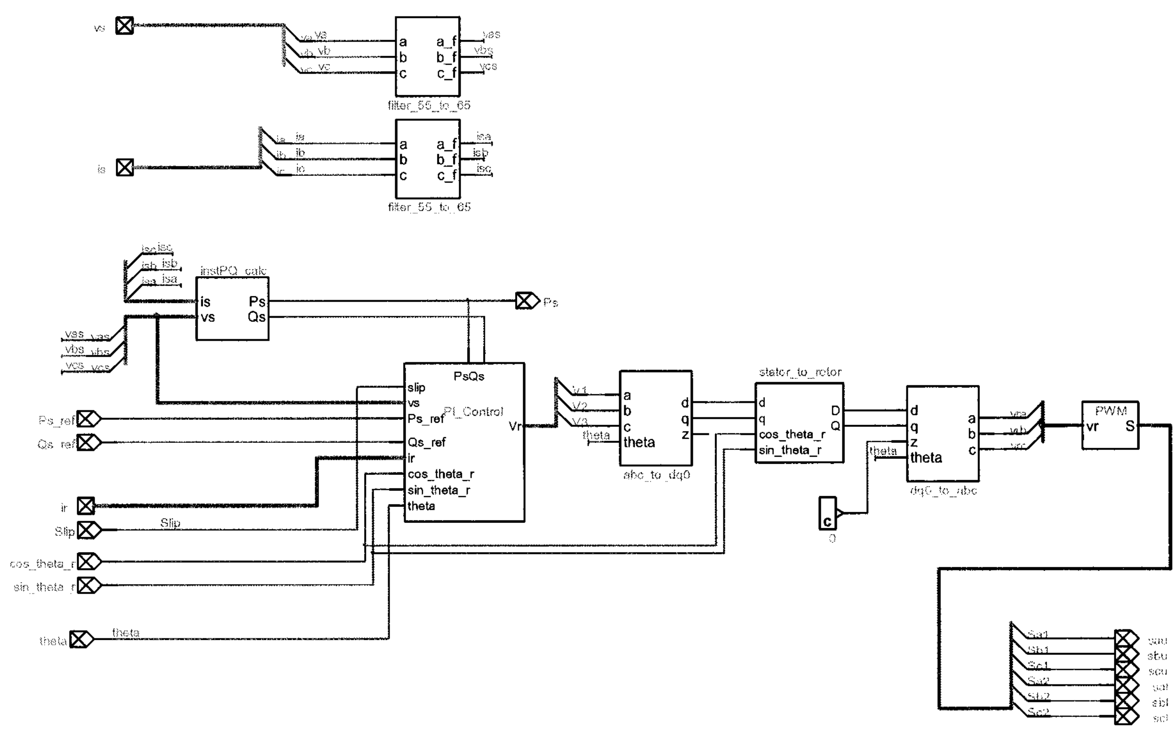

Fig. E.3 EMTP-RV representation of PQ control

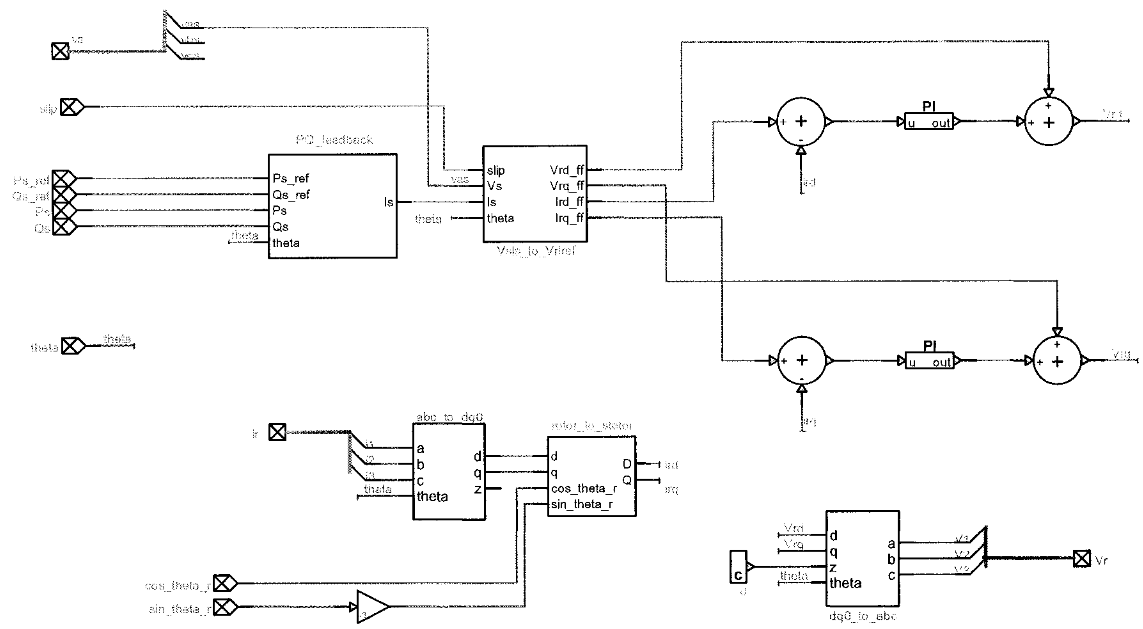

Fig. E.4 EMTP-RV representation of PI control for rotor side converter

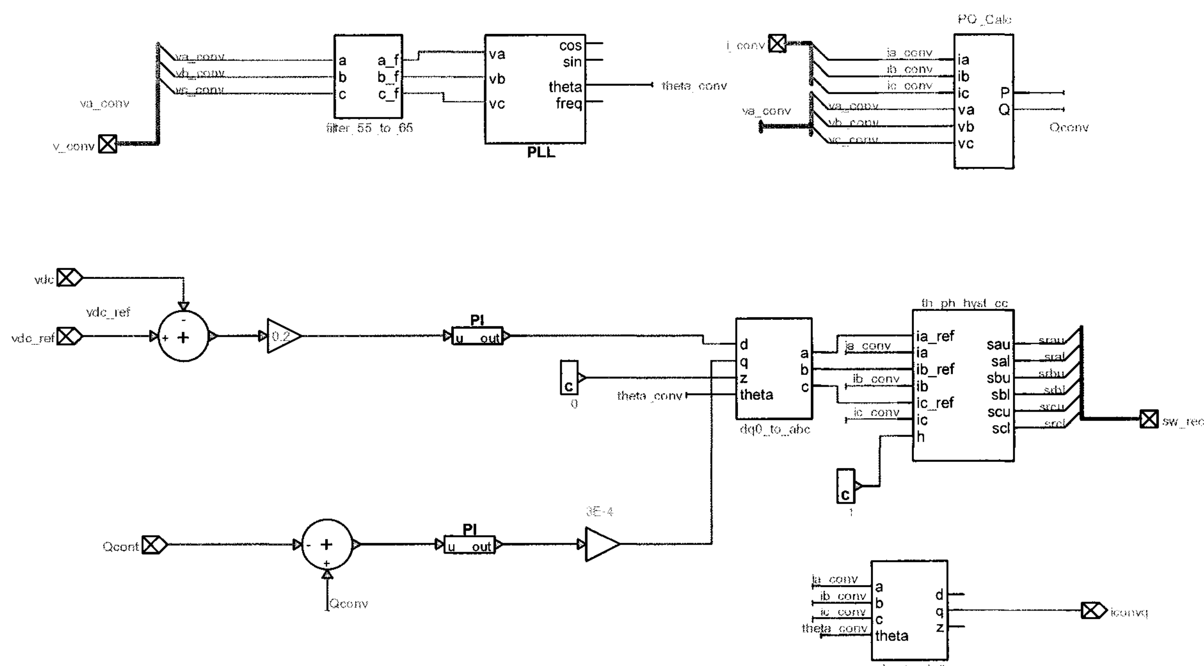

Fig. E.5 EMTP-RV representation of supply-side converter control

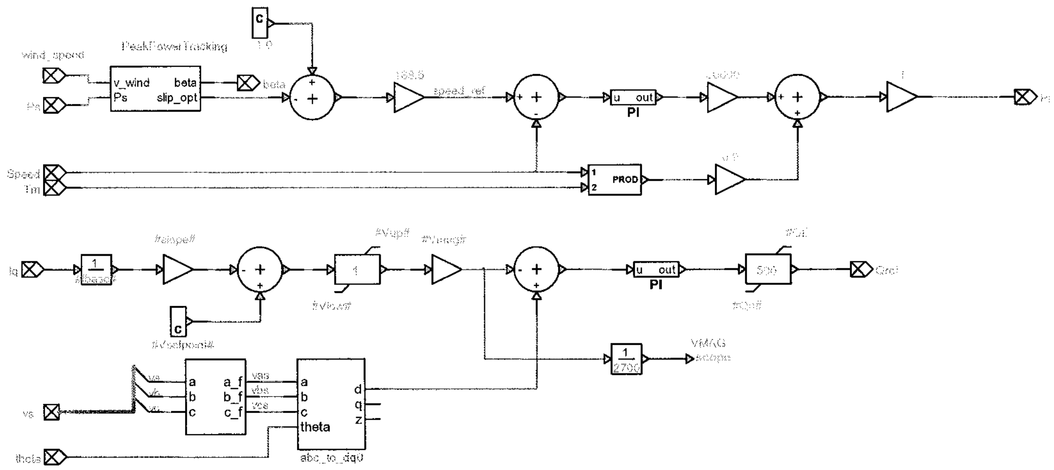

Fig. E.6 EMTP-RV representation higher level controls

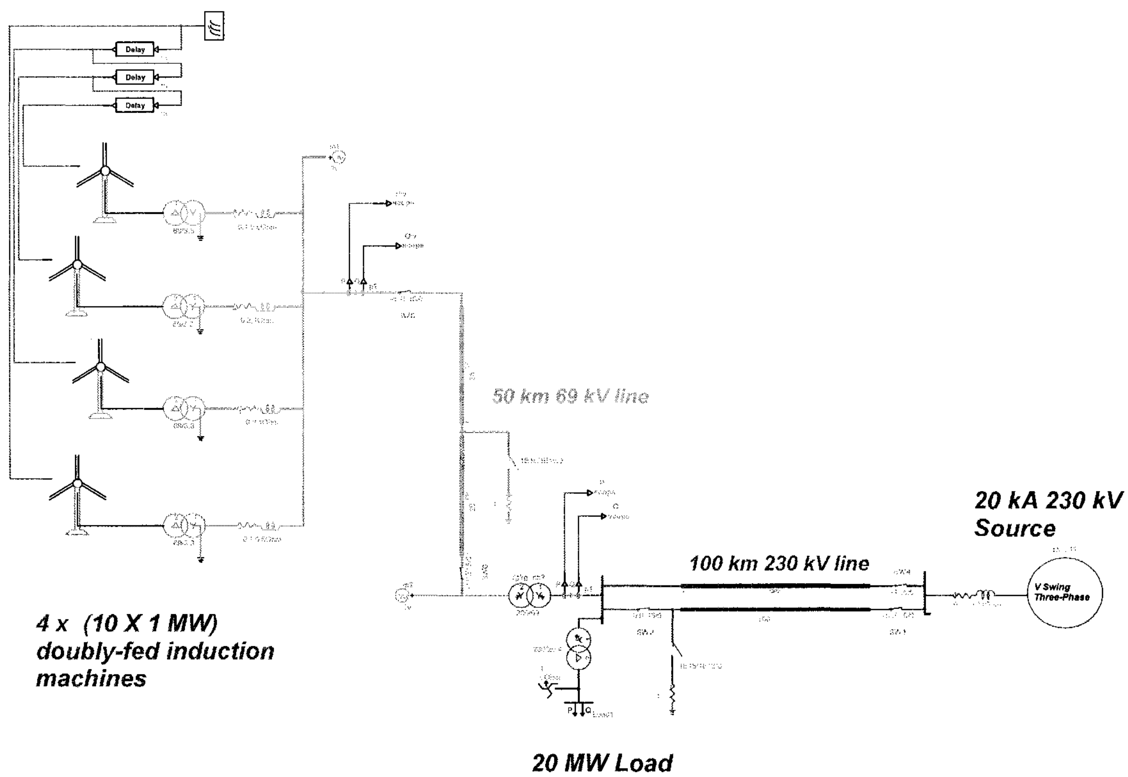

Fig. E.7 EMTP-RV representation of weak power system used