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Research Paper

SMES BASED DFIG GENERATOR REACTIVE POWER IMPROVEMENT USING SVPWM

Kannan Kaliyappan[1]*, S Sutha[2] and R Kathirvel[1]

*Corresponding Author: Kannan Kaliyappan, ✉ kannankmeped@gmail.com

The Doubly Fed Induction Generator (DFIG) equipped with self-commutated Insulated Gate Bipolar Transistor (IGBT) is one of the most popular topologies used in wind power systems. It has the ability to control active and reactive power independently. The reactive power capability is subject to several limitations which change with the operating point. This paper proposes a Superconducting Magnetic Energy Storage (SMES) based excitation system for DFIG used in wind power generation and used to store energy. The superconducting magnet connects to the DC side of the two converters, which can handle the active power transfer with the rotor of DFIG and the power grid independently. This paper investigates the thermal behavior of the converter using semiconductor losses. A Space Vector Pulse-Width Modulation (SVPWM) is necessary at around synchronous speed to increase the maximum permissible rotor current as well as reactive power capability.

Keywords: Doubly Fed Induction Generator (DFIG), Superconducting Magnet Energy Storage (SMES), Space Vector Pulse-Width Modulation (SVPWM), Motor Side Converter (MSC), Load Side Converter (LSC)

INTRODUCTION

Wind power has established itself as one of the most important renewable energy sources over the past decades. The contribution of wind power to electrical power supply is increasing rapidly. The worldwide installed capacity currently reached of about 200 GW and will double toward 2014. According to the grid code requirement, Wind Turbines (WTs) have to contribute not only to active power generation, but also to the provision of reactive power into the grid during voltage dips and also in the steady-state operation. Modern power electronic converters are able to control active and reactive power independently of one another.

The power capability of WTs generator is subject to several limitations resulting from the voltage, current, and speed. Based on the power system and generator technology, the

[1] AP/EEE, RVSCET, Dindigul, India.

[2] ASP/EEE.UCE-Dindigul, India.

power capability of the conventional turbine generator is determined by the field heating limit, end heating limit, stator heating limit, and steady-state stability limit (IEEE Guide for Operation and Maintenance of Turbine Generators, 1990; and Nilsson and Mercuriot, 1994). For the Doubly Fed Induction Generator (DFIG)-based WT, the power capability limiting factors involves mechanical power, stator current, and rotor current (Engelhardt *et al.*, 2011). The active-reactive power diagram has been presented considering the limiting factors. The authors have also investigated that a rotor current duration of a Machine Side Converter (MSC) is necessary at low frequencies that is around synchronous operating points to maintain maximum junction temperature of IGBTs at about the same level as at the rated speed. At synchronous speed, the junction temperature of IGBTs could exceed its maximum limit due to higher generated power losses which could affect overheating in the converter and lead to IGBTs failure (Bruns *et al.*, 2009; Jung and Hofmann, 2011; and Wei *et al.*, 2011).

Reduction in the rotor current consequently reduces the output power of the MSC. When active power is taken as the priority in the system, reduction in reactive power capability is needed. To improve the reactive power capability, the basic idea is to have lower power losses of the converter. One approach is by using a converter topology with low power loss performance. A three-level Neutral Point Clamped (NPC) converter seems to have lower power losses compared with a two-level converter for the same installed switch power, and has been investigated in Krug *et al*. (2003) and Alemi and Lee (2011), and it improved the reactive power capability of DFIG around synchronous speed (Sujod and Erlich, 2013). However, this solution is not preferable by the converter manufacturer due to higher cost and space constraint.

A more sophisticated approach to overcome this problem, while maintaining the size of IGBT module, is using a low switching frequency modulation technique. Discontinuous Pulse-Width Modulation (DPWM) type is a well-known modulation technique having a low switching frequency and superior switching loss performance. It has been investigated and presented in many literature studies (Hava *et al.*, 1998; Chung and Sul, 1999; Solomon and Famouri, 2006; Bierhoff *et al.*, 2007; and Wu *et al.*, 2008 and 2011). The switching losses of DPWM are lower than Continuous PWM (CPWM) and have been validated experimentally. At a different rotor speed operation mode of DFIG, a different DPWM type showed a different power loss performance, which dependent on rotor power factor angle (Sujod and Erlich, 2012).

The steady-state reactive power generation capability of a typical WT system using the DFIG around synchronous operating point using various PWM types. Parameters of the machine and the control system are based on manufacturer data, and the simulation results are intended to reflect the existing reality as accurately as possible. The active, reactive power diagram of the DFIG is developed step by step. First, IGBT and diode power loss model of MSC are developed using MATLAB/Simulink environment. Based on the thermal model of IGBT and diode, and the simulated power losses data, the junction temperature values are calculated. Then, they are used to characterize the permissible output current in relation to rotor frequency. Different PWM types are applied for the MSC and its results of power losses, junction temperature, output current, and reactive power capability are compared. These results help in the intelligent choice of the appropriate PWM type for DFIG application with improvement in the reactive power capability around synchronous operating point while maintaining the converter size.

This paper investigates the steady-state reactive power generation capability of a typical WT system using the DFIG around synchronous operating point using SVPWM type. Parameters of the machine and the control system are based on manufacturer data, and the simulation results are intended to reflect the existing reality as accurately as possible. The active- reactive power diagram of the DFIG is developed step by step. First, IGBT and diode power loss model of MSC are developed using MATLAB/Simulink environment and converter section MSC and LSC implemented in hardware. The SVPWM coding are fed in PIC microcontroller dsPIC30F2010.

DFIG BASED WIND TURBINE

The tip speed ratio ª is defined as:

$$\lambda = \frac{\omega R}{v} \qquad ...(1)$$

where, µ, *R* and *v* represent turbine rotational speed,

Turbine blade radius and the wind velocity respectively.

In general, the power captured from the wind turbine can be written as:

$$P_m = C_p(\lambda, \beta)\rho\frac{A}{2}v^3 \qquad ...(2)$$

where C_p(ª,) is the power coefficient, ° is the air density, *v* is the wind speed, *R* is the blade radius, is the blade pitch angle and ª is the tip speed ratio. The power curve speeds of a typical wind turbine are shown in Figure 1. The value of maximum wind turbine output power per unit can be obtained by putting zero pitch angle and Betz limit, when the velocity of wind turbine is 12 m/s.

It is not suitable for real time application. In this proposed paper, maximum power can be captured at different wind turbine speeds. Considering the generator efficiency ¦*G*, the total power produced by the WG *P* is:

$$P = \eta G P_m \qquad ...(3)$$

DFIGs are widely used in wind generation. It includes a slip ring induction generator, power electronic converter, and common DC-link capacitor. Power electronic converter, which encompasses a back-to-back Ac-DC-Ac VSC, has two main parts: the Line Side Converter (LSC) and MSC. The LSC is connected to the stator windings via LC filters, while the MSC is connected to the rotor windings. A schematic of a DFIG-based WT system is shown in Figure 2.

The SMES based excitation system is composed of the rotor - side converter, grid-side converter DC chopper, and superconducting magnet. In this excitation system, the energy storage unit must have the characteristic of high energy storage efficiency and quick power response, and the energy

Figure 1: Turbine Output Characteristics (Zero Pitch Angle)

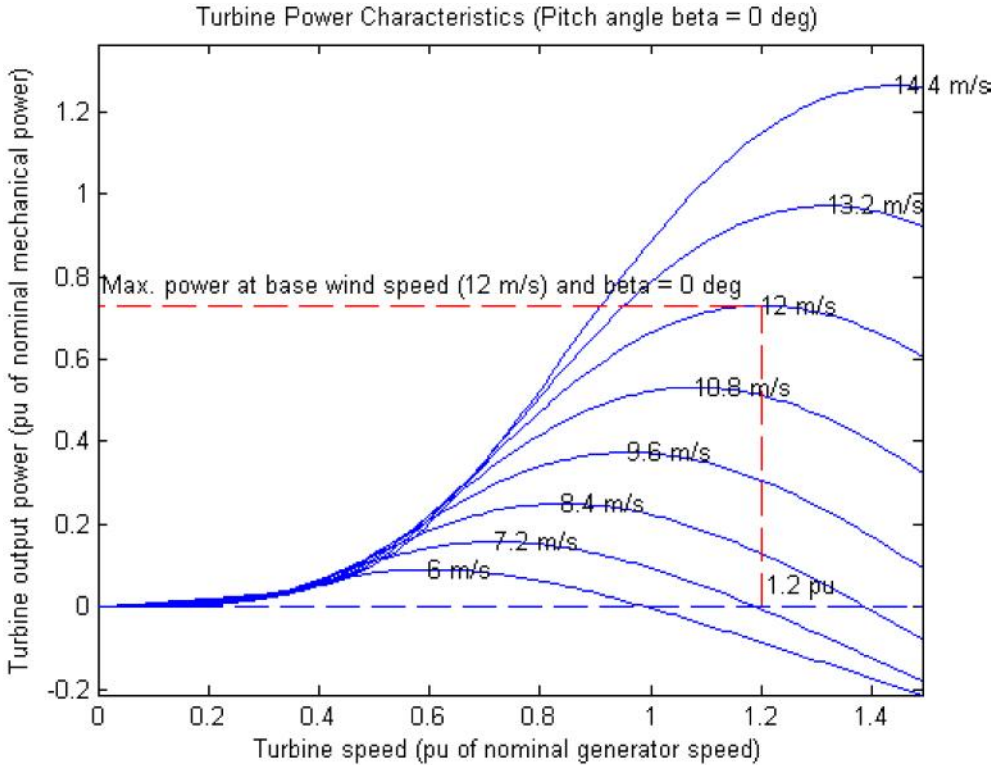
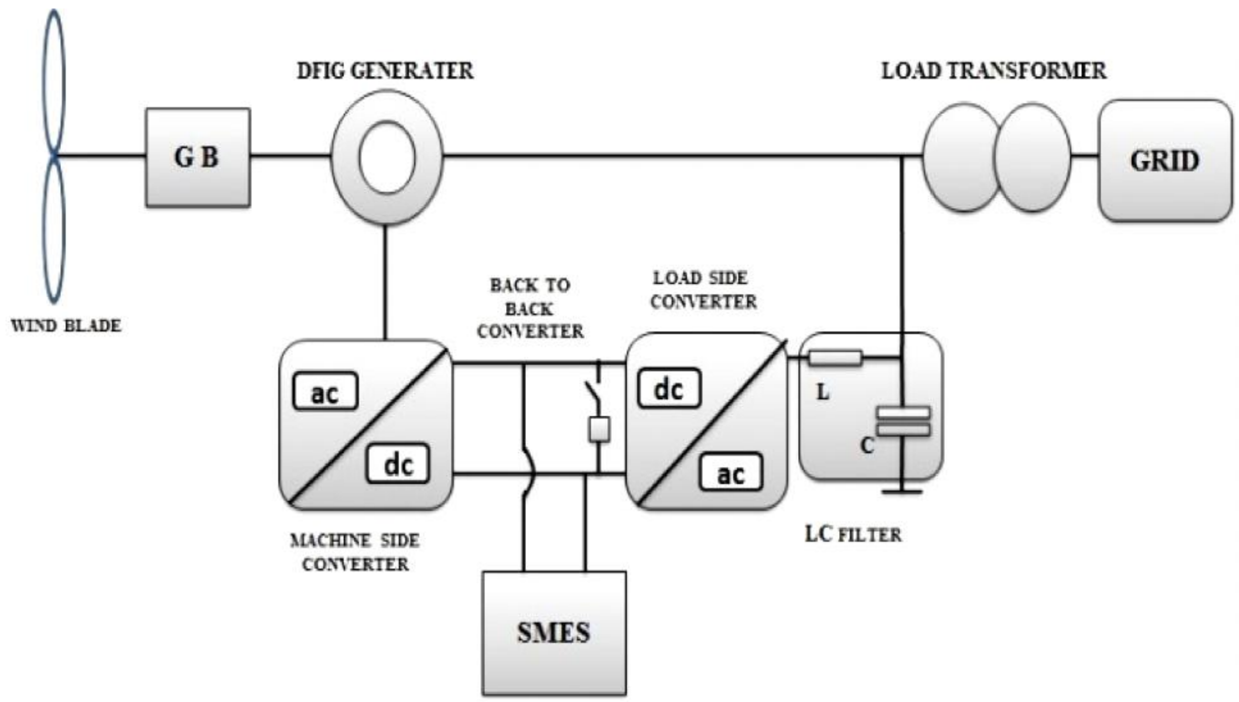


Figure 2: Schematic of a SMES Based DFIG Wind Turbine System



storage capacity is not the essential factor. So, the superconducting magnet is selected as the energy storage unit of the excitation system, it is set at the DC side of the two converters. The DC chopper is utilized to control the charging and discharging of the superconducting magnet. With the coordinate control of the converter, the power transfer between the super conducting magnet and the generator rotor or the power grid can be controlled effectively. In normally, the maximum power extraction from wind (*Pw*) opt is obtained using the indirect speed control technique.

The SMES based excitation system for doubly-fed induction generator can fulfill the following functions:

- In the condition that the energy storage capacity of superconducting magnet is large enough, the power transfer during the operation of Variable Speed Constant Frequency (VSCF) can be handled by the superconducting magnet. This operation mode can smooth the power fluctuation of wind farms, and improve the power quality issue induced by the wind power integration.
- During the system operation, the rotor-side converter and the grid-side converter is mutually independent. The system intuitively participates the operation and control of the power grid, which can improve the security and stability of the power system.
- In the condition of grid faults, the over current in the rotor can be suppressed using the energy storage of SMES. Moreover, the SMES and the grid-side converter are impervious to the grid fault, which can supply the power compensation to the grid and recover the power coupling point voltage.

The MSC and LSC are controlled in a dq reference frame. The control structure and controller design are explained in detail in IEEE Guide for Operation and Maintenance of Turbine Generators (1990). The LSC maintains the dc voltage and provides reactive current support for the optimization of reactive power sharing between MSC and LSC during the steady state. The MSC controls active and reactive power of the WT and follows a tracking characteristic to adjust the generator speed for optimal power generation depending on wind speed. Variable speed operation in the DFIG in accordance with the tracking curve results in higher power output from the wind. The direction of the power flow through the converters depends on the operating point of the generator. At low active power that is during the synchronous and subsynchronous speed, high reactive power capability is needed to allow the generator inject enough reactive current into the grid in the condition when a fault occurs at the grid side. This is important to fulfill the grid code requirement where the WT has to stay connected to the grid during such conditions. The simulation presented in this paper is carried out with MATLAB/Simulink with SimPowerSystems Toolbox in the time domain based on instantaneous values.

PWM TECHNIQUES

The commonly used MSC is based on a three-phase two level topology. It consists of three bridges with six IGBTs and its freewheeling diodes. The converter is supplied by a voltage source DC-link capacitor. This topology is the simplest VSC configuration as it requires a simple control. The IGBTs is controlled by a SVPWM circuit to achieve variable voltage and variable frequency output from a fixed DC voltage. The PWM circuit generates the switching instants to each of the IGBT's gates. It could generate different types of PWM which provide a different performance level of the converter, including harmonics, switching losses, and output voltage linearity (or DC bus utilization). Most common switching techniques use PWM which produces less harmonics compared to the other switching techniques, such as the six-step switching. Several PWM techniques have been developed and these can be generally classified into CPWM and DPWM types Examples of CPWM types include the Sinusoidal PWM (SPWM), Third-Harmonic Injection PWM (THIPWM), and Space Vector PWM (SVPWM). The improvement in reactive power capability could be achieved with low switching frequency of PWM which causes low power losses in the IGBTs. Among the PWM types, SVPWM is the best choice. A SVPWM generates a reference voltage vector (VREF) whose angular speed calculate the desired value of synchronous speed of the motor and its magnitude determines the required voltage (Vs) that will maintain a constant air gap flux. This reference voltage vector (VREF) is rotating with respect to a plurality of voltage vectors that each point out a respective one of the switching states of an inverter. The concept of space vector is derived from the rotating field of AC machine which is used for modulating the inverter output voltage. In this modulating technique the three phase quantities can be transformed to their equivalent 2-phase quantity either in synchronously rotating frame (or) stationary frame. From this 2-phase component the reference vector (VREF) magnitude can be found and used for modulating the inverter output.

POWER LOSSES

A power loss model is developed first, because its output data are required for the thermal model. There are different ways to calculate power losses of IGBT module. However, some complex models require many IGBT and diode parameters to perform the calculations. The proposed power losses estimator using MATLAB/Simulink presented is more flexible and shows similar results when compared with other simulation programs such as PSIM and SEMISEL (Semikron) (Jung and Hofmann, 2011). The power losses of the IGBT/diode are divided into the static power losses and the non static power losses. The static power losses are the conduction losses (on-state losses) and the blocking losses. The non static losses are divided into the switching losses (turn-on/off losses) and driving losses. The blocking losses and driving losses are neglected since they account for a small portion of the overall power losses.

IGBT is a not an ideal switch. Therefore, there will be a voltage drop across the IGBT and its freewheeling diode while it conducts current. Switching losses occur when there is a turn-on and a turn-off signal at IGBT's gate. The switching losses of the IGBT and diode are dependent on load current, DC-link voltage, and switching frequency. When SVPWM pulses are applied to the converter side, it reduces the conduction and switching losses. This creates a path to improve the reactive power capability.

SIMULATION RESULTS

As the MSC currents consist of active and reactive components, reduction of one component may be enough to limit the current magnitude by defining the priority in the control design. In this simulation, active current priority is defined in the MSC control. Therefore, the reactive current is reduced first, and the active current is kept unchanged when the magnitude exceeds the limit. To obtain the active-reactive current capability of DFIG based WT, the stator and LSC reactive current capabilities have to be defined. For the stator reactive current capability, the stator current limitation due to heating limit, the rated MSC current limitation and the maximum rated stator active power have to be considered. In this simulation, SVPWM is applied for LSC in the entire speed range. Combining the stator and LSC reactive current capability results in the reactive current capability of DFIG-based WT.

Figure 3 shows the grid voltage and current waveform. A grid current value is 0.01 amps. The Rotor speed and angle of DFIG Generator. A Rotor speed (p.u) is 1.2 RPM

Table 1: Typical Current Ratings

Wind Speed	10 m/s
Stator Current	0.08 amps
Machine Side Current	0.015 amps
Load Side Current	0.01 amps
Rotor Speed (p.u)	1.2 RPM
Grid Current	0.01 amps
Generator Input Voltage	460 volts
Generator Input Current	8 amps
Frequency	60 hertz
Output Frequency	60 hertz
Output Voltage	460 volts

Figure 3: Grid Voltage and Current Waveform

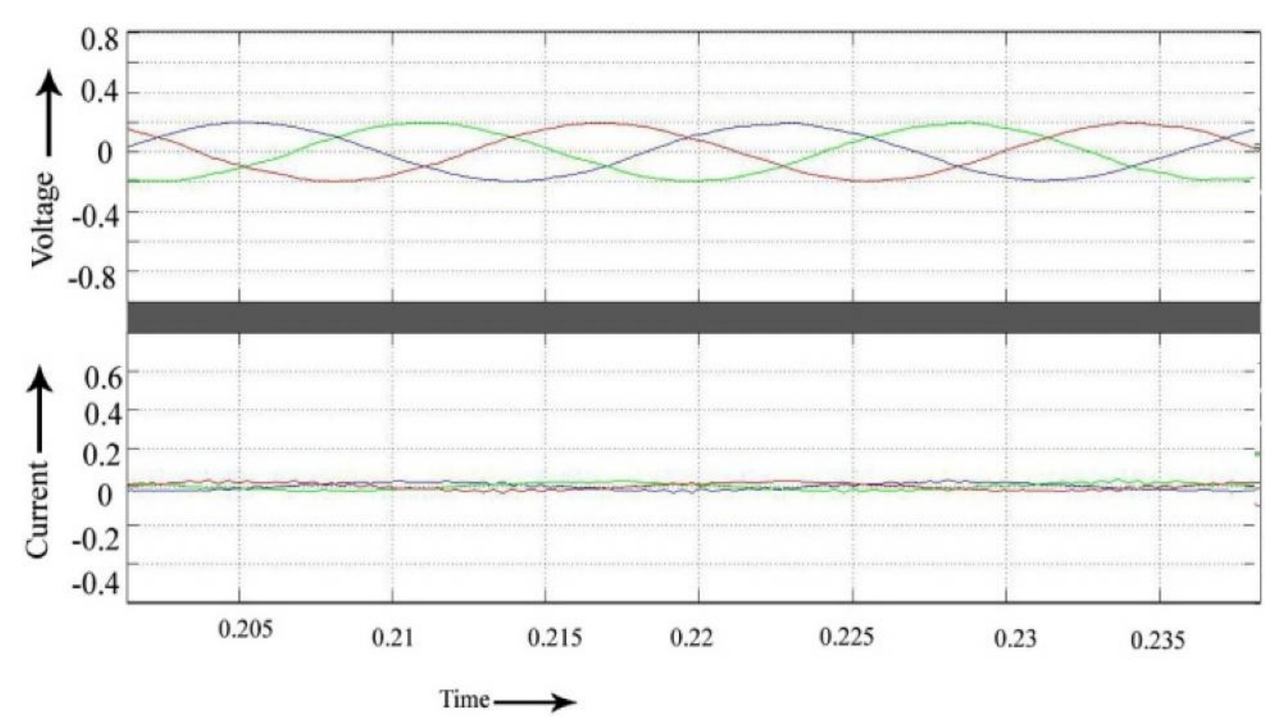


Figure 4: Motor Side Current (MSC)

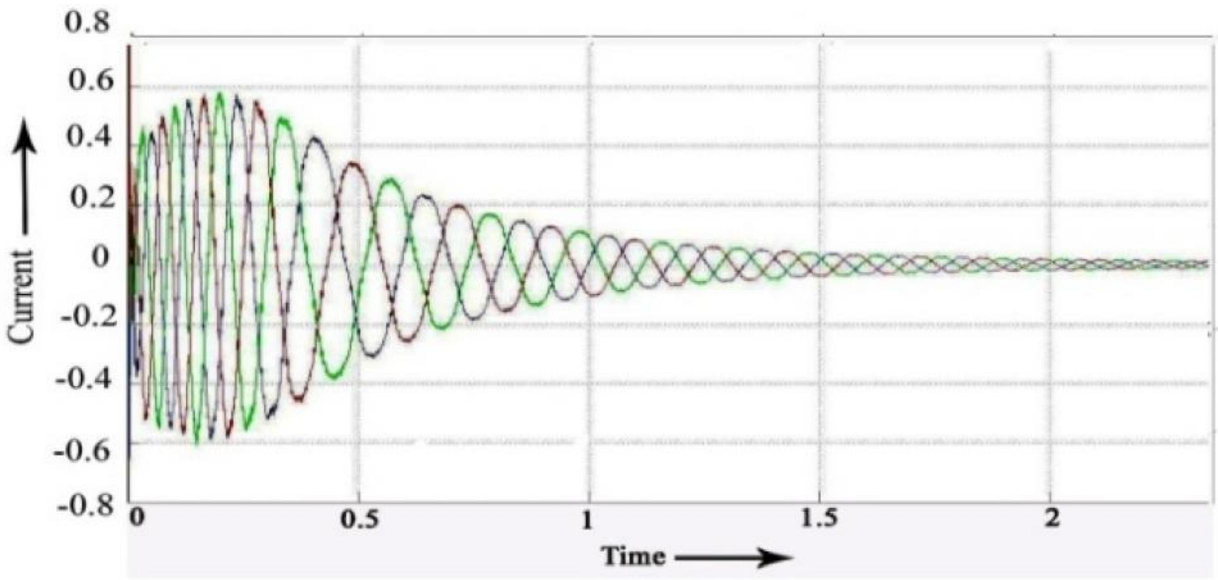


Figure 5: Motor Side Six SVPWM Pulses

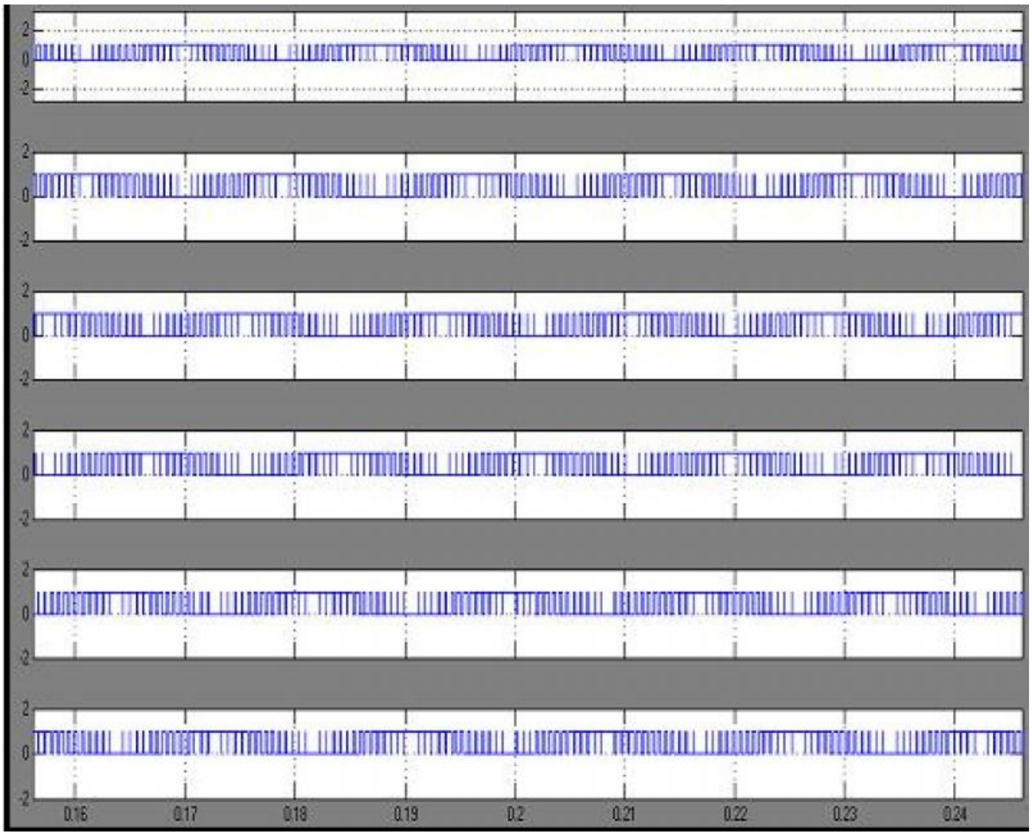


Figure 6: Load Side Current (LSC)

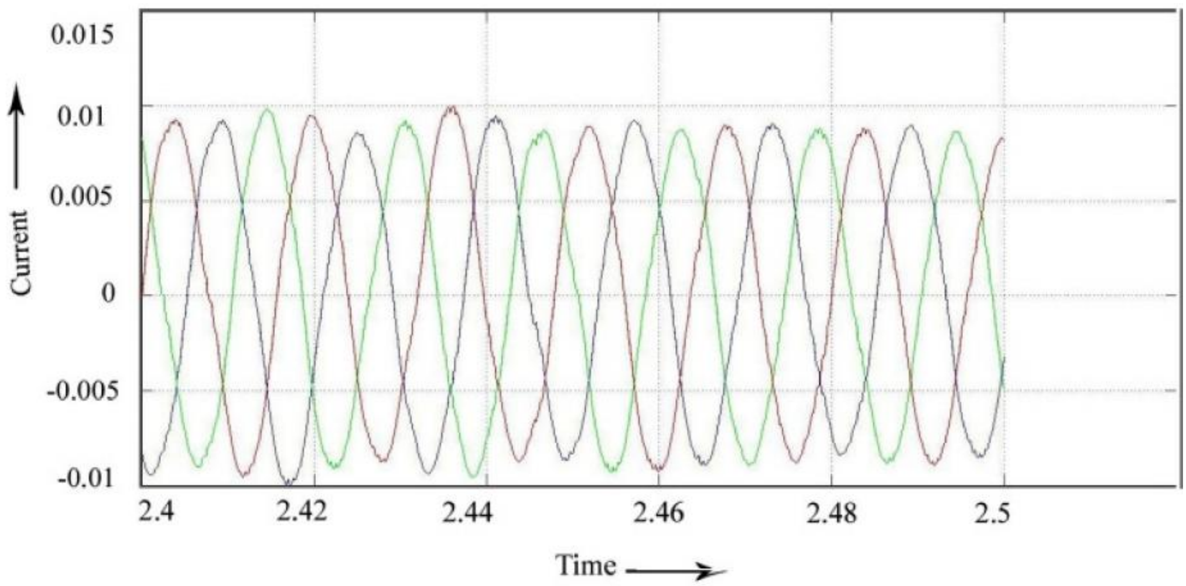


Figure 7: Load Side Six SVPWM Pulses

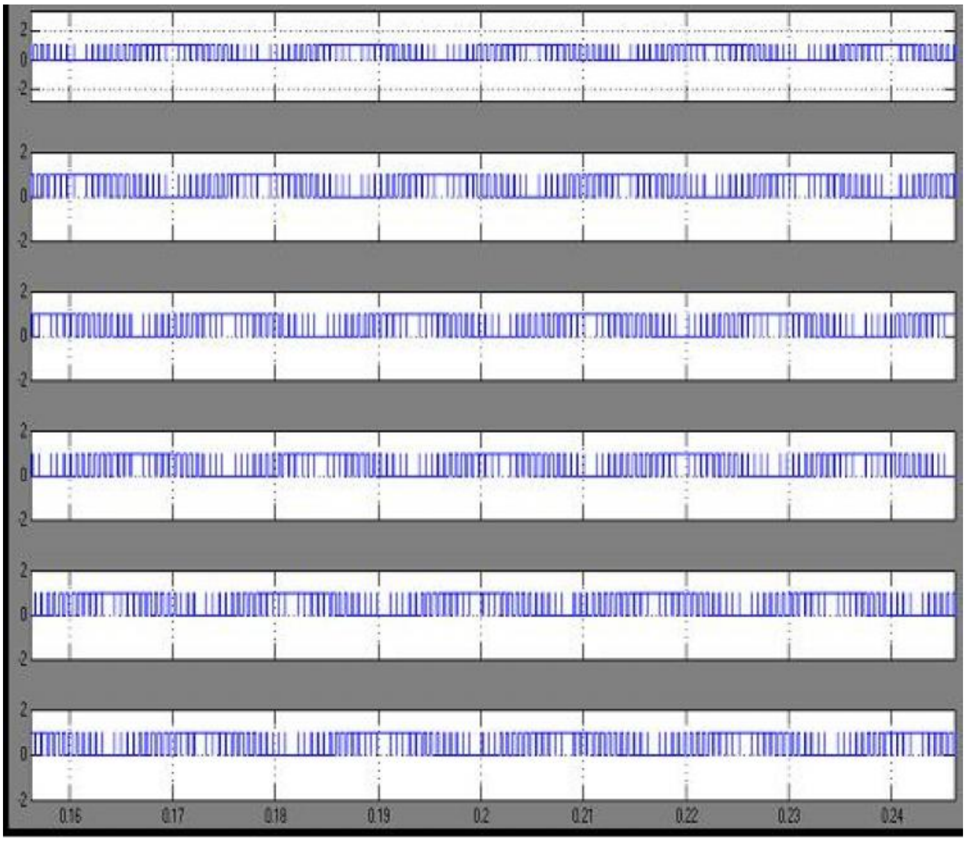
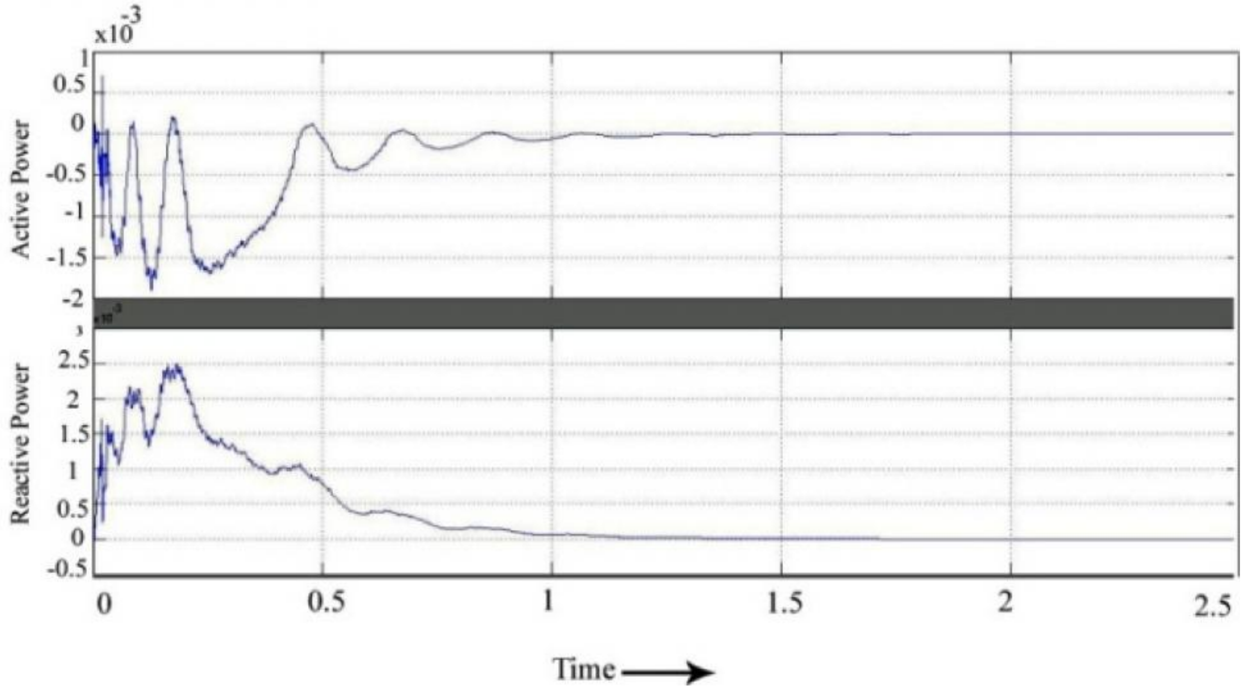


Figure 4 waveform describes the Motor side current. A n MSC current value is 0.015 amps. An MSC contains six Insulated Gate Bipolar Transistor (IGBT). A depends upon the pulse width modulation signals, an IGBT will turn on and turn off at a particular time interval. In this process a generator, AC output voltage converted to DC voltage (Rectifier) in back to back converter. A PWM pulses are given below.

Figure 6 shows the load side current waveform. This is the second procedure of back to back converter. A load side current is 0.01 amps. A LSC contains six Insulated Gate Bipolar Transistor. A depends upon the pulse width modulation signals, an IGBT will turn on and turn off a particular interval. In this process an MSC DC voltage converted into a voltage (Inverter) in back to back converter. In this back to back converter can do the both rectifier and inverter operation. A Inverter section six type PWM pulses are given below.

Figure 8 shows the reactive power versus active power characteristic by considering the relationship. All limitations discussed in the previous sections are considered. It can be shown that around synchronous operating point, derating in the MSC current due to the limitation in IGBT junction temperature imposes a limit on the overexcited reactive power output. In other approaches, the reactive power capability could be increased by using a converter of higher rating or by reducing the risk margin, which in most cases is impractical. Sizing the heat sink with a lower maximum temperature or using a forced external cooling could also reduce this effect. Another study also shows that using the three-level NPC converter improved the reactive power capability of DFIG around synchronous speed

Figure 8: Active and Reactive Power Waveform

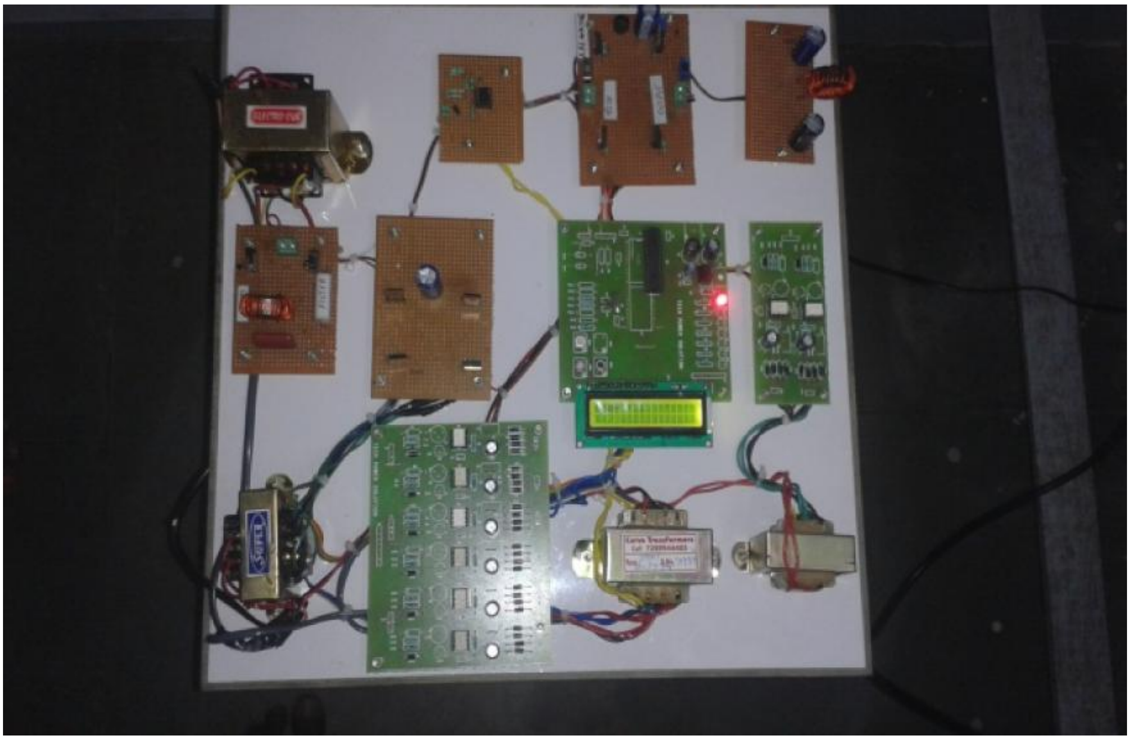


(Bruns *et al.*, 2009). However, all these techniques are not preferable by the converter manufacturer due to higher cost and space constraint.

HARDWARE RESULTS

The control circuit comprises of controller and driver ICs, the controller has a sequence of coding as instructions to produce necessary signals to trigger the particular solid state device and these signals are generated according to the requirements of the circuit by receiving the necessary input signals from the voltage and current feedback controllers. These signals are further modulated and processed to produce the control signals then these signals are given to the driver ICs these ICs produce high or low signal pulses to drive the particular switch. In this prototype PIC microcontroller PIC16F877A is used as a controller and the driver IC IR2112 is used as a driver. These two components control the switching sequence and drive the switches according to the requirement of the user. The PIC microcontroller dsPIC30F2010 is used as a controller in this prototype as an aim in designing the low cost and compact structured prototype dsPIC microcontroller is used in this prototype though promises an efficient operation, it has higher numbers of inputs and outputs while the requirement of the inputs and outputs here is very less, the cost of the dsPIC is also considerably low. Hence dsPIC microcontroller is considered to be more reliable and feasible controller for this particular prototype. The necessary component for the implementation of the hardware is chosen according to the capacity

Figure 9: Hardware Kit



of the circuit and the ratings of each component are analyzed from the datasheet then hardware is implemented. The hardware is implemented such that the components are connected according to the main circuit diagram in Figure 9.

The power supply circuit has a step-down transformer of rating 230 V/12 V when supply is given to this transformer the power is step-down from 230 V to 12 V and given to the full wave rectifier. A rectifier is an electrical device that converts Alternating Current (AC), which periodically reverses direction, to Direct Current (DC), which is in only one direction, a process known as rectification the term rectifier describes a diode that is being used to convert AC to DC here the diode IN5408 is used four diodes are used here form a full wave rectifier four diodes arranged this way are called a diode bridge or a bridge rectifier. A full-wave rectifier converts the whole of the input waveform to one of constant polarity (positive or negative) at its output. Full-wave rectification converts both polarities of the input waveform to DC (direct current), and is more efficient. The step-down voltage 12 V AC is rectified through the rectifier to 12 V DC full-wave rectification suffice to deliver a form of DC output, neither produces constant-voltage DC. In order to produce steady DC from a rectified AC supply, a smoothing circuit or filter is required.

In its simplest form this can be just a reservoir capacitor or smoothing capacitor, placed at the DC output of the rectifier. There will still remain an amount of AC ripple voltage where the voltage is not completely smoothed. A 330 μF and 25 mV capacitor is used as smoothing capacitor, sizing of the capacitor represents a tradeoff. For a given load, a larger capacitor will reduce ripple but will cost more and will create higher peak currents in the transformer secondary and in the supply feeding it. The circuit has an indicator LED to indicate the supply it is connected through a current limiting resistor of 1 K. The 12 V supply is given to two fixed voltage regulators to get two fixed voltages to control circuit; to get a fixed voltage of 5 V the supply is given regulator LM 7805 at terminal 1 and common point is connected to the negative terminal and we get an output of 5 V. To get a fixed voltage of 12 V supply is given to regulator LM 7812 and input is given to input terminal 1 and the negative terminal is connected to the common point and 12 V supply is received the output terminal.

The control circuit has two parts, one microcontroller and four MOSFET driver IC"s. The microcontroller is a programmable device that holds a sequence of codes that performs a sequence of tasks and transfers the given input as signals to the switches. The microcontroller PIC16F877A is used as a controller and input supply for the microcontroller is 12 V and the supply is given between the pins 1 and 12 those pins are MCLR/VPP and VSS. The dsPIC30F2010 microcontroller has a sequence of program

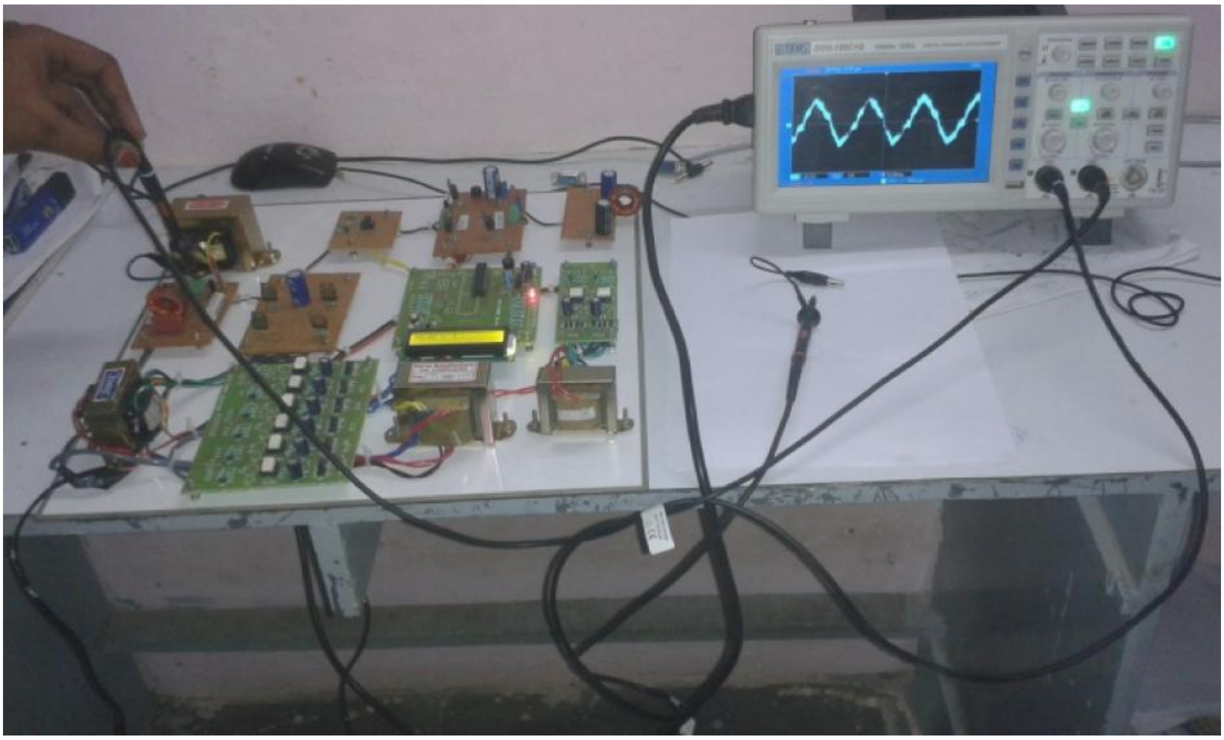
Table 2: Typical Hardware Values

Machine Side Current	0.015 amps
Load Side Current	0.01 amps
Grid Current	5 amps
Input Voltage	230 volts
Input Current	8 amps
Frequency	50 hertz
Output Frequency	50 hertz
Output Voltage	30 volts

codes. These codes help us to develop a sequence of instructions which is burnt on the microcontroller which in turn develops PWM signals by comparing saw tooth reference signal with control voltage signals from feedback controllers these signals are given to the MOSFET driver IC"s the driver IC"s used here is IR 2112.

The pins 20, 21, 26, 27, 28, 29 and 30 are the pins which generate PWM pulses these pins are bidirectional pins belong to PORT D they are parallel slave ports and they are digital input/ output ports which can act as input as wells as output these pins are connected to the MOSFET driver IC IR2112. Hence PORTD is a bidirectional I/O port or Parallel Slave Port. When interfacing to a microprocessor bus 64. The control signals are also received by these pins the pulses are fed to the IC IR2112 at the pins 9 and 12. The IR2112 is a high voltage, high speed power MOSFET and IGBT driver with independent high and low side referenced output channels. Logic inputs are compatible with standard CMOS or Low power Schottky TTL outputs, down to 3.3 V logic. The output drivers feature a high pulse current buffer stage designed for minimum driver cross-conduction. Propagation delays are matched to simplify use in high frequency applications. The floating channel can be used to drive an N-channel power MOSFET or IGBT in the high side configuration which operates up to 600 volts. The pins 7 and 10 produce High and Low outputs respectively, these signals are given as gate drive to the MOSFET IRF 840. The sequence of the pulses drives the MOSFETs in a sequence that ensures the clamping of the energy stored in a magnetizing inductor to

Figure 10: Mode 1 Operation



output through synchronous rectification circuit. Figure 10 shows the mode 1 period normal pwm pulses are applied. So the result of the output sine waveform contains oscillation and increase the junction temperature in converter section.

Figure 11 shows the mode 2 operation a SVPWM pulse is used in switching operation. In here a low frequency switching is 2.5 kHz. In this section a constant 30 voltage is fed to the grid section. A SVPWM reduce junction temperature in converter sections. A SMES is used to store energy. It contains inductor and capacitor. It stores energy from the MSC and supply to the LSC. It can act as a boost converter. The following coding is V-F control Space Vector and install in PIC microcontroller dsPIC30F2010.

A digital storage oscilloscope is an oscilloscope which stores and analyses the signal digitally rather than using analogue techniques. It is now the most common type of oscilloscope in use because of the advanced trigger, storage, display and measurement features which it typically provides. The input analogue signal is sampled and then converted into a digital record of the amplitude of the signal at each sample time. The sampling frequency should be not less than the Nyquist rate to avoid aliasing. These digital values are then turned back into an analogue signal for display on a Cathode Ray Tube (CRT), or transformed as needed for the various possible types of output-liquid crystal display, chart recorder, plotter or network interface.

Figure 11: Mode 2 Operation

CONCLUSION

This paper has provided a method to analyze the reactive power capability of the DFIG-based WT system. IGBT/diode power losses and thermal model have been developed using MATLAB/Simulink environment. The following conclusion can be made. A SMES is that the time delay during charge and discharge is quite short and a loss of power is less than other storage methods. Nowadays mostly used this technique in industry's. A SVPWM type is necessary in a different rotor speed operating mode, subsynchronous, synchronous, supersynchronous speed to have the lowest IGBT/diode power losses and increases in the permissible output current of MSC and its reduce the third harmonics in the output. This helps increase the reactive power capability of DFIG at such conditions. It also reduces the maximum junction temperature and helps in protecting the IGBT/diode from over temperature failures and hence could increase their failure.

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