Controlled Operation of Variable Speed Driven Permanent Magnet Synchronous Generator for Wind Energy Conversion Systems

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Abstract: - The introduction of distributed generation through renewable sources of energy has opened a challenging area for power engineers. As these sources are intermittent in nature, variable speed electric generators are employed for harnessing electrical energy from these sources. However, power electronic control is required to connect these sources to the existing grid. The grid interconnection issues are to be dealt with before connecting these to the local grid. Power conditioners using self commutating devices are necessary to have grid friendly inverters. In this paper, the MATLAB based simulation studies have been done to realize a grid friendly inverter system for harnessing energy from a variable speed wind energy system. The system is designed for low harmonic injection into the grid and fast control of voltage so as to meet the IEEE standard-1547 requirements.

Index Terms:- Power Conditioners, Power Quality, Variable Speed Generators, Wind Energy, Permanent Magnet Synchronous Generator.

1 Introduction

A wind turbine can be designed for a constant speed or variable speed operation. Variable speed wind turbines can produce 8% to 15% more energy output as compared to their constant speed counterparts, however, they necessitate power electronic converters to provide a fixed frequency and fixed voltage power to their loads. The major components of a typical wind energy conversion system include a wind turbine, generator, interconnection apparatus and control systems. Most turbine manufacturers have opted for reduction gears between the low speed turbine rotor and the high speed three-phase generators. Direct drive configuration, where a generator is coupled to the rotor of a wind turbine directly, offers high reliability, low maintenance, and possibly low cost for certain turbines.

At the present time and in the near future, generators for wind turbines will be synchronous generators, permanent magnet synchronous generators (PMSG), and induction generators (IG), including the squirrel cage type and wound rotor type. For small to medium power wind turbines, permanent magnet generators and squirrel cage induction generators are often used because of their reliability and cost advantages. Interconnection apparatuses are devices to achieve power control, soft start and interconnection functions. Very often, power electronic converters are used as such devices. Most modern turbine inverters are forced commutated PWM inverters to provide a fixed voltage and fixed frequency output with a high power quality. For certain high power wind turbines, effective power control can be achieved with double PWM (pulse width modulation) converters which provide a bi-directional power flow between the turbine generator and the utility grid [7-9].

Since wind speed is not constant, a wind farm's annual energy production is never as much as the sum of the generator nameplate ratings multiplied by the total hours in a year. The ratio of actual productivity in a year to this theoretical maximum is called the capacity factor. Typical capacity factors are 20-40%,

with values at the upper end of the range in particularly favorable sites [9].
There are several ways of designing the conversion system, depending on power electronics. For full power conversion, an AC/DC converter connected to the generator (generator side converter) and a DC/AC converter connected to the grid (grid side converter), with a DC-link between them is used. The DC link varies in an uncontrolled manner and a DC/DC converter is inserted between the rectifier and the inverter. The grid side inverter is controlled so as to keep minimum harmonic current injection in the grid. This paper is focused in a PMSG based direct drive turbine, connected to the grid by means of a full power converter. The variable speed fed PMSG with AC- DC- AC conversion system is modeled and simulated in MATLAB Simulink so as to verify the proposed system.[1,8]

2 Wind Turbine Generation Technologies

2.1 Fixed Speed Induction Generators (FSIG) Wind Turbines

The FSIG wind turbine is a simple squirrel cage induction generator, which can be directly coupled to the electricity supply network. The frequency of the network determines the rotational speed of the stator's magnetic field, while the generator's rotor speed changes as its electrical output changes. However, because of the well known hard torque- slip characteristic of the induction machine, the operating range of the generator is very limited. The wind turbine is therefore effectively fixed speed. FSIG's do not have the capability of independent control of active and reactive power, which is their main disadvantage. Their great advantage is their simple and robust construction, which leads to lower capital cost. In contrast to other generator topologies, FSIG's offer no inherent means of torque oscillation damping which places greater burden and cost on their gearbox [2,8]. The wind energy system and power quality aspects are discussed in detail in the literature [5, 18, 21-23].

2.2 Doubly Fed Induction Generators (DFIG) Wind Turbines

The DFIG is a wound rotor induction generator whose rotor is fed via slip rings by a frequency converter. The stator is directly coupled to the electrical power supply network. As a result of the use of the frequency converter, the network frequency is decoupled from the mechanical speed of the machine and variable speed operation is possible, permitting maximum absorption of wind power. Since power ratings are a function of slip, DFIGs operate over a range of speeds between about 0.75 and 1.25 pu of synchronous frequency, which requires converter power ratings of approximately 25%. A great advantage of the DFIG wind turbine is that it has the capability to independently control active and reactive power. Moreover, the mechanical stresses on a DFIG wind turbine are reduced in comparison to a FSIG. Due to the decoupling between mechanical speed and electrical frequency that results from DFIG operation, the rotor can act as an energy storage system, absorbing torque pulsations caused by wind gusts [3, 10, 11 , 19]. Other advantages of the DFIG include reduced flicker and acoustic noise in comparison to FSIGs. The main disadvantages of DFIG wind turbines in comparison to FSIGs are their increased capital cost and the need for periodic slip ring maintenance [4].

2.3 Direct Drive Synchronous Generator Wind Turbine

An alternative to the much-used induction machine generator is the use of a multipole synchronous generator, fed through a power electronic AC/DC/AC stage. The excitation of the synchronous generator can be given either by an electrical excitation system or by permanent magnets. The AC/DC/AC converter acts as a frequency converter and decouples the generator from the Grid. It consists of two back-to-back voltage source converters, usually with IGBT switches, which can independently control the active power transfer through the DC link and the reactive power output at each converter terminal .The speed range is generally similar to that of DFIGs. The multipole construction of the synchronous generator leads to a low mechanical rotational speed of the generator rotor and can permit direct coupling to the wind turbine. The possibility of reducing the number of stages in the gearbox or eliminating it completely is often quoted as an advantage of direct drive synchronous generator wind turbines. However set against this is the greater VA rating of the power electronic converter compared with DFIGs and the larger physical generator size. As a result of the increased mechanical stresses experienced by FSIG wind turbines at present there is a practical limit to the rating of commercial models of this technology. All present commercial models for multi-MW wind turbines in the range above 3MW are either DFIGs, or synchronous generators coupled to the network through back-to-back converters.
A comparison between the variable speed wind

turbine and the constant speed wind turbine shows that variable speed reduce mechanical stresses: gusts of wind can be absorbed, dynamically compensate for torque and power pulsations caused by back pressure of the tower. This backpressure causes noticeable torque pulsations at a rate equal to the turbine rotor speed times the number of rotor blades. The used of a doubly fed induction generator in WECS with the rotor connected to the electric grid through an AC-AC converter offers the following advantages:

- only the electric power injected by the rotor needs to be handled by the convert , implying a less cost AC-AC converter;
- Improved system efficiency and power factor control can be implemented at lower cost; the converter has to provide only excitation energy.

Hence, taking advantage of power electronic advances in recent years, WECS equipped with doubly fed induction generator systems for variable speed wind turbine are one of the most efficient configurations for wind energy conversion[12].

2.4 Permanent Magnet Synchronous

The scheme of a grid-connected PMSG for direct-drive wind turbines is shown in Fig. 2. The advantages of PM machines over electrically excited machines can be summarized as follows according to literatures:

- higher efficiency and energy yield,
- no additional power supply for the magnet field excitation,
- improvement in the thermal characteristics of the PM machine due to the absence of the field losses,
- higher reliability due to the absence of mechanical components such as slip rings,
- lighter and therefore higher power to weight ratio.

However, PM machines have some disadvantages, which can be summarized as follows:

- high cost of PM material,
- difficulties to handle in manufacture,
- Demagnetization of PM at high temperature.

In recent years, the use of PMs is more attractive than before, because the performance of PMs is improving and the cost of PM is decreasing. The trends make PM machines with a full-scale power converter more attractive for direct-drive wind turbines. Considering the performance of PMs is improving and the cost of PM is decreasing in recent years, in addition to that the cost of power electronics is decreasing, variable speed direct-drive PM machines with a full-scale power converter become more attractive for offshore wind powers.[2-5] On the other hand, variable speed concepts with a full-scale power converter and a single- or multiple-stage gearbox drive train may be interesting solutions not only in respect to the annual energy yield per cost but also in respect to the total weight. For example, the market interest of PMSG system with a multiple-stage gearbox or a single-stage gearbox is increasing [10-12, 20].

3 IEEE STD. 1547

IEEE std. 1547[7] defines distributed generation (DG) as: Electric generation facilities connected to an Area EPS through a point of common coupling (PCC); a subset of DR. And, distributed resources (DR) as: Sources of electric power that are not directly connected to a bulk power transmission system. Fig.1 shows the various forms of distributed generation.

- The power quality issues related to distributed resources are:
- The DR and its interconnection system shall not inject DC current greater than 0.5% of the full rated output current at the point of DR connection.
- The DR shall not create objectionable flicker for other customers on the area energy power system (EPS).
- When the DR is serving balanced linear loads, harmonic current injection into the Area EPS at the point of common coupling (PCC) shall not exceed the limits stated. The harmonic current injections shall be exclusive of any harmonic currents due to harmonic voltage distortion present in the Area EPS without the DR connected.
- For an unintentional island in which the DR energizes a portion of the Area EPS through the PCC, the DR interconnection system shall detect the island and cease to energize the Area EPS within two seconds of the formation of an island.

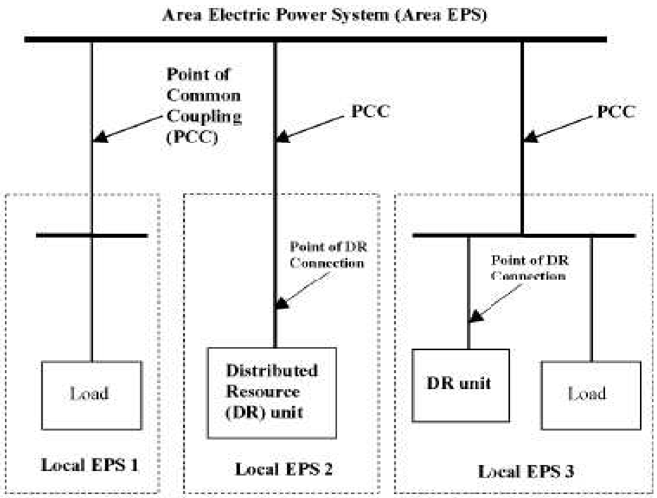

Fig .1. Distributed Generation

4 Grid Requirements

4.1 Voltage Regulation

A DR shall not cause the voltage at the Point of Common Coupling (PCC, see Figure 1) to go outside of Range A specified by Standard ANSI C84.1(or CSA CAN3-C235-83) [6]. For a 120/240V system, this specifies a maximum voltage of 126/252V and a minimum voltage of 114/226V.

4.1.1 Synchronization

When synchronizing, a DR shall not cause more than +/-5% of voltage fluctuation at the PCC.

4.1.2 Monitoring

A DR of 250 kW or larger shall have provisions for monitoring connection status and real and reactive power output at the DR connection.

4.1.4 Isolation Device

A readily accessible, lockable, visible-break isolation device shall be located between the DR and the EPS.

4.2 Safety and Protection Requirements

4.2.1 Voltage Disturbances

At abnormal voltages, a DR shall cease to energize the EPS within the specified clearing time.

4.2.2Frequency Disturbances

A DR shall cease to energize the EPS if the frequency is outside the range 59.3 - 60.5 Hz.
Loss of Synchronism: A DR of 250 kW or larger shall have loss of synchronism protection function.

4.2.3Reconnection:

A DR may reconnect to the power system 5 min. after the EPS voltage and frequency return to normal.

4.2.4 Unintentional Islanding

A DR shall cease to energize the EPS within 2 sec. of the formation of an island.

4.3 Power Quality Requirements

4.3.1 Harmonics

The total demand distortion of a DR, which is defined as the total rms harmonic current divided by the maximum demand load current, shall be less than 5%. Each individual harmonic shall be less than the specified level.

4.3.2 DC Current Injection

A DR shall have a dc current injection of less than 0.5% of its rated output current.
Flicker: A DR shall not create objectionable flicker for other customers on the area EPS.

5 Abnormal Grid Problems

In Europe, substantial wind penetration exists today and will only increase over time. The impacts on the transmission network are viewed not as an obstacle to development, but rather as obstacles that must be overcome. High penetration of intermittent wind power (greater than 20 percent of generation meeting load) and may affect the network in the following ways and has to be studied in detail:

5.1 Poor grid stability

For economic exploitation of wind energy, a reliable grid is as important as availability of strong winds. The loss of generation for want of stable grid can be 10% to 20% and this deficiency may perhaps be the main reasons for low actual energy output of WEGs compared to the predicted output in known windy areas with adequate wind data.

5.2 Low-frequency operation

Low frequency operation affects the output of WEGs in two ways. Many WEGs do not get cut-in, when the frequency is less than 48 Hz (for standard frequency of 50 Hz) through wind conditions are favorable, with consequent loss in output. This deficiency apart, the output of WEGs at low frequency operation is considerably reduced, due to reduced speed of the rotor. The loss in output could be about 5 to 10% on the account of low frequency operation.

5.3 Impact of low power factor
WEGs fitted with induction generators need reactive power for magnetizing. Normally in conventional energy systems, generators apart from supplying active power will be supplying a reactive power. But in case of WEGs fitted with induction generators, instead of supplying reactive power to the grid, they absorb reactive power from grid, which undoubtedly is a strain on the grid. Suitable reactive power compensation may be required to reduce the reactive power burden on the grid.

5.4 Power flow
It is to be ensured that the interconnecting transmission or distribution lines will not be over-loaded. This type of analysis is needed to ensure that the introduction of additional generation will not overload the lines and other electrical equipment. Both active and reactive power requirements should be investigated.

5.5 Short circuit
It is required to determine the impact of additional generation sources to the short circuit current ratings of existing electrical equipment on the network.

5.6 Power Quality
Fluctuations in the wind power may have direct impact on the quality of power supply. As a result, large voltage fluctuations may result in voltage variations outside the regulation limits, as well as violations on flicker and other power quality standards.

6. Various Topologies for Grid Connected Variable Speed PMSG
Variable speed use is good for extracting more prime mover power as in wind turbine or for providing optimum efficiency for the prime mover by increasing its speed with power. Variable speed also allows for a more flexible generator system. For wind turbines, a battery may be added to store the extra wind energy that is not momentarily needed for the existing loads or local power grids [13-17]. There are two main ways to handle the necessity of constant DC link voltage at variable speed:

- PMSG with diode rectifier and DC-DC chopper as shown in Fig. 2.
- PMSG with rectifier and DC-DC boost convertor as shown in Fig. 3.
- PMSG with PWM rectifier with battery for storing the extra wind energy as shown in Fig. 4.

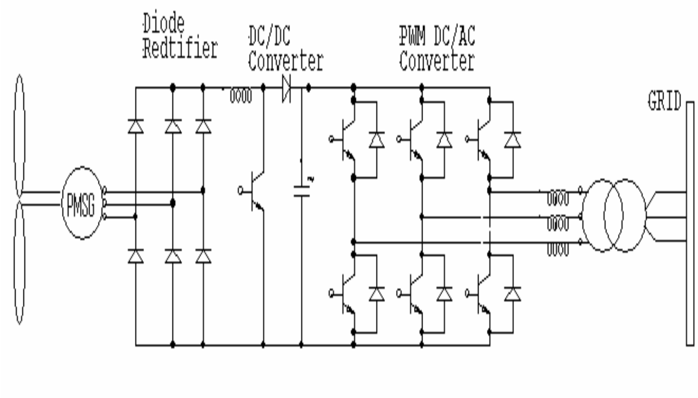

Fig.2.PMSG with diode rectifier and DC-DC chopper

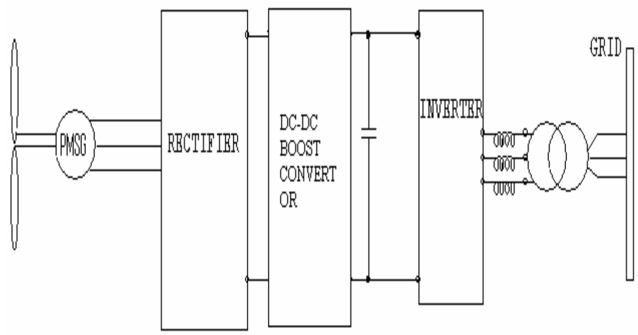

Fig .3. PMSG with rectifier and DC-DC Boost convertor

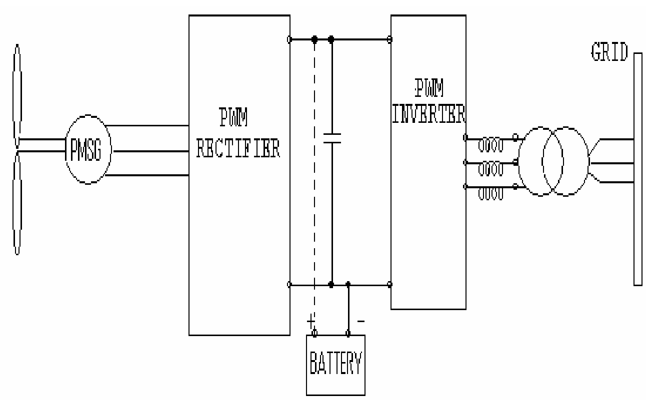

Fig .4. PMSG with PWM rectifier with battery for storing the extra wind energy

7 Proposed System and Modelling
A Permanent Magnet Synchronous Generator is driven by a variable speed wind energy conversion system. The PMSG block is fed from the speed controller. The speed fed is 94 rad/sec corresponding to 60 Hz supply system for four pair of poles. The AC output of PMSG is rectified with the help of uncontrolled rectifier. The DC-DC boost converter is

used to keep the DC-link voltage constant at the VSI inverter input. The inverter output is fed to the grid. The inverter is controlled so that the injected current is near to sinusoidal.

The supply system consists of wind turbine, three-phase PMSG, DC- AC-DC converter and voltage source inverter system.

7.1 Wind Turbine Modeling

This block implements a wind energy conversion system. The inputs are actual and desired speed and the output of the block is mechanical power (P_ω). The amount of power harnessed from the wind of velocity v is as follows.

$P_\omega = 1/2\ \rho A C_p \nu^3$

Where

P_ω = wind power in watts

ρ = air density in kg/m^3

A= swept area in m^2

C_p=power coefficient of wind turbine

ν= wind speed in m/s

7.2 Modeling of Permanent Magnet Synchronous Machine

The permanent magnet synchronous machine block operates in generating or motoring modes. The operating mode is dictated by the sign of the mechanical power (positive for generating, negative for motoring). The electrical part of the machine is represented by a sixth-order state-space model. The model takes into account the dynamics of the stator and damper windings. The equivalent circuit of the model is represented in the rotor reference frame (d-q frame). The following equations are used to express the model of the PMSG as:

$$V_d = R_s i_d + p\varphi_d - w_r \varphi_q \quad (1)$$

$$V_q = R_s i_q + p\varphi_q + w_r \varphi_d \quad (2)$$

$$V'_{fd} = R'_{fd} i'_{fd} + p\varphi'_{fd} \quad (3)$$

$$V'_{kd} = R'_{kd} i'_{kd} + p\varphi'_{kd} \quad (4)$$

$$V'_{kq1} = R'_{kq1} i'_{kq1} + p\varphi'_{kq1} \quad (5)$$

$$V'_{kq2} = R'_{kq2} i'_{kq2} + p\varphi'_{kq2} \quad (6)$$

where $\varphi_d = L_d\, i_d + L_{md}\,(i'_{fd} + i'_{kd})$ (7)

$$\varphi_q = L_q\, i_q + L_{mq}\, i'_{kq} \quad (8)$$

$$\varphi'_{fd} = L'_{fd}\, i'_{fd} + L_{md}\,(i_d + i'_{kd}) \quad (9)$$

$$\varphi'_{kd} = L'_{kd}\, i'_{kd} + L_{md}\,(i_d + i'_{fd}) \quad (10)$$

$$\varphi'_{kq2} = L'_{kq2}\, i'_{kq2} + L_{mq}\, i_q \quad (11)$$

where the subscripts used are defined as: d, q: d and q axis quantity, r, s: Rotor and stator quantity, l, m: Leakage and magnetizing inductance, f, k: Field and damper winding quantity. R_s represents stator resistance, L_{ls} stator leakage inductance, L_{md} and L_{mq} represent d-axis and q-axis magnetizing inductances. R_f' denotes field resistance and L_{lfd}' leakage inductance, both referred to the stator. Damper d-axis resistance R_{kd}' and leakage inductance L_{lkd}', Damper q-axis resistance $R_{kq}1'$ and leakage inductance L_{lkq1}' and the q-axis resistance R_{kq2}' and leakage inductance L_{lkq2}' All these values are referred to the stator. All rotor parameters and electrical quantities are viewed from the stator and are identified by primed variables. The simplified synchronous machine block implements the mechanical system described by:

$$\Delta w(t) = \int (Tm - Te)dt\ / (2H) - K_d \Delta w(t) \quad (12)$$

$$w(t) = \Delta w(t) + w_o \quad (13)$$

7.3 Excitation System

For simulation of PMSG, the excitation is kept constant at 1.0 p.u. in this model of synchronous generator.

7.4 Modeling of Control Scheme

The control scheme is mainly used to derive reference source currents, which are used in PWM current controller of VSI of BESS. These are derived in following section.

The reference source currents are having two components, in-phase component and a quadrature component. They are estimated in sequence as follows:

The unit vectors in-phase with v_a, v_b and v_c are derived as:

$$u_a = v_a / V_m;\ u_b = v_b / V_m;\ u_c = v_c / V_m \quad (14)$$

where V_m is the amplitude of the AC terminal voltage at the PCC and can be computed as:

$$V_m = 2/3\ \sqrt{(v_a^2+v_b^2+v_c^2)} \quad (15)$$

where v_a, v_b, and v_c are the instantaneous voltages at PCC and can be calculated as:

$$v_a = v_{san} - R_s\, i_{sa} - L_s\, pi_{sa} \quad (16)$$

$$v_b = v_{sbn} - R_s\, i_{sb} - L_s\, pi_{sb} \quad (17)$$

$$v_c = v_{scn} - R_s\, i_{sc} - L_s\, pi_{sc} \quad (18)$$

where L_s and R_s are per phase source inductance and resistance respectively. v_{san}, v_{sbn}, and v_{scn} are the three phase instantaneous input supply voltages at PCC and are expressed as:

$$\left.\begin{aligned} v_{san} &= v_{sm}\sin(\omega t) \\ v_{sbn} &= v_{sm}\sin(\omega t - 2\pi/3) \\ v_{scn} &= v_{sm}\sin(\omega t + 2\pi/3) \end{aligned}\right\} \quad (19)$$

where v_{sm} is the peak value and $\omega = 2\pi f$ is the frequency of the supply.

The unit vectors in-quadrature with v_a v_b and v_c may be derived by taking a quadrature transformation of the in-phase unit vectors u_a, u_b and u_c as:

$$w_a = -u_b/\sqrt{3} + u_c/\sqrt{3} \quad (20)$$

$$w_b = \sqrt{3}\, u_a/2 + (u_b - u_c)/(2\sqrt{3}) \quad (21)$$

$$w_a = -\sqrt{3}\, u_a/2 + (u_b - u_c)/(2\sqrt{3}) \quad (22)$$

The quadrature component of the reference source currents is computed as:

The voltage error V_{er} at PCC at the nth sampling instant is as:

$$V_{er(n)} = V_{ref(n)} - V_{m(n)} \quad (23)$$

The output of the PI controller at the nth sampling instant is expressed as:

$$I^*_{smq(n)} = I^*_{smq(n-1)} + K_p\{V_{er(n)} - V_{er(n-1)}\} + K_i V_{er(n)} \quad (24)$$

where K_p and K_i are the proportional and integral constants, respectively of the proportional integral (PI) controller and the superscript represents the reference quantity.

The quadrature components of the reference source currents are estimates as:

$$i^*_{saq} = I^*_{smq}\, w_a;\quad i^*_{sbq} = I^*_{smq}\, w_b;\quad i^*_{scq} = I^*_{smq}\, w_c \quad (25)$$

The in-phase component of the reference source currents is computed as:

$$i^*_{sad} = I^*_{smd}\, u_a;\ i^*_{sbd} = I^*_{smd}\, u_b;\ i^*_{scd} = I^*_{smd}\, u_c \quad (26)$$

where I^*_{smd} is considered fixed value corresponding to the constant source current for load leveling.

Reference source currents are computed as the sum of the in-phase components of the reference source currents and the quadrature components of the reference source currents given as:

$$i^*_{sa} = i^*_{saq} + i^*_{sad};\ i^*_{sb} = i^*_{sbq} + i^*_{sbd};\ i^*_{sc} = i^*_{scq} + i^*_{scd} \quad (27)$$

These source reference currents are compared with the sensed source currents in PWM current controller. The current errors of all the three phases are amplified. If the amplified reference source current error signal, i_{saerr}, is greater than the triangular wave carrier signal, switch S_1 is ON and switch S_4 is OFF, and the value of SA is 1. When the amplified reference source current error signal is less than the triangular wave carrier signal switch S_1 is OFF and switch S_4 is ON, and the value of SA is 0. Similar logic applies to other phases.

8 MATLAB Simulation of the Proposed Topology

The MATLAB simulation of the PMSG and the DC-DC boost converter is shown in the Fig. 5. The inverter and the grid system is shown in Fig. 6.

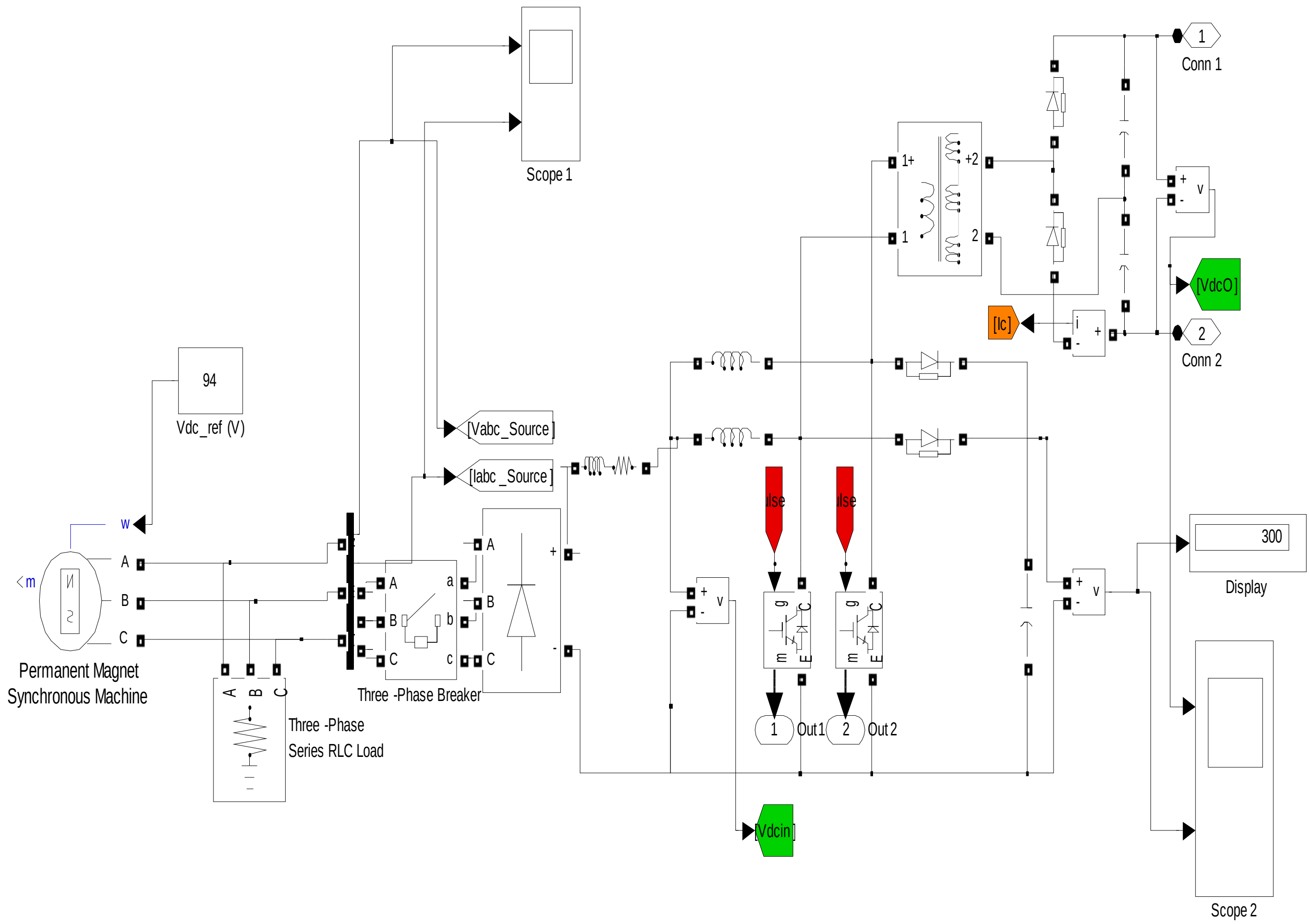

Fig. 5. MATLAB simulation of PMSG and DC-DC converter

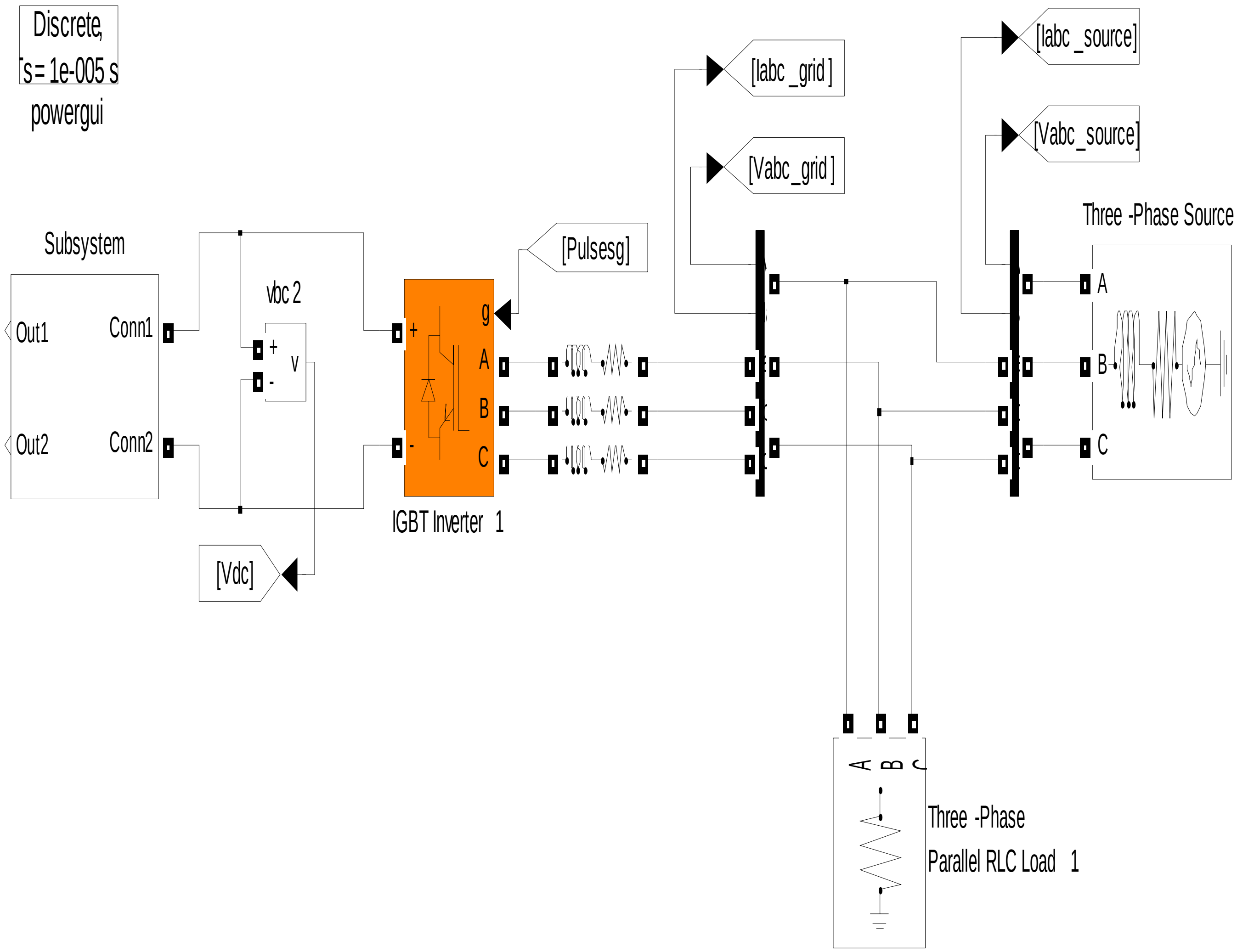

Fig. 6. MATLAB simulation of inverter and the grid

9. Simulation Results

The figures 7-9 show the source voltages (V_{abc}), source currents (I_{abc}), grid voltages (V_{grid}), grid currents (I_{grid}) and the DC- link voltage (V_{dc}). The rating of the PMSG is given in the Appendix.

9.1 Performance of the proposed system at rated wind speed:

The PMSG is run at 31.6 rad/sec. The PMSG generator voltage builds up to 100 volts. Once the steady state is reached, the generator output is connected to the uncontrolled rectifier. The uncontrolled DC is kept constant to 250 volts at the DC link with the help of DC-DC Boost Convertor as shown in Fig. 7. The inverter output I_{grid} is sinusoidal as shown in the Fig. 8 indicating the low harmonics

9.2 Performance of the proposed system at reduced wind speed:

The PMSG is now run at half of the rated speed at 15.8 rad/sec. The PMSG generator voltage builds up to 50 volts. Once the steady state is reached, the generator output is connected to the uncontrolled rectifier. The uncontrolled DC is again kept constant to 250 volts at the DC link as shown in Fig. 9. The inverter output V_{grid} and I_{grid} are sinusoidal as shown in the figure indicating the low harmonics. The power generated by PMSG is absorbed by the grid.

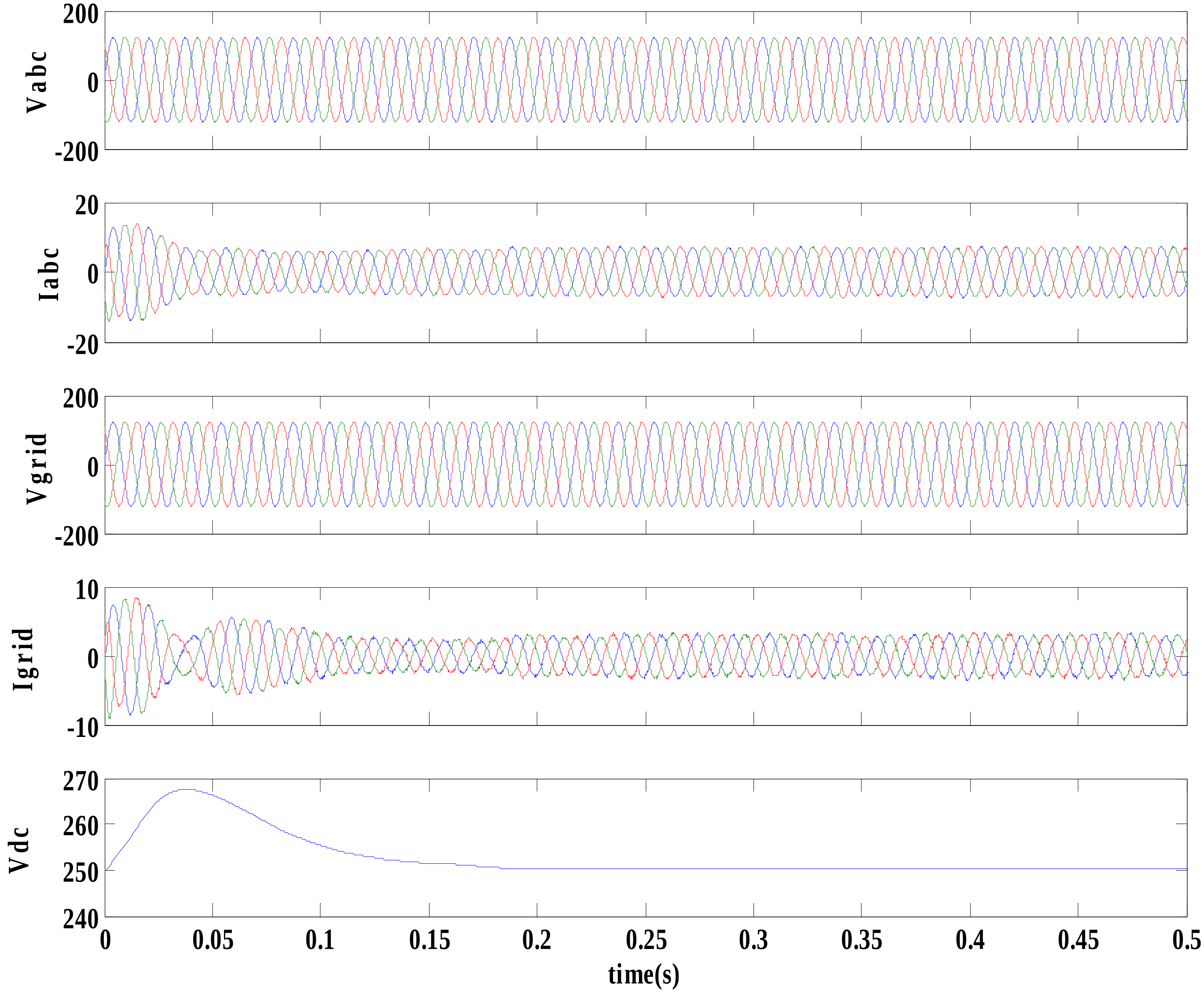

Fig. 7. Performance of PMSG system at rated speed

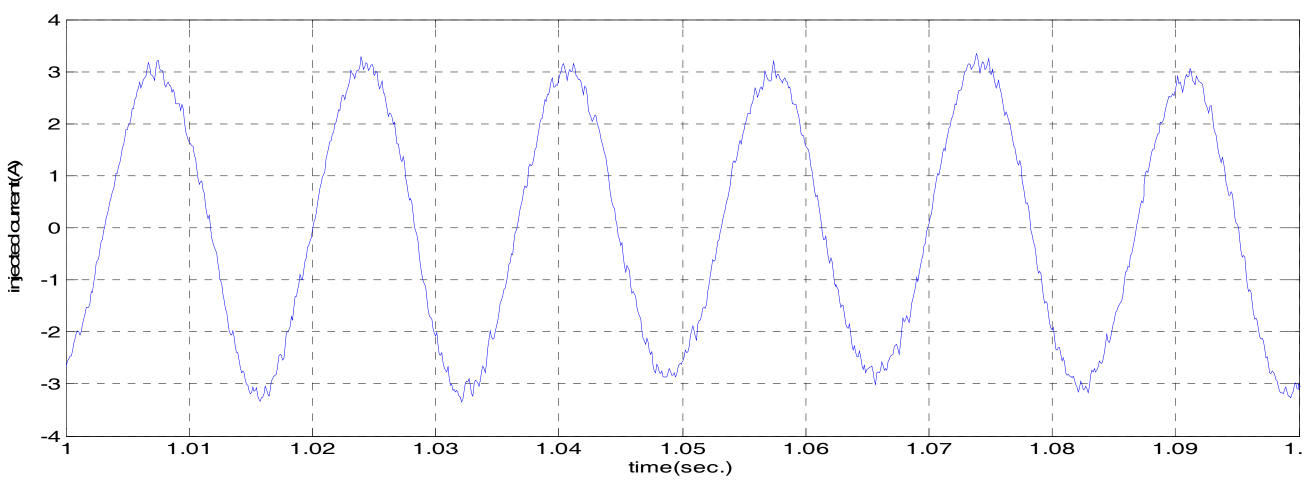

Fig. 8. Injected current at rated speed

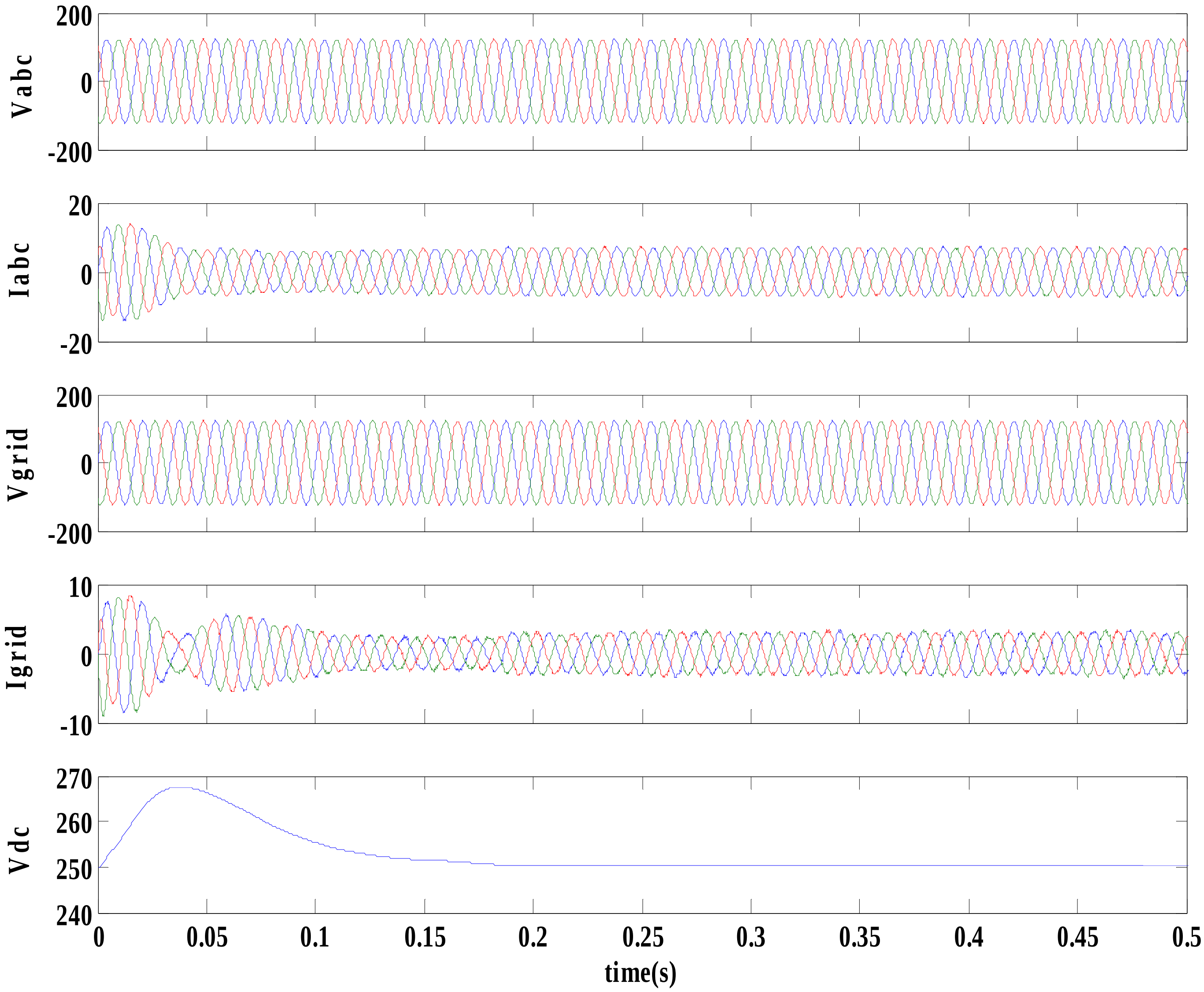

Fig .9. Performance of PMSG system at half of the rated speed

10 Conclusion

In this paper the power conditioning of variable speed driven PMSG fed AC-DC-AC system has been studied for reduced harmonics injection into the grid. The inverter is controlled so as to meet IEEE standard 1547 requirements for connection of distributed generation to the local grid. The simulated results validate the proposed topology.

Appendix:

Permanent Magnet Synchronous Generator:
3-Phase , 300 V, 60 Hz, 3000 rpm, 4-pole

Electromagnetic Torque	:	0.8 Nm
Stator Resistance(R_S)	:	18.7 Ω
Inductance : Ld(H) = Lq(H)	:	0.02682 H
Flux induce by magnets	:	0.1717 wb

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