Grid Voltage Control of Inverter Interfaced Wind Energy Conversion System (WECS)

Rajveer Mittal, K. S. Sandhu, and D. K. Jain

***Abstract*— In this paper the grid interconnection issues of AC-DC-AC inverter interfaced wind energy conversion system have been dealt. The power flow in context of load has now reversed in such local generating stations; the voltage rise at the point of common coupling (PCC) in the case of large scale wind farm is well known. The wind energy conversion system has to be taken out if the voltage exceeds beyond limit. Thus the capacity factor of the wind farm may be poor. In this case, the grid inverter can support the voltage at PCC by injecting reactive power along with the active power. The simulation results are given here for improving the voltage at PCC.**

***Index Terms*—Point of common coupling (PCC), permanent magnet synchronous generator (PMSG), wind energy, grid interconnection, electric power system(EPS)**.

I. INTRODUCTION

The major components of a typical wind energy conversion system include a wind turbine, generator, interconnection apparatus and control systems. Wind turbines can be classified into the vertical axis type and the horizontal axis type. Most modern wind turbines use a horizontal axis configuration with two or three blades, operating either down-wind or up-wind. 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. 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. Several manufacturers have opted for the direct drive configuration in the recent turbine designs. At the present time and in the near future, generators for wind turbines will be synchronous generators, permanent magnet synchronous generators, and induction generators, including the squirrel cage type and wound rotor type.

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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. Induction generators, permanent magnet synchronous generators and wound field synchronous generators are currently used in various high power wind turbines. 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. Both voltage source voltage controlled inverters and voltage source current controlled inverters have been applied in wind turbines. 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 [3-5].

The main problem with wind energy in weak grids is the quasi-static voltage level. In a grid without wind turbines connected the main concern by the utility is the minimum voltage level at the far end of the feeder when the consumer load is at its maximums as shown in fig1. So the normal voltage profile for a feeder without wind energy is that the highest voltage is at the bus bar at the substation and that it drops to reach the minimum at the far end. The settings of the transformers by the utility are usually so, that the voltage at the consumer closest to the transformer will experience a voltage, that is close to the maximum value especially when the load is low and that the voltage is close to the minimum value at the far end when the load is high. This operation ensures that the capacity of the feeder is utilised to its maximum. When wind turbines are connected to the same feeder as consumers which often will be the case in sparsely populated areas the voltage profile of the feeder will be much different from the no wind case. Due to the power production at the wind turbine the voltage level can and in most cases will be higher than in the no wind case. As is seen on the figure2 the voltage level can exceed the maximum allowed when the consumer load is low and the power output from the wind turbines is high. This is what limits the capacity of the feeder. The voltage profile of the feeder depends on the line impedance, the point of common coupling of the wind turbines and on the wind power production and the consumer load. [6-8]For a simple single load case the voltage rise over the grid impedance can be approximated as with using generator sign convention.

$$VE= (R*P+X*Q)/V \tag{1}$$

This formula indicates some of the possible solutions to the problem with absorption of wind power in weak grids. The main options are either a reduction of the active power or an increase of the reactive power consumption or a reduction of the line impedance. The major power quality issues are;

- Grid availability and capacity
- Reactive power
- Voltage unbalance
- Voltage ranges
- Frequency rang
- Harmonics and interharmonics
- Voltage fluctuations
- Islanding and overcompensation Grid availability and capacity

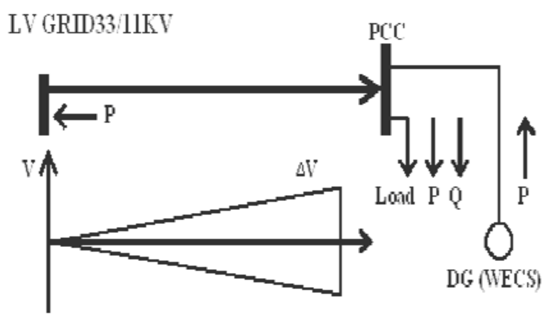

Fig.1. Voltage at pcc with load (conventional method)

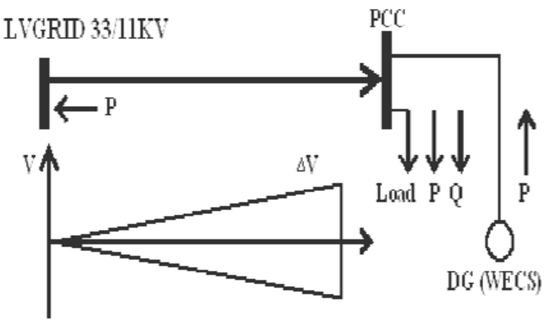

Fig. 2. Voltage at pcc with load and power injection

The major weakness has been the evacuation capacity. As a consequence of insufficient evacuation capacity, the wind farms have regularly been disconnected from the grid during the high wind seasons. Also the capacity of the substations has influenced the grid availability in the wind farms. The wind farm feeders have been disconnected regularly in the high wind season due to insufficient substation transformer capacity.

A. Reactive power Compensation

The majority of wind turbines installed are converting the mechanical power to electricity through directly connected induction generators. These induction generators require reactive power from the grid for excitation. The loads on the power system are also consuming a significant reactive power, mainly due to agricultural pumps and industrial load. The resulting reactive power demand causes losses in the transmission. The reactive power consumption results in poor power factor, due to which the capacities of the power stations are reduced. This is a critical issue, because the available power station capacity is insufficient to supply the peak demand. Also excessive reactive power consumption can be critical for the stability of the power system.

B. Voltage Unbalance

Single wind turbines or smaller groups of wind turbines have been connected to existing rural load feeders in some remote areas. There may be load shedding on individual phases during peak load hours. The load shedding causes significant voltage unbalance, with tripping of the wind turbines as a result.

C. Voltage Ranges

The variations in the steady state voltage should be within the range at the wind turbine terminals in the wind farms. Too low voltages can cause the relay protections to trip the wind turbines. The steady state voltage also influences the losses in the induction generators. For low voltages, the no-load losses decrease slightly due to reduced iron losses, whereas the full-load losses (i.e. losses at rated power) increase due to increased currents in the generator windings.

D. Frequency Range

The grid frequency should remain in the range of ±3%. Most of the time, the frequency is below the rated value. For wind turbines with induction generators directly connected to the grid, the rotor speed and thus the aerodynamic performance of the wind turbine will be modified by the frequency.

E. Harmonics and Interharmonics

The emission of harmonic and interharmonic currents from wind turbines with directly connected induction generators has been expected to be negligible in service. Wind turbines connected to the grid through power converters however emit harmonic and/or interharmonic currents and contribute to the voltage distortion. Inverters based on new technologies have a limited emission of harmonics at lower frequencies compared to the converters used in the first generation of variable speed wind turbines. Instead they produce interharmonics at higher frequencies which are easier to filter than at lower frequencies.

F. Voltage Fluctuations

Fluctuations in the voltage supplied to consumers may, depending on the frequency and the amplitude of the fluctuations, cause public annoyance due to flicker in the illumination from lamps. The power from wind turbines is fluctuating, and therefore the wind turbines contribute to the voltage fluctuations in the grid. Fluctuations in the voltage may in extreme conditions trig a voltage collapse, as a voltage drop causes increased reactive power consumption, which feeds back as an increased voltage drop.

G. Islanding and Overcompensation

For the power factor improvement of the wind turbine with induction generator capacitors are generally used, which may cause overcompensation. Overcompensation with capacitors may cause islanding with rapidly increasing voltages in the island grid.

H. Methods of Voltage Control

- Grid Reinforcement
- Disconnection
- Reduced Production
- Energy Storage
- Reactive Power Absorption Load

Grid reinforcement increases the capacity of the grid by increasing the cross section of the cables. This is usually done by erecting a new line parallel to the existing line for some part of the distance. Because of the increased cross section the impedance of the line is reduced and therefore the voltage variations as a result of power variations are reduced. Grid reinforcement increases both the amount of wind energy that can be connected to the feeder and the maximum consumer load of the feeder. Since the line impedance is reduced the losses of the feeder are also reduced. Grid reinforcement can be very costly and sometimes impossible due to planning restrictions.

Since grid reinforcement can be very costly or impossible other options are interesting. The simplest alternative is to stop some of the wind turbines when the voltage level is in danger of being exceeded. This can be done by the wind turbine controller monitoring the voltage level at pcc. At a certain level the wind turbine is cut off and it is then cut in again when the voltage level is below a certain limit. The limits can be precalculated and depends on transformer settings, line impedance and other loads of the feeder. This is a simple and crude way of ensuring that the voltage limits will not be exceeded. It can be implemented at practically no cost but not all the potentially available wind energy is utilised.

A method that is slightly more advanced is to continuously control the power output of the wind turbine in such a way that the voltage limit is not exceeded. This can be done on a wind farm level with the voltage measured at the point of common connection. The way of controlling the power output requires that the wind turbine is capable of controlling the output (pitch or variable speed controlled) and a bit more sophisticated measuring and control equipment, but the amount of wind energy that is dumped is reduced compared to the option of switching off complete wind turbines.

The storage is used to buffer the wind energy that cannot be feed to the grid at the point of connection without violating the voltage limits. Usually the current limit of the grid will not be critical. The energy in the storage can be fed back to the grid at a later time when the voltage level is lower. The situations where the voltage level will be high will occur when the consumer load of the grid is low and the wind power production is high. If the voltage level will be critically high depends on the characteristics of the grid (e.g. impedance and voltage control), the minimum load of the consumers, the amount of installed wind power and the wind conditions. The critical issues involved in the design of a power control system are the power and energy capacity, the control bandwidth as well as investment, installation and maintenance cost. The various types of power control systems have different characteristics giving different weights on capacity, investment and maintenance [9-15]. Different types of storage like batteries, pumped storage, flywheel, super conducting magnetic storage, compressed air and capacitors can be applied.

II. Interconnection With Electric Power Systems

IEEE Standards Coordinating Committee on Fuels, Photovoltaic's, Dispersed Generation, and Energy Storage had formed working groups to develop IEEE P1547, the Draft Standard for Interconnecting Distributed Resources with Electric Power Systems, and P1589, the Draft Standard for Conformance Tests Procedures for Equipment Interconnecting Distributed Resources with Electric Power Systems (EPS) [1-2,8]. Distributed resources connected with electric power systems are presented in Fig. 3 as typical configurations. The major interconnection requirements for distributed resources can be summarized in the following three categories: general requirement, safety and protection, and power quality.

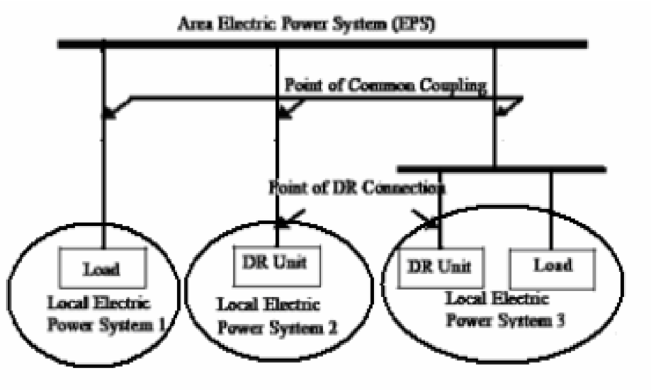

Fig.3. .Distributed resources connected to a power system.

A. General Requirements

Voltage Regulation: A DR shall not cause the voltage at the Point of Common Coupling (PCC, see Fig. 3) to go outside of Range as specified by Standard ANSI C84.1 (or CSA CAN3-C235-83). For a 120/240V system, this specifies a maximum voltage of 126/252V and a minimum voltage of 114/226V.

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

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.

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

B. Safety and Protection Requirements

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

Frequency 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.

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

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

C. Power Quality Requirements

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.

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 [16-18].

III. PROPOSED TOPOLOGY AND MODELING 0F THE SYSTEM

The proposed topology is shown in the Fig.4. 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.

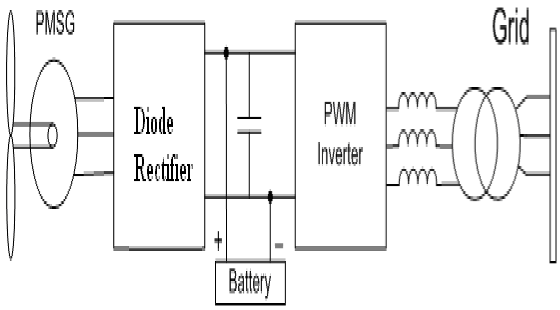

Fig.4. Proposed topology for voltage control at PCC

IV. MODELING OF THE SYSTEM

A. Wind Turbine Modeling

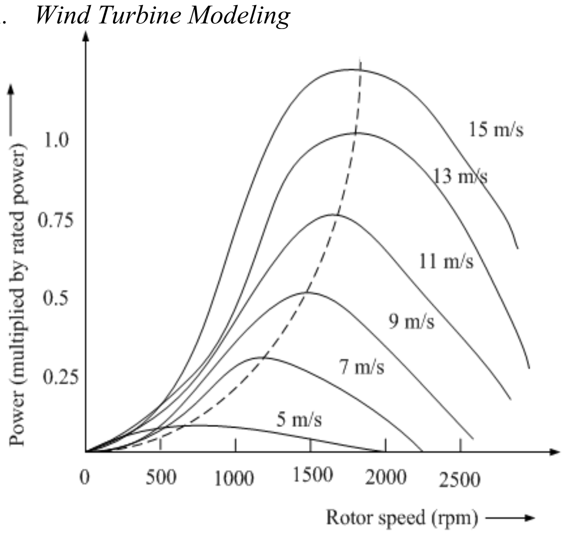

Fig. 5. A typical power versus speed characteristics of a wind turbine.

The wind turbine power curves as shown in Fig. 5 illustrate how the mechanical power that can be extracted from the wind depends on the rotor speed. For each wind speed there is an optimum turbine speed at which the extracted wind power at the shaft reaches its maximum value.

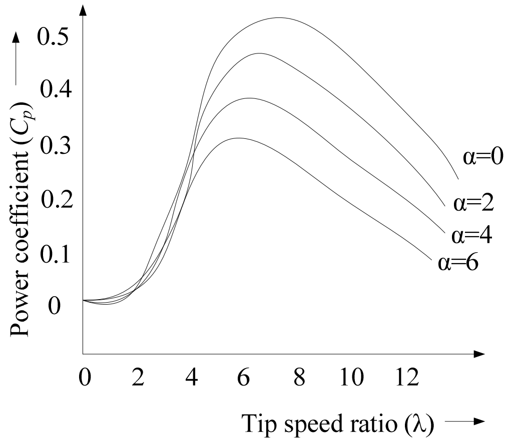

Fig.6. Typical curves of power coefficient versus tip speed ratio for various value of the pitch angle α.

For a given turbine, the power coefficient depends not only on the TSR but also on the blade pitch angle. The Fig.6 shows the typical variation of the power coefficient with respect to the TSR λ with blade pitch control.

From the following equations,

$$P_o = \frac{1}{2}\rho A V_\infty^3 \tag{2}$$

and

$$C_P = \frac{power\ output\ from\ the\ wind\ machine}{power\ contained\ in\ wind}$$

the mechanical power transmitted to the shaft is

$$P_m = \frac{1}{2}\rho C_p A V_\infty^3 \tag{3}$$

where C_p is a function of the TSR λ and the pitch angle α.

For a wind turbine with radius R, the above equation can be expressed as

$$P_m = \frac{1}{2}\rho C_p \pi R^2 V_\infty^3 \tag{4}$$

For a given wind speed, the power extracted from the wind is maximized if C_p is maximized. The optimum value of C_p, say $C_{p,opt}$, always occurs at a definite value of λ say λ_{opt}. This means that for varying wind speed, the rotor speed should be adjusted proportionally to adhere always to this value of λ (= λ_{opt}) for maximum mechanical power output from the turbine. Using the relation $\lambda = \omega R / V_\infty$ in above equation, the maximum value of the shaft mechanical power for wind speed can be expressed as

$$P_{\max} = \frac{1}{2}\rho C_{p,opt}\pi \left(\frac{R^5}{\lambda_{opt}^3}\right)\omega^3 \tag{5}$$

Thus the maximum mechanical power that can be extracted from wind is proportional to the cube of the rotor speed, i.e.,

$$P_{\max} \propto \omega^3 \tag{6}$$

B. Modeling of Permanent Magnet Synchronous generator

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:

$$V_d = -R_s i_d - p\varphi_d + \omega_r \varphi_q \quad (7)$$

$$V_q = -R_s i_q - p\varphi_q - \omega_r \varphi_d + \omega_r \varphi_f \quad (8)$$

$$T_e = \frac{3}{2}.p[(L_d - L_d)i_d iq + \varphi_f iq] \quad (9)$$

$$P = \frac{3}{2}[V_d i_d + V_q i_q] \quad (10)$$

$$Q = \frac{3}{2}[V_d i_q + V_q i_d] \quad (11)$$

where $\varphi_d = L_d i_d + \varphi_f$ (12)

$$\varphi_q = L_q i_q \quad (13)$$

C. Excitation System

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

D. 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:

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

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

$$V_a = v_{san} - R_s i_{sa} - L_s p i_{sa} \quad (16)$$

$$V_b = v_{sbn} - R_s i_{sb} - L_s p i_{sb} \quad (17)$$

$$V_c = v_{scn} - R_s i_{sc} - L_s p i_{sc} \quad (18)$$

where Ls and Rs are per phase source inductance and resistance respectively. Vsan, vsbn, and vscn are the three phase instantaneous input supply voltages at PCC and are expressed as:

$$v_{san} = v_{sm}\sin(\omega t); v_{sbn} = v_{sm}\sin(\omega t - 2\pi/3);$$
$$v_{scn} = v_{sm}\sin(\omega t + 2\pi/3) \quad (19)$$

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:

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

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

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

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:

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

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:

$$I^*_{saq} = I^*_{smq}\omega_a \; ; I^*_{sbq} = I^*_{smq}\omega_b \; ; I^*_{scq} = I^*_{smq}\omega_c \quad (25)$$

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:

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

V. Simulation Results

The simulation model has been designed in MATLAB using sim power tool box as shown in Fig.7.

The variation of PCC voltage (Vpcc), grid voltage (Vgiid) and dc link voltage (Vdc) is,shown in Fig.8.without providing any voltage control on pcc and with voltage control in fig.9 . There is a 20% voltage rise/fall on the grid side during 0.5ms to 0.6ms and.7ms to.8ms respectively. The voltage at PCC(Vpcc) is almost constant due to injection of reactive power along with the active power by the grid side inverter constant as shown in figure 9.

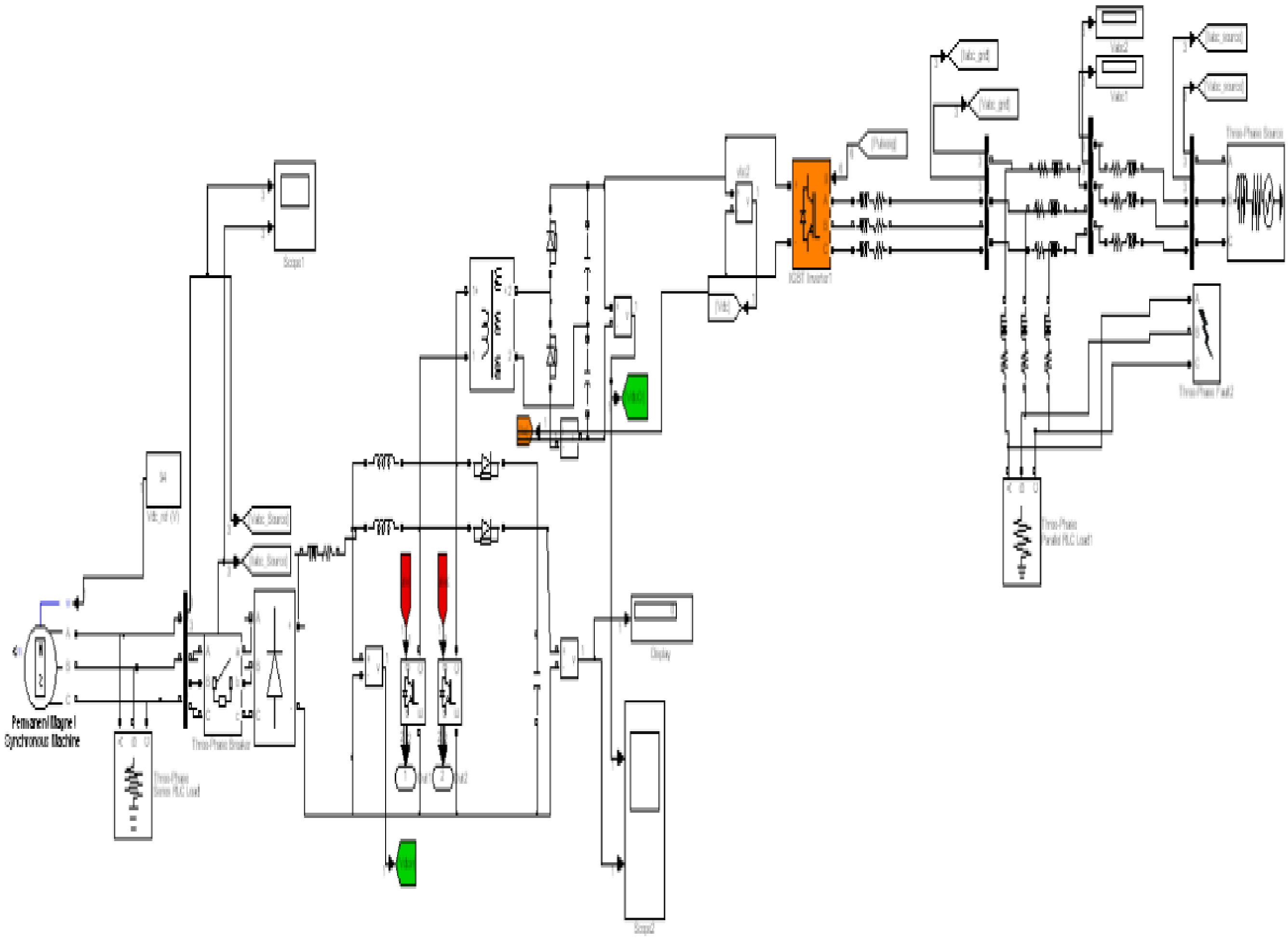

Fig. 7. MATLAB based Simulation Model

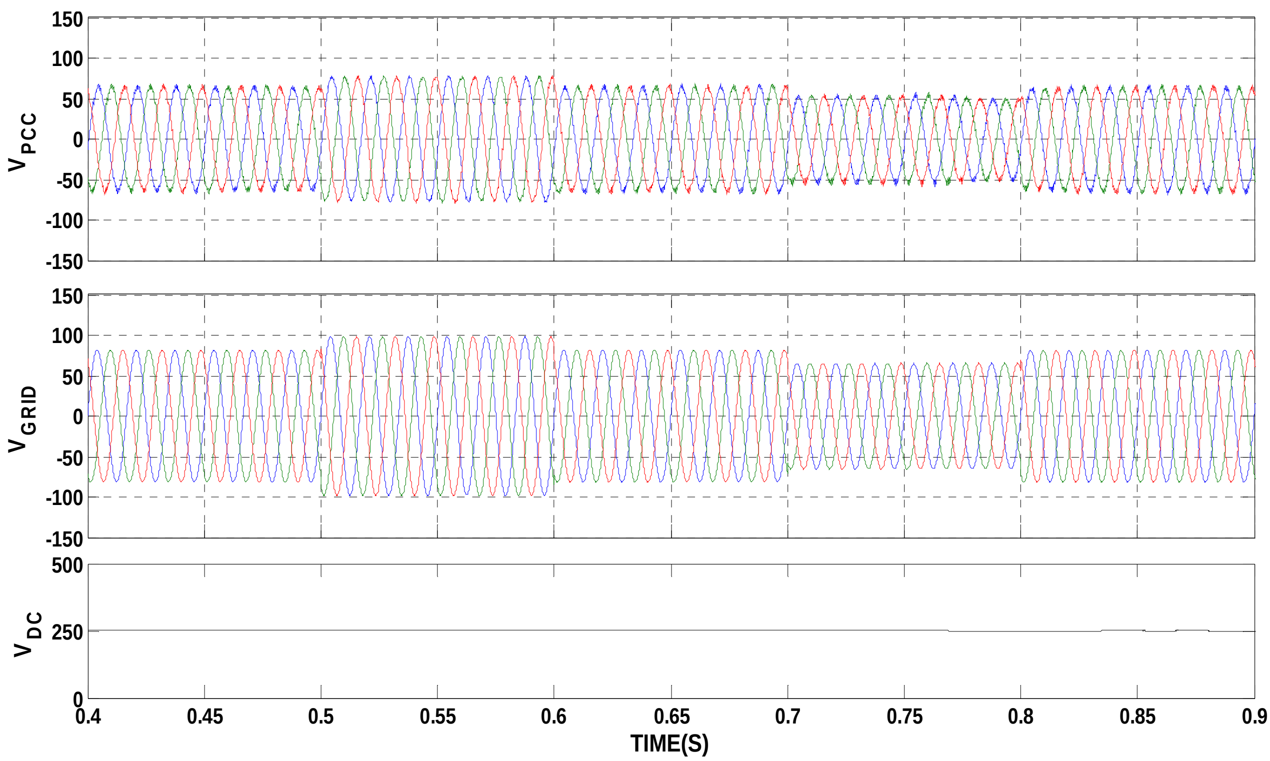

Fig.8. Variation of PCC Voltage, Grid Voltage and DC-Link voltage under 20% voltage rise/fall on the grid side without voltage control

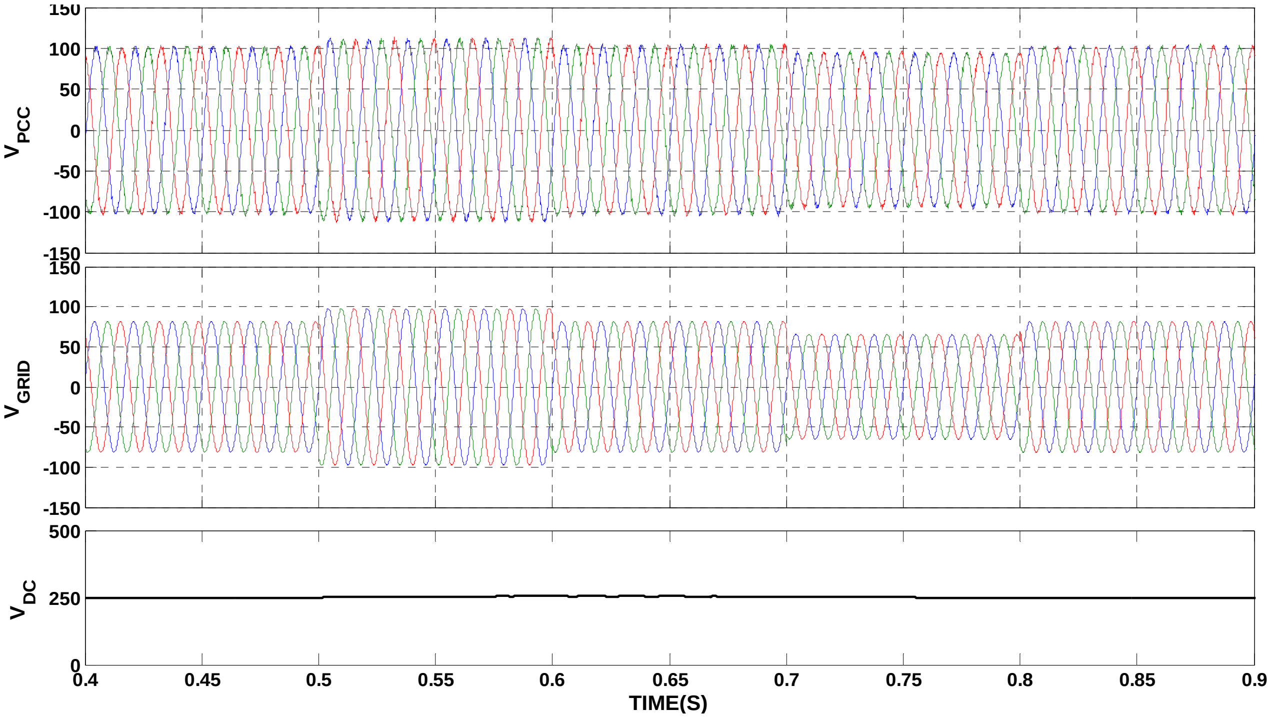

Fig.9. Variation of PCC Voltage, Grid Voltage and DC-Link voltage under 20% voltage rise/fall on the grid side with voltage control.

VI. Conclusions

The voltage variation at PCC due to voltage rise/fall on the grid or change in load is the main issue in case of grid connected WECS. The proposed topology provides the constant voltage at PCC due to injection of reactive power along with the active power by the grid side inverter.

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