Performance of Wind Energy Conversion System with Parallel Wind Turbines Topology

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Abstract

Worldwide, a significant growth has been noticed in wind turbine installed capacity which encourages the exploration of new Wind Turbine topologies and developed it. In this paper, a parallel connected Wind Turbine generation units based on variable speed directly coupled Permanent Magnet Synchronous Generator (Type-4) system is proposed. The proposed system is connected to grid source via a common back to back DC link connection between generating machine side power converter and grid side inverter. The modeling and control strategies for the proposed system is investigated. The controllers of generating machine-side and grid-side converters worked concurrently to meet unity power factor operation and under grid fault operation along with low voltage ride through capability. Two units of parallel connected Wind Turbine generation system with their respective control strategy and single grid side inverter along with common back to back DC link have been simulated in MATLAB Simulink using SimPowerSystem toolbox. The successfulness of the proposed system and their control strategies is verified by its simulation results.

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1. Introduction

In recent decades, the wind energy renewable source has becomes a most focused area due to its attractive feature of likes abundantly available in nature, cheaper in cost, pollution free and ecofriendly. In the nature, temperature variation on earth surface quite uneven round the clock in day which results in occurrence of a variable wind flow. The kinetic energy in this variable wind can be transform and extract in the form of electrical energy by using of some suitable electromechanical energy conversion system. Here, the wind power possessed by wind particles is utilized to move the blade of wind turbine which is mechanically coupled to electrical generator [1-2].

In nature, the wind velocity varies continuously around the clock due to geographical, climatic conditions and many more reasons. Therefore require a wind energy conversion system which has a high compatibility level with maximum power extraction capability under strong variable windy situation [2].

The wind turbine configurations are mainly categorized on the ground of its speed: fixed speed and variable speed.The variable speedconfiguration always has edge over due to its inherent capability of extracting maximum power at variable wind velocities and better utilization of power converters (up to 100%)[3-5].There are many options available for variable speed WECS comprising of various types of electrical machines like DFIG, SCIG, SG and PMSG. In offshore wind energy conversion system the most favorable and most suitable configuration is that which require less maintenance and installed in

lesser space. So, the configuration in which generator is directly coupled variable speed rotor of wind turbines is always most preferable.In offshore wind energy conversion system, this type of configuration having many benefits and extremely useful in terms of installation and maintenance of system which results in improvements in the overall system reliability, efficiency, power to weight ratio and size of the equipment[6-9].

The SCIG based WECS configurations are generally preferred and suitable where both fixed and semi-variable speed applications is required. This configuration having simple robust design with metallic bar on its rotor and required very less maintenance due to elimination of slip rings/brushes and simple. It draws reactive power from the grid source.Soitalways has to be compensated bya capacitive reactive power. The main design limitation of SCIG based configuration is that it requires a three stage gear box. Although, DFIG based WECS configuration are highly mature and widely used for variable speed operation with narrow range of ± 30% speeds. This configuration is supposed to be more complex as stationary part winding is directly connected to main grid source while rotor part winding is connected to grid via aback to back power electronics interface. Due to itssemi variable speed operation and required a three stage gear box for speed amplification with associated extra maintenance cost. Moreover, due to direct stator connection with grid makes it is more susceptible to grid side faults and thus have very limited fault ride through capability[10-12].

The synchronous generators are very popular for the variable speed direct-driven operations. The permanent magnet synchronous generating machine is preferred over rotor excited synchronous generator as the rotor excited synchronous generator requires a large size & weight of field excitation system. The PMSG is simple in design, construction and operation. In large capacity wind farm, the directly driven Variable speed PMSG are preferable where the stator is connected to grid via back to back connected power converters. Thus the WECS is fully decoupled from grid or its associated faults due to presence of DC-Link. Moreover, PMSG based WECS are more efficient due to absence of rotor winding, have compact design, higher power density, better fault ride through capability, no-gearbox and hence have less noise level as well as lesser tearing and bearing. It is also feasible to have multiple-pole directly driven variable speed back to back converters WECS configuration is possible for onshore/offshore wind farm applications.The converter topologies mainly used for PMSG based WECS are: Back to back converters with DC-link and matrix converter. There is a difficulty associated with matrix converters topology as it does not compliance the ride through capability requirements due to non-availability of DC-link capacitor which provide the direct decoupling between generator and grid[13-17].

By comparison of Series and Parallel wind turbines topologies on the basis of total power collection at DC link in WECS. The parallel wind turbine topology based WECS delivered more power as compared to the series topologyy under same wind conditions.In wind farm, the parallel wind turbine topology based wind farm system required lesser number of wind turbine units as compared to series wind turbine topology due to its more power handling capacity. That resulted in to a huge amount cost saving in terms of initial installation cost when hundreds of wind turbines have to be installed at wind farm. However, parallel wind turbine topology needs a DC voltage boost up device, whereas there is no such requirements in cascade wind turbine topologies So, a Trade-off approach has to be followed while selecting as per optimum utilization of system[18-19].

In the proposed parallel connected wind turbine topology, the individual unit generate power at variable speed by using a directly coupled wind turbine and PMSG. In this topology, single generating unit comprises: wind turbines, PMSG along with converter unit and these generating unit are connected in parallel electrically as shown in figure 1.The output power received from the terminals of each generator side converter and collected at a common DC link. Here, an optimum DC-link power is collected at common back to back DC-link by developing an effective control schemes. In this work, a parallel topology has been analyzed for DC power collection at common DC-link and transmits it in effective manner to main grid source under dynamic condition.

2. Proposed System and Control Strategies

The proposed wind turbine parallel topology has been explored the technical feasibility in terms of the grid connected WECS system. This work tries to explore the scope of parallel connected wind turbines along with PMSG and transfer their generated power it to grid via a common back to back DC-link i.e. grid integration of system. Generally at wind farm locations, the wind velocity varies abruptly throughout the whole time. So Type-4 WECS configuration is used to generate the power at variable speed. Here, each generating machine-side power converter is able to regulate their respective rotor speed and produce the rated DC output power at their terminals. After that total DC power from all the generating machine-side converters collected at common DC-link and transferred by the grid-side inverter to the main grid source at its frequency. So in this topology, the whole DC power is accumulated at Common DC-link which is generated by all parallel connected WT units and then transfers it successfully to the grid by using single grid side inverter. Conventionally, each generating unit always requires a separate DC-link, grid inverter along with their controller in order to transmit the power to grid. But here only one unit of DC-link, one unit of grid inverter along with its controller is used to transmit the power to grid. So it results lesser repair and maintenance charges, huge amount of cost reduction in terms of installation and space utility.

The parallel connected wind turbines units are integrated to single grid side inverter by using a common back to back dc link to decouple the both sides shown in figure 1. This topology comprises many number of WT units interconnected in parallel manner where each WT unit operates at its variable wind speed in order to extract utmost shaft power and its respective generating machine operate independently at corresponding most suitable speed. Each PMSG of wind turbine requires its separate converter switching system and with their control algorithms in order to take out optimum DC power at common DC-link as shown in figure 2.In the proposed generating machine side control algorithm, the wind turbine system is operated at variable medium speed on lower side so that active pitch angle control action can be easily eliminated from the system. So wind turbine system is now operated for maximum power extraction by using power speed characteristics at zero pitch angles. Therefore, generator side controller is used only to go with the electrical loading and match it with the maximum power extracted from the wind turbine. For that look up table data is used which contains the maximum generator output power at corresponding shaft speed. The wind turbine maximum power at a particular turbine speed may be taken from its look up table. In order to track the maximum power curve, synchronous speed of PMSG has to be adjusted and for that generator always give electrical power at variable frequency that may be seen from its generator current waveform figure 4 in result section. For

MPPT, the actual power demand at DC link is calculated and fed to look up table to get reference rotor speed. After that the error signal of actual and reference speed is given to conventional PI controller. Here, the outer speed control loop would give torque controlling quadrature-axis current whereas direct-axis current component is set to zero reference value so that minimum copper loss occurs and get highest value of torque at minimum current [14, 20].

In this proposed wind turbine topology, a large number of WT units are interconnected in parallel manner so that awhole desired DC power at rated DC-link voltage (V_{dc}) may be achieved and their respective rated Current like I_{dc1}, I_{dc2} etc. Here,only single unit of grid-side inverter has been used to transmit the DC-Link power and inject it to main grid source at unity power factor (UPF) with respect under non-linear load condition.It is also used to regulate dc-link voltage by balancing the power flow between dc-link, grid-source and electric loading under fluctuating windy situation as well as under grid disturbances. This control scheme has two loops: inner loop and outer loop as shown in figure3 which are utilized to set the reference direct-axis current for active power control and quadrature-axis current is set to almost zero to ensure the unity power factor implementation.

Under fault condition/ under abnormal grid condition, the generator side controller loses the MPPT control due to
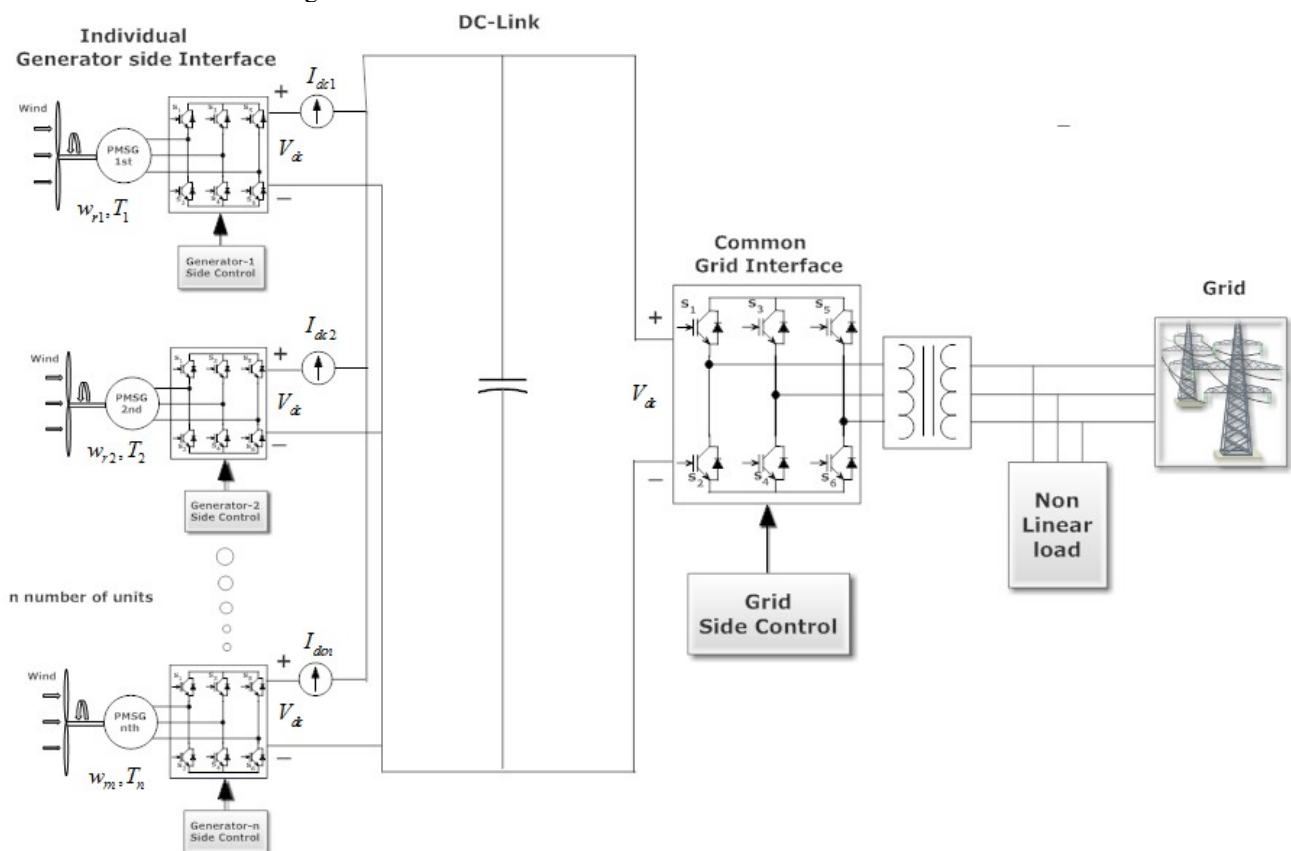

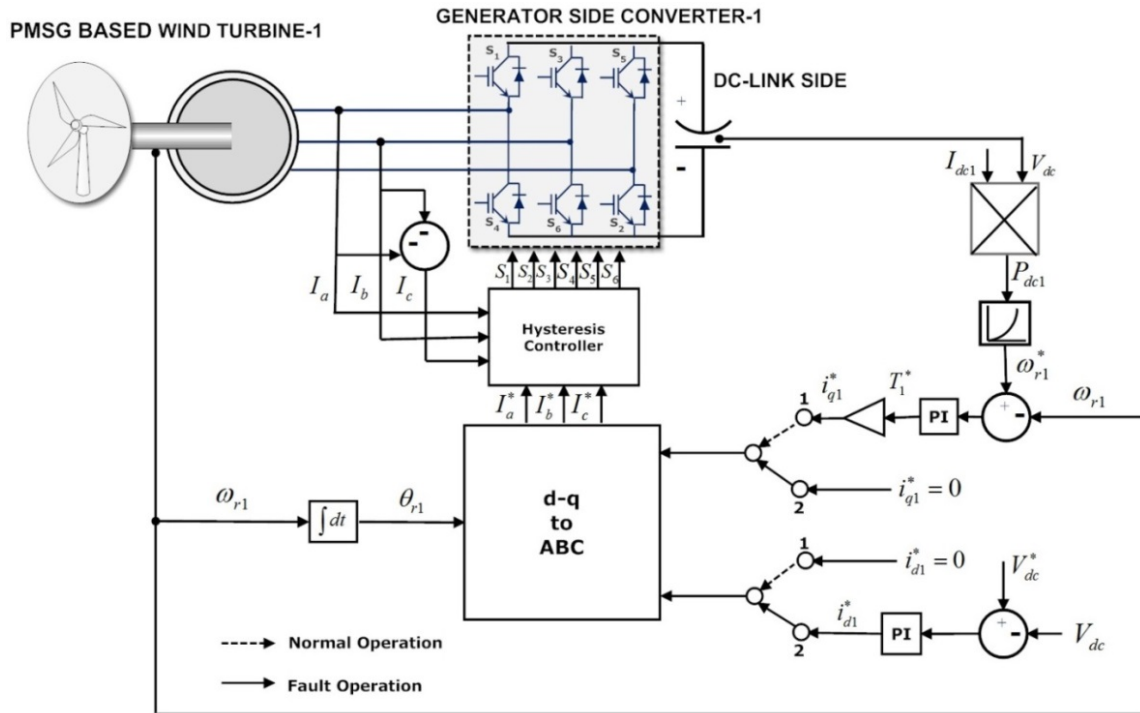**Figure 1.** Parallel Connected WT Topology

Figure 2. Control Strategy and operation of Generator Side Converters in Parallel Connected WT Topology under normal and fault conditions.
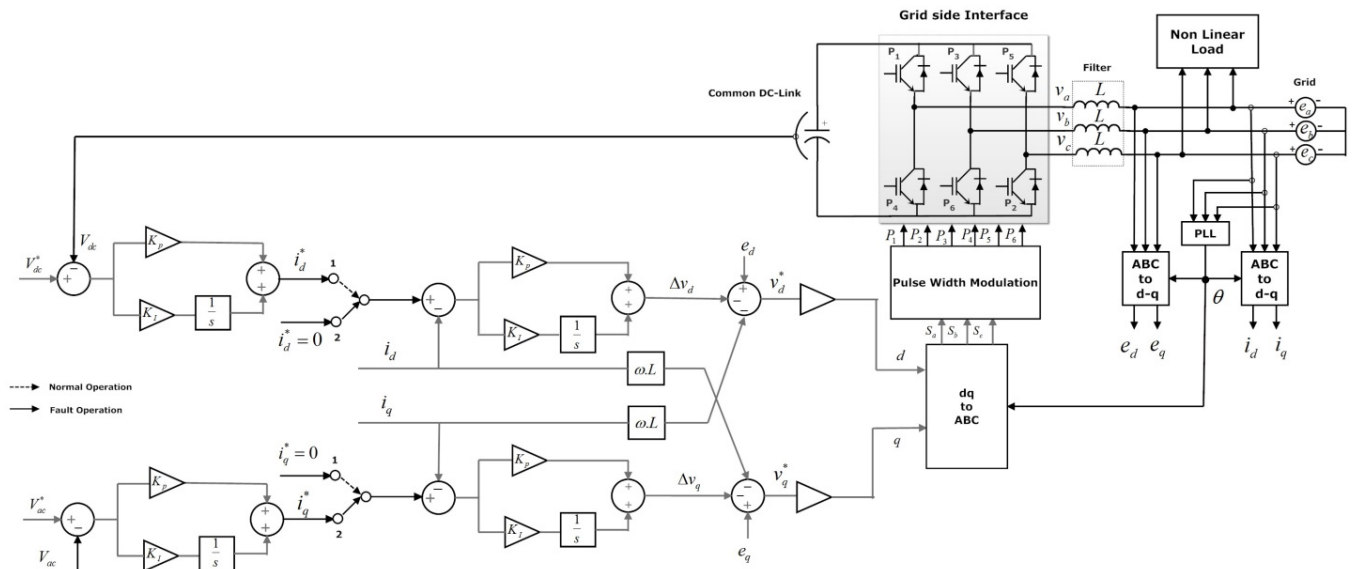

Figure 3. Control Strategy and operation of common Grid Side inverter in Parallel Connected WT Topology (i) under normal operation , (ii) under fault conditions.

minimum active power demand at grid side. As a result, controller reduces the power delivered to dc link by making torque controlling component almost equal to zero at given speed and deliver only minimum active power in order to feed the system copper-losses. At grid side system,the grid side inverter controller set the d-axis current component equal to zero which ensure minimum active power support to grid system and feed only copper losses of the system.Simultaneously, delivered maximum

reactive power by injecting the q-axis component to the grid side in order to feed the fault. After the recovery from fault, system controllers come back to its normal operating mode.

In the proposed system, the total DC power collected on generator side dc-link when all the WTs are connected in parallelat constant rated DC link voltage (V_{dc}) and their respective converter side rated DCcurrent.Therefore, whole DC power collected from the wind turbine

generator system having *'n'* number of WT units interconnected in parallel and expressed by

$$P_{dc} = P_{dc_1} + P_{dc_2} + \ldots\ldots\ldots\ldots + P_{dc_n} \qquad (1)$$

Alternatively, $\qquad P_{dc} = I_{dc}.V_{dc} \qquad (2)$

Where, P_{dc_1} = DC Power received from 1st WT unit

Similarly, P_{dc_2} = DC Power received from 2nd WT unit

P_{dc_n} = DC Power collected from nth WT unit

Total DC Current flow at common DC Linkis given by,

$$I_{dc} = I_{dc_1} + I_{dc_2} + I_{dc_3} + \ldots\ldots\ldots\ldots\ldots + I_{dc_n} \qquad (3)$$

Where, I_{dc_1} = DC Current delivered from 1st Generating Machine sideconverter.

Similarly, I_{dc_2} = DC Current delivered from 2nd Generating Machine side converter.

I_{dc_n} = DC Current delivered from nth Generating Machine side converter.

3. Results and Discussions

The proposed parallel wind turbine topology based WECS system has been developed and executed in MATLAB Simulink using SPS toolbox. For the verification of proposed system, a simulation study was carried out for two WT units at variable wind speed under load demand as exhibited in Figure1. The performance of the controllers has been evaluated by considering the various system parameters like generator speed, dc-link voltage, grid current, load current converter current and inverter current under unity power operation and under grid fault condition. The smooth and balanced power flow is also analyzed among dc-link, grid and load under variable speed.

As per parallel wind turbine topology for n=2, total DC power collected at dc-link which is delivered by the parallel interconnected PMSG side converters at variable speed is expressed by

$$P_{dc} = P_{dc_1} + P_{dc_2} \qquad (4)$$

Total DC Current delivers by the parallel connected generator side converters,

$$I_{dc} = I_{dc_1} + I_{dc_2} \qquad (5)$$

The DC Voltage on each Generator side-converter terminal, $V_{dc1} = V_{dc2} = V_{dc}$ = Constant

So, Total DC link power can also be written as

$$P_{dc} = P_{dc_1} + P_{dc_2} = V_{dc}(I_{dc_1} + I_{dc_2}) \qquad (6)$$

Here, Both WT units are installed at different locations and operated under fluctuating wind condition because wind varies abruptly from one location to another. Both WT units are PMSG based direct driven run at variable speeds. Here, W_{r_1} and W_{r_2} are actual speeds and W_{ref_1}, W_{ref_2} reference speeds respectively.

3.1. Performance of proposed system under variable speed condition

The simulation results in figure 4, the frequency variation in generator current indicates that wind turbine operates at variable wind speed. As the shaft of PMSG is mechanically coupled to wind turbine rotor shaft which means generator also run at variable speed. The results in figure 4 validate the effective control strategy as actual speed almost maps with reference rotor speed under wind variations.
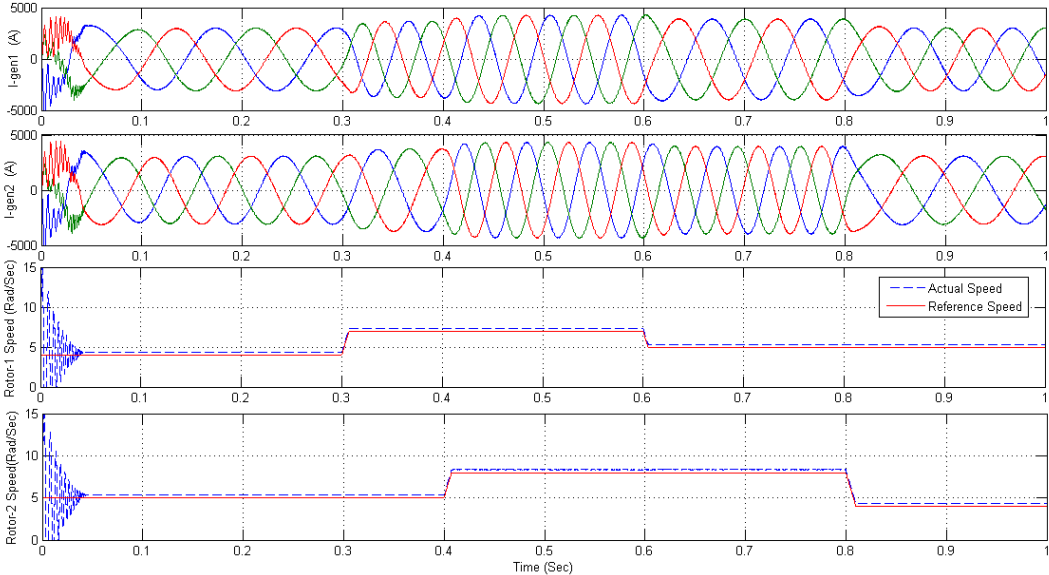

Figure 4. Performance of parallel connected units under variable speed

From figure 5, both parallel connected units are smoothly delivers the power to DC link and DC link

handle this power under variable speed. Further, whole DC link power deliveredby the grid side inverter to the

main grid source by maintaining DC link voltage constant at its rated value which validates the effective control strategies.The Total DC link current is the algebraic sum of currents of parallel connected units. Similarly, DC link power is also algebraic sum of powers of both parallel connected units validated the parallel connection. In the proposed parallel topology, common single grid side inverter is utilizing to handle the smooth power flow from wind turbine units to grid.

The main role of grid side control strategy is to transfer the DC link power at constant rated DC link voltage and deliver it to the connected load demandand grid source. From simulation results in figures 6a and 6b indicates that the grid side inverter injects the harmonics free sinusoidal current to the grid and able to delivers its rated power at PCC which validates the effectiveness of grid side control scheme.

Since the inverter output power may be less than or greater than the connected load demand therefore grid

side inverter control strategy is developed in such a manner that it will first fulfilled the load demand and then rest of the power will go to grid source as shown in figures. So here, there are two nonlinear loads 500KW and 1500KW has been connected at PCC one by one for the analysis i.e. between grid side inverter and grid source.

When, $I_{load} < I_{invt}$ then $I_{inv} = I_{load} + I_{grid}$ (7)

When, $I_{load} > I_{invt}$ then $I_{inv} + I_{grid} = I_{load}$ (8)

Hence, despite of variable load demand conditions inverter always delivered their rated power as shown in figures 7, 8 and 9. The role of grid source will come into picture when inverter output is less than the connected load demand, in this situation both inverter as well as grid source will feed the connected load demand. Here, inverter will feed the load up to their full capacity and rest of the demand is fulfilled by the grid source.
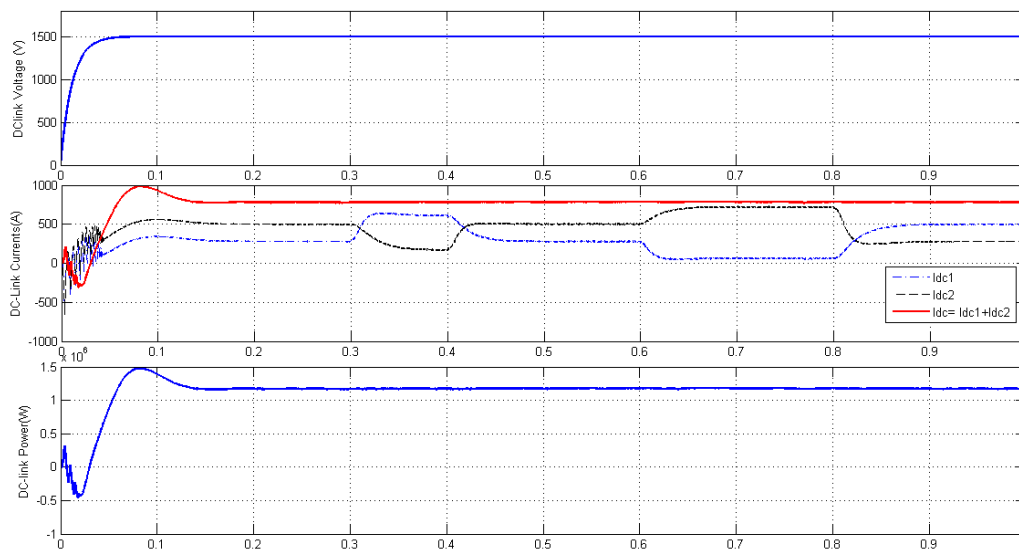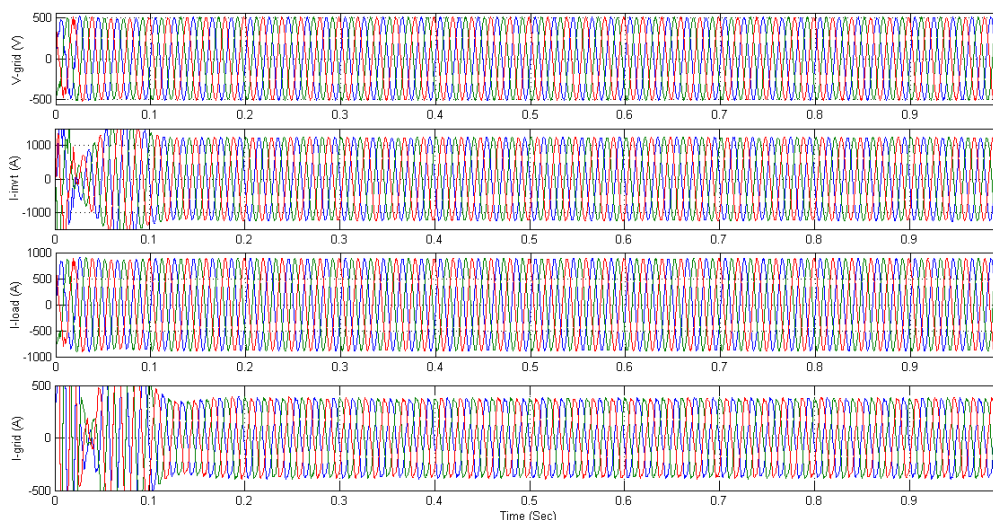

Figure 5. Performance of DC link under variable speed
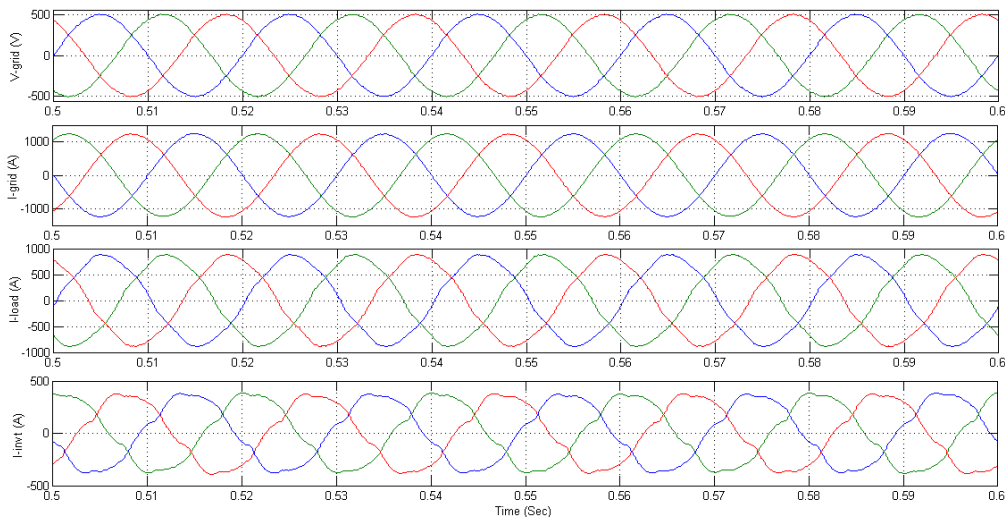

Figure 6a. Grid performance when $I_{load} < I_{invt}$
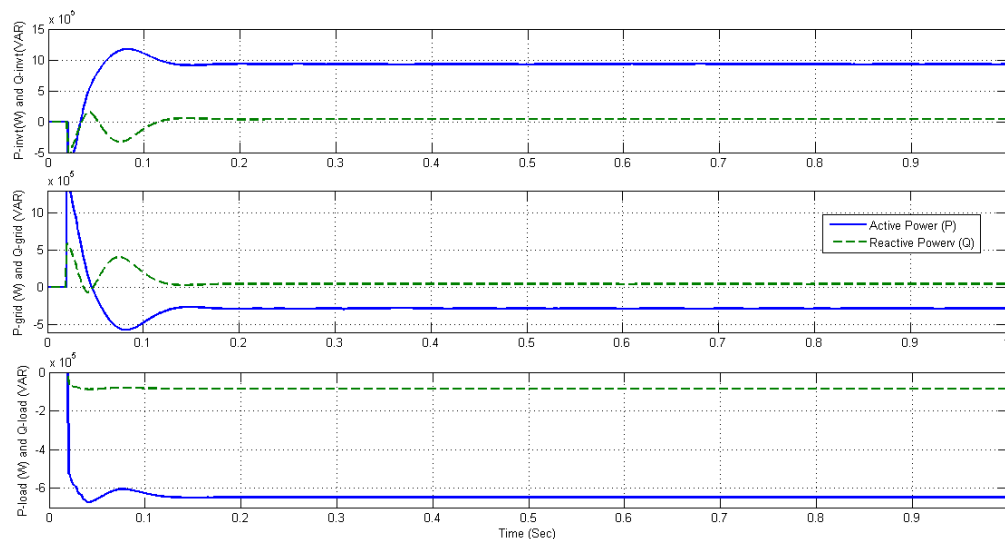
Figure 6b. Harmonics free operation

Figure 7. Power flow curves when $P_{load} < P_{invt}$

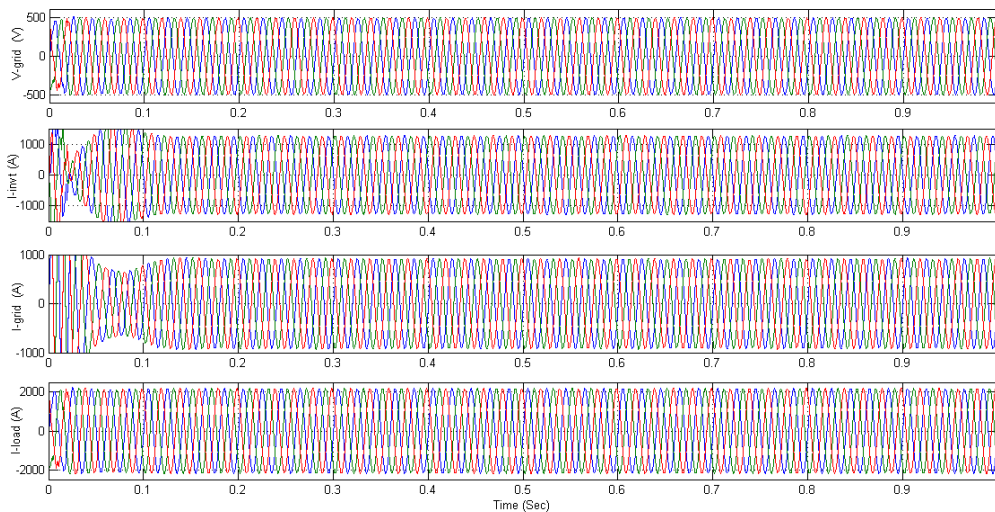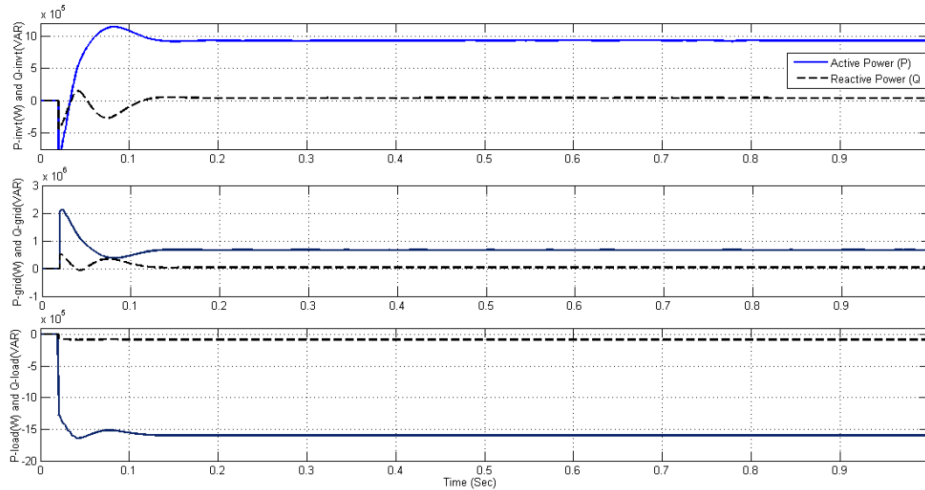**Figure 8.** Grid performance when $I_{load} > I_{invt}$

Figure 9: Power flow curves when $P_{load} > P_{invt}$

3.2 Performance of proposed system under grid fault condition

The simulation results in figure 10 shows that the frequency variation in generator current indicates that wind turbine operates at variable wind speed under fault condition. The results also validate the effective control strategy as actual speed almost maps with reference rotor speed under wind variations. The grid fault occurs at time t=0.4 sec, wind turbine units continuously generates the power due to its mechanical inertia issue and this excess power collected at DC link (as shown in figure11).

For stable operation, this excess power at DC link should be evacuated by grid side inverter so that DC link can be regulating properly under grid fault. When fault occurs, there has been a substantial voltage dip in grid voltage. Under fault condition, grid side inverter can handle power at almost twice of its rated current value and rest of the current demand is beard by grid source. (as shown in figure 12 and figure 13).

Under this situation, the grid side controller should inject only q-axis current component to get an improved grid voltage waveform profile and almost zero d-axis current. It means that the grid side inverter interface circuit should inject maximum reactive power to the fault along with minimum active power support for compensating the system losses.

The simulation results validate the effectiveness of grid controller as grid inverter is able to take away the excess power from DC-link by handling the high value current (almost twice of its rated value) and maintained the constant DC-link voltage (shown in figure11).Moreover, the grid controller able to inject necessary reactive power current component under fault so that system recover from fault (as shown in figure14). After the recovery from fault, the system operates normally and connected load demand is again fed by both grid converter and grid source.
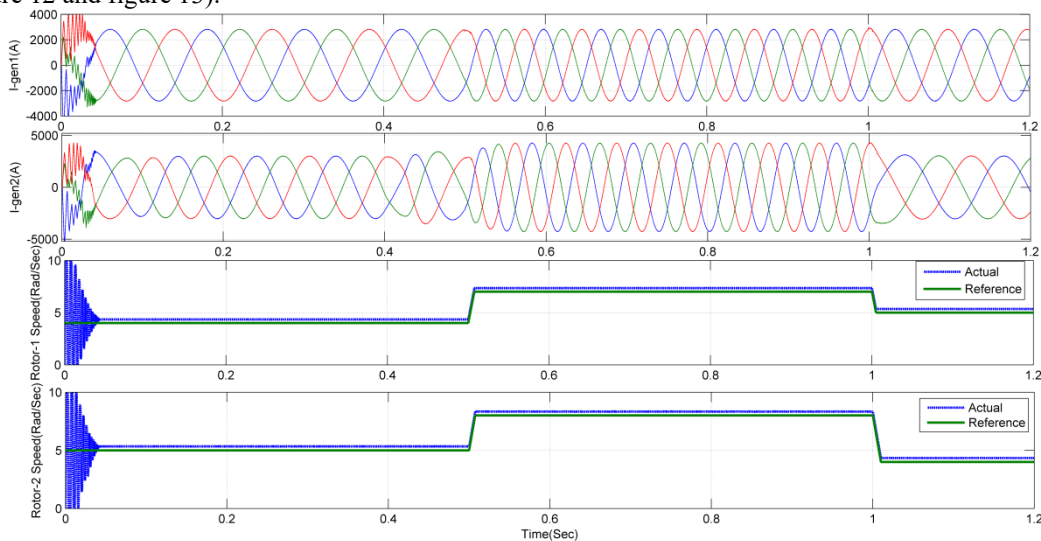

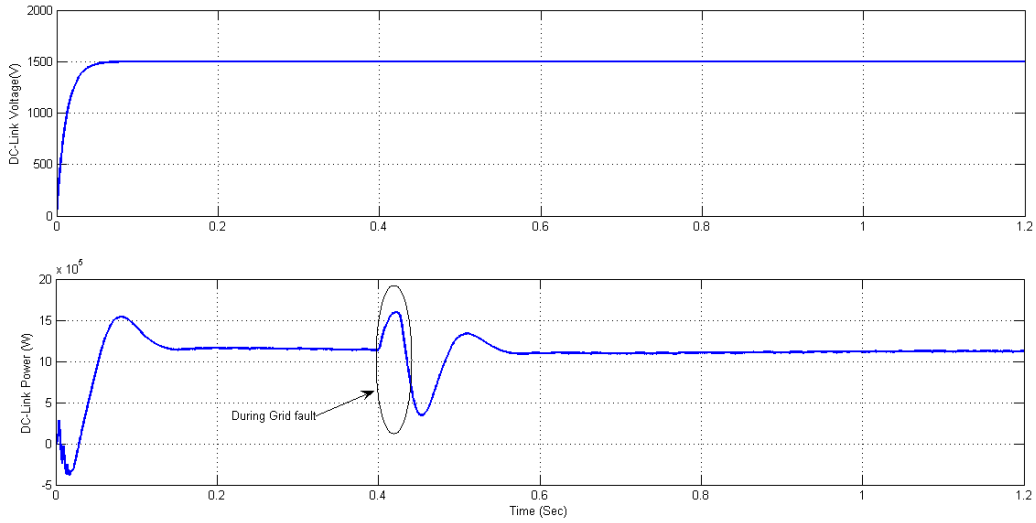**Figure 10.** Generator side performance under grid fault condition

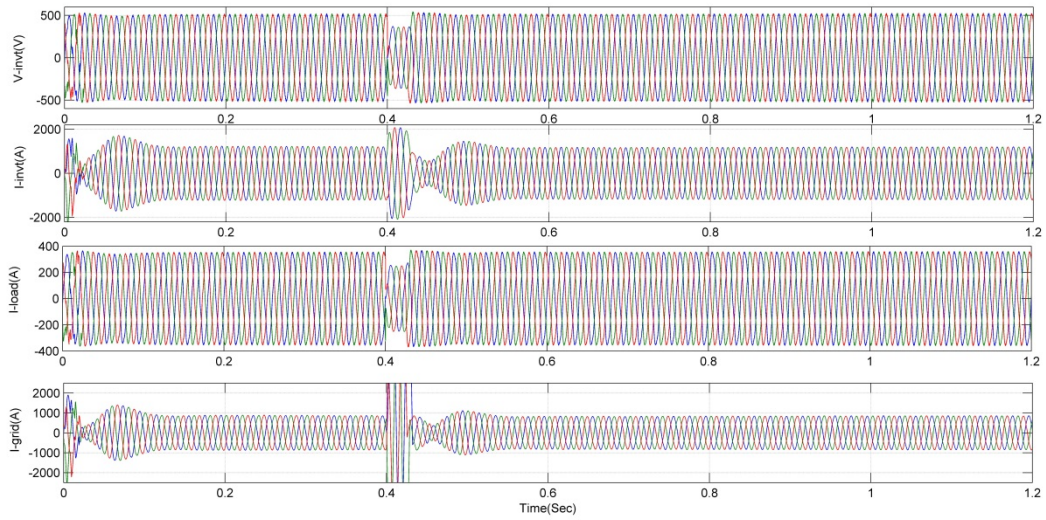**Figure 11.** DC-link profile under grid fault

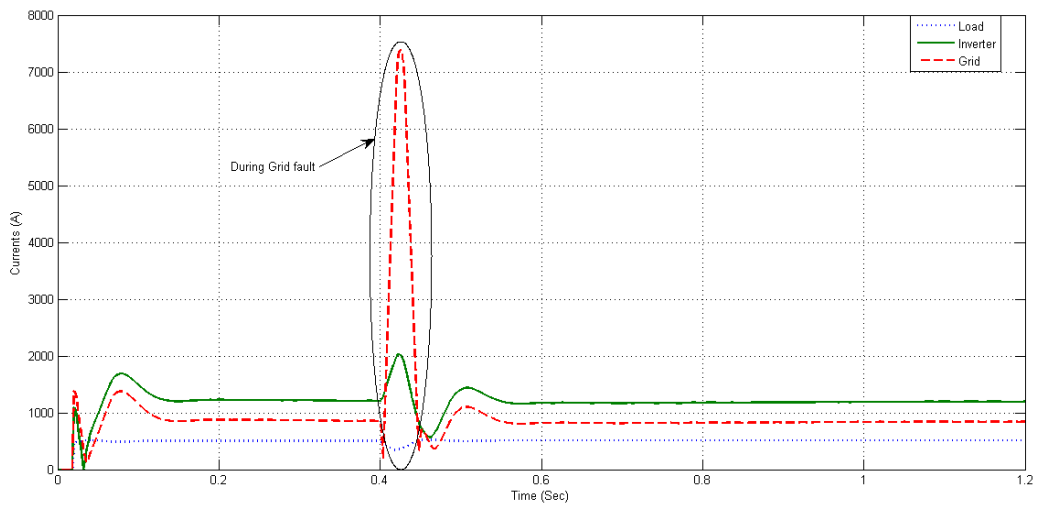**Figure 12.** Grid side profile under grid fault

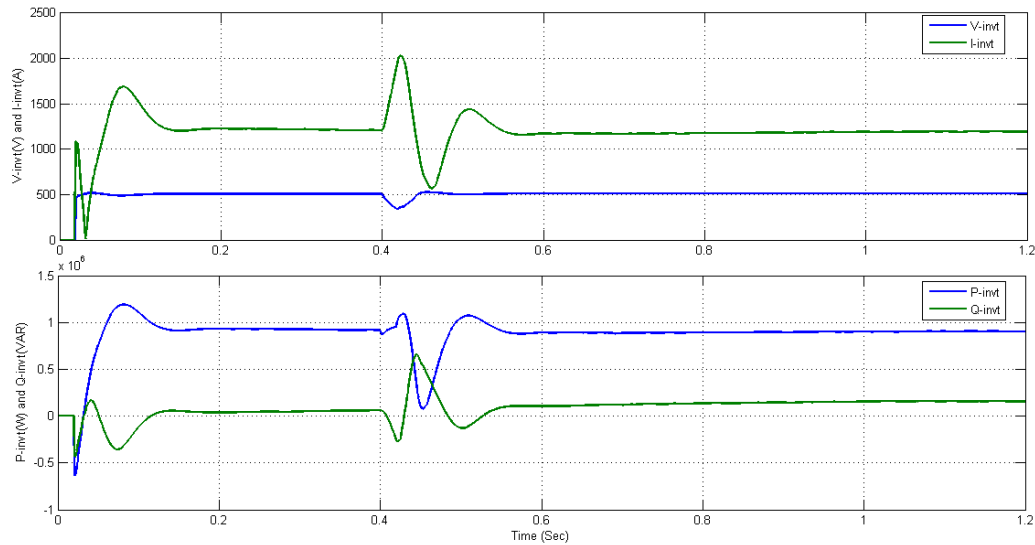**Figure 13.** Currents profiles at PCC under grid fault

Figure 14. Inverter performance under grid fault

4. Conclusion

In this work, a grid connected WECS with parallel connected wind turbine topology tested and validate under variable speed and grid fault operation. All generating machine side controllers operated on a respective given power-speed characteristics based MPPT control algorithm and exhibited a maximum power point tracking operation at variable wind velocities. The dynamic mapping of actual and set point rotor speeds underwrite the worthwhile execution of generating machine side control algorithm and each generating unit able to transmit the whole power to common DC-link. The grid side results validate its unity power factor performance under dynamic operation with non-linear load demand. The performance of single grid controller under non-linear load demand was quite satisfactory with a precise regulated dc-link voltage and also able to maintained smooth power flow at the point of common coupling. Moreover, the grid side inverter provides a pure sinusoidal harmonic free voltage at point of common coupling. At PCC, when power generated is greater than load demand, then grid side inverter feed both main grid source and connected nonlinear load. Here, the grid side inverter able to feed the total real, reactive and harmonics load demand. At the same time, it delivered rest of the real power to the main grid source with a pure sinusoidal current which certifies a unity power factor operation and validates the successful control strategy.

Under Fault condition, the grid side inverter feed only reactive power to grid and improves the grid voltage profile. During fault the grid inverter able to evacuates the extra power from the DC link and regulates its DC voltage. So from all the results under faults condition it is clear that the proposed system and their control strategies able to recover the system from fault and restored it to normal operation.

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