Investigations on interconnection of Wind-Solar Hybrid Renewable Energy Source to the ideal grid at the distribution level together with power quality improvement features

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Abstract: *one of the most challenging issues that modern man is facing nowadays is global warming and scarcity of fuel. To find a solution to the above problems the focus of research is directed towards Renewable Energy Sources (RES). Among all available RES the combination of wind-solar RES provides the most reliable solution to the utility as both of them are complimentary to each other. As all the energy sources including RES are scattered across the globe, it becomes necessity to extract available green energy at the distribution as well. Non-linear loads connected at the Point of Common Coupling (PCC) inject current harmonics into the system thereby pollutes the grid environment. Shunt active power filter is found to be one of the feasible solutions in addressing issues related to the non-linear loads. This paper deals with the study of integration of wind-solar hybrid energy system to the grid at the distribution level. Here the active power filter functionality has been added to the interfacing four leg inverter to reduce overall cost of the system. The system is studied under three different cases of RES=0, Load Demand>RES>0, RES>Load demand. Simulation results shows that for all the cases power quality improvement is taking place with the help of* I_d*-*I_q *control strategy.*

Key words*: active power filter, photovoltaic, wind system, power quality, current controlled voltage source inverter.*

1. Introduction.

There is a significant rise in energy demand from past one decade due to industrialization and urbanization. The existing conventional power plants are unable to meet the increase in load demand. The exhaustible nature of conventional energy sources and the damage they have created to the environment have motivated researchers to focus research in the field of Renewable Energy Sources (RES).

Amongst all the available RES, Wind and Solar sources are installed individually more in number due to their abundance in nature. As both the energy sources are complimentary to each other, reliability to the customer is offered by the combination of both [1]. In order to extract maximum power from the system several maximum power point tracking algorithms has been proposed.

Usage of chemical battery helps to store energy whenever there is an excess supply from RES and also helps to supply for the load whenever there is a lack of supply from RES [2-3]. As the usage of chemical batteries is associated with lot of problems such as chemical pollution, regular maintenance, high initial cost etc, researchers have come out with the solution of interfacing RES to the grid.

Since the energy sources including RES are scattered across the globe, there is a need to utilize available green energy by integrating RES based power plants at the distribution level to the grid as well. RES interconnecting to grid give rise to many issues like power quality issues, stability issues, protection issues and reliability issues [4]. All the aforementioned issues can be addressed with the growth of power electronics field. However Power quality issue still persists at the utility due to the proliferation of non-linear loads at the Point of Common Coupling (PCC). Effects of Non-linear loads are enormous, they inject current harmonics into the grid which multiplies with the source impedance and thereby pollutes the supply voltage. They increase losses in the system and hence reduce efficiency. Damages the sensitive loads connected at the same PCC, reduces power factor of the system etc [5-7]. Passive filters were used to address the issues related with non-linear loads in the earlier days, but they have certain limitations like they cause resonance in the system and they are also bulky in size etc [8]. Shunt active are found to be far superior over passive filters.

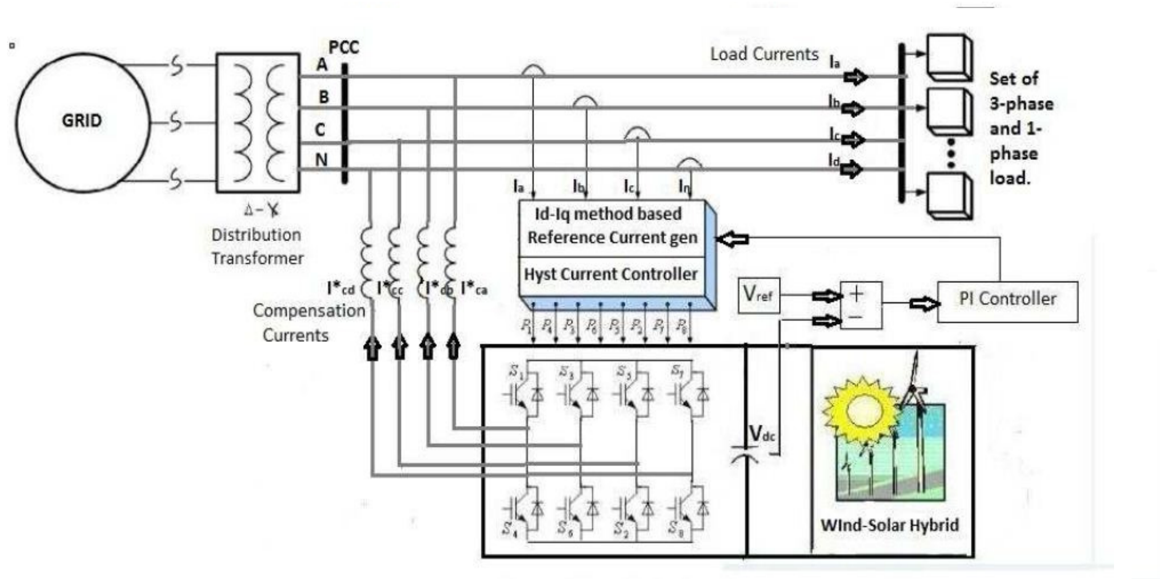

Fig.1. System Description

Two types of inverter topologies which are commonly used in shunt active filter modeling are current source inverter (CSI) type and Voltage Source Inverter (VSI) type [9]. Current controlled VSI is the most commonly used as it supports for reactive power compensation. Additional hardware cost of shunt active filters can be eliminated by adding shunt active power filter functionality to the inverter which interfaces RES to the grid [10].
In this paper section 2 describes the overall system. Detailed modeling of Wind/Solar hybrid model has been explained in 3rd section. Brief explanation of control strategy being used is been explained in section 4. In section 5 results and discussions are presented. In section 6 conclusions of the study are brought out.

2.System Description.

The system being studied is shown in figure1. It consists of balanced three phase four wire grid which represents ideal distribution system. Set of three phase and single phase non-linear loads are considered to inject harmonics into the system. Wind-Solar hybrid model is considered to mimic RES. Four leg VSI is considered to harvest real power supplied by RES to the grid as well as to execute the duties of shunt active power filter. I_d-I_q method of control strategy is used to incorporate shunt active power filter functionality to the interfacing inverter. PI controller is used as a voltage controller to stabilize the voltage across the DC link.

3.Wind-Solar Hybrid System Modeling.

Modeling of Wind-Solar hybrid system includes modeling of Wind and solar system separately and integrating them together with suitable topology.

3.1 Modeling of Wind system.

The wind turbine (WT) converts wind energy to mechanical energy. A model representing the wind turbine helps to evaluate the turbine performance and to study the effect of wind speed variations on the torque and power produced. The torque and power produced by the WT are functions of the blade radius R, air pressure, wind speed V_{wind}, coefficients C_q and C_p [11]. The mechanical power output P_m of wind turbine is given by the equation 1.

$$P_m = C_p(\lambda,\beta)\frac{\rho A}{2}V_{wind}^3 \quad (1)$$

C_P is known as the power coefficient, C_q is the torque coefficient and is related to C_P according to the equation 2.

$$C_q = \frac{C_p}{\lambda} \quad (2)$$

Torque of the turbine T is given by equation 3.

$$T = \frac{P_m}{\omega} = \frac{1}{2}\rho\pi R^3 C_q(\lambda,\beta)V_{wind}^2 \quad (3)$$

$$\lambda = \frac{R * \omega}{V_{wind}} \quad (4)$$

Where λ is the tip speed ratio as shown in equation 4, A is the turbine swept area, ω is the angular frequency of rotation of the turbine, ρ is the air density, V_{wind} is the wind speed, R is the radius of turbine blades and β is the blade pitch angle.

The performance coefficient C_p (λ, β), which depends on tip speed ratio λ and blade pitch angle β, determines the amount of wind energy can be captured by the wind turbine system. A nonlinear model describes C_p (λ, β) as in equation 5.

$$C_p(\lambda,\beta)=C_1\left(\frac{C_2}{\lambda_i}-C_3\beta+C_4\right)e^{\frac{-C_5}{\lambda_i}}+C_6 \quad (5)$$

Where, C_1=0.5176, C_2=116, C_3=0.4, C_4=5, C_5=21and C_6=0.0068. λ_i is expressed in terms of λ and β as in equation 6.

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \quad (6)$$

4.3.2 Modeling of PV Arrays.

The equivalent circuit of a PV cell is shown in figure 2. It consists of current source with series and parallel lead resistor R_s, R_p respectively [12-13].

I-V characteristic of the ideal PV cells can be expressed mathematically by equation 7 and 8.

$$I = I_{pv\_cell} - I_d \quad (7)$$

$$I_d = I_{0\_cell}\left[\exp\left(\frac{qV}{akT}\right)-1\right] \quad (8)$$

where $I_{pv,cell}$ is the current generated by incident light, I_d is the diode current, $I_{0,cell}$ is the reverse saturation or leakage current of the diode, q is the electron charge [1.60217646 x 10^{-19} C], k is the Boltzmann constant [1.3806503 x 10^{-23} J/K], T is the temperature of the p-n junction in K, a is the diode ideality constant.

Practical photovoltaic array consists of several photovoltaic cells and the basic equation 7 of the elementary photovoltaic cell is modified to equation 9 in order to make it suitable to practical photovoltaic arrays.

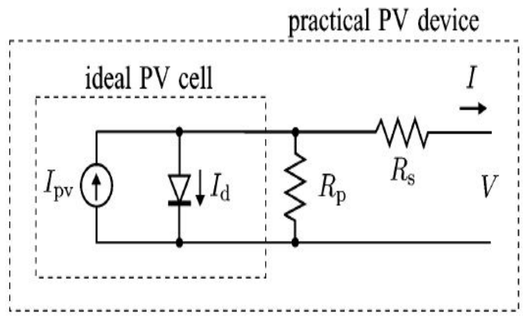

Fig.2. Equivalent circuit of a PV cell [12]

$$I = I_{pv} - I_o\left[\exp\left(\frac{V + IR_s}{V_t a}\right)-1\right] - \frac{V + IR_s}{R_p} \quad (9)$$

Where, R_s is the equivalent series resistance of the array and R_p is the equivalent parallel resistance, I_{pv} and I_o are the photovoltaic and saturation currents of the array and $V_t = N_s kT/q$ is the thermal voltage of the array with N_s cells connected in series. If the array is composed of N_{pp} parallel connections of cells the photovoltaic and saturation currents are expressed as: $I_{pv}=I_{pv,cell}N_{pp}$, $I_0=I_{0,cell}N_{pp}$ and if the array is composed of N_{ss} series connections of cells the photovoltaic voltage is expressed as: $V=V_t*N_{ss}$. Power extracted by the photovoltaic cell depends on the solar irradiation and also influenced by the temperature which is reflected in the equation 10 [13].

$$I_{pv} = \left(I_{pv,n} + K_I\Delta_T\right)\frac{G}{G_n} \quad (10)$$

Where, $I_{pv,n}$ *[A]* is the light-generated current at the nominal condition (at STP 25^0 C and 1000 W/m^2), $\Delta_T = T - T_n$ where, T is actual temperature and T_n is nominal temperatures in K, G is the irradiation on the device surface in W/m^2, and G_n is the nominal irradiation in W/m^2.

Saturation current of the diode I_o and the effect of temperature on it is given by equation 11.

$$I_o = I_{o,n}\left(\frac{T_n}{T}\right)^3 \exp\left[\frac{qE_g}{ak}\left(\frac{1}{T_n}-\frac{1}{T}\right)\right] \quad (11)$$

Where, Eg is the band gap energy of the semi conductor (Eg ≈ 1.12 eV for the polycrystalline si at 25^0 C) , and $I_{o,n}$ is the nominal saturation current.

$$I_{o,n} = \frac{I_{sc,n}}{\exp\left(\frac{V_{oc,n}}{aV_{t,n}}\right) - 1} \quad (12)$$

where $V_{oc,n}$ is the nominal open circuit voltage of the array, $V_{t,n}$ is thermal voltage of N_s series connected cells at the nominal temperature T_n and $I_{sc,n}$ is the nominal short circuit current of the array. The photovoltaic model described in the previous section can be improved if equation 11 is replaced by equation 13, which is obtained from equation 12 by including the current and voltage coefficients K_V and K_I. This adaptation tries to fit the open circuit voltages of the model with the experimental data for a very large range of temperature variations.

$$I_o = \frac{I_{sc,n} + K_I \Delta_T}{\exp\left(\frac{V_{oc,n} + K_V \Delta_T}{aV_t}\right) - 1} \quad (13)$$

The output voltage of PV cell is a function of photo current and it depends upon solar insolation level.

3.3 Integration of Wind and Photovoltaic Hybrid Energy System to the Grid

The PV system produces DC output whereas WT generates AC output voltage. For grid-connection of these two sources different power electronic interfaces are required. The DC-shunted grid-connected hybrid PV/wind power system shown in figure 2 is chosen in this work [14].

In DC-shunted grid-connected hybrid PV/wind power system, the output of PV array is connected to DC/DC boost converter and the dc link voltage is

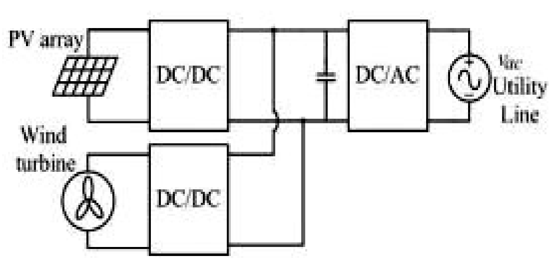

Fig.3. Block diagram of DC-shunted grid-connected hybrid PV/wind energy system [14].

regulated. AC output voltage of wind energy system is rectified using uncontrolled rectifier in the first stage and then a DC/DC boost converter is used to control DC link voltage. The VSI incorporated with shunt active power filter functionality is further used to interface the DC shunted wind-solar hybrid model to the grid.

4. Shunt Active power filter.

Due to the proliferation of non-linear loads at the PCC, current harmonics getting injected into the power system thereby pollutes the grid environment. Shunt active filters are generally used to mitigate the effects of non-linear loads. There are mainly three stages involved in the modeling of shunt active power filter.

a. Reference current generation.
b. Switching pulse generation.
c. Synthesize of compensation current.

a) Reference current generation.

In order to extract harmonics from the load current many control algorithms have been proposed till date. Among all, PQ method (instantaneous real power reactive power method) and I_d-I_q method (instantaneous real current- reactive current method) of reference current generation are most popular.

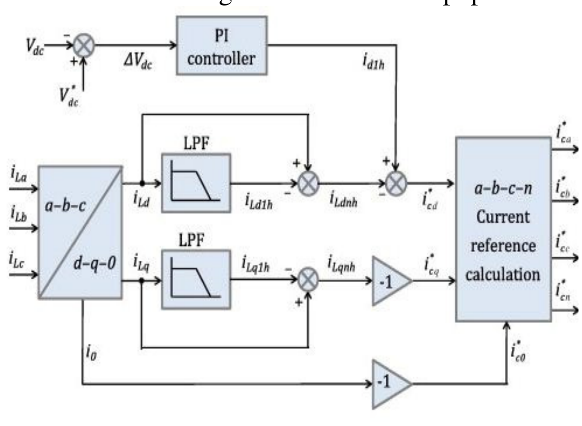

Fig.4. I_d-I_q method of control strategy [15]

However PQ method is limited to produce good results under healthy grid voltage conditions only [15].Hence in the present paper I_d-I_q method of reference current generation method has been used. The functionality of this control method can be better understood by referring to figure 4.

Reference current for the fourth leg is obtained by using reference currents of the phases and is been shown below.

$$I^*_{cn} = I^*_{ca} + I^*_{cb} + I^*_{cc} \quad (14)$$

b) Switching pulse generation.

This stage has the objective to generate switching pulses after comparing the actual and reference currents. A controller which minimizes the difference between reference and actual signals is properly chosen such that it should be robust, easy to model and dynamic enough to adjust with the variation of load. Hysteresis Current Controller (HCC) is the most commonly used controller which satisfies all the requirements of the controller. Process involved in switching pulse generation can be observed by referring to fig 5. If error is more than the upper band then upper switch of the corresponding leg will be given a switch-off pulse, and if the error is less than the lower band then the upper switch will be given a switch on pulse. The lower switches are always provided with the negated pulses of the corresponding upper switch to avoid the dead short circuit across the DC-link [16].

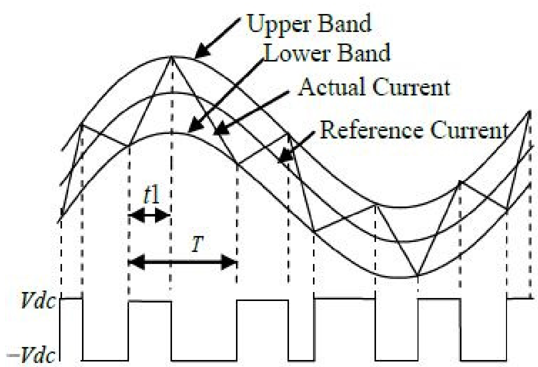

Fig.5. Hysteresis Current Controller [16].

c) Synthesize of reference currents.

After generating reference currents it has to be synthesized by the power converter. For shunt active filter functionality, current controlled Voltage Source Inverter is the most commonly used topology. Inverter receives switching pulses from the HCC and switches accordingly. Output of VSI is connected to the grid at the PCC through filters.

5. Results and discussions.

In this paper ideal grid supply voltage conditions are considered to represent ideal distribution level. Three phase diode bridge rectifier with RL load is considered as a three phase non-linear load and single phase diode bridge rectifier with RL load is considered as a single phase non-linear load and is connected between c phase and neutral. Wind-solar model with rated wind speed of 12 m/s and nominal solar irradiation level of 1000 W/m^2 is modeled and is interconnected to the grid at the PCC. The model which is built is tested under three possible cases of RES=0, Load Demand>RES>0 and RES> Load demand. The parameters which are used to model the system are displayed in Table 1.

Case 1: RES=0

This is the case when Wind-Solar hybrid energy system is not pumping any real power into the grid. Entire real power requirement of the load is been supplied by the grid alone. Grid interfacing inverter instead of setting idle acts as shunt active filter and improves power quality of the system. Matlab/Simulink model is simulated for 1s and the results obtained are plotted as follows.

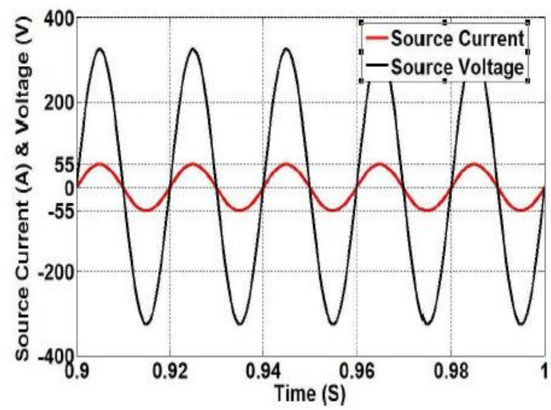

Fig.6. Source Voltage and Current

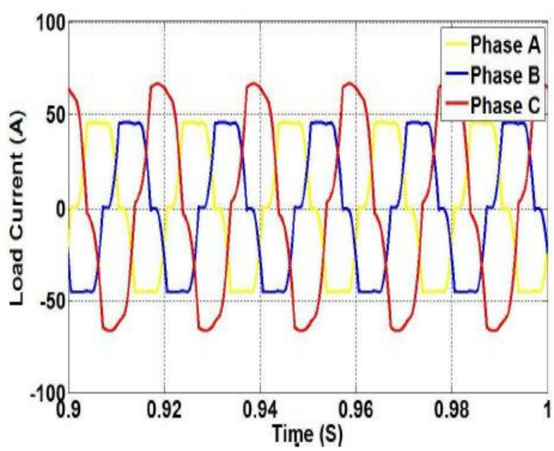

Fig.7. Load Current

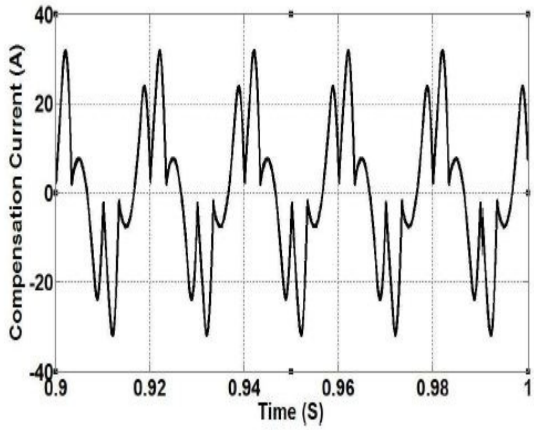

Fig.8. Compensation Current

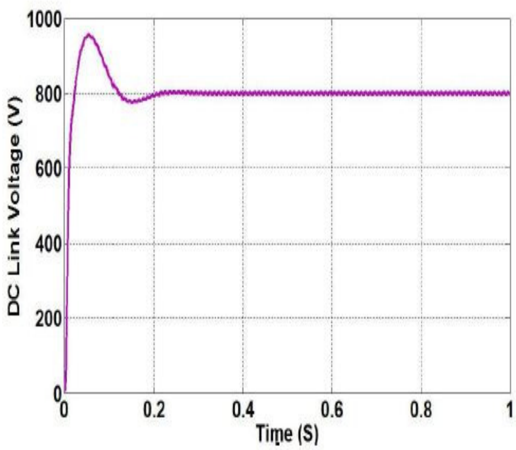

Fig.9. DC link Voltage

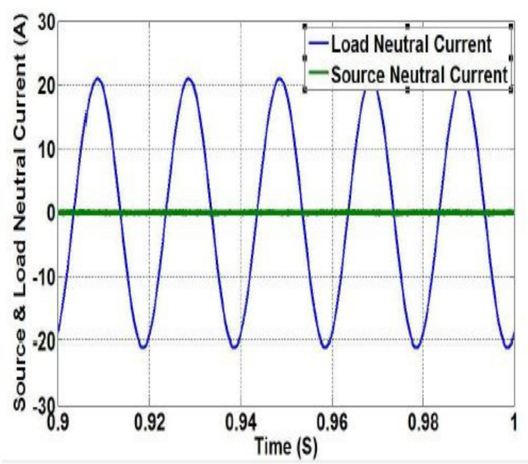

Fig.10. Load and Source Neutral Current

Fig 6 indicates that source current is sinusoidal and is in phase with the source voltage hence depicts shunt active power filter functionality of the inverter. Fig 7 shows the load currents of all the phases and it shows that it is rich in harmonics. Fig 8 depicts the compensation current synthesized by the VSI. Fig 9 shows that DC link voltage is maintained constant with the help of PI controller. Fig 10 shows that source neutral current is compensated and is made equal to zero by the fourth leg of the inverter.

Case 2: Load demand>RES>0.

In this case Wind speed is chosen as 6 m/s and solar irradiation is considered as 50 W/m^2. RES start feeding real power into the system, hence part of the real power requirement of the load is been supplied by RES and rest is supported by grid. Along with harvesting real power from RES to grid four leg inverter does the job of power quality improvement as well.

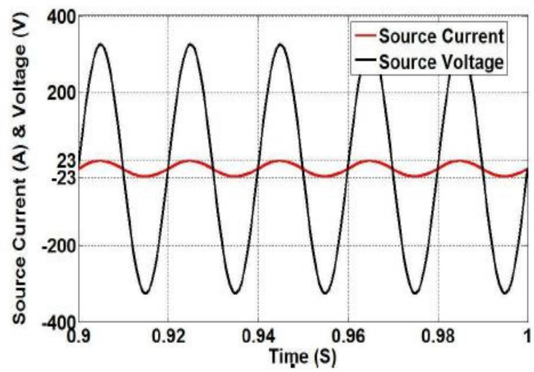

Fig.11. Source Voltage and Current.

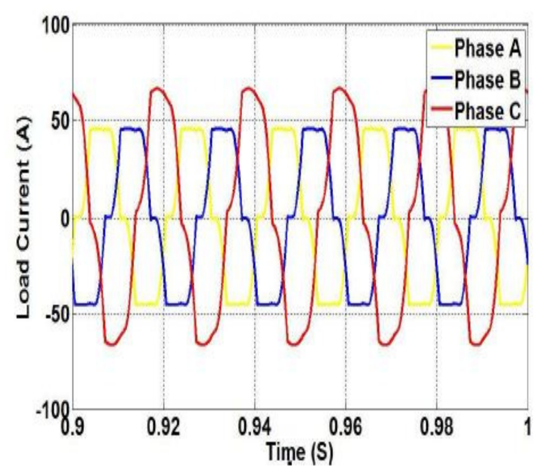

Fig.12. Compensation Current

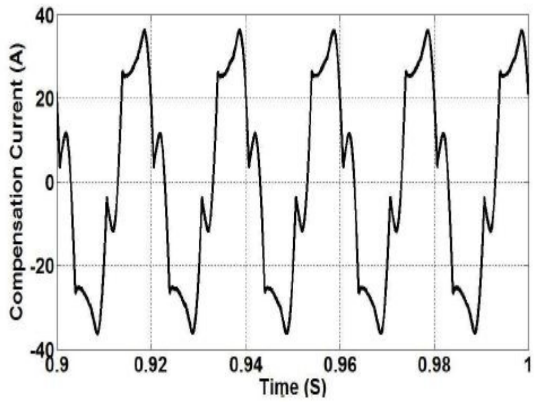

Fig.13. Compensation Current.

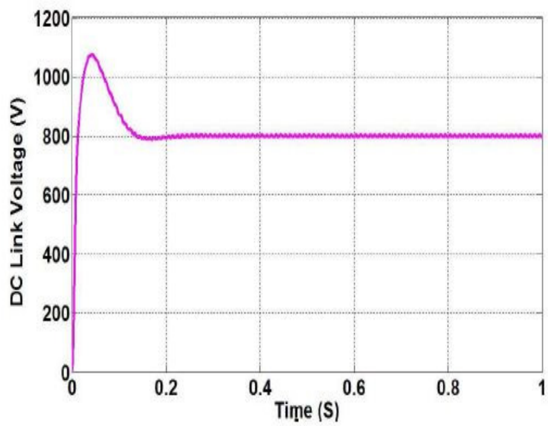

Fig.14. DC Link Voltage

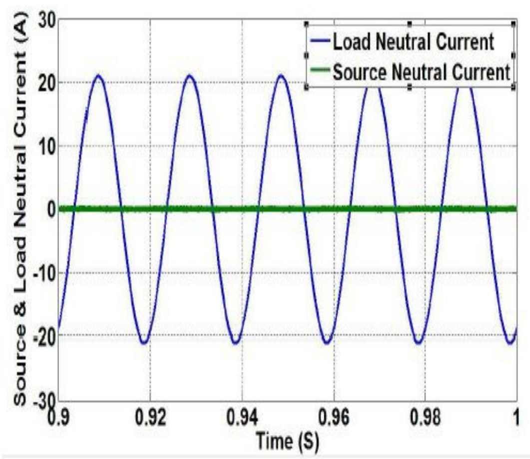

Fig.15. Load and Source Neutral Current

Fig 11 indicates that source current is sinusoidal and is in phase with the source voltage hence depicts shunt active power filter functionality of the inverter. Magnitude of source current in this case is less than that of the earlier one demonstrating real power sharing of RES with the grid. Fig 12 shows the load current of all the phases. Fig 13 depicts the compensation current synthesized by the VSI. Fig 14 shows that DC link voltage is maintained constant with the help of PI controller. Fig 15 shows that source neutral current is compensated and is made equal to zero by the fourth leg of the inverter.

Case 3: RES > Load demand.

In this case RES power supply exceeds that of the load requirement and excess real power is fed to the grid with unity power factor. In this case wind speed considered is 8 m/s and solar irradiation is 50 W/m^2. Along with harvesting real power from RES to grid four leg inverter does the job of power quality improvement as well.

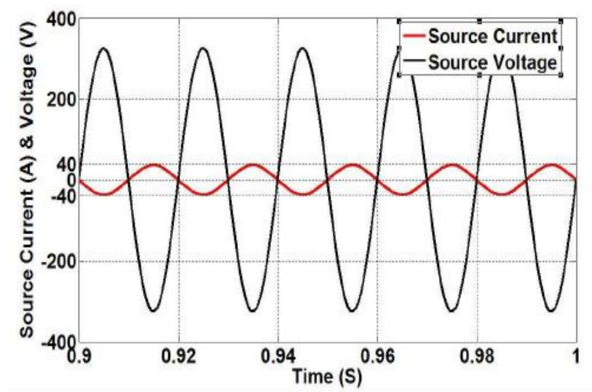

Fig.16. Source Voltage and Current

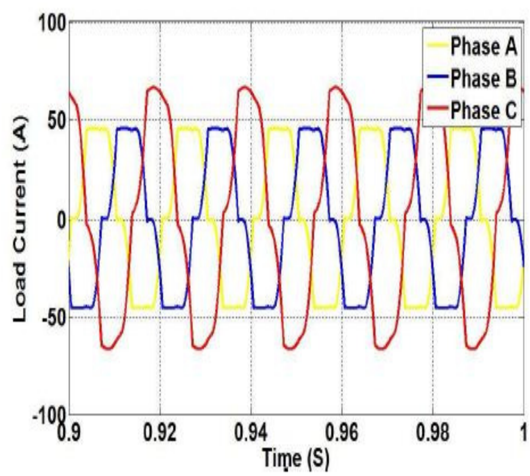

Fig.17. Load Current

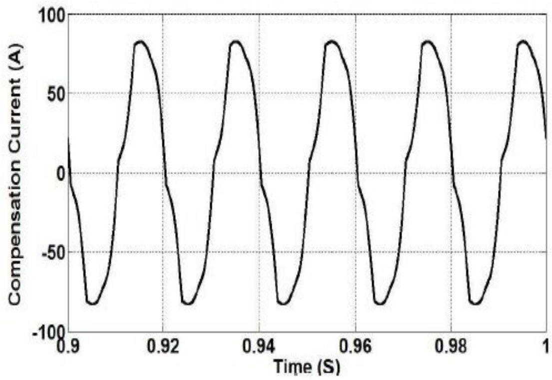

Fig.18. Compensation Current

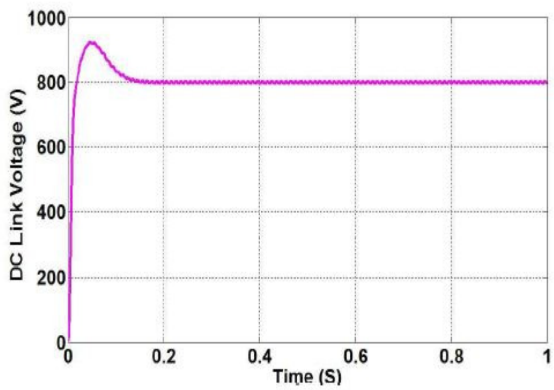

Fig.19. DC Link Voltage.

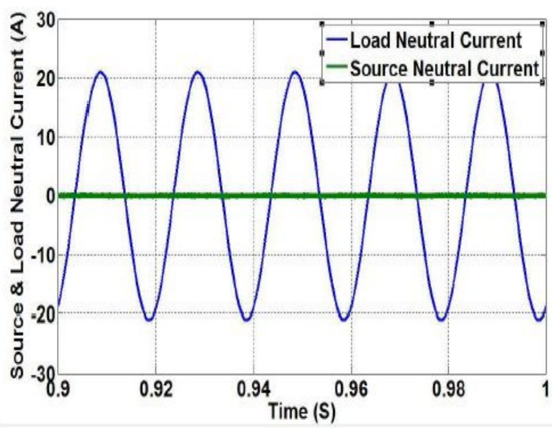

Fig.20. Load and Source Neutral Current

Fig 16 indicates that source current is sinusoidal and hence depicts shunt active power filter functionality of the inverter. Source current is out of phase with the supply voltage which indicates the flow of real power from RES to grid where grid acts as a linear resistive load. Load current is same as that of the earlier case and is shown in fig 17.

Fig 18 depicts the compensation current synthesized by the VSI. Fig 19 shows that DC link voltage is maintained constant with the help of PI controller. Fig 20 shows that source neutral current is compensated and is made equal to zero by the fourth leg of the inverter.

The results are displayed as shown in Table 2 and 3. It shows that for all the cases interfacing inverter acts as a shunt active filter. Obtained results indicate that source current Total Harmonic Compensation (THD) is well within IEEE 519 standards which demands source current THD to be within 5%. Reactive power Compensation is taking place and system power factor is raised to unity in all the cases. Negative power factor in the last case indicates that the real power is flowing from RES to the grid. Source neutral current is compensated with the help of fourth leg of the inverter.

6. Conclusion.

Wind-Solar Hybrid model is built and is interfaced with the grid at the same Point of Common Coupling (PCC) where non-linear loads are connected. Here interfacing inverter is assigned with an additional responsibility of improving power quality of the system. I_d-I_q method of control strategy is used to add shunt active power filter functionality to the four leg VSI. System is tested under all possible RES supply conditions like RES=0, Load demand>RES>0, RES > Load demand. For all the cases interfacing inverter successfully performs the assigned job of real power harvesting from RES to grid, harmonic compensation, reactive power compensation and neutral current compensation. Simulation results obtained indicate that THD of source current is within IEEE 519 standards and unity power factor of the system is achieved. Hence by adapting I_d-I_q method of control strategy the existing system can be utilized to perform dual function. Hence overall cost of the system is reduced.

Table.1. System parameters .

Sl no	Design parameters	Values
1	Supply Voltage, frequency	230 V, 50 Hz
2	Non-linear loads (diode bridge rectifier with RL load)	40Ω, 60mH.
3	Source	0.1Ω, 0.01mH

	inductance and Resistance	
4	DC link reference Voltage	800 V
5	DC link Capacitance	3mF
6	Coupling inductance and Resistance	0.1Ω,1mH
7	Kp,Ki (PI controller constants)	0.1414,7.5

Table.2. Harmonic Compensation by Four leg VSI.

Cases	Source Current THD before compensation		Source Current THD after compensation
	Phase A & B	Phase C	Phase A,B & C
RES=0	15.5 %	11.03 %	1.01 %
Load Demand>RES>0	15.5 %	11.03 %	2.17 %
RES > Load Demand	15.5 %	11.03 %	1.52 %

Table.3. Reactive Power Compensation by four leg VSI.

Cases	System Power factor before compensation	System Power factor after compensation
RES=0	0.87731	1
Load Demand>RES>0	0.87731	1
RES > Load Demand	0.87731	-1

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