GRID INTERCONNECTION OF HYBRID ENERGY SOURCES AT THE DISTRIBUTION LEVEL WITH POWER-QUALITY IMPROVEMENT

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ABSTRACT

Renewable Energy Source (RES) integrated at distribution level is known as Distributed Generation (DG). This paper presents a control strategy for achieving maximum benefits from these grid-interfacing inverters when installed in 3-phase 4-wire distribution systems. The inverter is controlled to perform as a multi-function device by incorporating active power filter functionality. The inverter can thus be utilized as: 1) power converter to inject power generated from RES to the grid, and 2) shunt APF and L,C Filter to compensate current unbalance, load current harmonics, load reactive power demand and load neutral current. Dynamic Voltage Restorer to compensating the Voltage sags and swells. All of these functions may be accomplished either individually or simultaneously. With such a control, the combination of grid-interfacing inverter and the 3-phase 4-wire linear/non-linear unbalanced load at point of common coupling appears as balanced linear load to the grid.

KEYWORDS

Power quality, Active power filter (APF), Dynamic Voltage Restorer (DVR), distributed generation (DG), distribution system, grid interconnection, power quality (PQ), renewable energy.

INTRODUCTION

Power quality (PQ) is very important to certain customers. For this reason, many utilities could sell electrical energy at different prices to their customers, depending on the quality of the delivered electric power. Since most end users are connected to secondary distribution networks, at medium voltage, it could be important to monitor and compensate the main disturbances on the medium voltage. As more sensitive loads, such as computers, automation equipments, communication equipments, medical equipments, and military equipments, have come into wide use, power quality has become a significant issue to both customers and the utility companies. Since these equipments are very sensitive in relation to input voltage disturbances, the inadequate operation or the fault of these loads brings about huge losses.

Renewable energy sources (RES) integrated at distribution level is termed as distributed generation (DG). The utility is concerned due to the high penetration level of intermittent RES in distribution systems as it may pose a threat to network in terms of stability, voltage regulation and power-quality (PQ) issues. Therefore, the DG systems are required to comply with strict technical and regulatory frameworks to ensure safe, reliable and efficient operation of overall network.

With the advancement in power electronics and digital control technology, the DG systems can now be actively controlled to enhance the system operation with improved PQ at PCC. However, the extensive use of power electronics based equipment and non-linear loads at PCC generate harmonic currents, which may deteriorate the quality of power [1], [2]. Generally, current controlled voltage source inverters are used to interface the intermittent RES in distributed system. Recently, a few control strategies for grid connected inverters incorporating PQ solution have been proposed.

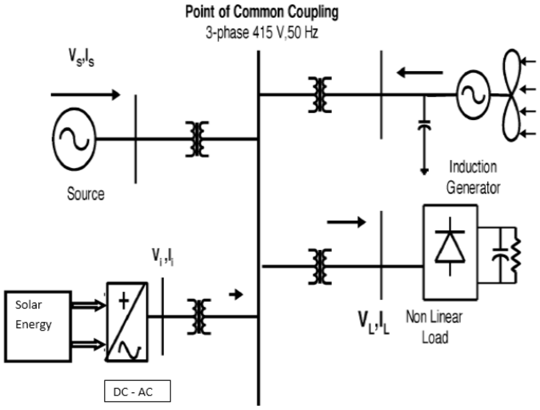
In [3] an inverter operates as active inductor at a certain frequency to absorb the harmonic current. But the exact calculation of network inductance in real-time is difficult and may deteriorate the control performance. A similar approach in which a shunt active filter acts as active conductance to damp out the harmonics in distribution network is proposed in [4]. In [5], a control strategy for renewable interfacing inverter based on theory is proposed.

In this strategy both load and inverter current sensing is required to compensate the load current harmonics. The non-linear load current harmonics may result in voltage harmonics and can create a serious PQ problem in the power system network. Active power filters (APF), LC filters are extensively used to compensate the load current harmonics and load unbalance at distribution level. Dynamic Voltage Restorer to compensating the Voltage sags and swells. This results in an additional hardware cost.

However, in this paper authors have incorporated the features of APF, LC filter in the, conventional inverter interfacing renewable with the grid, without any additional hardware cost. Here, the main idea is the maximum utilization of inverter rating which is most of the time underutilized due to intermittent nature of RES. It is shown utilized to perform following important functions: 1) transfer of active power harvested from the renewable resources (wind, solar, etc.); 2) load reactive power demand support; 3) current harmonics compensation at PCC; and 4) current unbalance and neutral current compensation in case of 3-phase 4-wire system. Moreover, with adequate control of grid-interfacing inverter, all the four objectives can be accomplished either individually or simultaneously. Dynamic Voltage Restorer to compensating the Voltage sags and swells. The PQ constraints at the PCC can therefore be strictly maintained within the utility standards without additional hardware cost.

SYSTEM DESCRIPTION

In this paper, it is shown that using an adequate control strategy, with a four-leg four-wire grid interfacing inverter, it is possible to mitigate disturbances like voltage unbalance. The topology of the investigated grid interfacing inverter and its interconnection with the grid is presented in Fig. 1.



Grid connected system for power quality improvement.

Fig.1 Single line diagram for Hybrid system

It consists of a four-leg four-wire voltage source inverter. The voltage source inverter is a key element of a DG system as it interfaces the renewable energy source to the grid and delivers the generated power. In this type of applications, the inverter operates as a current controlled voltage source. Fourth leg is used for neutral connection. The RES may be a DC source or an AC source with rectifier coupled to dc-link. In this paper wind energy is used as a RES, the variable speed wind turbines generate power at variable ac voltage. Thus, the power generated from these renewable sources needs to convert in dc before connecting on dc-link [8]–[10]. The simulink model of wind farm is given in Fig. Wind farm generates a variable ac supply; this variable ac supply is converted into dc by connecting a rectifier at output side.

CONTROL STRATEGY

The controller requires the three-phase grid current (Ia,,Ib, Ic), the three-phase voltage at the PCC (Va, Vb, Vc) and the DC-link voltage (VDC). As shown in Fig. 3, the sinusoidal waveform and the phase of the grid current reference (Ia*, Ib*, Ic*) comes from the line voltage thanks to a PLL. The control diagram of grid- interfacing inverter for a 3-phase 4-wire system. The fourth leg of inverter is used to compensate the neutral current of load. The main aim of proposed approach is to regulate the power at PCC during: 1) Pres =0; 2) Pres < total load power (PL); and 3) Pres > PL. While performing the power management operation, the inverter is actively controlled in such a way that it always draws/ supplies fundamental active power from/ to the grid. If the load connected to the PCC is non-linear or unbalanced or the combination of both, the given control approach also compensates the harmonics, unbalance, and neutral current.

The duty ratio of inverter switches are varied in a power cycle such that the combination of load and inverter injected power appears as balanced resistive load to the grid. The regulation of dc-link voltage carries the information regarding the exchange of active power in between renewable source and grid. Thus the output of dc-link voltage regulator results in an active current .The multiplication of active current component with (IM) unity grid voltage vector emplates (UA,UB,UC) generates the reference grid currents (IA,IB, and IC). The reference grid neutral current is set to zero, being the instantaneous sum of balanced grid currents. The grid synchronizing angle obtained from phase locked loop (PLL) is used to generate unity vector template.

$$UA = \sin(\Theta) \text{ -------------------------- } (1)$$

$$UB=\sin(\Theta-2\pi/3) \text{ ---------------------- } (2)$$

$$UC= \sin(\Theta+ 2\Pi/3) \text{ -------------------- } (3)$$

The actual dc-link voltage is sensed and passed through a first-order low pass filter (LPF) to eliminate the presence of switching ripples on the dc-link voltage and in the generated reference current signals. The difference of this filtered dc-link voltage and reference dc-link voltage is given to a discrete PI regulator to maintain a constant dc-link voltage under varying generation and load conditions. The dc-link voltage error at nth sampling instant is given as:

$$Vdcerr(n) =V^{*}dc(n) - Vdc(n) \text{ --------------------------------- } (4)$$

The output of discrete-PI regulator at th sampling instant is expressed as

$$Im(n) =Im(n-1)+Kpvdc(Vdcerr(n)-Vdecrr(n-1))+KIVdcVdecrr(n) \ (5)$$

Where Kpvdc=10 andKIVdc=0.05 are proportional and integral gains of dc-voltage regulator. The instantaneous values of reference three phase grid currents are computed as

$$Ia^{*}=Im.Ua \text{ ----------------------- } (6)$$

$$Ib^{*}=Im.Ub \text{ ------------------------ } (7)$$

$$Ic^{*}=Im.Uc \text{ ------------------------ } (8)$$

The neutral current, present if any, due to the loads connected to the neutral conductor should be compensated by forth leg of grid-interfacing inverter and thus should not be drawn from the grid. In other words, the reference current for the grid neutral current is considered as zero and can be expressed as

$$I^*n=0 \text{ --------------------------------- } (9)$$

The reference grid currents (Ia*,Ib* and Ic*) are compared with actual grid currents (Ia Ib and Ic) to compute the current errors as

$$Iaerr = I^*a - Ia \text{ ----------------- } (10)$$

$$Iberr = I^*b - Ib \text{ ---------------- } (11)$$

$$Icerr = I^*c - Ic \text{ ---------------- } (12)$$

$$Inerr = I^*n - In \text{ ----------------- } (13)$$

These current errors are given to hysteresis current controller. The hysteresis controller then generates the switching pulses (P1 to P8) for the gate drives of grid-interfacing inverter. The average model of 4-leg inverter can be obtained by the following.

$$(dI\ inva)/dt = ((Vinva-Va))/Lsh \text{----------------------- } (14)$$

$$(dI\ invb)/dt = ((Vinvb-Vb))/Lsh \text{-------------------------- } (15)$$

The three-phase ac switching voltages generated on the output terminal of inverter. These inverter output voltages can be modelled in terms of instantaneous dc bus voltage and switching pulses of the inverter as

$$(dI\ invc)/dt = ((Vinvc-Vc))/Lsh \text{ ----------------------- } (16)$$

$$(dI\ invn)/dt = ((Vinvn-Vn))/Lsh \text{ ----------------------- } (17)$$

$$(dVdc)/dt = ((Iinvad+Iinvbd+Iinvcd+Iinvnd))/Cdc \text{ --------- } (18)$$

Similarly the charging currents Iinvad,Iinvbd and Iinvcd on dc bus due to the each leg of inverter can be expressed as

$$Iinvad = Iinva(P1-P4) \text{ ----------------- } (19)$$

$$Iinvbd=Iinvb(P3-P6)\text{------------------}\ (20)$$

$$Iinvc=Iinvc(P5-P2)\text{-------------------}\ (21)$$

$$Iinvad=Iinva(P7-P8)\text{-------------------}\ (22)$$

The switching pattern of each IGBT inside inverter can be formulated on the basis of error between actual and reference current of inverter.

VOLTAGE SOURCE CONVERTER (VSC)

A Voltage Source Converter (VSC) is a power electronic device that connected in shunt or parallel to the system. It can generate a sinusoidal voltage with any required magnitude, frequency and phase angle. It also converts the DC voltage across storage devices into a set of three phase AC output voltages. It is also capable to generate or absorbs reactive power. If the output voltage of the VSC is greater than AC bus terminal voltages, is said to be in capacitive mode. So, it will compensate the reactive power through AC system. The type of power switch used is an IGBT in anti-parallel with a diode. The three phase four leg VSI is modeled in Simulink by using IGBT.

SWITCHING CONTROL

The hysteresis control has been used to keep the controlled current inside a defined band around the references. The status of the switches is determined according to the error. When the current is increasing and the error exceeds a certain positive value, the status of the switches changes and the current begins to decrease until the error reaches a certain negative value. Then, the switches status changes again. Compared with linear controllers, the non-linear ones based on hysteresis strategies allow faster dynamic response and better robustness with respect to the variation of the non-linear load. A drawback [13] [14] of the hysteresis strategies is the switching frequency which is not constant and can generate a large side harmonics band around the switching frequency.

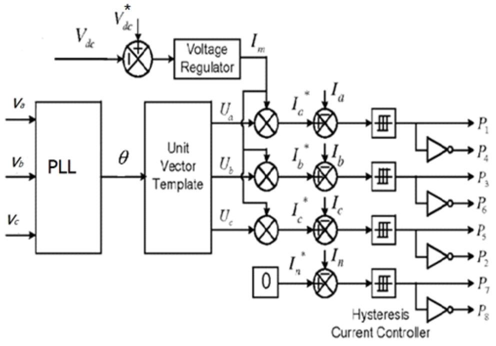


Fig 2.Control Scheme

HYSTERESIS CURRENT CONTROL

The hysteresis current control (HCC) is the easiest control method to implement; the shunt APF is implemented with three phase current controlled VSI and is connected to the ac mains for compensating the current harmonics. The VSI gate control signals are brought out from hysteresis band current controller. A hysteresis current controller is implemented with a closed loop control system and waveforms are shown in Fig .3. An error signal is used to control the switches in a voltage source inverter. This error is the difference between the desired current and the current being injected by the inverter. If the error exceeds the upper limit of the hysteresis band, the upper switch of the inverter arm is turned off and the lower switch is turned on. As a result, the current starts decaying.

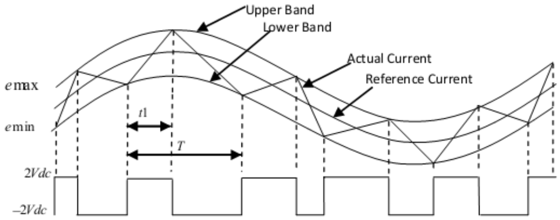


Fig 3.Waveform of Hysteresis current controller

If the error crosses the lower limit of the hysteresis band, the lower switch of the inverter arm is turned off and the upper switch is turned on. As a result, the current gets back into the hysteresis band. The minimum and maximum values of the error signal are emin and emax respectively. The range of the error signal emax-emin directly controls the amount of ripple in the output current from the VSI.

MODELING THE PV ARRAY

The direct conversion of the solar energy into electrical power is obtained by solar cells. A PVG is composed by many strings of solar cells in series, connected in parallel, in order to provide the desired values of output voltage and current. Fig. 4 shows the equivalent circuit of a PVG, from which non linear I–V characteristic can be deduced.

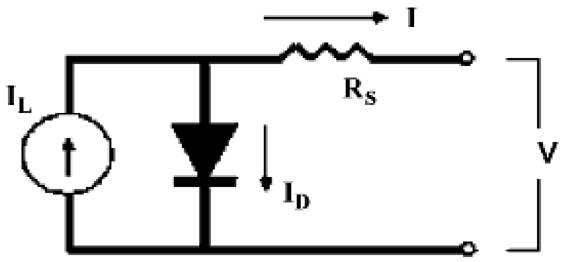


Fig 4.Solar-Cell Equivalent Circuit

The cells are connected in series and in parallel combinations in order to form an array of the desired voltage and power levels.

WIND TURBINE SYSTEM MODELLING

Although there are many types of wind turbines, either synchronous or asynchronous, the scope of this investigation is limited to asynchronous wind turbines that are presently and widely used in wind turbines due to their low cost and convenient maintenance. Generally, a complete wind turbine model consists of an aerodynamic model, mechanical drive model, and induction generator model. The aerodynamic rotor extracts the kinetic power from the wind and exchanges this power into mechanical power. The relation between the wind speed and mechanical power is given by Equation

$$Pw = (1/2)\ \rho\pi\ R2\ Vw\ 3\ Cp\ (\theta, \delta)$$

Where, Pw is the power extracted from wind (W), ρ is

The air density (kg/m3), R is the radius of the rotor of wind turbine (m), Vw is the wind speed (m/s), θ is the pitch angle of the rotor (deg) , λ =Wrot R/Vw

λ = the tip speed ratio, where, Wrot is the rotor speed of wind turbine (rad/sec), Cp is the aerodynamic efficiency of the rotor which can be expressed as a function of the tip speed ratio (λ) and the pitch angle (θ) by the following equation [11]:

$Cp = 0.22(116/\beta - 0.4\theta - 5)\ e\ 12.5/\ \beta$

And also, β can be expressed by:

Produced mechanical power is transferred into the electrical energy by generator and is fed into the grid.

CONTROL OF WIND FARM SIDE CONVERTER

The main scope of the wind farm side converter in this investigation is to control the reactive power generated or absorbed by the VSC. This reactive power is controlled by the magnitude of the converter AC voltage, which in PWM conversion is determined by modulation index. The simplified control block diagram of the wind farm side converter is also included in grid side. Shift signal is the phase angle order in degrees derived from open loop power controller. It is the angle by which the voltage across the sending end transformer is phase shifted in order to control the power flow. The firing unit uses the PWM reference signals at fundamental frequency. The magnitude of the reference signal is controlled by the signal r m and its phase is controlled by the signal shift. Firing pulses are generated with comparison between reference signals and triangular signals [14].

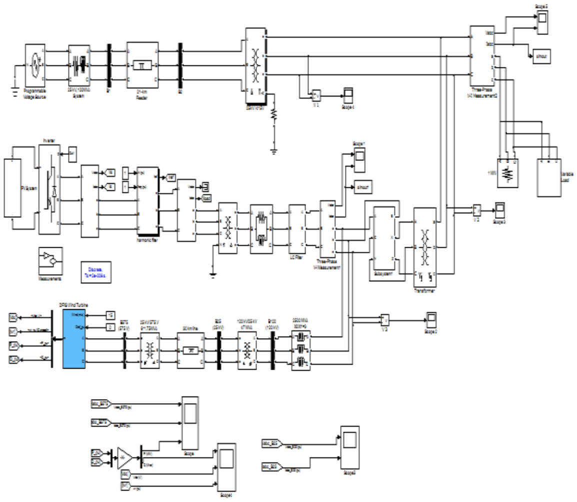


Fig 4.1 Simulation Diagram for Hybrid systems

CONTROL OF GRID SIDE CONVERTER

The main schematic of this controller is revealed in too. This control aims to adjust the phase angle of receiving end converter at the AC side. Also, when the DC link voltage is higher than normal condition, the phase angle is adjusted to push power into the receiving end AC system. If the DC link voltage tends to be lower than reference value, the angle is altered in a way to receive the power from receiving end AC system in order to charge the DC link. The mi is the modulation index of the output of controller in order to control the voltage magnitude of the grid side converter. The firing unit acts as similar as cited in wind farm side converter controller [14].

POWER QUALITY IN POWER

DISTRIBUTION SYSTEMS

Most of the more important international standards define power quality as the physical characteristics of the electrical supply provided under normal operating conditions that do not disrupt or disturb the customer's processes. Therefore, a power quality problem exists if any voltage, current or frequency deviation results in a failure or in a bad operation of customer's equipment. However, it is important to notice that the quality of power supply implies basically voltage quality and supply reliability.

Voltage quality problems relate to any failure of equipment due to deviations of the line voltage from its nominal characteristics, and the supply reliability is characterized by its adequacy (ability to supply the load), security (ability to withstand sudden disturbances such as system faults) and availability (focusing especially on long interruptions). Power quality problems are common in most of commercial, industrial and utility networks. Natural phenomena, such as lightning are the most frequent cause of power quality problems. Switching phenomena resulting in oscillatory transients in the electrical supply, for example when capacitors are switched, also contribute substantially to power quality disturbances.

Also, the connection of high power non-linear loads contributes to the generation of current and voltage harmonic components. Between the different voltage disturbances that can be produced, the most significant and critical power quality problems are voltage sags due to the high economical losses that can be generated. Short-term voltage drops (sags) can trip electrical drives or more sensitive equipment, leading to costly interruptions of production [10]. For all these reasons, from the consumer point of view, power quality issues will become an increasingly important factor to consider in order to satisfy good productivity.

On the other hand, for the electrical supply industry, the quality of power delivered will be one of the distinguishing factor for ensuring customer loyalty in this very competitive and deregulated market. To address the needs of energy consumers trying to improve productivity through the reduction of power quality related process stoppages and energy suppliers trying to maximize operating profits while keeping customers satisfied with supply quality, innovative technology provides the key to cost-effective power quality enhancements solutions. However, with the various power quality solutions available, the obvious question for a consumer or utility facing a particular power quality problem is which equipment provides the better solution.

SOLUTIONS TO POWER QUALITY

PROBLEMS

There are two approaches to the mitigation of Power Quality problems. The first approach is called load conditioning, which ensures that the equipment is less sensitive to power disturbances, allowing the operation even under significant voltage distortion. The other solution is to install line conditioning systems that suppress or counteracts the power system disturbances. A flexible and versatile solution to voltage quality problems is offered by active power filters. Currently they are based on PWM converters and connect to low and medium voltage distribution system in shunt or in series. Series active power filters must operate in conjunction with shunt passive filters in order to compensate load current harmonics. Shunt active power filters operate as a controllable current source and series active power filters operates as a controllable voltage source. Both schemes are implemented preferable with voltage source PWM inverters, with a dc bus having a reactive element such as a capacitor. Active power filters can perform one or more of the functions required to compensate power systems and improving power quality. As it will be illustrated in this paper, their performances depend on the power rating and the speed of response.

SIMULATION RESULTS

The total active and reactive powers of grid, load and inverter In the APF mode of operation, the inverter consumes a small amount of active power to maintain the dc-link voltage and to overcome the losses associated with inverter, while most of the load reactive power need is supported by inverter effectively. Thus, this mode of operation validates the concept of utilization of grid-interfacing inverter as shunt APF when there is no power generation from the RES. The experimental results demonstrate the effective compensations of load current unbalance, harmonics and reactive power.

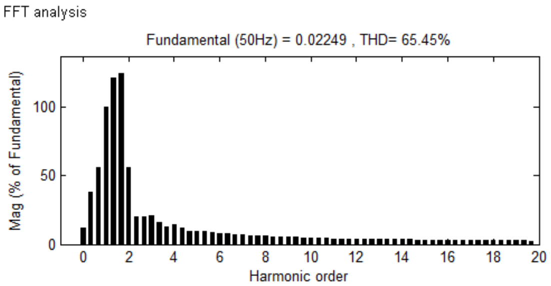


Fig 5: THD without Hybrid Filter

VOLTAGE AND CURRENT WAVEFORM WITH AND WITHOUT HYBRID FILTER

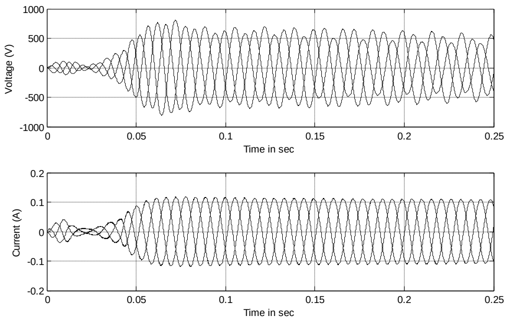


Fig 6: Input waveform without hybrid filter

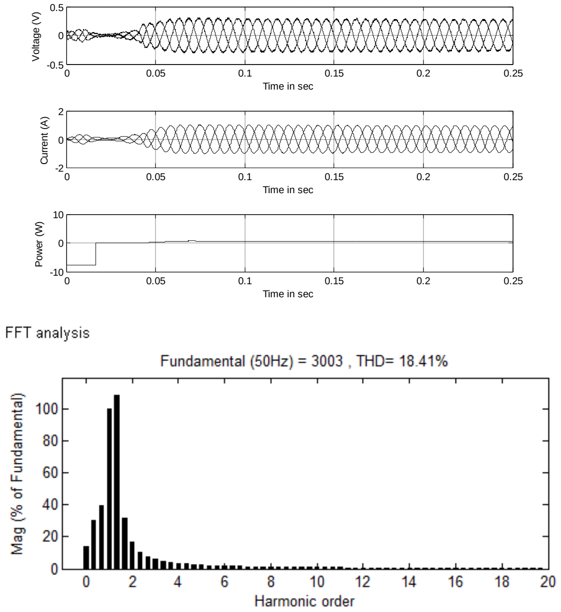


Fig 7: output wave form for Hybrid system and THD level

HARMONICS

The harmonic results due to the operation of power electronic converters. The harmonic voltage and current should be limited to the acceptable level at the point of solar energy connection to the network. To ensure the harmonic voltage within limit, each source of harmonic current can allow only a limited contribution shown in Fig 8, as per the IEC-61400-36 guideline. The rapid switching gives a large reduction in lower order harmonic current compared to the line commutated converter, but the output current will have high frequency current and can be easily filter-out.

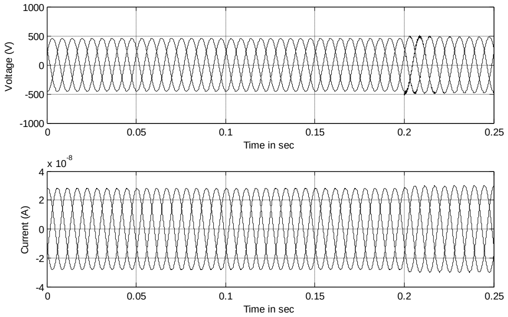


Fig 8: Load side Output wave form with hybrid filter

CONCLUSION

This paper has presented a novel control of an existing grid interfacing inverter to improve the quality of power at PCC for a 3-phase 4-wireDGsystem. It has been shown that the grid-interfacing inverter can be effectively utilized for power conditioning without affecting its normal operation of real power transfer. The grid-interfacing inverter with the proposed approach can be utilized to: i) inject real power generated from RES to the grid, and/or, ii) operate as a shunt Active Power Filter (APF), L,C Filter. Dynamic Voltage Restorer to compensating the Voltage sags and swells. This approach thus eliminates the need for additional power conditioning equipment to improve the quality of power at PCC.

Extensive MATLAB/Simulink simulation as well as the DSP based experimental results have validated the proposed approach and have shown that the grid-interfacing inverter can be utilized as a multi-function device. It is further demonstrated that the PQ enhancement can be achieved under three different scenarios: The current unbalance, current harmonics and load reactive power, due to unbalanced and non-linear load connected to the PCC, Dynamic Voltage Restorer to compensating the Voltage sags and swells are compensated effectively such that the grid side currents are always maintained as balanced and sinusoidal at unity power factor. Moreover, the load neutral current is prevented from flowing into the grid side by compensating it locally from the fourth leg of inverter. When the power generated from RES is more than the total load power demand, the grid-interfacing inverter with the proposed control approach not only ful fills the total load active and reactive power demand (with harmonic compensation) but also delivers the excess generated sinusoidal active power to the grid at unity power factor.

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