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Active and Reactive Power Control of Single Phase Transformerless Grid Connected Inverter for Distributed Generation System

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Abstract

This paper presents a novel approach by which enhancement in power quality is ensured along with power control for a grid interactive inverter. The work presented in this paper deals with modeling and analyzing of a transformer less grid-connected inverter with active and reactive power control by controlling the inverter output phase angle and amplitude in relation to the grid voltage. In addition to current control and voltage control, power quality control is made to reduce the total harmonics distortion. The distorted current flow can compensate for the disturbance caused by nonlinear load. The Simulation of the grid interactive inverter is carried out in MATLAB/SIMULINK environment and experimental results were presented to validate the proposed methodology for control of transformer less grid interactive inverter which supplies active and reactive power to the loads and also makes the grid current to a sinusoidal one to improve the power factor and reduce the harmonics in grid current. This work offers an increased opportunity to provide distributed generation (DG) use in distribution systems as reliable source of power generation to meet the increased load demand which helps to provide a reasonable relief to the customers and utilities to meet the increasing load demand

Keywords: Grid interactive inverter, Voltage Controller, Current Controller, THD improvement, reactive power compensation, intelligent power module

INTRODUCTION

Distributed Generators (DG) utilizing Environmental-friendly energy sources, like wind, small hydro, and solar have become a major part of future smart grid/micro grid concept. These energy sources meet both the increasing demand of electric power and environmental regulations.

Photovoltaic energy is one of the most popular renewable sources since it is clean, inexhaustible and requires little maintenance and distributed throughout the earth. Normally DGs are small size active power generators of 1 KW to 100 MW that is connected at distribution level [1, 2]. Active government policies are made to promote the need for tapping energy from the sun which is abundant in nature and to install standalone Photovoltaic (PV roof top) technology to meet the increasing load demand and reduce the electricity bill of the customer. Moreover this gives a motivation to use green power for power generation. PV module cost is also decreasing, solar based DG units –plays an increasing role in power system of near future.

The development of power electronics technology plays a key role in the integration of DG units which change the vertical power system to a horizontal one. DGs can be designed to provide ancillary services to the utility such as reactive power support, load balancing, voltage support, and harmonic mitigation [3].The main types of electrical systems interfaces are synchronous machine, asynchronous machine and power electronics converters [4]. The synchronization and current control plays a major role to meet the standards for interconnection of DG units to utility grid. Therefore control

Strategies applied to the interconnection of DG unit is very important.

An important aspect related to the PV system connected to the electric grid is that it can operate as both active power generator and reactive power compensator [5]. The proper power factor is selected according to active and reactive power that the grid demands. The power factor deterioration can be avoided by active and reactive power interaction between the AC grid and DG system. The acceptable penetration of DG units in the low voltage distribution network without exceeding voltage and harmonic limits as defined in EN 50160 and IEEE 1547 standards [6, 7]. An over view of grid synchronization and their influence in control were discussed [8] Grid interactive inverter can be designed as voltage controlled (VC) or current controlled (CC) type. Voltage source inverter with current control is used for reactive power compensation in grid interconnection of solar based DG [9]. DG system can feed power into the AC grid through a grid connected inverter, there is no need for a storage battery, and this will leads to minimize the cost of installation. The development of grid interactive inverter still faces challenges in performance and cost. To overcome these challenges, improvements are to be made in the inverter configuration& design of filters. This will reduce the size and weight of the inverter for convenient installation. Conventional grid connected inverters have galvanic isolation (either in dc or ac side). The transformer less inverter have the advantage of low cost, higher efficiency, smaller size and lower weight [10].

By using switched pulse width modulated technologies, harmonics problems have to be reduced. The compensation for grid-voltage harmonics has been the main topic of an inverter-based DG with an L-filter at the connection point to the grid has been considered [11, 12].

The basic requirement of a grid interactive inverter operation are active power generator, reactive power compensator and must able to maintain the voltage magnitude at the point of common coupling(PCC) to a desired value. A low cost utility interactive inverter for fuel cell is considered in [13]. Single phase grid interactive inverter in grid connected mode with resistive load has been presented in [14].The control of active and reactive power between the DG unit and the grid, seam less transfer of power flow balance between the input side converter and the grid, output power quality and maintaining synchronization with the grid which is compliance with the grid code [15].The main functions of the controllers are to maintain the power quality by controlling the active and the reactive power of the grid. The acceptable penetration of PVDG units in the low voltage distribution network without exceeding voltage and harmonic limits as defined in EN 50160 and IEEE 1547 standards.

The main norms that grid connected inverters have to comply with 1) total harmonic distortion (THD) levels, 2) power factor (PF), 3) level of injected dc current 4) voltage and frequency range for normal operation [16, 17].Var control of PV inverters was discussed in[18,19].Now days the relevance of alternative energy sources are increasing much. Govt of India is giving a lot of encouragement to promote this. At present efficiency is less and investment required is more for alternative energy sources especially for Photovoltaic systems. By introducing new technologies, the use of alternative energy sources could be made acceptable one

The aim of this work is to select a control and switching strategy for an inverter which is to be used as part of a single-phase rooftop grid-connected PV system capable of improving the power quality in terms of power factor and low THD. Transformer less grid connected inverter topology is used in this study.

The simulation of the grid connected inverter has been conducted with non-linear load and the results obtained from the simulations shows that this method improves the THD and the power factor. As the system is grid connected, the objective can be summarized as a pure sinusoidal current in phase with the grid voltage wave form.

SYSTEM CONFIGURATION AND CONTROL

In conventional grid connected system, the power conversion unit is directly connected to the grid without load. Fig 1 shows the system configuration of a single phase DG operating in grid connected mode. The system consists of a DC source, voltage source inverter (VSI), an output LC filter, local load and utility grid

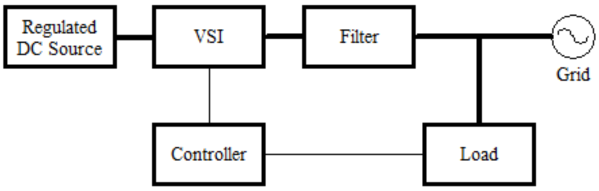

Figure 1: Schematic diagram of grid connected system

The purpose of the DG system is to supply power to its local load in addition to the grid power/ transfer the surplus power to the utility grid at point of common coupling (PCC). To generate high quality power, the current that DG transfers to the grid should be balanced, sinusoidal and have low THD. Because of the grid voltage distortion and nonlinear local load that exists in power system A model of grid connected DG system is developed. In this model ,first consider VSI of the DG is modeled as a voltage source(V_i) and the inverter transfer a grid current I_g to the utility grid(V_g) with local load(no load condition)to load

Rf and Lf are the equivalent resistance and inductance of the inductor Lf

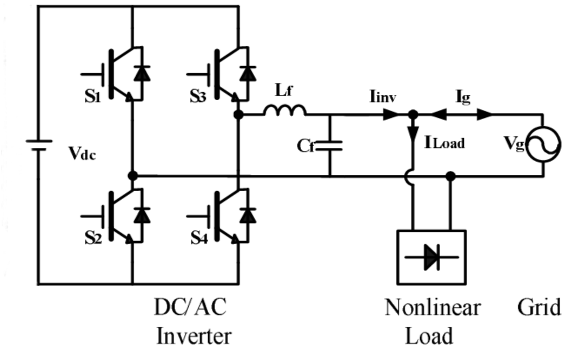

Figure 2: grid tie inverter

In this work, Single phase grid interactive inverter with nonlinear load which is connected parallel to the grid is considered. Assuming, input power of VSI is constant and the system consists of DG source represented by a regulated dc supply, voltage source inverter, LC filter, a load and grid. The output filter is used to reduce the high frequency harmonics in the current waveform due to PWM switching and reduce output current THD. Constant frequency modulation is used for the generation of the gate signal for the full bridge inverter. The Switching States are as follows

Table 1: switching strategy of inverter switches

S1	S2	S3	S4	Output V0
on	off	off	on	V0
off	on	on	off	-V0
off	on	off	on	0
on	off	on	off	0

The full bridge inverter comprises four switches, two upper arm switches(S1,S3) and two lower arm switches(S2,S4).the control strategy is performed in such a way that at a time a pair of switches(S1,S4) is turned ON and S2,S3 is turned OFF.PWM method is commonly used.

Figure 3: Calculation of switching pulses

The PWM inverter is synchronized and connected to the grid. The inverter current (I_{inv}) should be controlled not only to compensate the reactive current of the grid depending on the load, but also to produce its active current corresponding to the load. The voltage equation of the system is

$$V_i - Vg - Lf\frac{dIg}{dt} - Rf * Ig = 0 \quad (1)$$

Both the grid voltage and inverter voltages are composed of the fundamental and harmonic components, the voltage equation of (1) is changed into

$$V_i = V_{i1} + \sum_{h\neq1} V_i\, h \quad (2)$$

$$V_g = V_{g1} + \sum_{h\neq1} V_g\, h \quad (3)$$

Equating fundamental and harmonic components into equation (1)

$$V_{i1} - V_{g1} - Lf\frac{di_{g1}}{dt} - Rf * i_{g1} = 0 \quad (4)$$

$$\sum V_i h - \sum V_g h - Lf\frac{dIgh}{dt} - Rf * Igh = 0 \quad (5)$$

The local load is represented as a current source l_{DG}

$$l_{DG} = I_L + l_g \quad (6)$$

$$I_L = I_{DG} + I_g \quad (7)$$

$$I_L = l_{L1} + \sum_{h\neq1} l_L\, h \quad (8)$$

$$I_{L1} + \sum_{h\neq1} l_L h = I_{DG} + I_g \quad (9)$$

$$I_{L1} + \sum_{h\neq1} l_L h - I_{DG} = I_g \quad (10)$$

If I_L is low, transfer of excess DG current I_{DG} to the grid which include harmonic component that can compensate the load current.

The system active power can be expressed as

$$P_{load}=P_{inv}+P_{grid} \quad (11)$$

The required grid current amplitude can be developed from the load power and grid voltage

$$I_b=P_{load}/V \quad (12)$$

$$I_g^*=(P_{Load}/V_g)-I_{dc}^* \quad (13)$$

Where, Re[I_{Load}] is the active current component of the load current and I_{dc*} is the output of the dc-link voltage controller. The DC link voltage V_{dc} is sensed and compared with reference V_{dc}^* and error signal is given to the PI controller which gives I_{dc*}.

The inverter is connected to the grid through an LC filter

$$V_{inv} - Vcf = Rf * If + Lf\frac{dIf}{dt} \quad (14)$$

$$I_{inv}-I_g=Cf(dVcf/dt) \quad (15)$$

$$I_l=I_{inv}+I_g \quad (16)$$

The control circuit is shown in fig 2.

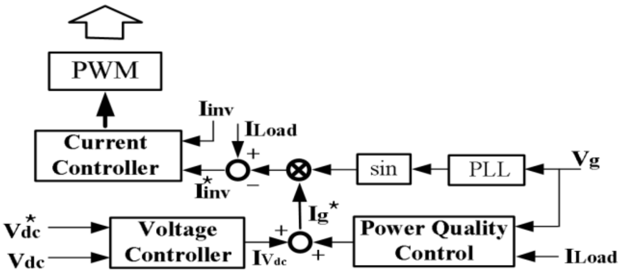

Figure 4: The control circuit

The required grid current amplitude can be found that the grid current includes only the active current is as follows. The system supplies the active and reactive power to the loads. A controlled rectifier is considered as load in this work. The main purpose is to produce a nonlinear current wave form.

$$I^*_{inv} = I_{load} - I^*_g \times \sin^* \omega t \quad (17)$$

Where, sin*ωt is a unity sinusoidal waveform in phase with voltage by phase-lock-loop (PLL).

Grid synchronization- Phase locked Loop (PLL)

PLL has a major role in the variation of system control as it is responsible for phase angle and adapting the changing conditions on the grid. The PLL block operation of current control loop defines the accuracy of active and reactive power control

The DC-link voltage controller is used to control the voltage loop to produce the dc reference current (I_{vdc}). The load current and the grid voltage are used in the PQ controller block to generate the active current component of the load current. Using (17), the required grid current amplitude for the active power can be calculated. The load current and required grid current amplitude which is multiplied by sin*ωt are used to produce the inverter reference current command I*inv. This reference is used to control the reactive power and THD of the load. Then, the PWM inverter decides the PWM switching pattern via the PI current controller which have the reference current (I_{inv}^*) and the real output current (I_{inv}) of the inverter as the inputs. All the controllers inside the system are PI based topologies.

SIMULATION RESULTS

Case-1 fully controlled rectifier as load

MATLAB/SIMULINK simulator was used for simulation in order to investigate the operational characteristics of the system with nonlinear load. Fully controlled rectifier load is used as nonlinear load in MATLAB/SIMULINK using same algorithm (fig5) is shown below

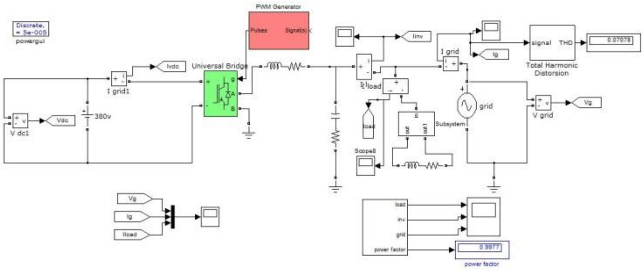

Figure 5: MATLAB simulation circuit

The inverter capacity was assumed to be 2.5kVA at 230V rms. In grid connected mode of operation, the design of inverter is made to satisfy some specifications. The grid voltage Vg=230V±10%.Frequency of grid is 50Hz.The power factor at 50% load should be greater than 0.95.The minimum usefulness DC link voltage at 10% over voltage in the grid equal to 360V.Maximum DC link voltage is specified to 400V.So a good choice for V_{dc} =380V.The selection of the inductor is related to the ripple current and power. To enable fast and accurate grid angle tracking under real time conditions, filters are selected to tune to the grid frequency. The voltage regulation capability of the system with the local load and the injected active and reactive powers are made. Normally ripple current is limited to 15% to 20% of rated current. To prevent the influence of voltage ripple caused by the inverter current flow, it is necessary to design DC link capacitance properly. Higher the capacitance lowers the voltage ripple. But the value of capacitance is limited because of its size and cost.

$$\text{Imean}=2\sqrt{2}\,\text{Irms}/\pi \tag{18}$$

5% of rated input voltage is taken as maximum of ripple voltage for selecting the capacitance

Details of system specifications and parameters are given

Table 1: The system specifications

PARAMETER	VALUE
Rated apparent power	2.5 KVA
Output Voltage	230Vrms
Rated input Voltage-Vdc	380V
Rated output current	12A
Switching frequency	10-30kHz
Filter inductor	34mH
Filter capacitor	4.7uf

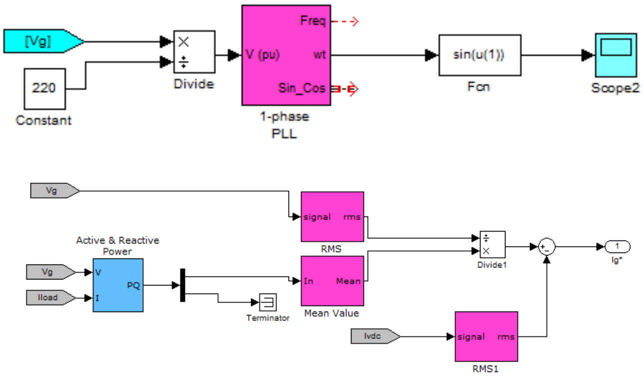

Figure 6: Simulation diagram of PLL and PQ controller

The fig 6 shows the simulation diagram of PLL and PQ controller. PLL is employed to create a sinusoidal function whose frequency and angle are equal to grid voltage and frequency .Instead of using abc to dq/αβ transformation, a delay block is used to derive the signal perpendicular to Vgrid signal, that is to generate a sinusoidal, phase shifted by 90degree

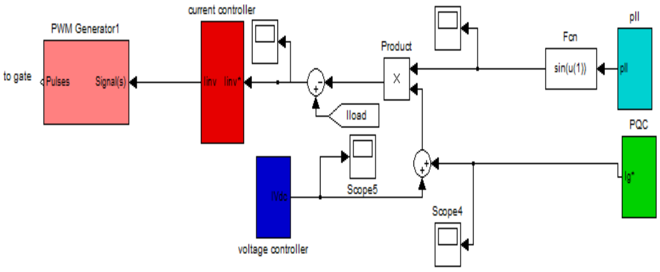

Figure 7: Complete control circuit

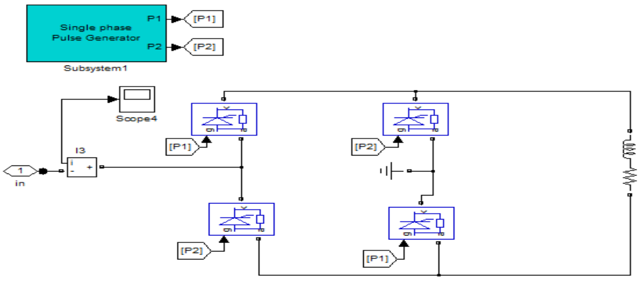

Figure 8: Load circuit using controlled rectifier

Fig7 shows complete control circuit simulated with the proposed control and fig-8 shows the load circuit. The output waveforms obtained are shown in fig9(a),the load current Figure 9(b) shows the inverter current considering a controlled rectifier as load. The inverter current filtered and is is to be injected to the grid which is in phase with the grid voltage The figure 9 (c) shows the grid current. After the compensation the waveform is found to be sinusoidal

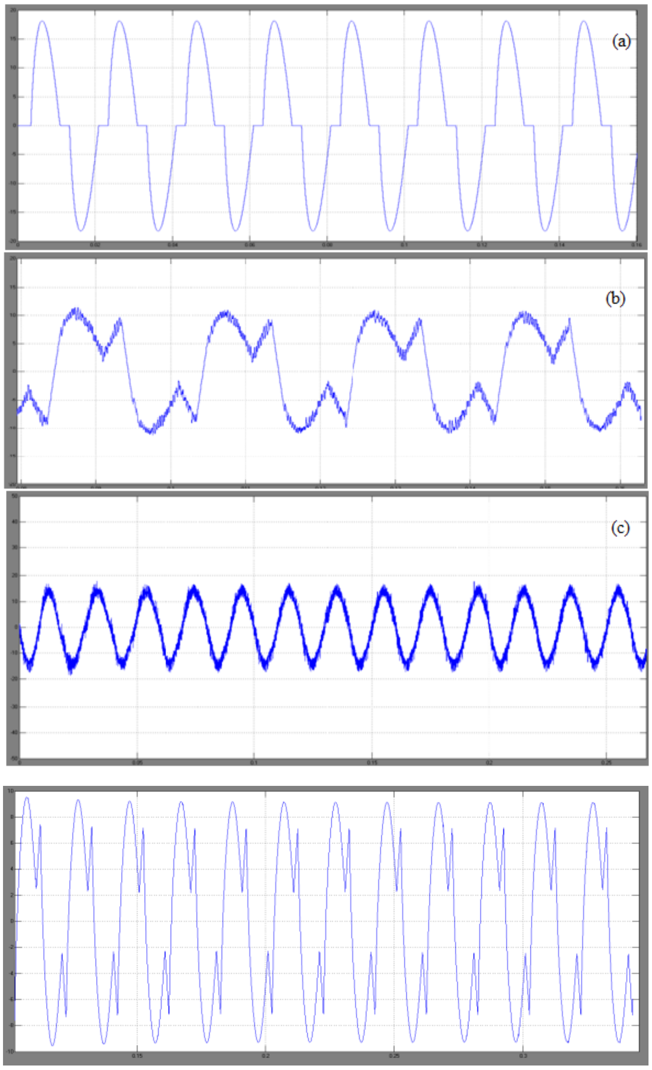

Figure 9: Simulation waveforms of current a) when load is controlled rectifier b) inverter current c) grid current d) the reference current

Fig 9 (d) shows the reference current generated .

The figure 10 shows the power flow graph. The plot (a) and (b) shows the active power of 1800 watts and reactive power of 850 watts drawn by the load. The second graph shows the active power of 500 watts and reactive power of 850 watts supplied by the inverter. Plot (c) shows the reactive power supplied by the inverter and the plot (d) shows the active power supplied by the inverter. The third graph shows the power drawn from the grid. The plot (e) shows the active power drawn from the grid which is 1300and plot (f) shows the reactive power drawn from the grid. It is seen that the reactive power drawn from the grid is zero and the complete reactive power is fed by the inverter. Voltage regulation is made at the point of coupling.

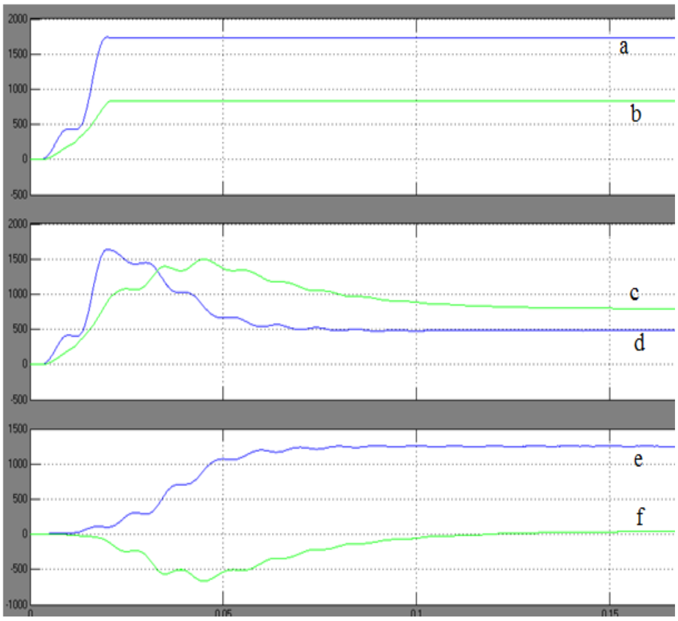

Figure 10: Power flow graph.

The volt-current graph (fig11) shows that the Grid power factor =0.9977 and Load power factor =0.8909.

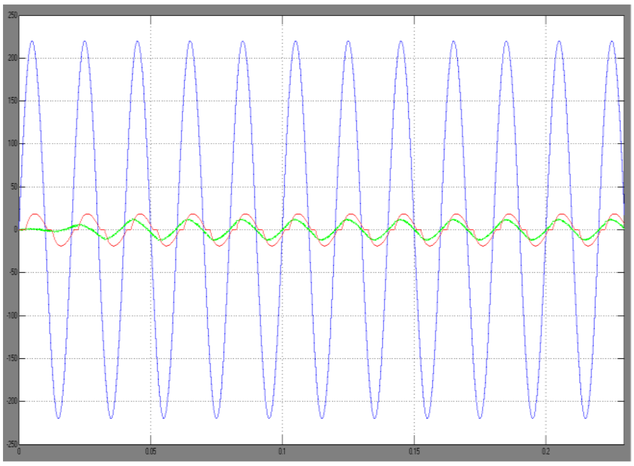

Figure 11: grid voltage, load current & grid current

The figure 11 shows the voltage of the grid, load current and the source current after compensation.

FFT analysis has been conducted on the grid current and the THD is found to be 3.74%. and the result is shown below(fig 12)

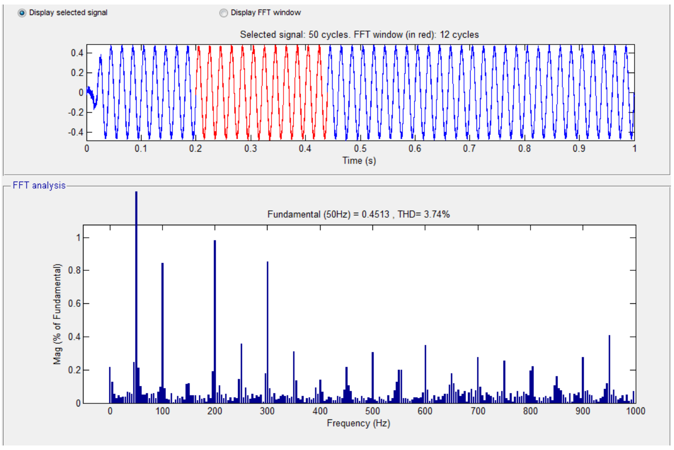

Figure 12: FFT analysis

SIMULATION RESULTS

Case 2 when Load Is Half Wave Rectifier

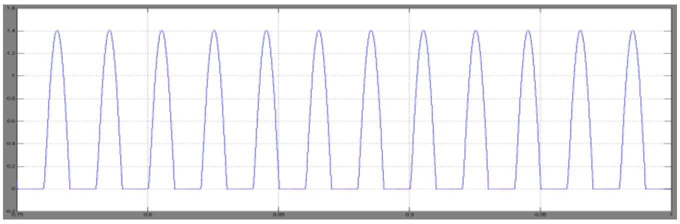

Figure 12: load current

The reference current has been calculated and the error is fed to the constant PWM. The PWM gives the switching signal for the inverter so that inverter feeds compensating current to the grid and a small amount of active power

When the compensating current is fed to the grid, the non-sinusoidal current waveform in the grid changes to sinusoidal. Thus the THD is improved and the grid current wave form after compensation is shown in the figure 13

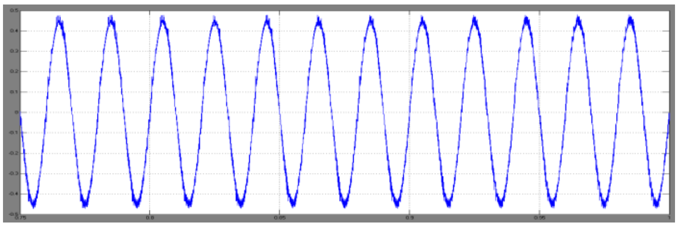

Figure 13: Injected current

For the implementation of the hardware the real time workshop of the MATLAB is used. For hardware implementation the half wave rectifier is used as load.

HARDWARE IMPLEMENTATION AND RESULTS

The prototype design is made to cooperate with 230V, 50Hz has been selected and the switching frequency is sufficiently high to provide the inverter operation safely. By using the real time workshop in the MATLAB. In real time workshop, it requires the real time data has been fed to the computer.

Figure 15: Hardware implementation

It has been done using a data acquisition card. The card used here is pci-1711 made by Advantech. The PCI-1711 is a multi-function data acquisition card for the PCI bus. The advanced circuitry allows the user to utilize measurement and control functions such as 12-bit A/D conversion, D/A conversion, digital input, digital output, and counter/timer. The card provides 16 analog input channels 16 digital output channels. The pwm is generated in 10 KHz frequency and a time delay of 5ms is given for the purpose of turning off of IGBT. Then the signal is taken out from the MATLAB using the data card digital output pins The switching signal obtained from the MATLAB is fed to the IPM module and a rheostat and the an inductive load in series is connected to inverter in series. The Simulink model used to obtain the sine PWM is shown in the figure 16

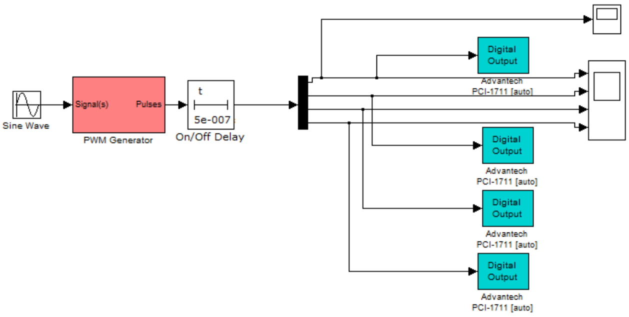

Figure 16: Simulink model for generating spwm

On/off delay is used to provide the dead time for the inverter. Then the switching pulse is given to the inverter and the waveform obtained is observed in a digital storage oscilloscope. The waveform obtained is shown in the figure 17.

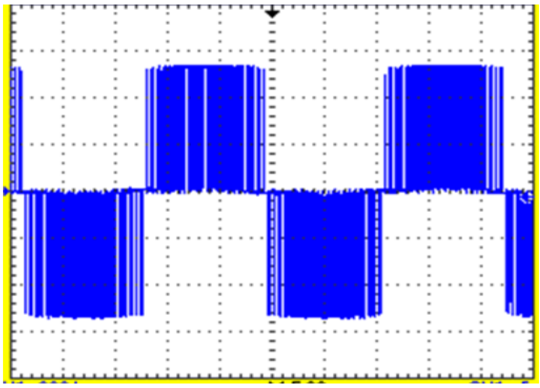

Figure 17: output of inverter before filter

The source current before compensation is same as that of the half wave rectifier.To verify the reactive power compensation the load current waveform and the source voltage waveform is considered. The corresponding waveform is shown in the figure 18The figure shows that the current lags the voltage by an angle. The waveforms obtained after the compensation are shown in the figure 19. The figure shows that after the compensation the source current and the grid voltage is found to be in phase, so that the power factor is improved.

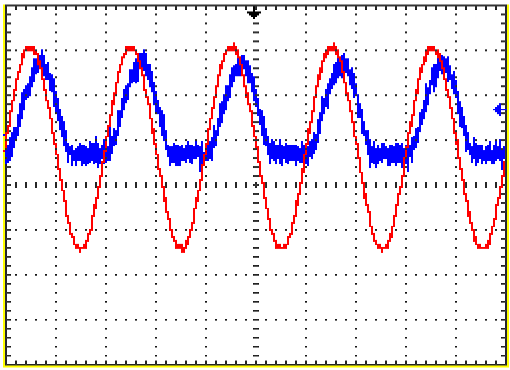

Figure 18: Volt-current waveform before compensation.

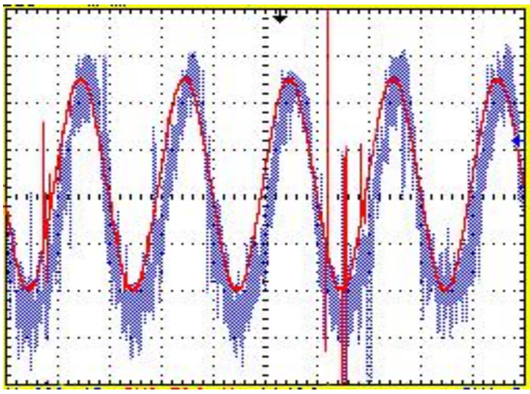

Figure 19: Volt-current waveform after compensation

CONCLUSION

The simulation of single phase grid interactive inverter has been carried out with non-linear load and the results obtained from the simulations shows that this control technique improves the power quality ie THD and the power factor. The simulation also shows that power transfer of active and reactive power from the inverter to grid is possible. The reactive power required for the load is completely provided from the inverter.The hardware implementation of the interactive inverter has been conducted using real time workshop in the MATLAB Simulink environment. The half wave rectifier is used as load in the hardware implementation. The results show that the controller is capable for reactive power compensation, and maintaining constant voltage at the grid satisfying standard for grid interconnection. That is the THD is lessthan5% 3.74 and the power factor is .9977 which is near to unity. Energy conservation by load management is possible and a reasonable relief to the customer and voltage profile is maintained at the grid. This work can be extended to cascaded inverter configuration and reliability analysis has to be made as a better option for future studies.

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