The Journal of CPRI,
Vol. 10, No. 4, December 2014 pp. 775-784

Novel control strategy of three phase grid tied inverters for power quality improvement

Chandrasekhar B*, Sanjay Lakshminarayanan**, Sudhakara Reddy S***

Renewable energy sources (RES) are being increasingly connected in distribution systems utilizing power electronic converters. This paper presents an advanced control strategy for achieving maximum power quality benefits from the grid interfacing inverters when installed in 3-phase distribution systems. The grid tie inverter can be utilized as i) Power converter to inject power generated from RES to the grid and ii) shunt active power filters to compensate current imbalance, load current harmonics, reactive power demand and load neutral current. All of these functions may be accomplished either individually or simultaneously. This control concept is clearly explained with MATLAB/SIMULINK simulation results and THD is less than 5%.

Keywords: *Renewable energy sources, grid tied inverter, active power filter, power quality*

1.0 INTRODUCTION

Electric utilities and end users of electric power are becoming increasingly concerned about meeting the growing energy demand.75% of total global energy demand is supplied by the burning of fossil fuels.But increasing air pollution, global warming concerns, depletion of fossil fuels is a great cause of concern and is inevitable to look forward for renewable energy sources. Since the past decade, many countries have adopted renewable energy as an alternate source for electricity generation. The policy of liberalization, privatization and globalization has resulted in drastic changes in thepower market. In addition, the initiative from the government to encourage green power through incentives, subsidies are also key factors for the growth of renewable energy sector. The integration of these renewables with the existing grid and the interactions are a major challenge these days, specifically country like India.

Renewable energy sources (RES) [2] integrated at the distribution level is termed as distribution generation (DG) [1]. The utility is concerned due to the high perception level of integration RES in distribution systems. As it may problem with existing network like stability, voltage regulation and power quality [PQ] [2] issues. Therefore the DG systems are required to comply with strict technical and regulatory frameworks to ensure safe, reliable and efficient operation of the total network. With the advancement in power electronics and digital control technology, the DG systems is now actively enhancing the system operation with improved PQ [3] at the point of common coupling (PCC). However the extensive use of power electronic based equipment and nonlinear loads at PCC generate harmonics, which may affect the quality of the power.

Commonly current controlled voltage source inverters are used to interface the integration

*Senior Research Fellow, Energy Efficiency&Renewable Energy Division, Central Power research Institute, Bangalore - 560 080.
E-mail: bchandrasekhar777@gmail.com, Mobile:+91-9663300655
**Associate Professor, Electrical & Electronics Engineering, MS Ramaiah Institute of Technology, Bangalore - 560054.
E-mail: sanjay.laks@gmail.com, Mobile: +91-9986870937
***Joint Director, Energy Efficiency & Renewable Energy Division, Central Power Research Institute, Bangalore - 560080.
E-mail: ssreddy@cpri.in, Mobile: +91-9449056941

of RES in distributed systems. Recently a few control strategies for grid connected inverters incorporating PQ solution have been presented. In 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 damage the control performance.

A similar approach in which a shunt active filter acts as active conductance to damp out the harmonics in the network. A control strategy for renewable energy interfacing inverter based on theory is developed. In this strategy ,both load and inverter current sensing is required to compensate the load current harmonics.

The nonlinear load current harmonics may result in voltage harmonics and can create a serious PQ problem in the power system network. Active power filters (APF) [4] are extensively used to compensate the load current harmonics and load unbalance at distribution level. This results in an additional hardware cost. However, in this paper authors have incorporated the features of APF 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 the intermittent nature of RES. It is shown in this paper that the grid interfacing can effectively beutilized to perform following important functions: i) transfer of active power harvested from the renewable resources (wind, solar, etc.) ii) load reactive power demand support, iii) current harmonics compensation and d) current unbalance and neutral current compensation in case of 3-phase system. Moreover, with adequate control of grid-interfacing inverter, allthe four objectives can be accomplished either individually or simultaneously.

2.0 DISTRIBUTED ENERGY SYSTEMS (DES)

Today, new advances in technology and new directions in electricity regulation encourage a significant increase of distributed generation resources around the world. As shown in Figure the currently competitive small generation units and the incentive laws to use renewable energies force electric utility companies to construct an increasing number of distributed generation units on its distribution network, instead of large central power plants. Moreover, DES can offer improved service reliability, better economics and a reduced dependence on the local utility. Distributed Generation Systems have mainly been used as a standby power source for critical businesses. For example, most hospitals and office buildings had a standby diesel generation as an emergency power source for use only during outages. However, the diesel generators were not inherently cost-effective, and produce noise and exhaust that would be objectionable on anythingexcept for an emergency basis.

Meanwhile, recently, the use of Distributed Energy Systems under the 500 kW level is rapidly increasing due to recent technology improvements in small generators, power electronics, and energy storage devices. Efficient,clean fossil fuel technologies such as micro-turbines and fuel cells, and environmentally friendly renewable energy technologies such as solar/photovoltaic, small wind and hydro are increasingly used for new distributed generation systems.

These DES are applied to a standalone, a standby, [5-7] a grid-interconnected, a cogeneration, peak shavings, etc. and have a lot of benefits such as environmental-friendly and modular electric generation, increased reliability, high power quality, uninterruptible service, cost savings, on-site generation, expandability, etc.

2.1 Problem statements

DES technologies have very different issues compared with traditional centralized power sources. For example, they are applied to the mains or the loads with a voltage of 480 volts or less; and require power converters and different strategies of control and dispatch. All of these energy technologies provide a DC output which requires power electronic interfaces with the distribution power networks and its loads. In most cases the conversion is performed by using a voltage source inverter (VSI) with a possibility of pulse width modulation (PWM) that provides fast regulation for voltage magnitude. Power electronic interfaces introduce new control issues, but at the same time, new possibilities.

However, without any medium voltage network adaptation, this vast expansion can affect the quality of supply as well as the public and equipment safety because distribution networks have not been designed to connect a significant amount of generation. Therefore, a new voltage control system to facilitate the connection of distributed generation resources to distribution networks should be developed.In many cases there are also major technical barriers to operating independently in a standalone AC system, or two connecting small generation systems to the electrical distribution network

2.2 Problem description

These new distributed generations interconnected to the lower grid voltage or low load voltage cause new problems which require innovative approaches to managing and operating the distributed resources. In the fields of Power Electronics, the recent papers have focused on applications of a standby generation, a standalone AC system, [1] a combined heat and power (cogeneration) system, and interconnection with the grid of distribution generations on the distribution network, and have suggested technical solutions which would permit to connect more generators on the network in good conditions and to perform a good voltage regulation. Depending on the load, generation level, and local connection conditions, each generator can cause the problems described in the previous chapter. The main goals which should be achieved will thus be: to increase the network connection capacity by allowing more consumers and producer customers connection without creating new reinforcement costs, to enhance the reliability of the systems by the protections, to improve the overall quality of supply with a best voltage control.

2.3 Configurations for DES

Case I: A Power Converter connected in a Standalone AC System or in Parallel with the Utility Mains

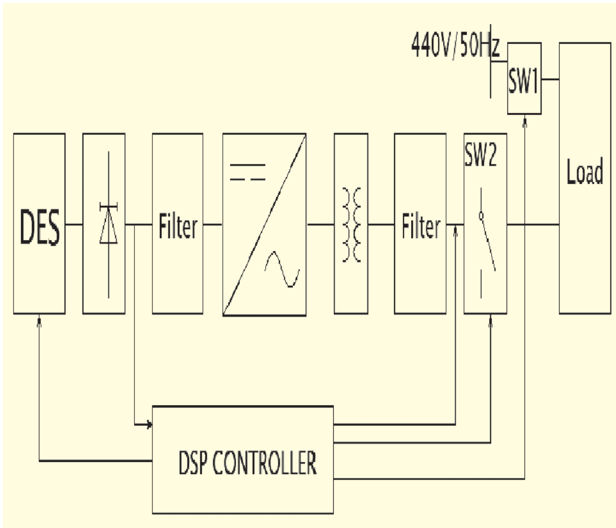

FIG. 1 BLOCK DIAGRAMSTANDBYMODE

Figure 1 shows a stand by mode power system which is connected to directly load or in parallel with utility mains, according to its mode. This system consists of a generator, an input filter, an AC/AC power converter, an output filter, an isolation transformer, output sensor (V, I, P), and a DSP controller. In the Figures 1-3, a distributed generator may operate as one of three modes: a standby, a peak shaving, and a standalone power source. In a standby mode shown in Figure 1 generator set serves as a UPS system operating during mains failures. It is used to increase the reliability of the energy supply and to enhance the overall performance of the system.

The static switch SW 1 is closed during normal operation and SW 2 is open, while in case of mains failures or excessive voltage drop detection SW 1 is open and SW 2 is simultaneously closed. In this case, control techniques of DES are very similar to those of UPS. If a transient load increases, the output voltage has relatively large drops due to the internal impedance of the inverter and filterstage, which frequently result in malfunction of sensitive load.

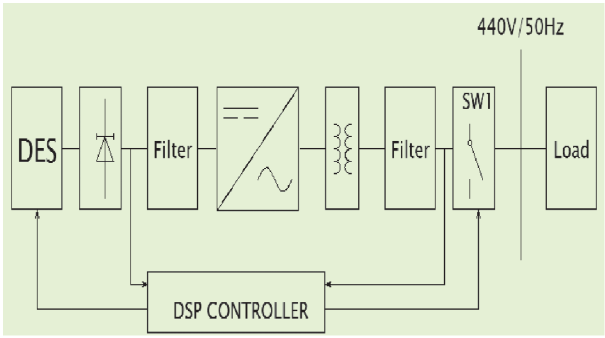

FIG. 2 BLOCK DIAGRAM OF PEAK SHAVING MODE

Figure 2 can serve as a peak shaving or interconnection with the grid to feed power back to the mains.

In both modes, the generator is connected in parallel with the main grids. In a peak shaving mode, this generator is running as few as several hundred hours annually because the SW 1 is only closed during the limited periods. Meanwhile, in an interconnection with the grid, SW 1 is always closed and this system provides the grid with continuous electric power. In addition, the converter connected in parallel to the mains can serve also as a source of reactive power and higher harmonic current components.

In a standalone AC system shown in Figure 3 the generator is directly connected to the load lines without being connected to the mains and it will operate independently. In this case, the operations of this system are similar to a standby mode, and it serves continuously unlike a standby mode and a peak shaving mode.

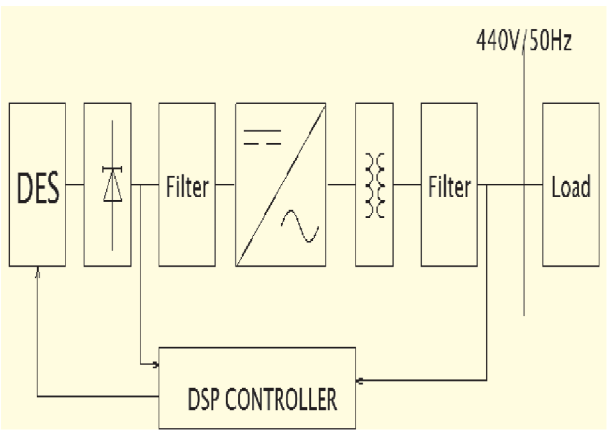

FIG. 3 STANDALONE MODE

As shown in Figure 3 the output voltage of the generator is fed to a DC/AC converter that converts a DC output of the generator to be fixed voltage and frequency for utility mains or loads. The DSP controller monitors multiple system variables on a real time basis and executes control routines to optimize the operation of the individual subsystems in response to measured variables. It also provides all necessary functions to sense output voltages, current, and power, to operate protections, and to give reference signals to regulators. The output power of the converter is controlled according to the reference signal of the control unit. As described above, in order to compensate for reactive power and higher harmonic components or to improve power factor, the active power (P) and reactive power (Q) should be controlled independently. Moreover, the above system needs over-dimensioning some parts of the power converter in orderto produce reactive power by the converter at rated active power. Because a power converter dimensioned for rated current can supply reactive power only if the active component is less than rated. Therefore, a control strategy easy to implement is required to ensure closed loop control of the power factor and to provide a good power quality.

Case II: Power Converters supplying power in a standalone mode or feeding it back to the utility mains Figure 4 shows a block diagram of multiple power converters for a standalone AC system or feeding generated power back to the utility mains.

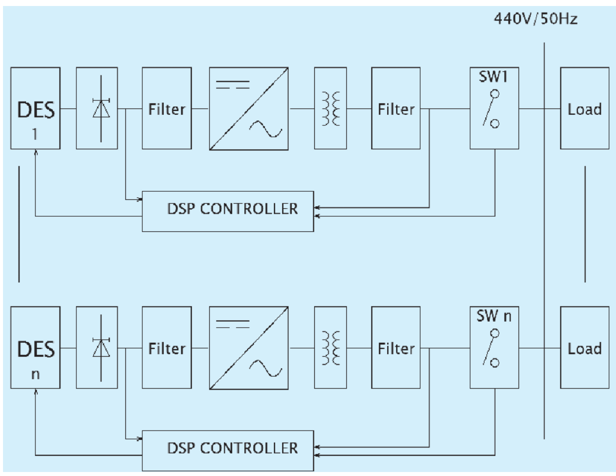

FIG. 4 BLOCK DIAGRAM POWER CONVERTERS CONNECTED IN PARALLEL

If all generators are directly connected to the loads, the systems operate as a standalone AC system. Meanwhile, if these are connected in parallel to the mains, these provide the utility grids with an electric power. Each system consists of a generator, an input filter, an AC/AC power converter, an output filter, an isolation transformer, a control unit (DSP), a static switch (SW 1) and output sensors (V, I, P). The function of the static switch (SW 1) is to disrupt the energy flow between the generator and mains or loads in the case of disturbances in the mains voltage. As shown in Figure 4, this configuration is very similar to parallel operation of multiple UPS systems except that the input sources of inverters are independent generation systems such as micro turbines, fuel cells, and photovoltaic, etc. instead of utility mains.

In case of parallel operation of UPS systems, a recent critical research issue is to share linear and non-linear load properly by each unit. In general, the load sharing is mainly influenced by non-uniformity of the units, component tolerance, and line impedance mismatches. Another issue is a proper control scheme without any control interconnection wires among inverters because these wires restrict the location of the inverter units as well as these can act as a source of the noise and failure. Moreover, in three-phase systems they could also cause unbalance and draw excessive neutral currents.

Even if conventional passive L-C filters were used to reduce harmonics and capacitors were employed to improve the power factor of the ac loads, passive filters have the demerits of fixed compensation, large size, and resonance. Therefore, the injected harmonic, reactive power burden, unbalance, and excessive neutral currents definitely cause lower system efficiency and poor power factor. In particular, a power factor can be improved as AC/AC power converters function a complete active filter for better power quality and the above problems should be overcome by a good control technique to assure the DES to expand increasingly around the world.

3.0 MODELLING OF CASE STUDY & SYSTEM DESCRIPTION

The below system consists of RES connected to the dc-link of a grid-interfacing inverter as shown in Figure 5. The voltage source inverter [8-10] is a key element of a DG system as it interfaces the renewable energy source to the grid and delivers the generated power. The RES may be a DC source or an AC source with rectifier coupled to dc-link. Usually, the fuel cell and photovoltaic energy sources generate power at variable low dc voltages, while the variable speed wind turbines generate power at variable ac voltage.

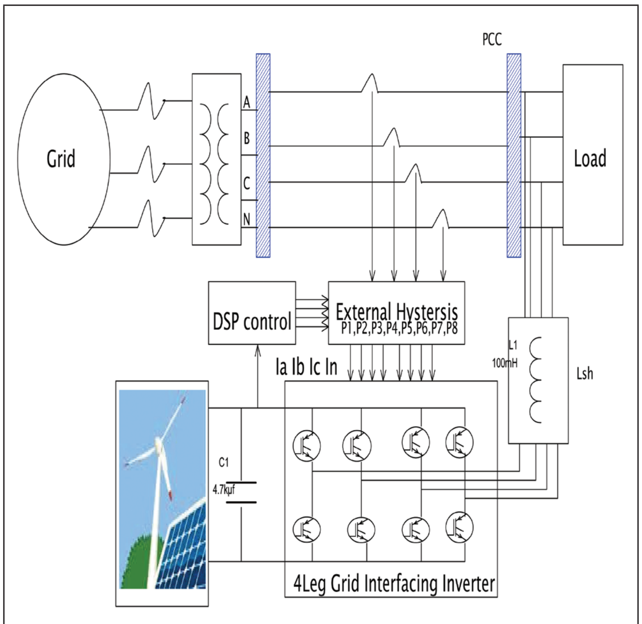

FIG. 5 SCHEMATIC OF RENEWABLE BASED DISTRIBUTED GENERATION SYSTEM

Thus, the power generated from these renewable sources needs power conditioning (i.e., dc/dc or ac/dc) before connecting to dc link.The dc-capacitor decouples the RES from the grid and also allows independent control of converters on either side of dc-link.

3.1 DC link voltage and power control operation

Due to the intermittent nature of RES, the generated power is of varying nature. The dc-link plays an important role in transferring this variable power from renewable energy source to the grid.

RES are represented as current sources connected to the dc-link of a grid-interfacing inverter. Figure 6 shows the systematic representation of power transfer from the renewable energy resources to the grid via the dc-link.

The current injected by renewable into dc-link at voltage level V_{dc} can be given as

$$I_{dc1} = P_{RES} / V_{dc} \quad \text{....(1)}$$

Where P_{RES} is the power generated from RES.

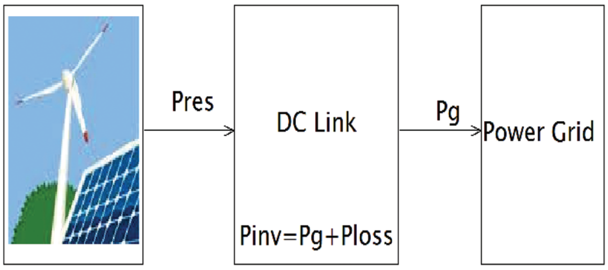

FIG. 6 DC LINK EQUIVALENT DIAGRAM

The current flow on the other side of the dc link can be represented as,

$$I_{dc2} = P_{inv}/V_{dc} = (P_G+P_{Loss}) / V_{dc} \quad \text{....(2)}$$

Where P_{inv}, P_G and P loss are total power available at grid-interfacing inverter side, active power supplied to the grid and inverter losses, respectively. If inverter losses are negligible, then $P_{RES}=P_G$.

3.2 Control strategy for grid interfacing inverter

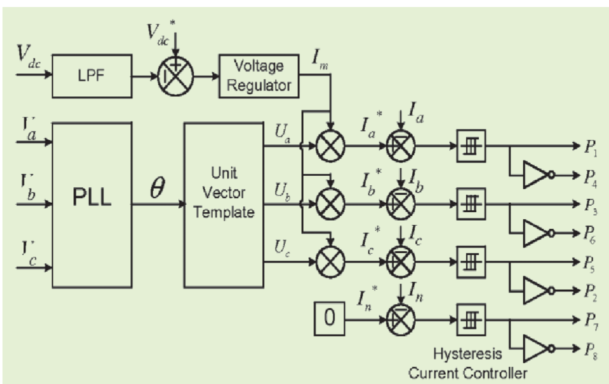

FIG. 7 BLOCK DIAGRAM REPRESENTATION OF GRID-INTERFACING INVERTER CONTROL

The control diagram [9] of grid- interfacing inverter for a 3-phase 4-wire system is shown in Figure 7. The fourth leg of inverter is used to compensate the neutral current of the load. The main aim of proposed approach is to regulate the power at PCC during: 1) $P_{RES}=0$; 2) $P_{RES}<$ total load power (P_L); and 3) $P_{RES}>P_L$. 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 is 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 I_m. The multiplication of active current component (I_m) with unity grid voltage vector templates (U_a, U_b and U_c) generates the reference grid currents (I_a*, I_b* and I_c*). The reference grid neutral current (In*) is set to zero, being the instantaneous sum of balanced grid currents. The grid synchronizing angle (θ) obtained from phase locked loop (PLL) is used to generate a unity vector template.

$$Ua = \sin(\theta) \quad \text{....(3)}$$

$$Ub = \sin(\theta - 2\pi/3) \quad \text{....(4)}$$

$$Uc = \sin(\theta + 2\pi/3) \quad \text{....(5)}$$

The actual dc-link voltage (V_{dc}) is sensed and passed through a first-order low pass filter (LPF) to eliminate the presence of switching ripples of the dc-link voltage and in the generated reference current signals. The difference of this filtered dc-link voltage and reference dc-link voltage (V_{dc}*) 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 ($V_{dcerr(n)}$) at nth sampling instant is given as:

$V_{dc\ err\ (n)} = V^*_{dc\ (n)} - Vdc_{\ (n)}$ …(6)

The output of the discrete-PI regulator at n^{th} sampling instant is expressed as

$I_{m(n)}=I_{m(n-1)}+K_{PVdc}(V_{dcerr(n)}-V_{dcerr(n-1)})+K_{IVdcVdcerr(n)})$ ….(7)

Where K_{PVDC}=10 and K_{IVDC}=0.05 are proportional and integral gains of the dc-voltage regulator. The instantaneous values of reference three phase grid currents are computed as

$I^*_a = I_m.U_a$ ….(8)

$I^*_b = I_m.U_b$ ….(9)

$I^*_c = I_m.U_c$ ….(10)

The neutral current, present if any, due to the loads connected to the neutral conductor should be compensated by the fourth 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

$I^*_n=0$ ….(11)

The reference grid currents (I_a*, I_b* ,I_c* and I_n*) are compared with actual grid currents

(I_a, I_b,I_c and I_n) to compute the current errors as

$I_{\ a\ err} = I^*_a-I_{\ a}$ ….(12)

$I_{\ b\ err} = I^*_b-I_{\ b}$ ….(13)

$I_{\ c\ err} = I^*_c-I_{\ c}$ ….(14)

$I_{\ n\ err} = I^*_n-I_{\ n}$ ….(15)

These current errors are given to the hysteresis current controller. The hysteresis controller then generates the switching pulses (P_1 *to* P_g) for the gate drives of the grid-interfacing inverter. The average model of 4-leg inverter can be obtained by the following state space equations

$dI_{Inva}/dt = (V_{Inva}-V_a) / Lsh$ ....(16)

$dI_{Invb}/dt = (V_{Inv}b-V_b) / Lsh$ ….(17)

$dI_{Invc}/dt = (V_{Invc}-V_c) / Lsh$ ....(18)

$dI_{Invn}/dt = (V_{Invn}-V_n) / Lsh$ ….(19)

$dV_{dc}/dt = (I_{Invad}+I_{Invbd}+I_{Invcd}+I_{Invnd}) / C_{dc}$ ….(20)

WhereV_{Inva},V_{Invb},V_{Invc}, and V_{Invn} are the three-phase ac switching voltages generated on the output terminal of the inverter. These inverter output voltages can be modeled in terms of instantaneous dc bus voltage and switching pulses of the inverter as

$$V_{Inva}=\frac{(P1-P4)}{2}V_{dc} \quad ....(21)$$

$$V_{Invb}=\frac{(P3-P6)}{2}V_{dc} \quad ....(22)$$

$$V_{Invc}=\frac{(P5-P2)}{2}V_{dc} \quad ….(23)$$

$$V_{Invn}=\frac{(P7-P8)}{2}V_{dc} \quad ....(24)$$

Similarly the charging currents I I_{nvad}, I $I_{nv\ bd}$, I $_{Inv\ cd}$ and I $_{Inv\ nd}$ on dc bus due to the each leg of inverter can be expressed as

$I_{\ Inv\ ad} = I_{\ Inv\ a}\ (P_1-P_4)$ ….(25)

$I_{\ Inv\ bd} = I_{\ Inv\ b}\ (P_3-P_6)$ ….(26)

$I_{\ Inv\ cd} = I_{\ Inv\ c}\ (P_5-P_2)$ ….(27)

$I_{\ Inv\ nd} = I_{\ Inv\ n}\ (P_7-P_8)$ ….(28)

The switching pattern of each IGBT inside inverter can be formulated On the basis of error between actual and reference current of the inverter, which can be explained as:

If $I_{Inva}<(I^*_{Inva}-h_b)$, then upper switch S_1 will be OFF (P_1=0) and lower switch will be ON(P_4=1) in the phase "a" leg of the inverter. If $I_{Inva}>(I^*_{Inva}-h_b)$ then upper switch will be ON (P_1=1) and lower switch S_4 will be OFF (P_4=0) in the phase "a" leg of the inverter.

Where h_b is the width of hysteresis band.

On the same principle, the switching pulses for the other remaining three legs can be derived.

4.0 MATLAB™ DESIGN OF CASE STUDY

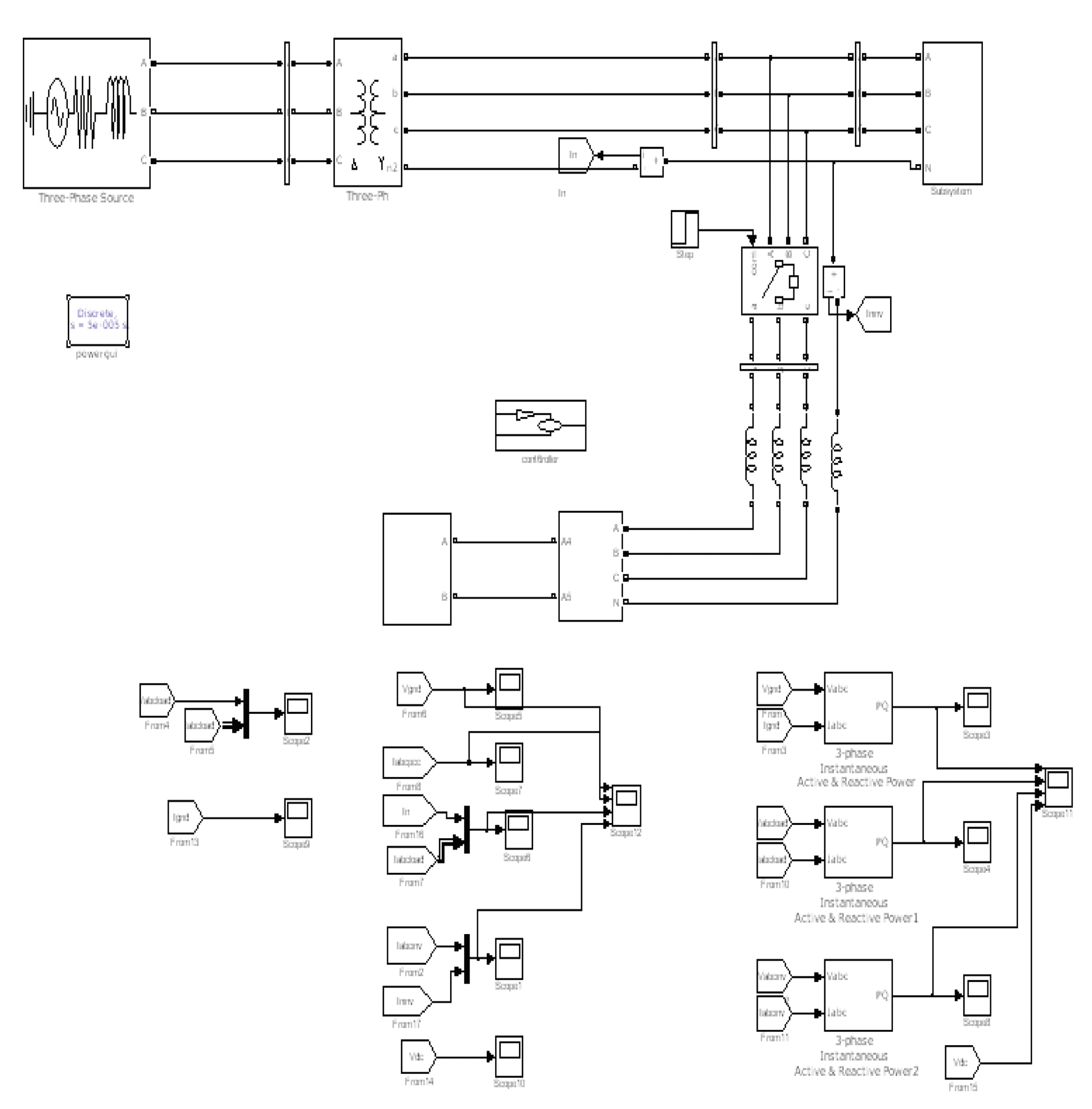

FIG. 8 MATLAB/SIMULINK MODEL FOR THREE PHASE GRID INTERFACING INVERTER

5.0 SIMULATION RESULTS

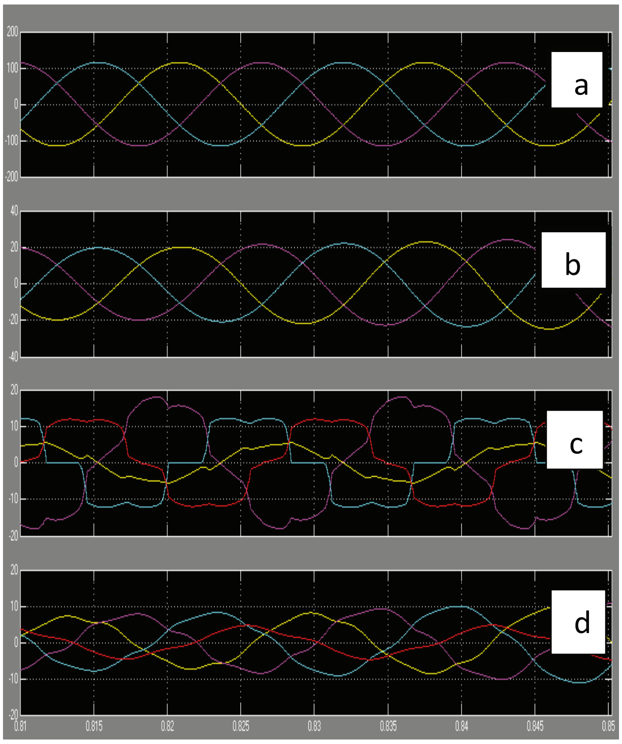

FIG. 9 SIMULATION RESULTS: (A) GRID VOLTAGES, (B)GRID CURRENTS (C) UNBALANCEDLOAD CURRENTS, (D) INVERTER CURRENTS

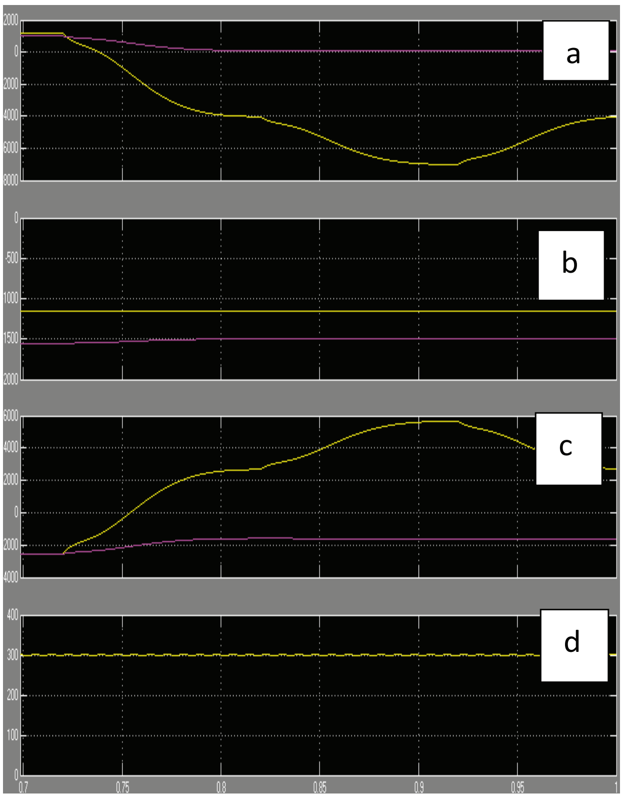

FIG.10 SIMULATION RESULTS: (A) PQ-GRID, (B) PQ-LOAD, (C) PQ-INVERTER,(D) DC-LINK VOLTAGE.

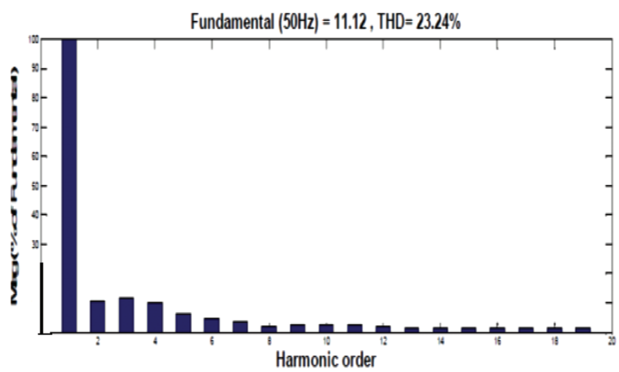

FIG. 11 THD % OF THE INJECTED CURRENT WITHOUT FILTER

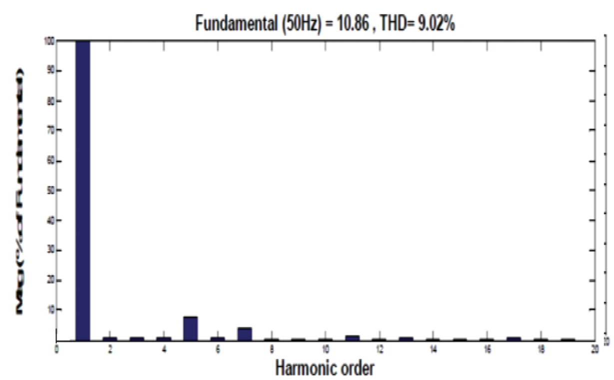

FIG. 12 THD % OF THE INJECTED CURRENT WITH ORDINARY FILTER

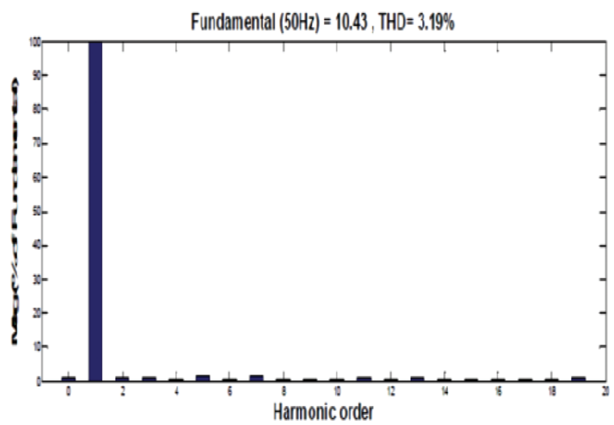

FIG. 13 THD % OF THE INJECTED CURRENT WITH SHUNT ACTIVE FILTER

From THD spectrum Figures 11-13 we can observe % of THD [Table 1].

TABLE 1

THD % COMPARISON

Without filter	With Ordinary filter	With Shunt active filter
23.24	9.02	3.19

The MATLAB™/Simulink parameters [Table 2] for simulation and simulated results are shown in Figures 9-10.

TABLE 2	
SPECIFICATION PARAMETERS	
Phase voltage and frequency	V_s = 230 V (rms), f_s = 50Hz
Supply/ line inductance	$L_{sa} = L_{sb} = L_{sc}$ = 2mH
Rectifier front-end inductance	$L_{la} = L_{lb} = L_{lc}$ = 30mH
For V-S Type Load resistance, load capacitance	$R_L = 20\Omega$, $C_L = 500\mu F$
For C-S Type Load resistance, load inductance	$R_L = 30\Omega$, L_L = 10mH
Passive filter parameters	L_{pf} = 14mH, $C_{pf} = 24\mu F$
Inverter DC-bus voltage and capacitance	V_{dc} = 50v, $C_{dc} = 3000\mu F$
Controller Parameter	K_p = 335. 35, K_i = 0. 004

6.0 CONCLUSION

The grid-interfacing inverter with the proposed approach can beutilized to: i) Inject real power generated from RES to the grid and, ii) Operate as a shunt Active Power Filter (APF). This approach thus eliminates the need for additional powerconditioning equipment to improve the quality of power. MATLAB/Simulink simulation results have validated the proposed approach. Hence,from the THD comparison the injected current is reduced to less than 5%, which is within the permissible limits specified in the IEEE-519-1998 standard.

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