General Control Strategies of Grid-Connectred Converters using 3-Level SVPWM

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***Abstract*— The penetration of DG in distribution network creating concerns about power system stability. This leads to continuous evolution of grid interconnection requirements towards a better controllability of generated power and enhanced contribution of distributed power generation systems to power system stability. This work concerned with the assessment and ability to control the active and reactive power flowing from the converter to the point of common connection to the grid and a local inductive load. The simulation results were confined to the evaluation of active and reactive power flow obtained by using the developed algorithm, with DSP based implementation. The control strategy utilizes grid voltage tracking with a proportional integral (PI) current controller. In order to check the validity of these results by 3-level SVPWM, they were compared with those obtained from an equivalent 2-level converter. The result obtained by simulation are fairly acceptable and confirm the effectiveness and reliability of the proposed Distributed Generation system.**

Keywords*— *Three-level grid connected inverter; space vector pulse width modulation; current control; dispersed generation

I. INTRODUCTION

One important part of a distributed system is control. The control tasks can be divided into two major parts.

First, input-side controller with the main property to extract the maximum power from the input source. Naturally protection of the input-side converter is also considered in this controller.

Second, grid-side power processor which perform the following tasks providing the required feedback variables to feed the overall control system unit for the control of the generated active power reactive power control transferred between the DG and the grid dc-link voltage, power quality control and grid synchronization.

The control strategy applied to the grid-side converter consists mainly of two cascaded loops. Usually there is a fast internal current loop which regulates the grid current and an external voltage loop which controls the dc-link voltage. The current loop is responsible for power quality issues and current protection, thus harmonic compensation and dynamics are the important properties of the current controller. The dc-link voltage controller is designed for balancing the power flow in the system. Usually the design of this controller aims for system stability having slow dynamics. In some works the control of grid-side controller is based on a dc-link voltage loop cascaded with an inner power loop instead of a current loop. In this way the current injected into the utility network is indirectly controlled.

The control strategies may be divide into three categorize, Synchronous Reference Frame Control, Stationary Reference Frame Control, and Natural Frame Control

II. CONTROL OF GRID CONNECTED VSC

A. Synchronous Reference Frame Control

Synchronous reference frame control also called *dq* control uses a reference frame transformation module, e.g., $abc \rightarrow dq$ to transform the grid current and voltage waveforms into a reference frame that rotates synchronously with the grid voltage. By means of this the control variables become dc values thus filtering and controlling can be easier achieved. A schematic of the *dq* control is represented in Fig. 1

In this structure the dc-link voltage is controlled in accordance to the necessary output power. Its output is the reference for the active current controller whereas the reference for the reactive current is usually set to zero if the reactive power control is not allowed. In the case that the reactive power has to be controlled a reactive power reference must be imposed to the system. The *dq* control structure is normally associated with proportional–integral (PI) controllers since they have a satisfactory behavior when regulating dc variables. The matrix transfer function of the controller in *dq* coordinates can be written as:

$$G_{PI}^{dq} = \begin{bmatrix} K_p + \frac{k_i}{s} & 0 \\ 0 & K_p + \frac{k_i}{s} \end{bmatrix} \quad (1)$$

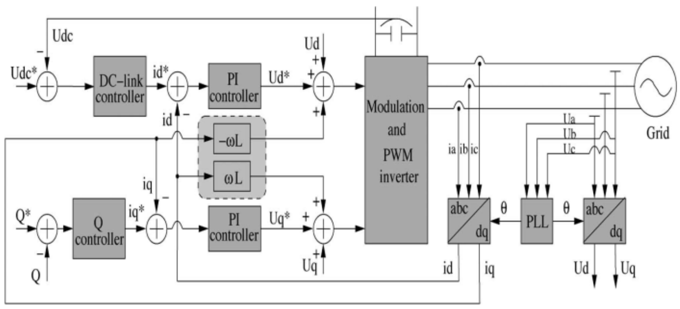

Fig.1 General structure for synchronous rotating frame control structure

Where *Kp* is the proportional gain and *Ki* is the integral gain of the controller. Since the controlled current has to be in phase with the grid voltage, the phase angle used by the *abc* → *dq* transformation module has to be extracted from the grid voltages. As a solution filtering of the grid voltages and using arctangent function to extract the phase angle can be a possibility. In addition the phase-locked loop (PLL) technique became a state of the art in extracting the phase angle of the grid voltages in the case of distributed generation systems.

B. Stationary Reference Frame Control

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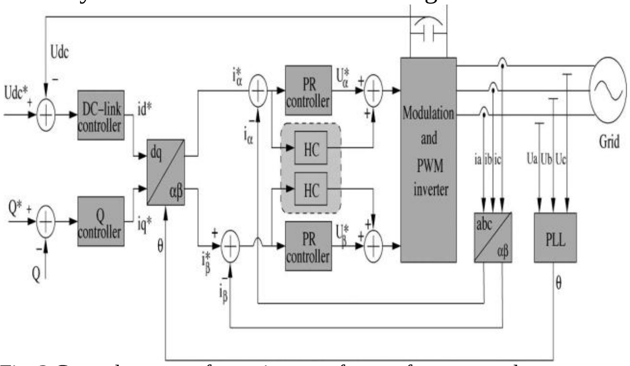

Fig. 2 General structure for stationary reference frame control strategy

In this case the grid currents are transformed into stationary reference frame using the *abc* → *αβ* module. Since the control variables are sinusoidal in this situation and due to the known drawback of PI controller in failing to remove the steady-state error when controlling sinusoidal waveforms employment of other controller types is necessary. Proportional resonant (PR) controller gained a large popularity in the last decade in current regulation of grid-tied systems. In the PR case the controller matrix in the stationary reference frame is given by

$$G_{PR}^{\alpha\beta}(s) = \begin{bmatrix} K_p + \frac{k_i s}{s^2+\omega^2} & 0 \\ 0 & K_p + \frac{k_i}{s^2+\omega^2} \end{bmatrix} \qquad (2)$$

where *ω* is the resonance frequency of the controller, *Kp* is the proportional gain and *Ki* is the integral gain of the controller.

Characteristic to this controller is the fact that it achieves a very high gain around the resonance frequency thus beingcapable to eliminate the steady-state error between the controlled signal and its reference. The width of the frequency band around the resonance point depends on the integral time constant *Ki*. A low *Ki* leads to a very narrow band whereas a high *Ki* leads to a wider band.

C. Natural Frame Control

The idea of *abc* control is to have an individual controller for each grid current. However the different ways to connect the three-phase systems, i.e., delta, star with or without isolated neutral, etc., is an issue to be considered when designing the controller. In the situation of isolated neutral systems the phases interact to one another hence only two controllers are necessary since the third current is given by the Kirchhoffcurrent law. In any case the possibility of having three independent controller is possible by having extra considerations in the controller design as usually is the case for hysteresis and dead-beat control. Normally, *abc* control is a structure where nonlinear controllers like hysteresis or dead beat are preferred due to their high dynamics. It is well known that the performance of these controllers is proportional to the sampling frequency hence the rapid development of digital systems such as digital signal processors or field-programmable gate array is an advantage for such an implementation. A possible implementation of *abc* control is depicted in Fig. 3 where the output of dc-link voltage controller sets the active current reference. Using the phase angle of the grid voltages provided by a PLL system, the three current references are created. Each of them is compared with the corresponding measured current, and the error goes into the controller. If hysteresis or dead-beat controllers are employed in the current loop, the modulator is not anymore necessary. The output of these controllers is the switching states for the switches in the power converter. In the case that three PI or PR controllers are used, the modulator is necessary to create the duty cycles for the PWM pattern.

PI controller is widely used in conjunction with *dq* control but its implementation in *abc* frame is also possible.

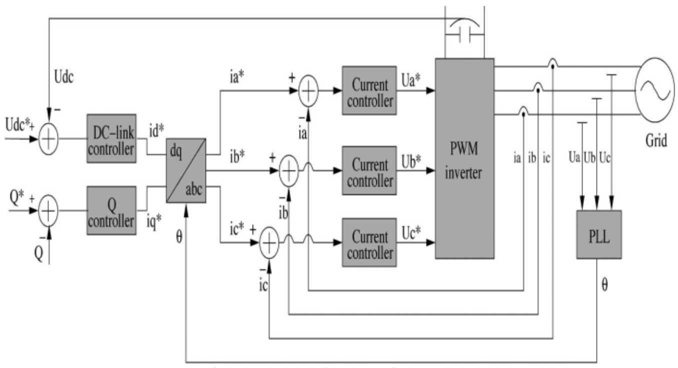

Fig. 3 General structure for natural reference frame control strategy.

PI controller is widely used in conjunction with *dq* control but its implementation in *abc* frame is also possible.

The transfer function of the controller in this case becomes:

$$G_{PI}^{abc}(s)=\frac{2}{3}\begin{bmatrix} K_p+\frac{k_i S}{s^2+\omega^2} & -\frac{k_p}{2}-\frac{k_i s+\sqrt{3}k_i\omega_0}{2(s^2+\omega_0^2)} & \frac{k_p}{2}-\frac{k_i s-k_i\omega_0}{2(s^2+\omega_0^2)} \\ -\frac{k_p}{2}-\frac{k_i-\sqrt{3}k_i\omega_0}{2(s^2+\omega_0^2)} & K_p+\frac{k_i s}{s^2+\omega_0^2} & -\frac{K_p}{2}-\frac{k_i s+k_i\omega_0}{2(s^2+\omega_0^2)} \\ -\frac{K_p}{2}-\frac{k_i s+\sqrt{3}k_i\omega_0}{2(s^2+\omega_0^2)} & -\frac{K_p}{2}-\frac{k_i s-\sqrt{3}k_i\omega_0}{2(s^2+\omega_0^2)} & K_p+\frac{k_i}{s^2+\omega_0^2} \end{bmatrix} \tag{3}$$

And the complexity of the controller matrix in this case due to the significant off-diagonal terms representing the cross coupling between the phases is noticeable.The implementation of PR controller in *abc* is straightforward since the controller is already in stationary frame and implementation of three controllers is possible as illustrated in equation (4).

$$G_{PR}^{abc}(s) = \begin{bmatrix} K_p+\frac{k_i s}{s^2+\omega_0^2} & 0 & 0 \\ 0 & K_p+\frac{k_i s}{s^2+\omega_0^2} & 0 \\ 0 & 0 & K_p+\frac{k_i s}{s^2+\omega_0^2} \end{bmatrix} \tag{4}$$

Again in this case the influence of the isolated neutral in the control has to be accounted hencethe third controller is not necessary in eq.(4). However it is worth noticing that the complexity of the controller in this case is considerably reduced compared to eq.(3) Again in this case the influence of the isolated neutral in the control has to be accounted hence the third controller is not necessary in eq.(4). However it is worth noticing that the complexity of the controller in this case is considerably reduced compared to eq.(3) It is worth noticing that in the case of hysteresis control implementation, an adaptive band of the controller has to be designed to obtain fixed switching frequency. Since the output of the hysteresis controller is the state of the switches, considerations about the isolated neutral are again necessary. The dead-beat controller attempts to null the error with one sample delay. Since dead-beat controller regulates the current such that it reaches its attempts to null the error with one sample delay. Since dead-beat controller regulates the current such that it reaches its reference at the end of the next switching period the controller introduces one sample time delay. To compensate for this delay, an observercan be introduced in the structure of the controller, with theaim to modify the current reference to compensate for the delay Fig.4

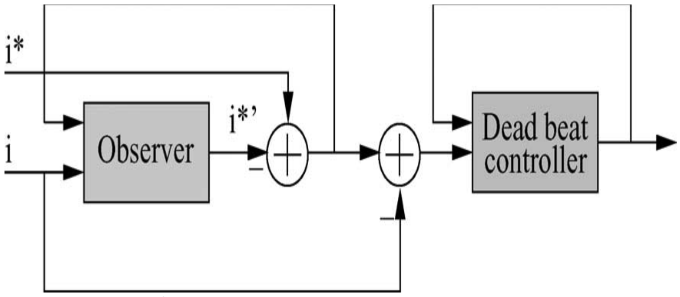

Fig.4. Structure of the dead-beat controller using an observer to compensate for the delay introduced by the controller

As a consequence, a very fast controller containing no delay is finally obtained. Moreover the algorithms of the dead-beat controller and observer are not complicated, which is suitable for microprocessor-based implementation. In addition in the case of *abc* control two modalities of implementing the PLL are possible. The first possibility is to use three single-phase PLL systems. Thus the three phase angles are independentlyextracted from the grid voltages. In this case the transformation module *dq* → *abc* is not anymore necessary with the active current reference being multiplied with the sine of the phase angles. The second possibility is to use one three-phase PLL. In this case the current references are created, as shown in Fig.3 There are two control principles, voltage angle control [1], [4], [5] and the vector current control [6], [7], [8], [2], [3], [10], [11]. Both controllers use the rotating dq-coordinate system. [6] Proposed a control loop with a Fuzzy Logic Controller for voltage regulation. In this work Fuzzy Logic Control (FLC) is implemented to replace the conventional PI controller for the sake of voltage regulation.

The superiority of FLC is the result of its ability to manage the nonlinear behavior of many practical systems of complex control structures by taking advantage of heuristics and expert knowledge of the process being controlled. The active power control is achieved through the d -component of the DG current. The reactive power control can be employed to either achieve a unity PF operation by compensating for the reactive power demand of the connected load or to regulate the voltage by compensating for the losses of the distribution lines. The value of the current is chosen according to the desired operation. For the unity PF operation zero is assigned to and the processing unit is allowed to produce the required control signal that is responsible for the total compensation of the load reactive power. [12] Presents active power and voltage control scheme for inverters and a droop control method for the power sharing among the parallel inverter-interfaced distributed energy resources. The proposed control method is tested in two scenarios, a single inverter operated in the islanding mode and two parallel inverters operated in the islanding mode. [13] give a current controller for three-phase grid-connected VSIs. A grid harmonic feed-forward compensation method is employed to depress the grid disturbance. Based on a dual-timer sampling scheme a software predictor and filter is proposed for both the current feedback loop and grid voltage feed-forward loop to eliminate the system nonlinearity due to the control delay. In [7] authors give a control method of PV grid connected system. The control strategy based on SVPWM -based PI current control. They write the equations of voltage, active and reactive power in dq reference frame. In order to compensate for the grid harmonics the voltage across the conductor between the inverter and the grid should be directly controlled in real time instead of voltage in the grid which can be controlled indirectly by superimposing inductor voltage to grid voltage [16] Give the same methodology but instead of PI controller they used Fuzzy Logic Controller. [17], [11] and [10] also has same method of current control principle. [17] employ a DC/DC boost converter to get the Maximum Power Point Tracking (MPPT) function and make the DC capacitor keep balance

III. CONTROL OF ACTIVE & REACTIVE POWER

Most manufacturers use two-level pulse width modulation (PWM) voltage-source inverters (VSI) because this is the state-of-the-art technology used for wind systems. The possibility of high switching frequencies combined with proper control circuits makes these converters suitable for grid interface in the case of distributed generation, which may also have a large contribution to the improvement of generated power quality. Three-level neutral-point-clamped VSI is an option for high power systems to avoid the necessity for using high-voltage power devices. Attempts of using higher level or matrix converters have been made, but the use of these technologies is not validated yet in the field of distributed generation [14].

A. A proposed control scheme for multi-level inverter

There are many control schemes which could be adopted to achieve a particular goal. In this research work one of the main objectives is to design a reliable control scheme which would guarantee a consistent synchronization, adequate protection of inverter and flexible capabilities to control the amount of active power fed into the local load and grid and the amount of reactive power exchanged with the grid and load. The configuration of grid and local load should be specified very clearly because the resultant performance of the controllers depends on the net load impedance at the inverter output terminals which is the point of common connection (PCC). Protection against islanding problems is not included in this research work. A few systems may also be designed such that when a fault occurs on the grid side the grid connection is isolated and the inverter continues to supply the local load. The protection relays for such a system may be connected as shown in Fig. 5

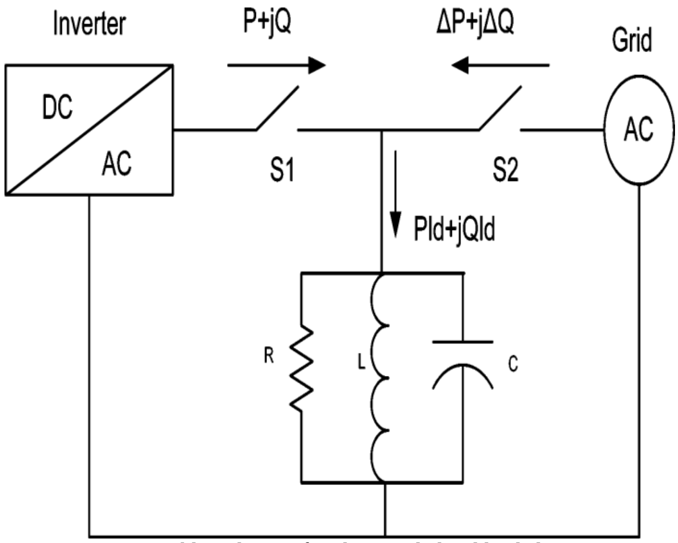

Fig.5 Possible isolation of grid to supply local load alone.

When the inverter is supplying the local load alone, then the input controller which normally tracts the maximum power which can be produced by the DG unit has to be modified. In such a case the maximum active power and reactive power is dictated by the load supplied by the inverter provided the DG-Inverter set has enough capacity. Otherwise some load shedding is necessary in order to satisfy the input and output power balance. If the inverter is supplying only an isolated load, then the required control apparatus is much simplified because there are no synchronization problems and the whole arrangement becomes similar to an uninterruptible power system (UPS). The rms voltage may also be controlled by a PI compensator. The output of the compensator adjusts the modulation index of the 50 Hz sine PWM inverter driver. This type of simple control provides stable output in the steady state, but transient performance may not be adequate for aggressive load transients such as starting of compressor-driven loads [9]. Instantaneous voltage control provides more reliable control during transients. It is more difficult to design he compensator which would work properly at both steady state and transient operations.

B. General Controller controller

The general structure for Distributed Generation systems is composed of an input power which is transformed into electricity by means of a power conversion unit, whose configuration is closely related to the input power nature. The electricity produced can be delivered to the local loads or to the utility network as shown in Fig. 6.

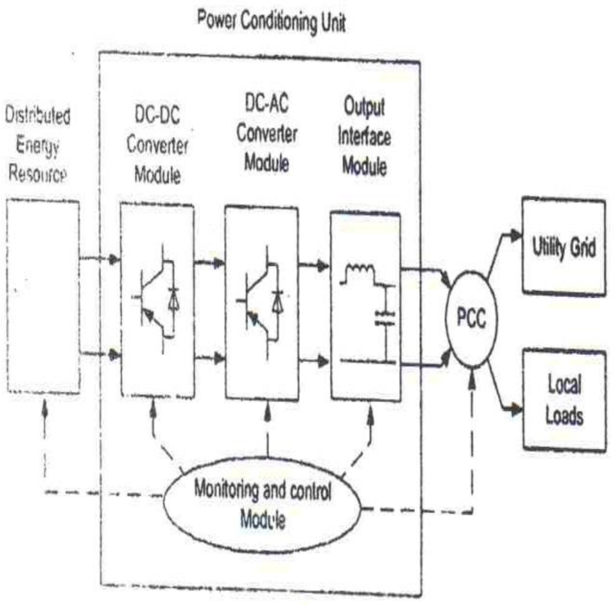

Fig. 6 various components of typical control system of DG

The most important part for the proper operation of a distributed generation system is its control. The control tasks can be divided into two major parts.

1) Input-side controller, with the main property to extract the maximum power from the input source.
2) Grid-side controller, which can have the following tasks:

- Control of active power generated to the grid;
- Control of reactive power transfer between the DPGS and the grid;
- Control of dc-link voltage;
- ensure high quality of the injected power;
- Grid synchronization.

In spite of the present established practices, each of the above topics provides a rich field for research, to resolve the large number of problems, and improve the performance with respect to reliability and power quality.

In this research work only the grid-side controller has been tackled with emphasis on control of active power fed to the grid and control of reactive power transfer between the DPGS and the grid together with the important issue of grid synchronization.

C. Theory of Active & reactive Power Flow Control

Fig. 7 shows the inverter voltage $V < \delta$ connected to the utility grid $E < 0$ through a coupling impedance Z.

$$\bar{S} = P + jQ = \bar{E}\bar{I} = \bar{E}\frac{(\bar{V}-\bar{E})}{Z} \qquad (5)$$

Where P is the real power, Q is the reactive power

$$\bar{S} = E\frac{(V\cos\delta + jV\sin\delta - E)}{R+jX} \qquad (6)$$

Multiplying the numerator and denominator of the above

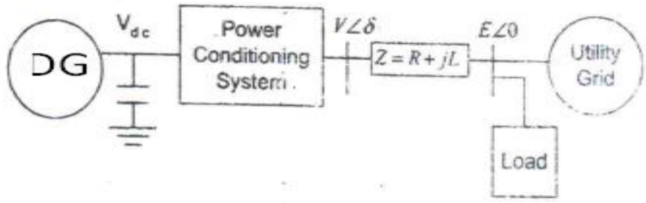

Fig. 7 AC circuit of DG system under steady state

equation by the conjugate of the line impedance i.e. R − jX ,

$$\frac{(R(V\cos\delta - E) + XV\sin\delta)}{R^2+X^2} \qquad (7)$$

$$Q = E\frac{(X(V\cos\delta - E) - RV\sin\delta)}{R^2+X^2} \qquad (8)$$

These two equations represent the active and reactive power transfer from DG to the utility grid and local load.

The two equations may be written as:

$$P = E\frac{(R(mV_{dc}\cos\delta - E) + XmV_{dc}\sin\delta)}{R^2+X^2} \qquad (9)$$

$$Q = E\frac{(X(mV_{dc}\cos\delta - E) - RmV_{dc}\sin\delta)}{R^2+X^2} \qquad (10)$$

Where m is the modulation index, V_{dc} is the DC Link voltage, and δ is the load angle (the angle between E and V vectors)

Assuming that the grid voltage at the Point of Common Connection is approximately constant, then the values of active and reactive powers is controlled by varying the magnitudes and phase angle of the inverter output voltages. It is clear that inverter voltage and phase angle relative to PCC depends on the magnitude and current supplied by the inverter, which causes voltage drops across the small impedance, R + ωL, of the Filter. Very precise control of the inverter output current magnitude and phase angle is necessary in order to control the output active and reactive power of the inverter, according to some prescribed demands. The control problem is difficult because two voltage sources composed of the inverter and the grid act on the two ends of the small impedance of the Filter. What is required is to control the inverter terminal voltage magnitude and phase angle so as to produce the demanded active and reactive powers. In order to produce some demanded active and reactive power, the inverter current phasor must be controlled by command to produce the terminal voltage vector which would produce the demanded active and reactive powers according to equations (3) and (4). It is clear that commanding the current vector to have a particular value in phase and magnitude can be achieved by driving the inverter with V_{ref} and phase angle so that the inverter output voltage together with the grid voltage produce the required current vector through the filter small series impedance. It is advantageous to transform the dynamics into a reference frame where the desired waveform is a dc quantity rather than sinusoids of a given frequency. This allows the use of integral control action to remove steady-state error. Since the controlled current has to be in phase with the grid voltage, the phase angle used by the *abc → dq* transformation module has to be extracted from the grid voltages. This could be done by filtering the grid voltages and using arctangent function to extract the phase angle. In addition, the phase-locked loop (PLL) technique became a state of the art in extracting the phase angle of the grid voltage vector, in the case of distributed generation systems.

To achieve this, a synchronously rotating reference frame is used, whose transformation matrix is given by:

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = \frac{2}{3}\begin{bmatrix} cos\varphi & sin\varphi \\ -sin\varphi & cos\varphi \end{bmatrix} \cdot \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \cdot \begin{bmatrix} V_m cos\theta \\ V_m cos\left(\theta - \frac{2\pi}{3}\right) \\ V_m cos\left(\theta + \frac{2\pi}{3}\right) \end{bmatrix} \quad (11)$$

he electrical dynamic equations of the inverter after the transformation are given by:

$$v_d(t) = Ri_d(t) + L\frac{di_d}{dt} - \omega L i_q(t) + e_d(t) \quad (12)$$

$$v_q(t) = Ri_q(t) + L\frac{di_q}{dt} + \omega L i_d(t) + e_q(t) \quad (13)$$

Dynamics in one axis are dependent on the current state of the other axis. (This is analogous to the cross-coupling experienced in electric machines where direct axis flux produces quadrature axis back electromotive force (emf) and vice versa.) This introduces a coupled multi-input–multi-output (MIMO) system that is dependent on the product of two states, current and frequency. The coupling term can be estimated by the measured currents and compensated. The utility voltage can be modeled as a disturbance to the system or can be compensated based on measurements. After feed-forward compensation and decoupling, the linear model of the first order plant to be controlled is:

$$G(s) = \frac{1/R}{s\left(\frac{L}{R}\right)+1} \quad (14)$$

The structure of the controller was chosen to be a PI controller,

which has the transfer function:

$$D(s) = \frac{K_p s + K_i}{s} \quad (15)$$

The amount of desired output power delivered to the utility is controlled through the current regulation algorithm. The accuracy of the current regulation algorithm is important for effective maximum power processing.

Many control algorithms have been proposed to control inverter output current for utility interactive operations. Hysteretic type controllers with different closed loop compensators have been used running at varying or constant switching frequencies. An easily implementable and effective current regulation algorithm is presented here that works harmoniously with grid synchronization methods.

Fig. 8 shows the block diagram of the current regulation algorithm. It is derived in terms of d-q rotating axis variables.

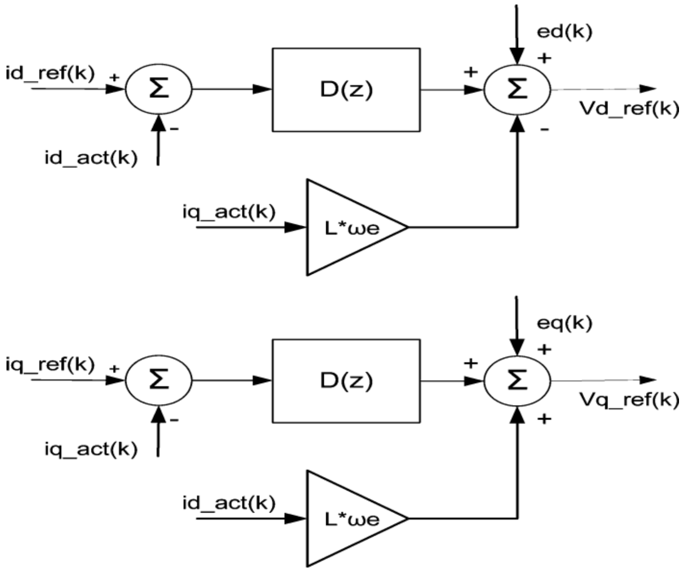

Fig. 8 Proposed current control to enable active and reactive power control

The angle and speed of rotation are obtained precisely from the PLL simple Controller shown in Fig. 9. Both the main DG controller and its coupled PLL use a simple error detection from a negative feedback loop and then use filters and PI controllers in order to achieve close tracking of the demanded currents and angles.

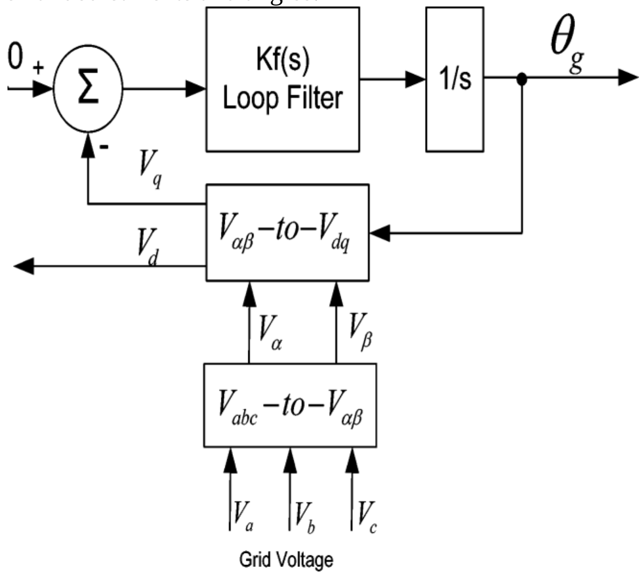

Fig. 9 Three-Phase PLL Algorithm

In some cases a feed-forward signal is added to above block.

IV. RESULTS & DISCUSSTION

A. Main Control Circuit of Inverter

The control Circuit used to control the active and reactive power flow in both the sine PWM 2-level inverter and the Space Vector 3-level inverter is shown in Fig. 10.

The complete circuit for the 2-level inverter is shown in Fig.11

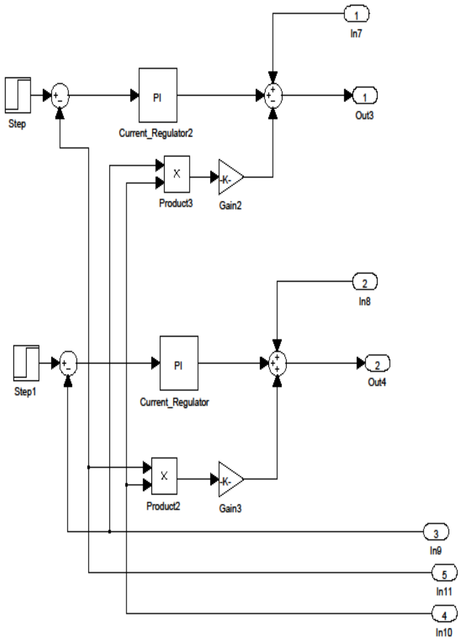

Fig. 10 Main control circuit

The discrete 3-phase PLL controller produces an accurate value of the grid voltage phase angle. The 3-phase inverter current and grid voltage are transformed to d-q rotating axes, using the standard transformation matrix in terms of the grid phase angle obtained from the PLL. The main Current Controller uses, as input, the measured inverter current, i_d and i_q, and the grid voltage, e_d and e_q and the frequency f. The output of the main controller is V_{dref} and V_{qref} , which when applied to the inverter driver, in the proper form, should produce the required current and active and reactive power.

B. 2-Level Inverter

The 2-level inverter selected used a simple sine PWM driver, whose input is a 3-phase reference voltage with grid phase angle. The output of the main controller is the d-q axes reference voltage which is transformed back to the abc 3-phase voltage using the reverse transformation, to provide the required modulating signal to the PWM driver.
The main active and reactive power controller of Fig. 5 was tested on the sine PWM.
2-level grid connected inverter shown in Fig. 11. The converter is assumed to be bi-directional in order to allow active or reactive power to flow in either direction.
Because the sine PWM driver of the 2-level inverter is very simple, then its response is fast, and it is more likely to have a better accuracy of the simulation results. For this reason the sine PWM 2-level inverter simulation results are assumed to be the correct reference , and the space vector 3-level inverter simulation results shall be compared with it. A step change in demanded reference current i_d , without any change in i_q , will produce a change in V_{dref} and V_{qref}. produce a small change in the output voltage vector magnitude V and phase angle δ. It is shown from equations 3 and 4 that both active power P and reactive power Q are changed by a step value.

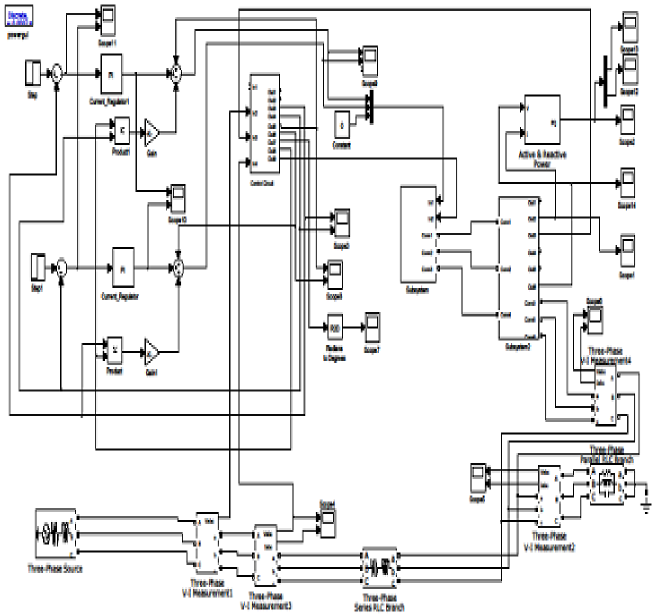

Fig. 11 2-level PWM grid connected inverter circuit

This is due to the interaction between the direct axis and quadrature in the dynamic mathematical representation, as shown in equation 12 and 13.

The main objective of this work is to demonstrate the capability of producing step change in active and or reactive power by commands to the reference currents I_{dref} and i_{qref}, shown in the main control circuit of Fig. 8. A fast response of active power and reactive power at the prescribed instant of the start of the commanded step in reference current, i_d and i_q, confirms the integrity of the main controller Algorithm

C. Simulation results for 2-level sine- PWM inverter

The simulation was conducted on an interactive inverter connected to a power distribution line having a 415 V line to line voltage, with a phase voltage of 240 V, at a frequency of 50 Hz. Fig. 12 (a) shows the simulated results, for the 2-level inverter for an initial direct axis reference current i_d of 40 Amp
which is then suddenly stepped to 80 A at t = 0.1 sec, and at the same instant of time (0.1 sec) the quadrature axis current i_q is stepped from 0 to 40 A. The transient response of the main controller gave a clear sudden change of active power from 2000 W to 5500 W per phase. At the same time the reactive power is concurrently changed from about zero VAR to - 4500 VAR per phase, as shown in Fig. 12 (b). The transient response of the 2-level inverter terminal voltage (after the filter), when regulated by the Main Controller, is shown in Fig. 12 (c). It is seen that the output voltage of the inverter stays reasonably constant. If the voltage across the filter is subtracted, as vector, then the voltage at the terminals of the inverter (before the filter), is also constant having the same frequency as the grid supply. This proves that the Main Controller is working quite satisfactorily in harmony with the PLL, in order to keepthe inverter perfectly synchronized with the grid supply, during the transient and steady state periods, subsequent to the step changes in inverter currents. It is also

noticed that there is a small increase in the magnitude of the line to ground phase voltage. This small increase is necessary in order to produce the step increase in current.

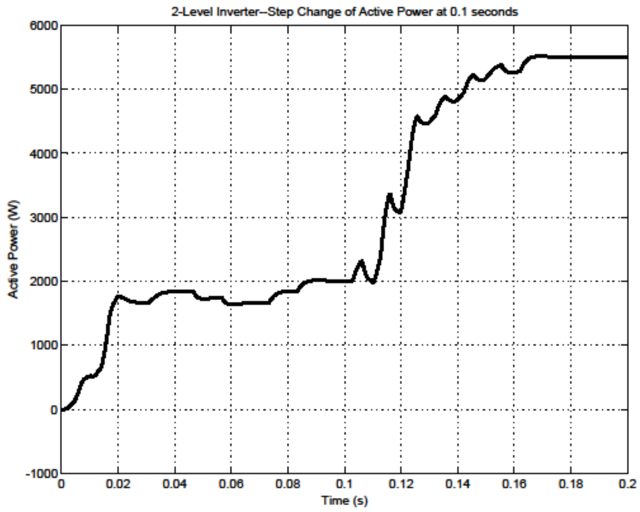

Fig. 12 (a) Transient response of Active Power for commanded step Currents

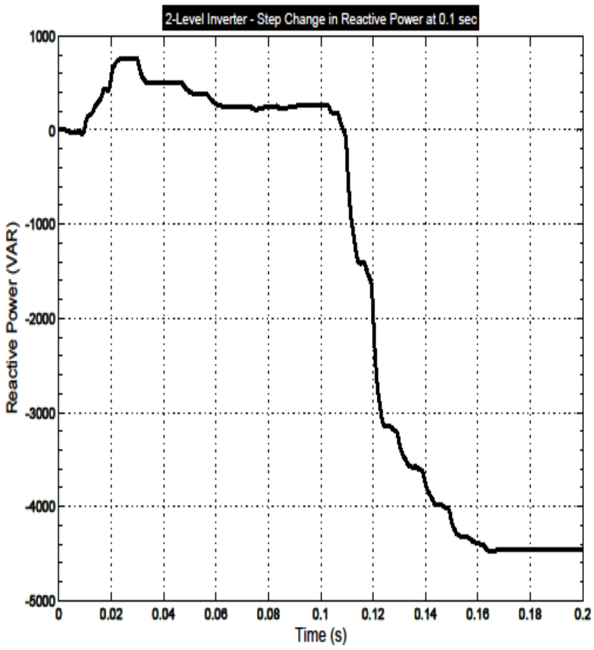

Fig. 12 (b) Transient response of Reactive Power for commanded step currents

The transient response of the 2-level inverter current, when regulated by the Main Controller, is shown in Fig. 12 (d). It is seen that the amplitude of output current of the inverter changes by a step value at the same instant of time as the step change in the reference currents i_{dref} and i_{qref} . This confirms the fact that the inverter output current magnitude follows the demanded step increase in current at the specified instant of time, (t = 0.1 sec).

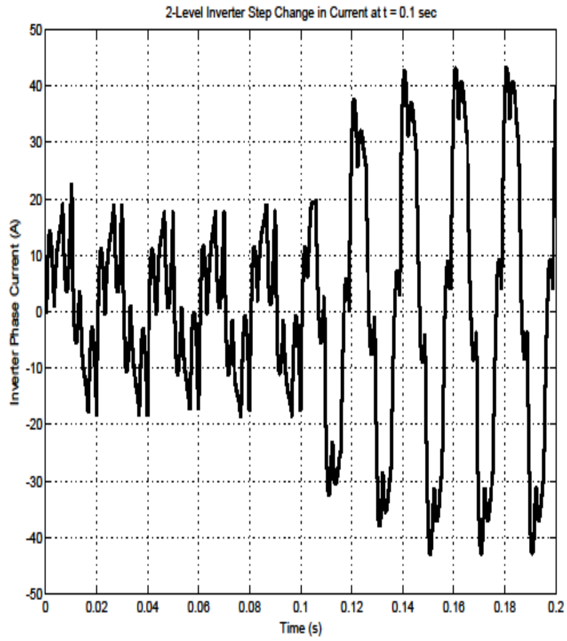

Fig. 12 (d) Transient response of inverter current for commanded step Currents

D. Simulation results for 3-level space vector

Similar simulation procedures were conducted again using the same main controller of Fig. 8, but connected to the 3-level Space Vector Inverter, as shown in Fig. 13.

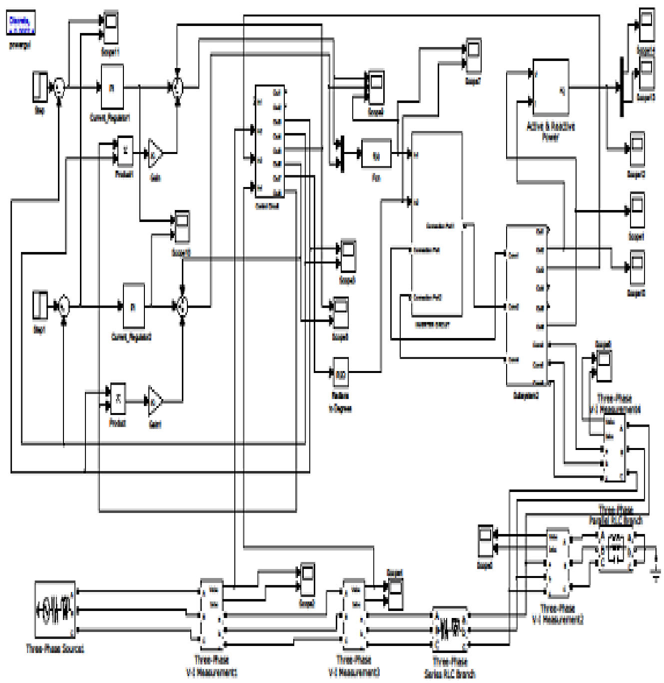

Fig. 13 3-level space vector grid connected inverter circuit

Fig 14 (a) shows the simulated results, for the 3-level Space Vector Inverter, for an initial direct axis reference current i_d of 40 Amp which is then suddenly stepped to 80 A at t = 0.1 sec, and at the same instant of time the quadrature axis current i_q is stepped from 0 to 40 A. The transient response produced by the Main Controller gave a clear change of active power to 5500 W per phase, at t = 0.1, although the initial Power from 0 to 0.1 sec was not constant at 2000 W, as in the case of the 2-level inverter. The cause is most likely due to the complex drive Algorithm of the 3-level space vector inverter with the extensive pre-processor computations. At the same time the reactive power is concurrently changed as shown in
Fig.14(b).

It noticed that the simulation results for the reactive power for the 3-lelel space vector inverter did not give a sharp step like the 2-level inverter. The curve was still moving towards the

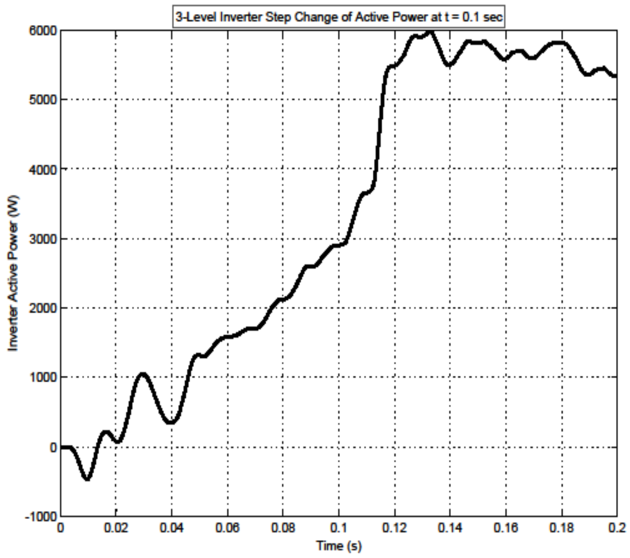

Fig. 14 (a) Transient response of Active Power for commanded step Currents

The transient response of the 3-level inverter terminal voltage (after the filter), when regulated by them main controller, is shown in Fig. 14 (c). It is seen that the output voltage of the inverter stays reasonably constant. If the voltage across the filter is subtracted, as vector, then the voltage at the terminals of the inverter (before the filter), is also constant having the same frequency as the grid supply. This proves that the main controller is working quite satisfactorily in harmony with the PLL, in order to keep the inverter perfectly synchronized with the grid supply, during the transient and steady state periods, subsequent to the step changes in inverter currents. It is also noticed that there is a small increase in the magnitude of the line to ground phase voltage. This small increase is necessary in order to produce the step increase in current.

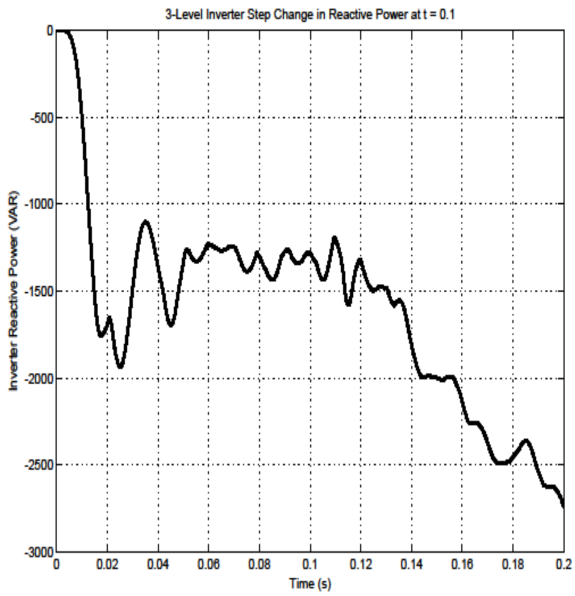

Fig. 14 (b) Transient response of Reactive Power for commanded step Currents

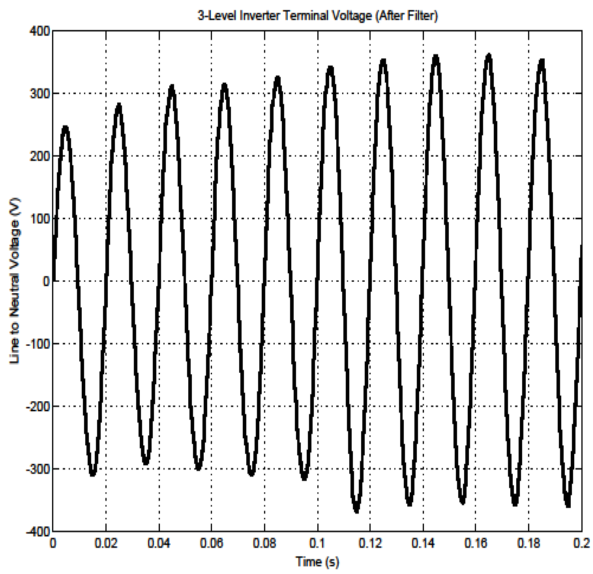

Fig. 14 (c) Transient response of Output Voltage for commanded step Currents

The transient response of the 3-level inverter current, when regulated by the Main Controller, is shown in Fig. 14 (d). It is seen that the amplitude of output current of the inverter changes by a step value at same instant of time as the step change in the reference currents i_{dref} and i_{qref} . This confirms the fact that the inverter output current magnitude follows the demanded step increase in current at the specified instant of time, (t = 0.1 sec).

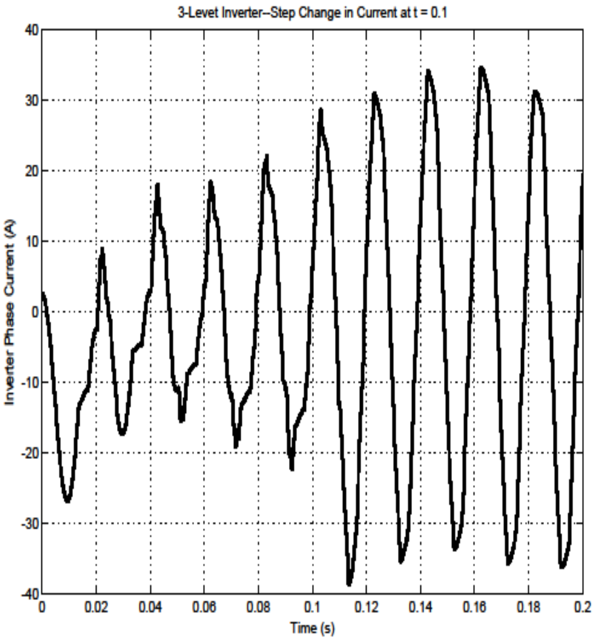

Fig. 14 (d) Transient response of inverter current for commanded step Currents

E. Simulation results for 2-level inverter with step change in grid frequency

The grid frequency used in all above tests was fixed at 50 Hz. In practice the frequency of the grid supply fluctuates slightly about the specified standard. If the synchronization process is not precise, the connection of the inverter to the grid would immediately produce serious damage to the system. In order to test the reliability of the Main Controller and its ability to withstand grave swings of the grid frequency, a programmable 3-phase voltage source was used in place of the fixed frequency power source used in the other tests. Because the main objective is to test the synchronizing capabilities of the Main Controller, it is better to use the robust 2-level sine PWM inverter, which has a faster speed of response. The programmable voltage source was set to a 415 V line to line voltage, with a phase voltage of 240 V, and an initial frequency of 50 Hz. The frequency of power source is then by a step from 50 Hz to 55 Hz. If the Main Controller is unable to track this sudden change, synchronization would be lost, and the inverter will have to be disconnected from the grid line.

Fig. 15 (a) shows the simulated results, for the 2-level inverter, for a step change of frequency, and an initial direct axis reference current i_d of 40 Amp which is then suddenly stepped to 80 A at t = 0.1 sec, and at the same instant of time (0.1 sec) the quadrature axis current i_q is stepped from 0 to 40 A. The transient response of the main controller gave a clear sudden change of active power from 2000 W to 5500 W per phase. At the same time the reactive power is concurrently changed from about zero VAR to - 4500 VAR per phase.

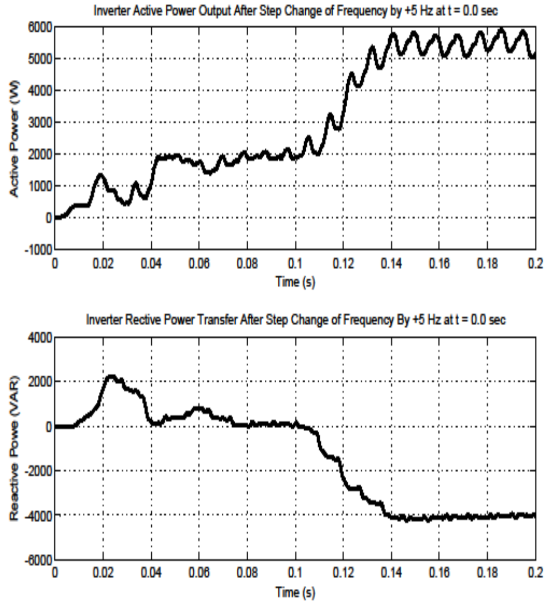

Fig. 15 (a) Transient response of Active and Reactive Power for step change of frequency and current

The transient response of the 2-level inverter terminal voltage (after the filter), and phase current, when regulated by the Main Controller, and subjected to a step change of frequency, is shown in Fig. 15 (b). It is seen that the output voltage of the inverter stays reasonably constant. If the voltage across the filter is subtracted, as vector, then the voltage at the terminals of the inverter (before the filter), is also constant having the same frequency as the grid supply. This proves that the Main Controller is working quite satisfactorily in harmony with the PLL, in order to keep the inverter perfectly synchronized with the grid supply, during the transient and steady state periods, subsequent to the step changes in grid frequency and inverter currents. It is also noticed that there is a small increase in the magnitude of the line to ground phase voltage. This small increase is necessary in order to produce the step increase in current.

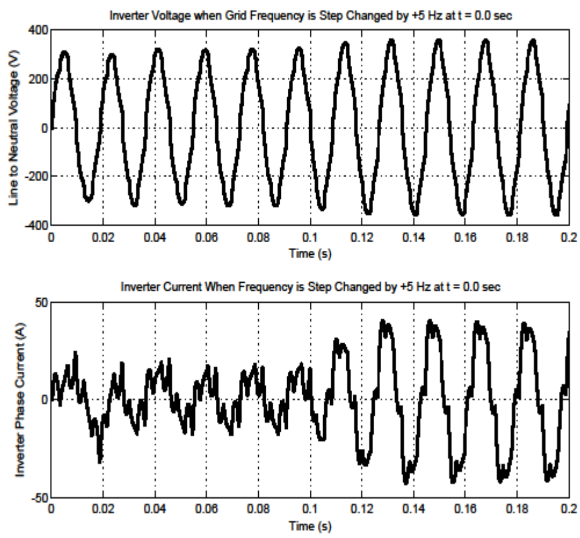

Fig. 15 (b) Transient response of Output Voltage and phase current for step change in frequency and Reference Currents

It is noticed that the performance of the main controller is outstanding and synchronization was maintained, allowing the inverter to continue exchanging active and reactive power with the grid, even when the frequency was changed by the large step of 5 Hz

CONCLUTION

One fundamental requirement for the inverter is to operate in synchronism with grid for all common swings of grid voltage and frequency. It should also be easy to control the flow of power from the DG source to the grid and local load, while exchange of reactive power between the DG source and the grid should also be manageable. All this requires the use of an appropriate Algorithm in conjunction with a digital signal processor, in order to control the inverter, and achieve the above goals.

A main controller has been selected, using a standard discrete PI controller and compensators in order to control the axes currents according to a reference command. This controller utilizes a discrete PLL controller which provides a very accurate value of the grid phase angle and frequency.

The same Main Controller was used to drive a 2-level sine PWM inverter and a 3-level inverter with space vector configuration. The 2-level sine PWM configuration was found to give simulation results which are closer to expectation, with clear step change in active power, reactive power and phase current, and with minimum offset of various curves. Hence the simulation results for the 2-level sine PWM inverter were assumed to be close to the true values.

The corresponding results for the 3-level space vector inverter were found to be fairly good but the responses were a bit slower and there was a marked offset of several curves from the zero datum. This could have been caused by the extensive computation load undertaken by the processors.

The third set of results was concerned with a test of the synchronization capabilities of the Main Controller. The simulation tests were conducted on the 2-level sine PWM inverter. A step change of frequency equal to 5 Hz is considered as a large perturbation of frequency relative to practical conditions. It was found that the performance of the Main Controller was outstanding, and synchronization was maintained, allowing the inverter to continue feeding active power into the grid and exchanging reactive power with the grid under step changes of current, active and reactive power and grave frequency step change.

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