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A VERSATILE HARMONIC CONTROL APPROACH FOR THREE PHASE INVERTER IN GRID CONNECTED PV SYSTEM WITHOUT CRITICAL ISLANDING DETECTION

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ABSTRACT

A versatile harmonic control approach for three phase inverter in DG for PV cell with MPPT based on P&O Technique that enables both islanded and grid-tied modes of operations with no need for switching between two corresponding controllers/critical islanding detection is implemented using MATLAB/Simulink. The demonstrated versatile harmonic control approach composes of an inner inductor current loop and a simple voltage loop in the SRF. The inverter is regulated as a current source just by the inner inductor current loop in grid-tied operation and the voltage controller is automatically activated to regulate the load voltage upon the occurrence of islanding. An inductor current control loop is essential for obtaining high power quality in grid connection of inverters. It provides three-phase balanced current injection to the grid. Another advantage of using current control is that non linearities, such as inverter switching and external disturbances such as changes in the dc-link voltage Vdc and disturbance of the grid voltage Vg , are dealt within that loop. Thus, the control approach does not need a forced switching between two distinct sets of controllers. Moreover, the waveforms of the grid current in the grid-tied mode and the load voltage in the islanding mode are distorted due to the presence of non linear local loads with the conventional control strategies. This issue is addressed by explaining a versatile harmonic load current feed forward control approach.

KEYWORDS: PV Cell, P& O Technique for MPPT, Distributed Generation (DG), Islanding & Grid Tied modes of Operations, Inverter.

INTRODUCTION

In contemporary world inter connection ofDistributed Generations (DG) which operate in parallel with electrical power networks, is currently changing the paradigm we are used to live with. Distributed generation is gaining world wide interest because of environmental issues and rising in energy prices and power plant construction costs. Distributed generations are relatively small and many of them make use of renewable energy such as fuel cells, gas turbines, micro-hydro, wind turbines and photovoltaic. Many DGs use power electronic inverters, instead of rotating generators. The inverters typically have fast current limiting functions for self protection, and may not be damaged by out-of-phase reclosing. The operation of distributed generation will enhance the power quality in power system and this interconnection especially with reverse power flow may lead to some problems like voltage and frequency deviation, harmonics, reliability of the power system and islanding phenomenon.

Islanding is one of the most technical concerns associated with the proliferation of distributed generation connected to utility networks. Islanding can be defined as a condition in which a portion of the utility system contains both load and distributed generation remains energized while being isolated from the remainder of the utility system. Islanding detection is a mandatory feature for grid-connected inverters as specified in international standards and guidelines. Inverters usually operate with current control and unity power factor and employ passive monitoring for islanding detection methods based on locally measured parameters. Under islanding conditions, the magnitude and frequency of the voltage at the point of common coupling (PCC) tend to drift from the rated grid values as a function of the power imbalance (ΔP and ΔQ).

However, with Distributed Generation this pre -assumption is no longer valid. In current practice DG is required to disconnect the utilities from the grid in case of islanding. The main issues about

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islanding are: 1) Safety issues since a portion of the system remains energized while it is not expected. 2) Islanded system may be inadequately grounded by the DG inter connection. 3) Instantaneous reclosing could cause out of phase in the system. 4) Loss of control over voltage and frequency in the system 5) Excessive transient stresses upon reconnection to the grid.6).Uncoordinated protection.

In the hybrid voltage and current mode control, there is need to switch the controller when the operation mode of DG is changed. During the interval from the occurrence of utility outage and switching the controller to voltage mode, the load voltage is neither fixed by the utility, nor regulated by the DG, and the length of the time interval is determined by the islanding detection process. Therefore, the main issue in this approach is that it makes the quality of the load voltage heavily reliant on the speed and accuracy of the islanding detection method [1]–[3]. In the grid-tied mode, the output current of DG is generally desired to be pure sinusoidal [4].

Thereby, a versatile harmonic control approach is introduced that avoids the aforementioned shortcomings. First, the traditional inductor current loop is employed to control the three-phase inverter in DG to act as a current source with a given reference in the synchronous reference frame (SRF). Second, a novel voltage controller is presented to supply reference for the inner inductor current loop, where a proportional-plus-integral (PI) compensator and a proportional (P) compensator are employed in d-axis and q-axis, respectively. In the grid-tied operation, the load voltage is dominated by the utility, and the voltage compensator in d-axis is saturated, while the output of the voltage compensator in q-axis is forced to be zero by the PLL.Therefore, the reference of the inner current loop cannot regulated by the voltage loop, and the DG is controlled as a current source just by the inner current loop. Moreover, the proposed control approach, benefiting from just utilizing the current and voltage feedback control, endows a better dynamic performance, compared to the voltage mode control.

VERSATILE HARMONIC CONTROL APPROACH

A. Power Stage

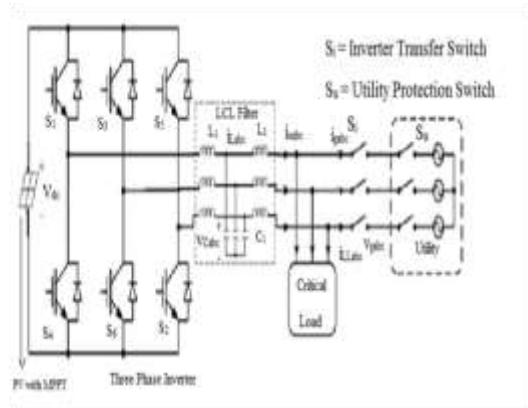

Fig.1 Schematic diagram of the DG based on the versatile harmonic control approach

The schematic diagram of the DG based on the proposed control approach is shown by Fig.1. The DG is equipped with a three-phase interface inverter terminated with a LCL filter. The primary energy is converted to the electrical energy, which is then converted to dc by the front-end power converter, and the output dc voltage is regulated by it. Therefore, they can be represented by the dc voltage source V_{dc} in Fig.1 In the ac side of inverter, the local critical load is connected directly .It should be noted that there are two switches, denoted by S_u and S_i, respectively, in Fig.1, and their functions are different. The inverter transfer switch S_i is controlled by the DG, and the utility protection switch S_u is governed by the utility. When the utility is normal, both switches S_i and S_u are ON, and the DG in the grid-tied mode injects power to the utility. When the utility is in fault, the switch su is tripped by the utility instantly, and then the islanding is formed. After the islanding has been confirmed by the DG with the islanding detection scheme [5]–[6], the switch S_i is disconnected, and the DG is transferred from the grid-tied mode to the islanded mode. When the utility is restored, the DG should be resynchronized with the utility first, and then the switch S_i is turned ON to connect the DG with the grid.

B. Basic Logic

With the hybrid voltage and current mode control [9]–[10], the inverter is controlled as a current source to generate the reference power $P_{DG}+jQ_{DG}$ in the grid-tied mode. And its output power $P_{DG}+jQ_{DG}$

should be the sum of the power injected to the grid $P_g + jQ_g$ and the load demand $P_{load}+jQ_{load}$ which can be expressed as follows by assuming that the load is represented as a parallel RLC circuit:

$$P_{load} = 3/2\ V_m^2/R \quad (1)$$

$$Q_{load} = 3/2\ V_m^2\ (1/\omega L - \omega C) \quad (2)$$

In (1) and (2), V_m and ω represent the amplitude and frequency of the load voltage, respectively. When the non linear local load is fed, it can still be equivalent to the parallel RLC circuit by just taking account of the fundamental component.

During the time interval from the instant of islanding happening to the moment of switching the control system to voltage mode control, the load voltage is neither fixed by the utility nor regulated by the inverter, so the load voltage may drift from the normal range [7]. And this phenomenon can be explained as below by the power relationship. During this time interval, the inverter is still controlled as a current source, and its output power is kept almost unchanged. However, the power injected to utility decreases to zero rapidly, and then the power consumed by the load will be imposed to the output

power of DG. If both active power P_g and reactive power Q_g injected into the grid are positive in the grid-tied mode, then P_{load} and Q_{load} will increase after the islanding happens, and the amplitude and frequency of the load voltage will rise and drop, respectively, according to (1) and (2) With the previous analysis, if the output power of inverter $P_{DG}+jQ_{DG}$ could be regulated to match the load demand by changing the current reference before the islanding is confirmed, the load voltage excursion will be mitigated. And this basic analysis is utilized in this paper.

In the proposed control approach, the output power of the inverter is always controlled by regulating the three-phase inductor current i_{Labc} , while the magnitude and frequency of the load voltage v_{Cabc} are monitored. When the islanding happens, the magnitude and frequency of the load voltage may drift from the normal range, and then they are controlled to recover to the normal range automatically by regulating the output power of the inverter.

C. Control Scheme

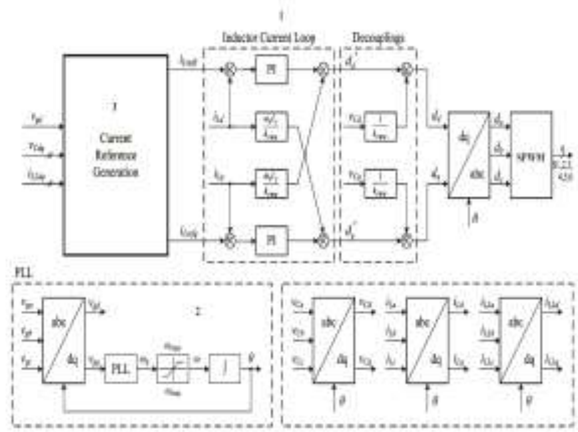

Fig.2 Overall block diagram of the versatile harmonic control approach

Fig.2 describes the overall block diagram for the proposed versatile harmonic control approach, where the inductor current i_{Labc}, the utility voltage v_{gabc} the load voltage v_{Cabc} and the load current i_{LLLabc} are sensed. And the three-phase inverter is controlled in the SRF, in which, three phase variable will be represented by dc quantity. The control diagram is mainly composed by the inductor current loop, the PLL, and the current reference generation module. In the inductor current loop, the PI compensator is employed in both D- and Q-axes, and a decoupling of the cross coupling denoted by $\omega_o L_f$ / k_{PWM} is implemented in order to mitigate the couplings due to the inductor. The output of the inner current loop d_{dq}', together with the decoupling of the capacitor voltage denoted by $1/k_{PWM}$, sets the reference for the standard space vector modulation that controls the switches of the three-phase inverter. It should be noted that k_{PWM} denotes the voltage gain of the inverter, which equals to half of the dc voltage in this paper.

The PLL in the proposed control approach is based on the SRF PLL, which is widely used in the three-phase power converter to estimate the utility frequency and phase. Furthermore, a limiter is inserted between the PI compensator G_{PLL} and the integrator, in order to hold the frequency of the load voltage within the normal range in the islanded operation.

In Fig. 2, it can be found that the inductor current is regulated to follow the current reference i_{Lrefdq}, and the phase of the current is synchronized to the grid voltage v_{gabc}. If the current reference is constant, the inverter is just controlled to be a current source, which is the same with the traditional grid tied inverter. The new part in this paper is the currentreference generation module shown in Fig.3, which regulates the current reference to guarantee the power match between the DG and the local load and enables the DG to operate in the islanded mode. Moreover, the versatile harmonic load current feed forward, to deal with the non linear local load, is also implemented in this module.

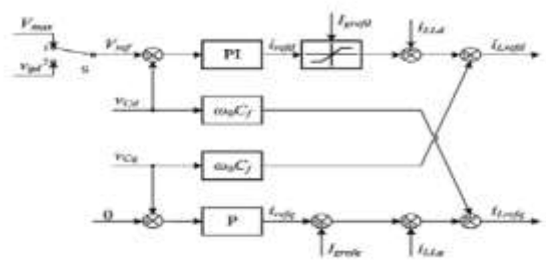

Fig. 3 Block diagram of the current reference generation module

The block diagram of the proposed current reference generation module is shown in Fig.5, which provides the current reference for the inner current loop in both grid-tied and islanded modes. In this module, it can be found that an unsymmetrical structure is used in D and Q-axes. The PI compensator is adopted in D-axes, while the P compensator is employed in Q-axis. Besides, an extra limiter is added in the D-axis. Moreover, the load current feed forward is implemented by adding the load current i_{LLdq} to the final inductor current reference i_{Lrefdq}. The benefit brought by the unique structure in Fig.3 can be represented by two parts:

1) seamless transfer capability without critical islanding detection; and 2) power quality improvement in both grid tied and islanded operations. The current reference i_{Lrefdq} composes of four parts in D-and Q-axes respectively-1) the output of voltage controller i_{refdq} 2) the grid current reference I_{grefdq} 3) the load current i_{LLdq} and 4) the current flowing through the filter capacitor C_f.

In the grid-tied mode, the load voltage v_{Cdq} is clamped by the utility. The current reference is irrelevant to the load voltage, due to the saturation of the PI compensator in D-axis, and the output of the P compensator being zero in Q-axis, and thus, the inverter operates as a current source. Upon occurrence of islanding, the voltage controller takes over automatically to control the load voltage by regulating the current reference, and the inverter acts as a voltage source to supply stable voltage to the local load; this relieves the need for switching between different controls architectures.

Another distinguished function of the current reference generation module is the load current feed forward. The sensed load current is added as a part of the inductor current reference i_{Lrefdq} to compensate the harmonic component in the grid current under non linear local load. In the islanded mode, the load current feed forward operates still, and the disturbance from the load current, caused by the non linear load, can be suppressed by the fast inner inductor current loop, and thus, the quality of the load voltage is improved.

MODES OF OPERATION OF DG

The different modes of operation of DG with the versatile harmonic control approach will be illustrated as follows:-

A. Grid-Tied Mode

When the utility is normal, the DG is controlled as a current source to supply given active and reactive power by the inductor current loop, and the active and reactive power can be given by the current reference of D and Q- axis independently. First, the phase angle of the utility voltage is obtained by the PLL, which consists of a Park transformation expressed by (3), a PI compensator, a limiter, and an integrator is denoted by the equation (3) as –

$$\begin{matrix} x_d \\ x_q \end{matrix} = 2/3 \begin{matrix} \cos\theta & \cos(\theta-2\pi/3) & \cos(\theta+2\pi/3) \\ -\sin\theta & -\sin(\theta-2\pi/3) & -\sin(\theta+2\pi/3) \end{matrix} \quad (3)$$

Second, the filter inductor current, which has been transformed into SRF by the Park transformation, is fed back and compared with the inductor current reference i_{Lrefdq} and the inductor current is regulated to track the reference i_{Lrefdq} by the PI compensator G_I.

The reference of the inductor current loop i_{Lrefdq} seems complex and it is explained as below. It is assumed that the utility is stiff, and the three-phase utility voltage can be expressed as-

$$\left.\begin{aligned} v_{ga} &= V_g \cos\theta^* \\ v_{gb} &= V_g \cos(\theta^* - 2\Pi/3) \\ v_{gb} &= V_g \cos(\theta^* + 2\Pi/3) \end{aligned}\right\} \quad (4)$$

where V_g is the magnitude of the grid voltage, and $\theta^*$is the actual phase angle. By the Park transformation, the utility voltage is transformed into the SRF, which is shown as –

$$\left.\begin{aligned} v_{gd} &= V_g \cos(\theta^* - \theta) \\ v_{gq} &= V_g \sin(\theta^* - \theta) \end{aligned}\right\} \qquad (5)$$

where v_{gq} is regulated to zero by the PLL, so v_{gd} equals the magnitude of the utility voltage v_g .As the filter capacitor voltage equals the utility voltage in the gird-tied mode, v_{Cd} equals the magnitude of the utility voltage V_g, and v_{Cq} equals zero, too.

In the d-axis, the inductor current reference i_{Lrefd} can be expressed by (6) according to Fig.4

$$i_{Lrefd} = I_{grefd} + i_{LLd} - \omega_0 C_f * v_{Cq} \qquad (6)$$

The first part is the output of the limiter. It is assumed that the given voltage reference V_{max} is larger than the magnitude of the utility voltage vCd in steady state, so the PI compensator, denoted by G_{VD} in the following part, will saturate, and the limiter outputs its upper value I_{grefd}. The second part is the load current of D-axis, i_{LLd} which is determined by the characteristic of the local load. The third part is the proportional part - $\omega_0 C_f * v_{Cq}$, where ω_0 is the rated angle frequency, and. C_f is the capacitance of the filter capacitor. It is fixed as v_{Cq} depends on the utility voltage. Consequently, the current reference i_{Lrefd} is imposed by the given reference I_{grefd} and the load current i_{LLd} , and is independent of the load voltage.

In the q-axis, the inductor current reference i_{Lrefq} consists of four parts as

$$i_{Lrefq} = v_{Cq} * k_{Gvq} + I_{grefq} + i_{LLq} + \omega_0 C_f * v_{Cd} \quad (7)$$

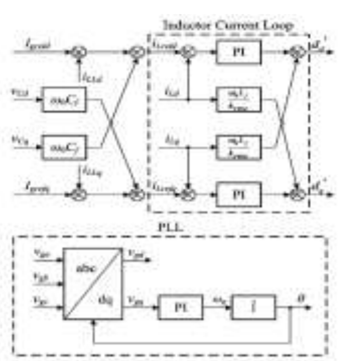

Fig.4 Simplified block diagram of the versatile harmonic control approach when DG operates in the grid-tied mode.

where k_{Gvq} is the parameter of the P compensator, denoted by G_{VQ} in the following part. The first part is the output of G_{VQ} which is zero as the v_{Cq} has been regulated to zero by the PLL. The second part is the given current reference I_{grefq} , and the third part represents the load current i_{LLq} in Q-axis. The final part is the proportional part $-\omega_0 C_f * v_{Cd}$ which is fixed since v_{Cd} depends on the utility voltage. Therefore, the current reference i_{Lrefq} cannot be influenced by the external voltage loop and is determined by the given reference I_{grefq} and the load current i_{LLq}.

With the previous analysis, the control diagram of the inverter can be simplified as Fig.4 in the grid-tied mode, and the inverter is controlled as a current source by the inductor current loop with the inductor current reference being determined by the current reference I_{grefdq} and the load current i_{LLdq}. In other words, the inductor current tracks the current reference and the load current. If the steady state error is zero, I_{grefdq} represents the grid current actually.

B. Islanded Mode

In the islanded mode, switching S_i and S_u are both in OFF state. The PLL cannot track the utility voltage normally, and the angle frequency is fixed. In this situation, the DG is controlled as a voltage source, because voltage compensator G_{VD} and G_{VQ} can regulate the load voltage v_{Cdq}. The voltage references in D and Q-axis are V_{max} and zero, respectively. And the magnitude of the load voltage equals to V_{max} approximately. Consequently, the control diagram of the three-phase inverter in the islanded mode can be simplified as shown in Fig. 5. In Fig. 7, the load current i_{LLdq} is partial reference of the inductor current loop. So, if there is disturbance in the load current, it will be suppressed quickly by the inductor current loop, and a stiff load voltage can be achieved.

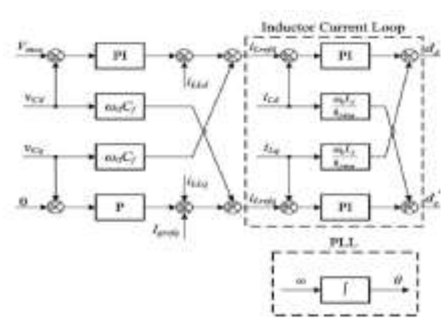

Fig.5 Simplified block diagram of the versatile harmonic control approach when DG operates in the islanded mode.

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RESULTS & DISCUSSIONS

A PV Cell with P&O Control Algorithm has been designed and the SIMULINK model is:-

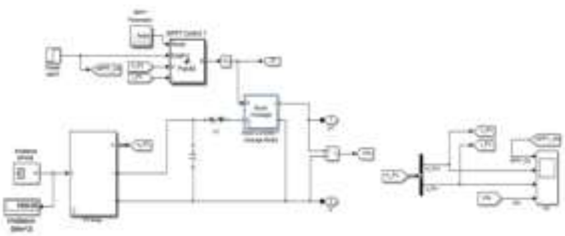
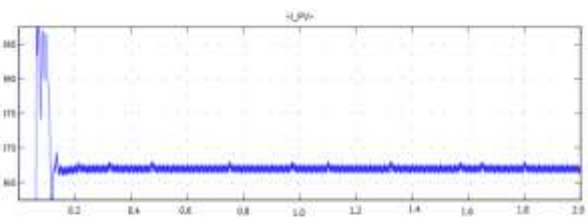


Fig.6 PV Cell based on P& O Algorithm Simulink Model

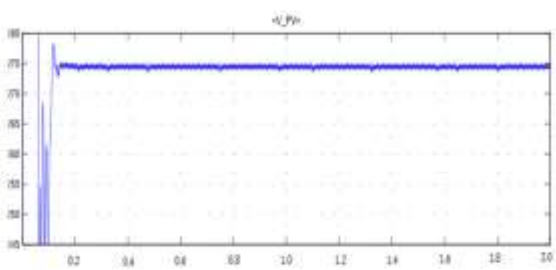
Current (A)



Time (seconds)

Fig.7 PV Cell Current Output

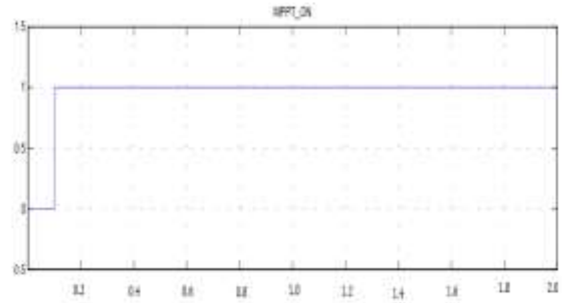
Voltage (Volt)



Time (seconds)

Fig.8 PV Cell Voltage Output

Gate Pulse



Time (seconds)

Fig. 9 Gate Pulse of MPPT Control Algorithm

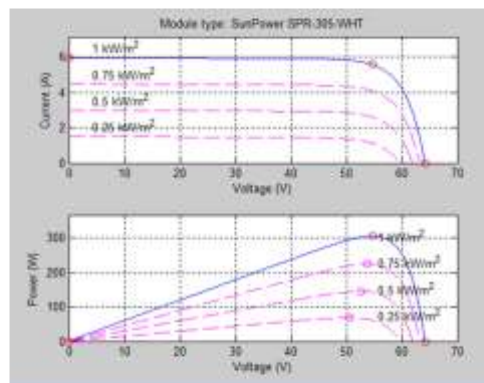
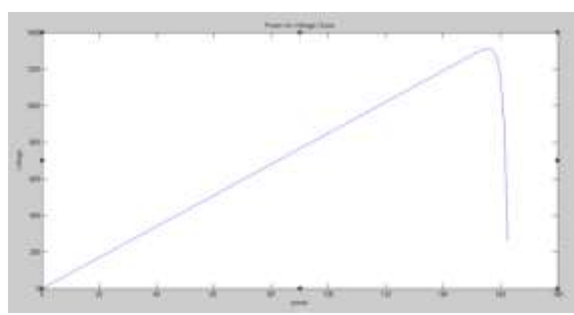


Fig.10 PV Cell PV & IV Curves for different irradiation levels

Voltage (Volt)



Power (Watts)

Fig.11 PV Characteristics for PV Cell

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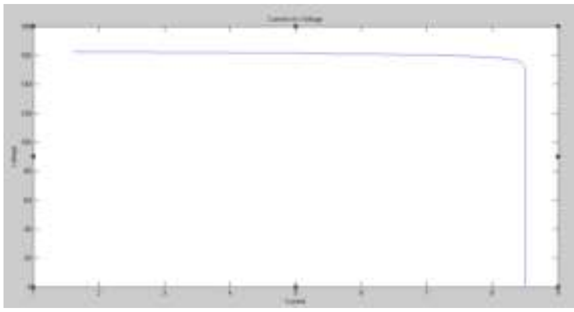
Voltage (Volt)



Current (Amps)

Fig.12 IV Characteristics for PV Cell

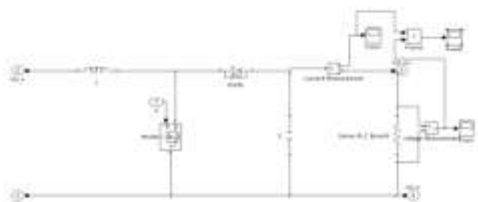
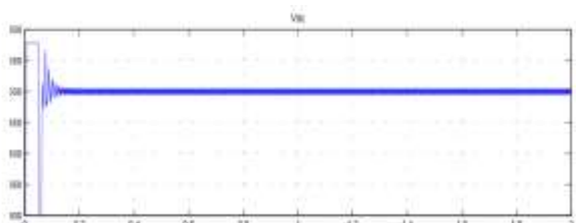


Fig 13 DC- DC Boost Converter Simulink Model

Voltage (Volt)



Time (seconds)

Fig.14 DC- DC Boost Converter Output

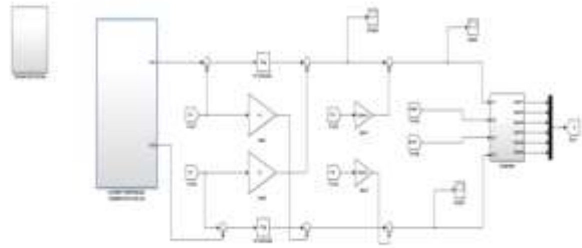


Fig 15 Overall Simulink Model for Grid tied & Islanding Operations

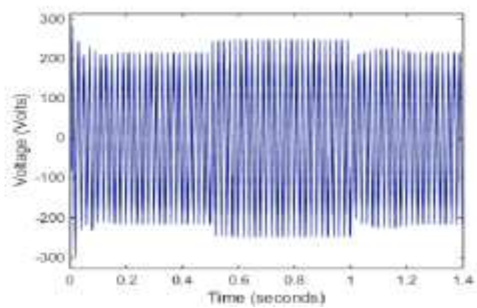


Fig.16 Load Voltage (v_{Ca}) Output

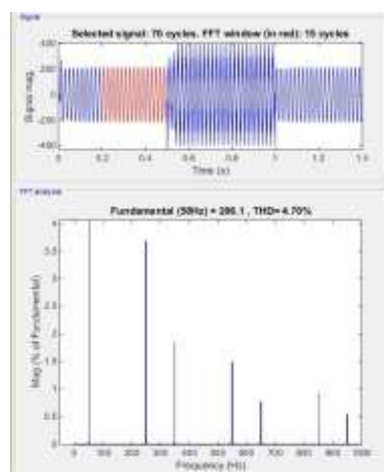


Fig.17 FFT plot for load voltage (v_{Ca}) in grid tied mode of operation

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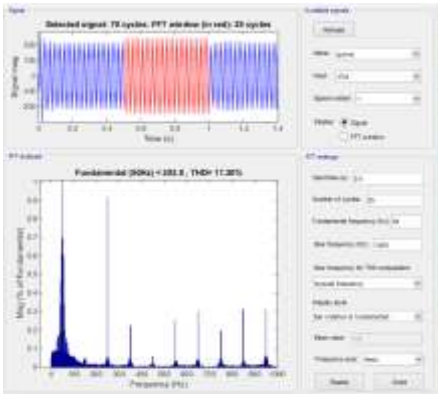


Fig.18 FFT plot for load voltage(v_{Ca}) in islanded mode of operation

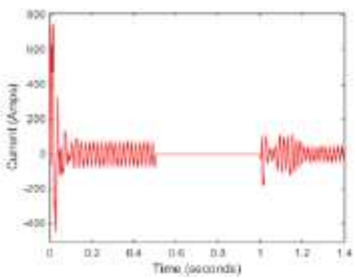


Fig.19 Grid Current (i_{ga}) Output

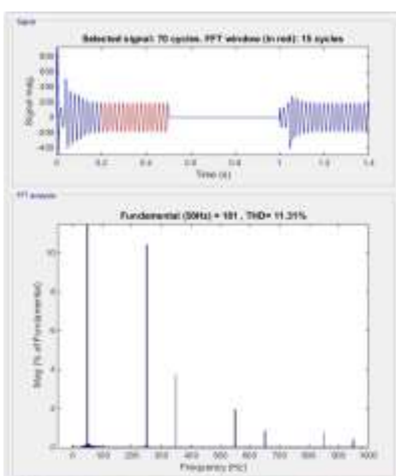


Fig.20 FFT analysis of grid current (i_{ga})

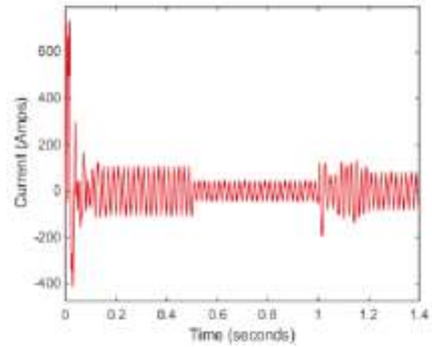
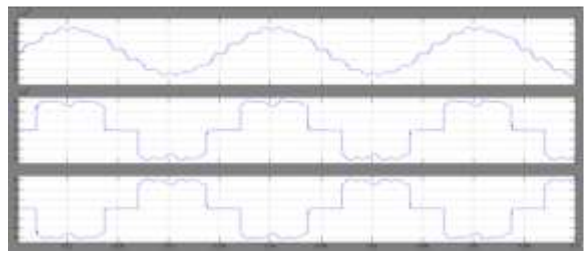


Fig.21 Inductor Current (i_{La}) Output Waveform

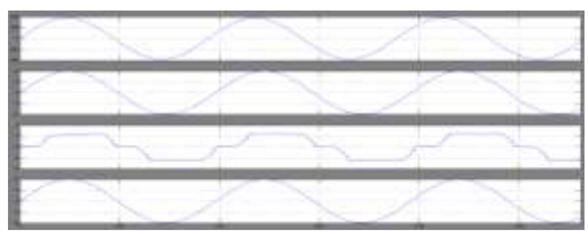
Voltage (Volt)



Time (secs)

Fig.22 Effect of Load Current (i_{LLd})Feed Forward Control Strategy for DG feeding Non Linear Local Loads in Islanded operation

Voltage (Volt)



Time (secs)

Fig.23 Effect of Load Current (i_{LLd})Feed Forward Control Strategy for DG feeding Non Linear Local Loads inGrid tied mode of operation

CONCLUSION

A versatile harmonic control approach has been implemented for three phase inverter in DG for PV cell with MPPT based on P&O Technique to operate in both islanded and grid-tied modes, with no need for switching between two different controllers. A simple voltage controller was designed and it is inactivated in the grid-tied mode, and the DG operates as a current source with improved dynamic performance with fast acting controllers. Upon the utility outage, the voltage controller can automatically be activated to regulate the load voltage. Moreover, a versatile harmonic load current feed forward was modeled in MATLAB/Simulink and it can improve the waveform quality of both the grid current in the grid-tied mode and the load voltage in the islanded mode.

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