Design and Simulation of Adaptive Controller for Single Phase Grid Connected Photovoltaic Inverter under Distorted Grid Conditions

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***Abstract*—This paper presents an adaptive controller for single-phase grid-connected photovoltaic inverter under abnormal grid conditions. The main problem associated with the controllers of the grid-connected inverter is that they are tuned for some assumed values of the electrical grid parameters. However, when the parameters, such as voltage and frequency are changed or the grid is subjected to uncertain distortion, these controllers unable to track those variations of the grid parameters and handle the output power within the allowable limit. To overcome such problem, a suitable control strategy is proposed, which is based on frequency adaptive current control and an accurate grid detection. For validity confirmation, a controlled 3KW system, with specific features was designed and simulated. The simulation results confirmed that the strategy is an effective way of control.**

Keywords—Single phase grid-connected photovoltaic inverter; adaptive controller; grid parameter variations

I. Introduction

The continuous increasing demands for electric energy, combined with the environmental pollution caused by the conventional electric energy generating units, has led to a worldwide concern on the grid-connected photovoltaic system (GCPVS) [1], [2]. Nowadays a high penetration of single-phase transformerless inverter really raises the concern about photovoltaic (PV) integration of low voltage. It is expected that the future of a single-phase GCPVS can not only maintain the stability and the quality of the grid but also have some ancillary functions, such as reactive power support and fault ride through capability. In that case, reliable control strategies and synchronization technique should be ready for PV applications [3]. The limitations in the classical controllers of the grid-connected inverter are that they mainly tuned for some assumed values of the electrical grid parameters. However, the parameters such as voltage and frequency can change. Therefore the control should be able to track those changes [4] in order to maintain the desired output current. A control structure for a single-phase single-stage grid-connected PV system using a proportional-resonant (PR) current controller is proposed in [5]. The current injected into the grid has a low total harmonic distortion (THD) and unity power factor under different levels of insolation of sun. However, the control is tuned for 325V/50Hz voltage and frequency parameter. Moreover, the system efficacy is not confirmed for voltage or frequency other than this input parameters. A control strategy for a single-phase PV inverter is presented in [6]. The synchronization in this strategy is made with the so called dual transport delay based PLL (DTDPLL) controller. The performance of proposed DTDPLL controller is validated under varying frequency conditions. Though, it is not mentioned that this technique can be used under distorted grid conditions.

The main objective of this paper is to present an adaptive and effective controller for a single-phase single-stage transformerless inverter of PV system under abnormal grid conditions like the distorted grid. The proposed control strategy is based on the accurate grid detection and synchronization, in which the grid frequency is obtained by the simple method. The method is based on counting the period of the half cycle with respect to the zero-crossings of the grid voltage, thus the information of the frequency of the fundamental is estimated. Then, the frequency information inside PR current controller is online provided, using the estimated value. However, significant line voltage distortion can easily corrupt the output of a conventional zero-crossing detection (ZCD). Therefore, the ZCD of the grid voltage needs to extract its fundamental component at the line frequency. This task is made by a bandpass filter without delay. Additionally, the grid voltage amplitude information is obtained by the traditional method of RMS calculation.

This paper is organized as follows: In Section 2, the requirements of the grid-connected PV system is highlighted. In Section 3, the significance of the penetration of single-phase transformerless inverter for the grid-connected system is described. The control strategy of the single-phase grid-connected PV system inverter is presented in Section 4. To verify the proposed strategy, a controlled 3KW/50Hz GCPVS, with specific features was designed and simulated, using PSIM software tools. The simulation results are interpreted in Section 5. The conclusion is addressed in the last of this work.

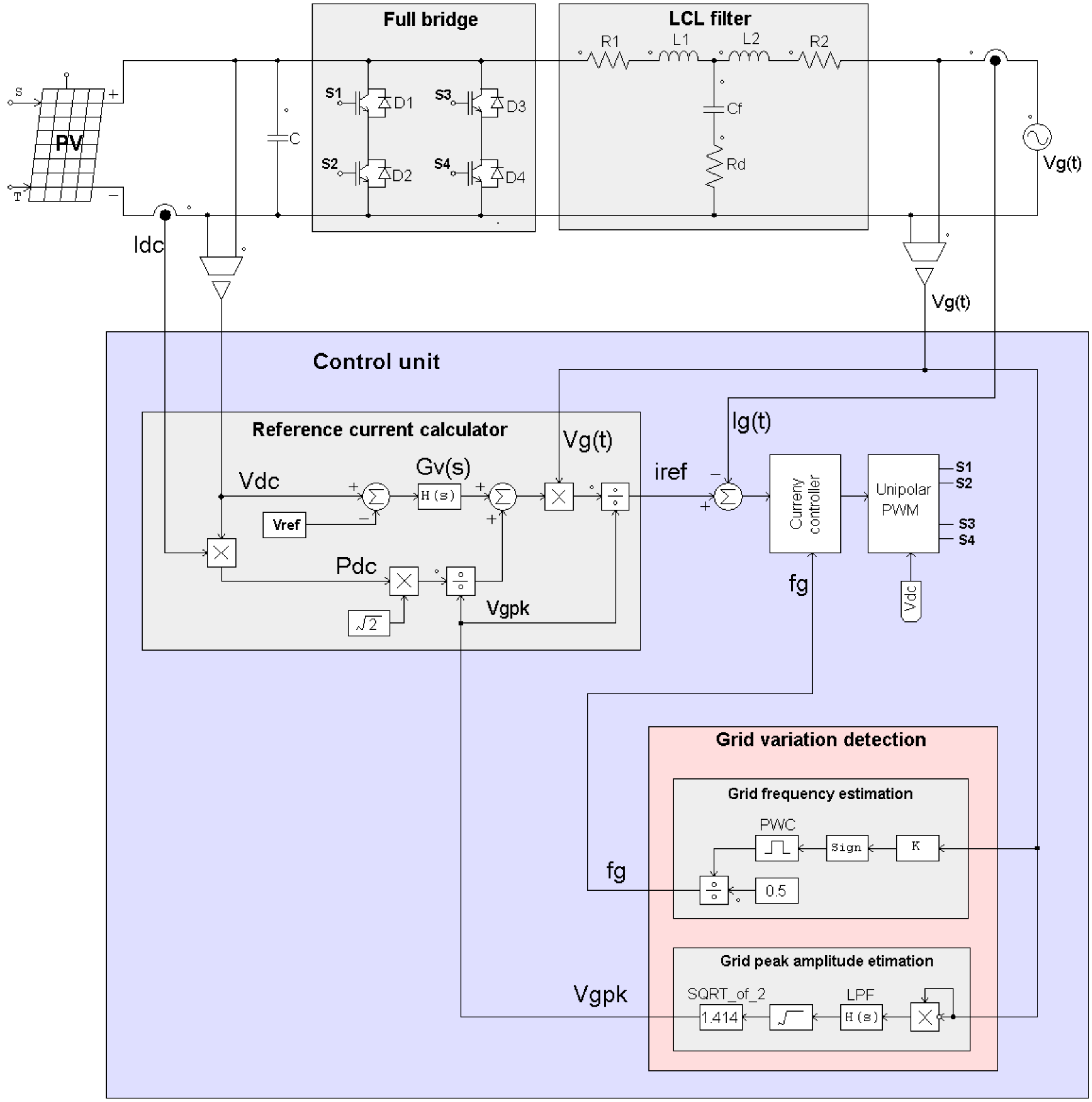

Fig. 1. Single-phase single-stage transformerless inverter of grid-connected PV system

II. Requirements of Grid-Connected PV System

The photovoltaic system connected to the grid involves two major tasks: a) it must be ensured that the solar panels are operated at maximum power point tracking (MPPT); and b) the injected current into the grid ($i_g(t)$) has to comply with some specific standards that are regulated by the utility in each country such as IEEE 1547.1-2005, VDE0126-1-1, EN 50106, and IEC61727. These standard deal with matters like total harmonic distortion (THD) and individual harmonic current levels, injected DC current level and leakage current, the range of voltage and frequency for regular operation, power factor (PF) …etc. [7]. The main requirements for the inverter to be connected to the grid are [7]-[9]:

- Voltage magnitude and phase of inverter must be same as a grid.

- The inverter output frequency must match the grid frequency.

III. Single-Phase Grid-Connected Inverter of PV System

While most of the current research concentrates on large-scale PV system (LSPVS), there appears to be the market for small-scale PV power generation has grown rapidly [9]. In addition, the market of residential PV power generations has grown rapidly in recent years by the encouragement of local governments and utility companies. Some authorities of renewable power have been launched stimulation programs to provide opportunities for homeowners, farmers, and small business owners to develop renewable electricity generation projects. With the help of such stimulation programs, a growing market exists for residential PV inverters. Many companies such as National Semiconductor and Enphase are expanding their business in the area of residential PV inverters.

Unlike LSPVS, residential PV (RPV) system require the inverters to be small, low-power and single-phase units [10]. The RPV, particularly low-power systems (up to 5kW), are becoming more important worldwide. They are usually private systems where the owner tries to get the maximum system profitability. So issues such as reliability, high efficiency, small size and weight, and low price are of great importance to the conversion stage of the PV system [11]. Aiming towards the achievement of this goal, the transformerless inverters are widely used. There are, many topologies of transformerless full-bridge inverters have been proposed [7], [12]-[14]. However, each of those topologies has some advantages and disadvantages, and it is difficult to narrate which topology is better than other. Therefore, the selection of a topology with low components can lead to less complexity of control, and more reliability and efficiency [7].

IV. A Control Strategy for Single-Phase Single-Stage Full Bridge Inverter Topology

The circuit structure of a simple inverter topology of PV system with included output filter and control parts are shown in Fig. 1. The series connected L_1+R_1, L_2+R_2 and C_f+R_d that compose the LCL-type filter, attenuate the harmonics injected into the grid generated from the inverter with the pulse width modulation (PWM) technique [15], [16]. The DC output of the PV array is connected to the inverter through a filter capacitor (C_{dc}) in order to limit the harmonic currents in the array. The current controller sets the inverter output current, such that the desired reference current is injected into the grid. A synthesized AC output voltage is produced by appropriate switching control and consists of a controlled series of positive and negative pulses that correspond to the positive and negative half cycles of a grid sinusoidal waveform.

A unipolar PWM technique with a carrier frequency of 25 KHz is used as the switching controller. This is because this switching technique offers a higher efficiency and higher power output than bipolar switching technique [17].

A. *Reference Current Calculator*

The reference current calculator shown in Fig. 1 is used to convert the maximum extracted power from PV array to maximum current. The reference current (i_{ref}) is obtained in accordance with PV power per grid voltage parameters, as given by (1).

$$i_{ref} = I_{ref} \times ((u_g(t), v_g(t)) / V_{gpk}) \quad (1)$$

Where,

$$I_{ref} = (V_{dc} - V_{ref}) \times G_v(s) + (P_{dc} \times \sqrt{2}) / V_{gpk} \quad (2)$$

Where, I_{ref} is the DC reference source current, i_{ref} is the AC reference current, V_{dc} is the DC link voltage, V_{ref} is the reference voltage of the PV panels, $G_v(s)$ is the transfer function of the proportional integrator (PI) DC voltage controller, P_{dc} is the DC input power, $u_g(t)$ and $v_g(t)$ are the instantaneous grid voltage with and without filtering respectively, and V_{gpk} is the grid voltage peak amplitude.

The amplitude of the I_{ref} is generated on the basis of the error between the dc link voltage (V_{dc}) and the reference voltage (V_{ref}) of the PV panels. The maximum power point tracking (MPPT) algorithm is commonly used to vary V_{ref} according to the environmental conditions in order to keep the operating point of the PV panels close to the maximum power point. However, in this work, V_{ref} is assumed a fixed value close to the V_{dc} and MPPT will not be discussed in the paper.

B. *Current Controller*

It has been demonstrated in [4] that the proportional-resonant (PR) controller gives better steady-state and dynamic performance when compared with the classical PI controller. The PR controller tracks the current, introducing an infinite gain (G_{PR}) at a selected resonant frequency (ω_0) and it is expressed, as given by (3) [15].

$$G_{PR} = K_p + K_i \times s / (s^2 + \omega_0^2) \quad (3)$$

Where, k_p & k_i are the proportional and integral gain, respectively.

However, the infinite gain of the controller at ω_0 leads to an infinite quality factor of the system which cannot be achieved in either analog or digital control implementation. Furthermore, since the gain of an ideal PR compensator at other frequencies is low, it is not adequate to react either to grid amplitude or frequency variation [10].

C. *Frequency Adaptive PR current Controller*

The frequency adaptive PR (FAPR) controller is based on that, the frequency information inside the PR is online provided by the frequency estimator, (Fig. 2). In this way, the control system can be adapted to the frequency changes [4].

D. Grid Variations Detection

The grid variations detection unit is used to detect the values of the specified parameters (*fg*, V_{gpk}) and to provide the reference current calculator with detailed information of the parameter changes [3], [4].

As shown in Fig. 1, it consists of two main parts, voltage peak amplitude calculator, and fundamental frequency estimator (GFE). In GFE (shown in Fig. 1), the sign function converts the ideal sinusoidal signal to a square wave with respect to the zero cross of the input signal. Then the pulse period counter (PWC), counts the period of the half cycle (T/2) of the input signal*. After that, the frequency is calculated by the "1/(2(T/2))" formula. The V_{gpk} value is achieved by using the traditional method of RMS calculation.

When the ideal sinusoidal $v_g(t)$ is assumed, the grid detection structure presented in Fig. 1 is quite adequate to perform the control performance. The synchronization is accurately achieved with respect to the fundamental, as shown in Fig. 4.

When the distorted grid is assumed, an inaccurate synchronization occurs. The GFE cannot choose the exact zero cross point of the fundamental from many zero cross points existed in the input voltage signal, thus an incorrect value of grid fundamental frequency (*fg*) can be provided. As a consequence, the adaptive tuning of the PR controller with respect to its resonant frequency ω_0 cannot be obtained. As a result of this, the current injected into the grid (*ig(t)*) does not exactly have the same phase as the fundamental component of the grid (Fig. 5). This is, in turn, inconsistent with the requirements mentioned in Section 2. Therefore an accurate grid detection and synchronization is required.

E. Accurate grid detection and synchronization

The structure of the accurate grid detection is introduced in Fig. 3. The structure is based on adaptive bandpass filter (ABPF) with no delay (also called second-order generalized integrator (SOGI)) [4].

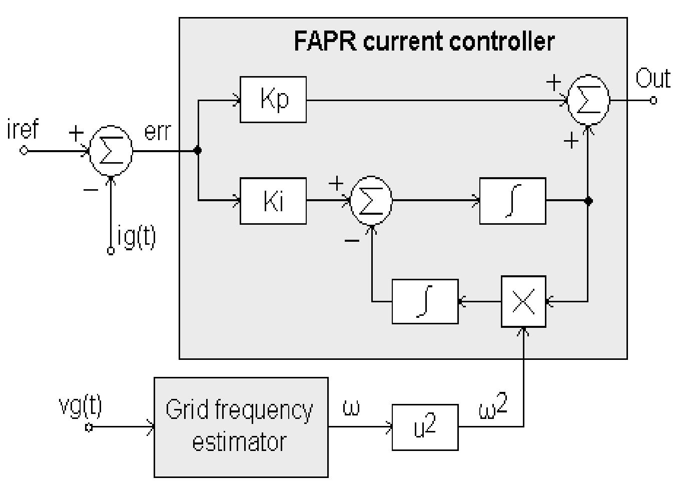

Fig. 2. Frequency adaptive PR current controller.

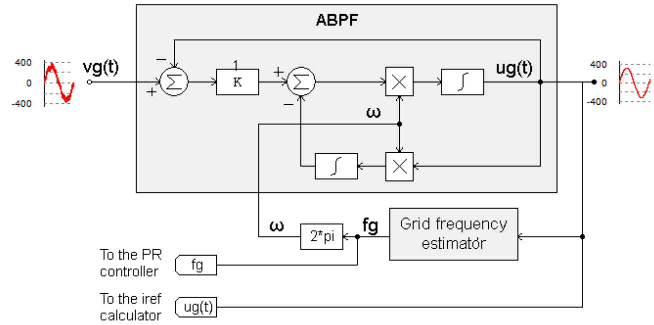

Fig. 3. Structure of the accurate grid detection.

The *fg* and V_{gpk} values are estimated according to the filter output voltage signal ($u_g(t)$). The component $u_g(t)$ has the same phase and amplitude as the fundamental of the input voltage signal ($v_g(t)$), as it can be seen from Fig. 6.

The adaptive tuning of the ABPF is frequency dependent, thus an inaccurate synchronization can occur when grid frequency has fluctuations [4]. Therefore, the resonance frequency of the ABPF is adjusted online using estimated voltage frequency (ω) as provided by GFE.

V. Simulation Results and Discussion

To confirm the control strategy analysis in the previous sections, a GCPVS shown in Fig. 1 with considering the parameters listed in Table 1, was designed and simulated, using (PSIM) software tools.

Fig. 4 shows a perfect performance of the system when $v_g(t)$ is assumed pure sinusoidal. As shown in the top of Fig. 4, the output power remains within the limit boundary of the PV power, even if the V_{gpk} changes from 240 to 320V at 0.5s, the insulation changes from 1000 to 700(W/ m^2) at 1s or the frequency changes from 50 to 55Hz at 1.5s.

Fig. 5 shows the output waveform of the system when the distorted grid is assumed and without using accurate grid detection. It is obvious from the figure that neither the *ig(t)* in phase with the $v_g(t)$ nor the estimated frequency equal the fundamental. Fig. 6 shows how the ABPF is able to generate a clean voltage signal $u_g(t)$ using a highly distorted input signal. As presented in Fig. 6, the $u_g(t)$ has the same phase and amplitude as the fundamental of the input signal. Fig. 7 shows a comparison of the *ig(t)* phase and the phase of the grid when ABPF is used.

TABLE I. List of Parameters Used in System Simulation

Item	Parameter	Value
PV array	***Module in Series and Parallel***	23 and 2
	Irradiance and temperature	700-1000(W/ m^2), 25C°
	PV Output voltage	400V
	PV reference voltage (Vref)	390V
	Output power	3KW
Inverter	***Switching frequency***	25KHz
LCL filter	***L1=L2 and R1=R2***	3mH and 0.02Ω
	Cf and Rd	4.7µF and 10Ω
Grid	***Voltage and frequency***	240-320V and 45-55Hz

* http://www.Powersimtech.com.

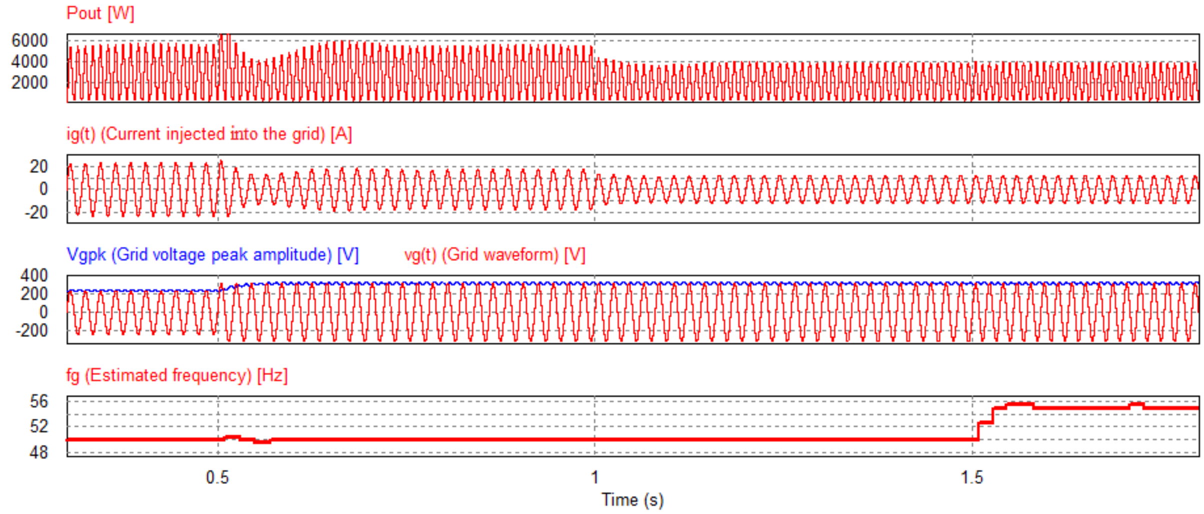

Fig. 4. System output waveform with pure grid assumption.

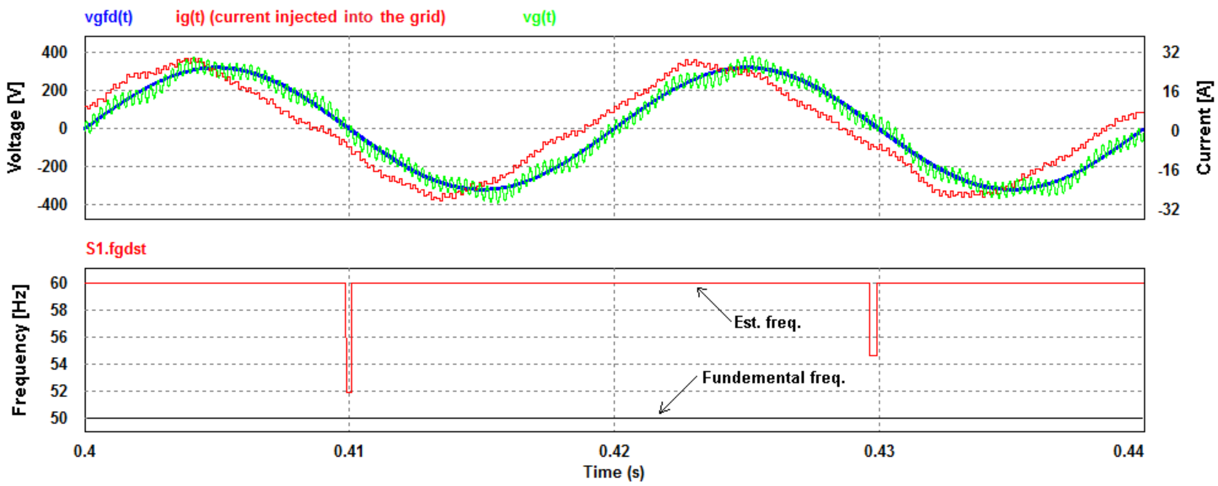

Fig. 5. System output waveform when the distorted grid is assumed and without using accurate detection: (top) Phase of the ig(t) vs the actual phase of $v_g(t)$, (down) Estimated frequency vs fundamental grid frequency.

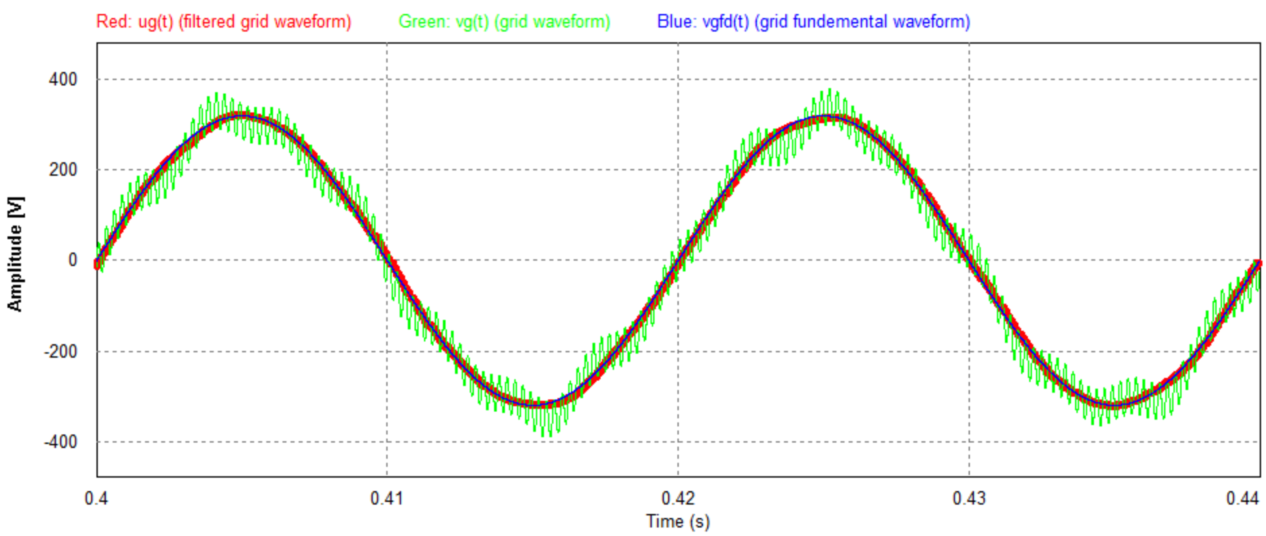

Fig. 6. Phase and amplitude of the ABPF output vs distorted $v_g(t)$.

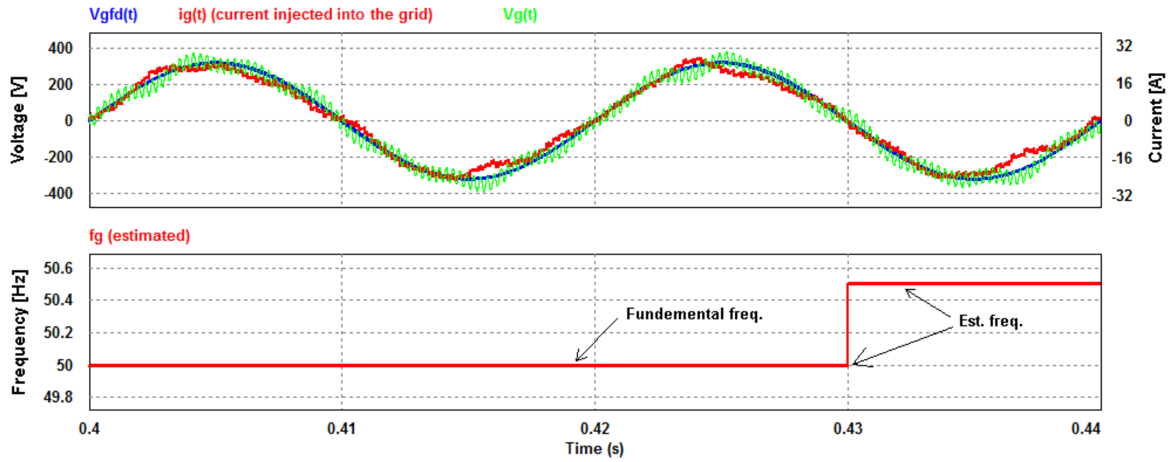

Fig. 7. System output waveform when the distorted grid is assumed and with using accurate detection: (top) Phase of the ig(t) vs the actual phase of the $v_g(t)$, (down) Estimated frequency vs fg.

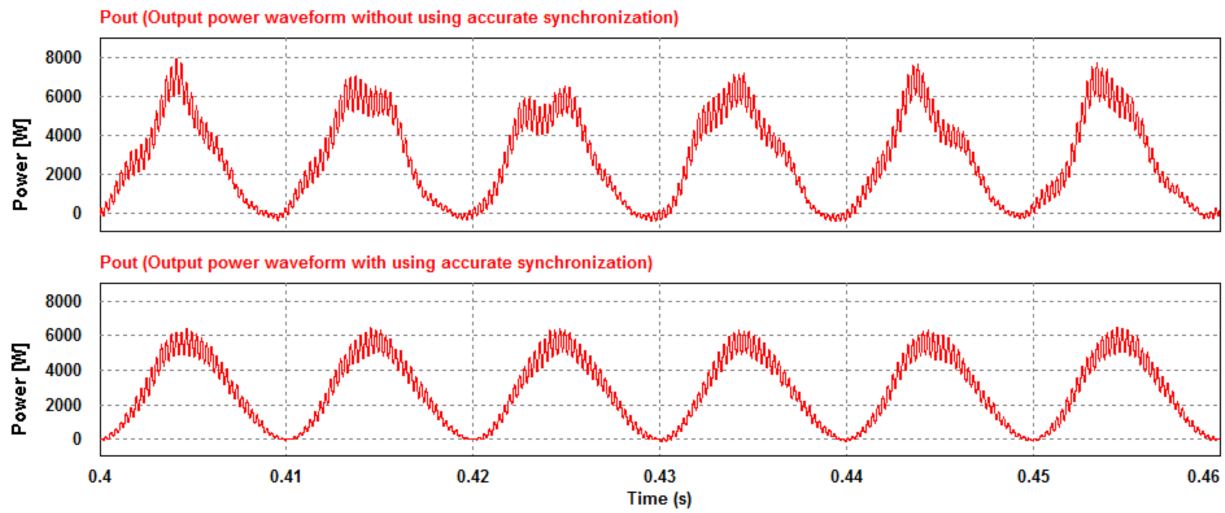

Fig. 8. System output power behavior when distorted grid is assumed: (top) Without using accurate grid detection, (down) With using accurate detection.

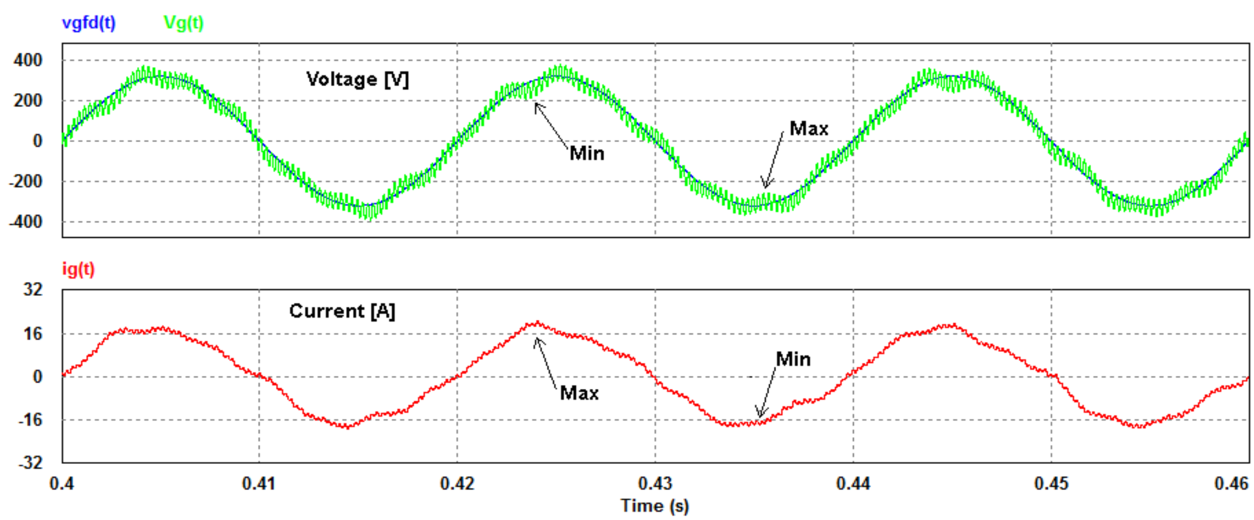

Fig. 9. Instantaneous behavior of the ig(t) vs instantaneous deviation of $v_g(t)$ around the fundamental.

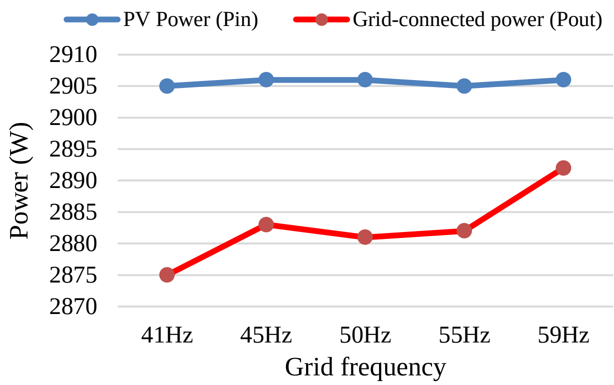

Fig. 10. Grid-connected power vs frequency.

As it can be seen from Fig 7, the *ig(t)* and $v_g(t)$ are in the same phase whereas the estimated frequency is consistent with fundamental.

Fig. 8 shows the behavior of the output power for the case when the distorted grid is assumed. It is obvious from the lower part of Fig. 8 that the output power waveform is more regular with using accurate grid detection. The interpretation of this regularity is that the deviation of the grid around the fundamental waveform (*vgfd(t)*) is compensated by an opposite one in the inverter output current, as indicated in Fig. 9. These in turn yield to the improvement in the output power wave shape.

In order to show the dynamic performance of the proposed control strategy under frequency variation, simulation results of the grid-connected power (Pg-c) under different grid frequency are shown in Fig. 10. It can be observed that the (Pg-c) is kept within the slight change when the grid is having other than 50Hz frequency.

VI. Conclusion and Future Work

This paper presents an adaptive controller for single-phase transformerless inverter of GCPVS under grid abnormal conditions like the distorted grid. An interesting alternative topology using a single-stage inverter, where the dc-dc converter is avoided, has been demonstrated. The advantages of the one-stage inverters are good efficiency, a lower price, and easier implementation. It has been addressed that when the grid-frequency has fluctuations, problems in regulating the current injected into the grid occur. As a solution to these problems, an adaptive tuning of the PR controller with respect to the grid fundamental component has been made. When the distorted grid is assumed, a significant limitation of the synchronization can occur. To overcome this limitation an accurate strategy of control has been introduced. The strategy based on extracting the fundamental component of the grid without delay**.** For validity confirmation, a controlled 3kW system was designed and simulated, in which the parameters shown in Table 1 is considered. The simulation results confirmed that the proposed strategy is an effective way of a GCPVS control under grid variation conditions.

Future work will try to improve the performance of the system with implementing MPPT embedded algorithm in the inverter and verify the proposed system practically.

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