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# Performance Evaluation of an Extended Gain Three-Phase Grid Connected Boost-inverter

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**Abstract**: Three-phase boost-inverter consists of three DC-to-DC boost converters with a common point and operates with boosting capability to feed three-phase star connected Load. The main advantage of that inverter is the use of only six IGBTs and small passive elements to obtain an AC output larger than the DC input. This inverter can amplify power sources such as fuel-cells, small turbines, and photovoltaic arrays (i.e. it is suitable for distributed power applications). In this paper, two main contributions are presented; first is applying the third harmonic injection scheme to increase the boost-inverter gain. This method permits 15% increase in the output voltage without causing any distortion to line-to-line voltages. Second one studying performance of the grid connected boost-inverter. Simulation and experimental results show the effectiveness of that inverter in grid connection applications.

**Keywords**: Boost-inverter, Third harmonic injection, Grid connected inverters, Distributed power

## I. INTRODUCTION

The conventional voltage source inverter is probably the most important power converter topology. It is used in many distinct industrial and commercial applications. One of the characteristics of the conventional inverter is that the instantaneous output voltage is always lower than the input DC voltage. As a result, when an output voltage larger than the input one is needed, a boost converter must be used between the DC source and the inverter.

A single-phase voltage source inverter (single phase boost-inverter) is proposed by Ramón Cáceres and Ivo Barbi [1],[2]. The single stage boost-inverter can generate an output AC voltage larger than the input DC voltage depending on the duty cycle [3].A novel three-phase boost-inverter is proposed in [4], the system consists of three DC to DC bi-directional boost converters with a common point (O) as shown in Fig 1. These converters produce a DC biased sine wave output. The AC component of each converter is 120 degrees out of phase with the other, the main advantage is the use of only six IGBTs with small passive elements to generate an output AC voltage larger than the input DC voltage (i.e. this system can amplify power sources such as renewable energy sources). The main contributions of this paper are:

- Applying the third harmonic injection technique to increase the gain of boost-inverter.
- Studying the performance of grid connected three-phase boost-inverter.

This paper is organized as follow: Section I gives the Introduction of boost-inverter nature. Section II is helpful to understand the principles of boost-inverter topology. Section III explains how to extend the gain of boost-inverter by third harmonic injection. Section IV shows the performance of three-phase grid-connected boost-inverter. Section V validates the concept experimentally, and the last section VI concludes the paper and followed by the references.

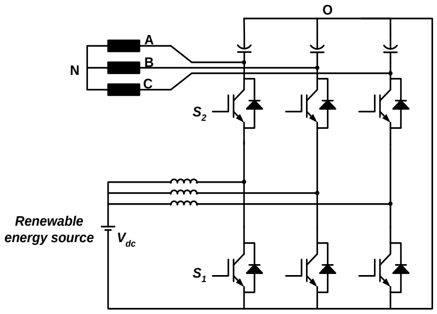


Fig. 1 three-phase boost-inverter

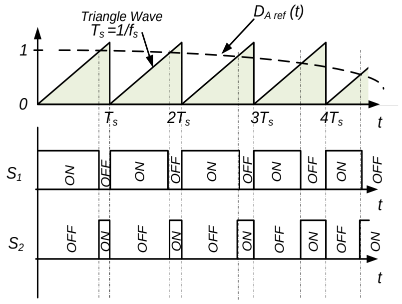


Fig.2 Pulses generation

## II. PRINCIPLE OF OPERATION

Each phase in the three-phase boost-inverter consists of two IGBTs, one inductor and one capacitor. There is a common point for capacitors (O) which connected with the negative terminal of the DC supply. The load is connected to inverter terminals and creates another common point (N) which must not be connected to capacitors common point.

The reference voltage of each capacitor has two components:

- DC component ($K_{dc}$): is the same for all phases and it must be greater than the summation of AC component peak ($K_{ac}$) and DC input voltage ($V_{dc}$).
- AC component: AC component of each converter is with the same magnitude but 120 degrees out of phase with the other converters. As shown in (1)

The load is connected differentially across the capacitors (Fig. 1) to prevent DC component from appearing across the load terminals. Eq (2) shows the converter output line-to-line voltages which can feed any three-phase load.

$$\begin{aligned} V_{AOref} &= K_{dc} + K_{ac}\sin(\omega t+\theta) \\ V_{BOref} &= K_{dc} + K_{ac}\sin(\omega t+\theta-\frac{2\pi}{3}) \\ V_{COref} &= K_{dc} + K_{ac}\sin(\omega t+\theta\frac{2\pi}{3}) \end{aligned} \qquad (1)$$

$$\begin{aligned} V_{AB} &= V_{AO}-V_{BO} = \sqrt{3}K_{ac}\sin(\omega t+\theta+\frac{\pi}{6}) \\ V_{BC} &= V_{BO}-V_{CO} = \sqrt{3}K_{ac}\sin(\omega t+\theta-\frac{\pi}{2}) \\ V_{CA} &= V_{CO}-V_{AO} = \sqrt{3}K_{ac}\sin(\omega t+\theta+\frac{5\pi}{6}) \end{aligned} \qquad (2)$$

For phase-A, the output voltage relation for the continuous conduction mode can be obtained as in (3), where D is the duty cycle of DC-to-DC converter. To get $V_{AOref}$ across the capacitor of phase-A, the instantaneous value of reference duty cycle for this phase can be obtained from (4),

$$\frac{V_{AO}}{V_{dc}} = \frac{1}{1-D} \qquad (3) \qquad\qquad D_{Aref}(t) = 1-(\frac{V_{dc}}{v_{AO_{ref}}(t)}) \qquad (4)$$

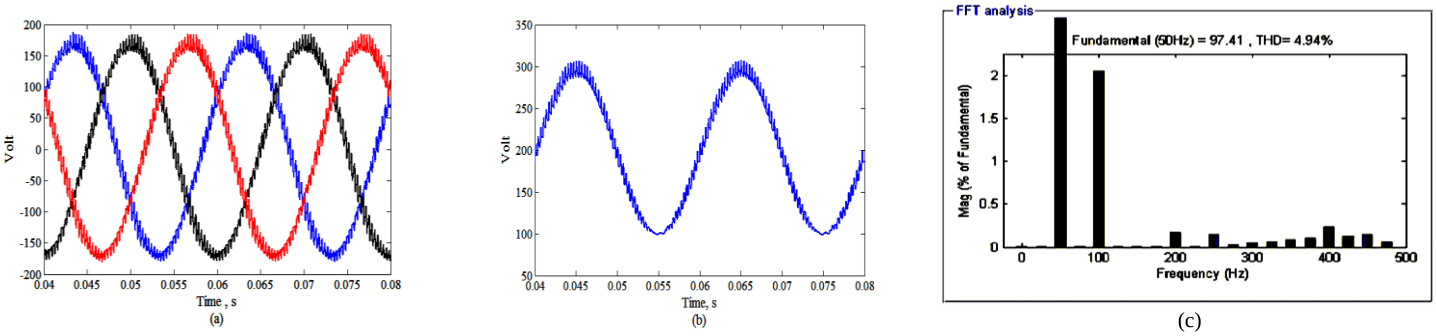
PWM pulses can be generated easily as shown in Fig. 2 where $f_s$is the switching frequency of the inverter. This can be done similarly to phases B and C.MATLAB/SIMULINK package is used to build a model for the three-phase inverter circuit. By adjusting the model parameters with values shown in table I, the simulation results will be as shown in Fig. 3.Fig 3b shows that the AC component of $V_{AO}(t)$ is unsymmetrical due to duty cycle variation; the capacitor voltage ripples in boost converters are linearly dependent on value of duty cycle. This asymmetry means that there is an even harmonic component in the output voltage. Fig. 3c shows the values of even harmonics relative to the fundamental component, it has to be noted that the even harmonics values are within the acceptable limits and less than the IEEE standard values [5].

## III. THIRD HARMONIC INJECTION

Harmonic injection can be used to produce flat-topped phase waveforms which improve the efficiency of the inverter [6-8]. This method has potential for extending the rating of all PWM inverters (increase the output voltage of an inverter). The method involves the addition of third harmonic to the AC component. Third harmonic in a three-phase supply is eliminated from the line-to-line waveforms.

TABLE I. Three-phase Boost-inverter Parameters

| | |
|---|---|
| $V_{dc}$ | 100 V |
| Inverter inductance , capacitance | 1 mH, 40 µF |
| Switching frequency | 3kHz |
| $V_{AOref}$ | 200+100 sin(314t) V |
| AC load | 10 Ω per phase |



(a) (b) (c)

Fig. 3 MATLAB/SIMULINK simulation output(a) Line voltages, (b) capacitor voltage and (c) FFT of phase voltage.

The addition of one-sixth of third harmonic to the AC component has the effect of reducing the peak by a factor of 0.866 without changing the amplitude of the fundamental [9]. This process is illustrated in Fig. 4. It is then possible to increase the amplitude of the modulating wave by certain factor so that the full output voltage range of the inverter is again utilized. By adjusting this factor, the peak of the AC component can equal unity. From Fig. 4 the previous peak was 0.866. Therefore,

$$\frac{1}{0.866} = 1.15$$

Thus as Fig. 4 shows, the addition of one-sixth of third harmonic produces a 15% increase in the amplitude of the fundamental of the phase voltage waveform and, therefore, in the line voltage waveform. The line-to-line waveform is undistorted since the third harmonic components in the phase waveforms will be cancelled.

For DC supply of 100V and DC component of 250V, without Harmonic injection, output phase voltage magnitude up to 150V can be obtained, i.e. 150V is the maximum allowable voltage.

In case of third Harmonic injection output phase voltage magnitude up to 172.5V (1.15*150V) can be obtained. The simulation results for reference input equal to 25% and 50% of maximum allowable voltage are shown in Fig. 5 and 6 respectively. The output voltage is applied across three-phase resistive load (30 ohm per phase). The simulation results are summarized in table II. The simulation results confirmed that, it is possible to increase the output voltage of a three-phase boost-inverter by adding a third harmonic to AC component. The maximum increase in output voltage is obtained when the amplitude of the third harmonic is one-sixth that of the fundamental. The method permits 15% increase in the output voltage.

TABLE II.Magnitude of output phase voltage

| **(Reference AC input ÷ maximum allowable voltage)*100%** | **25%** | **50%** |
|---|---|---|
| **Without 3rd Harmonic injection** | 37.5 V | 74.92 V |
| **With 3rd Harmonic injection** | 43.21 V | 86.31 V |

## IV. GRID CONNECTED MODE

Renewable energy sources require the DC-AC conversion stage meet grid voltage and frequency requirements. In island mode, the inverter regulates the AC bus voltage and frequency to master the AC load. When the grid is restored, the inverter should retain the grid-connection operating mode, where the grid masters the bus voltage and frequency.

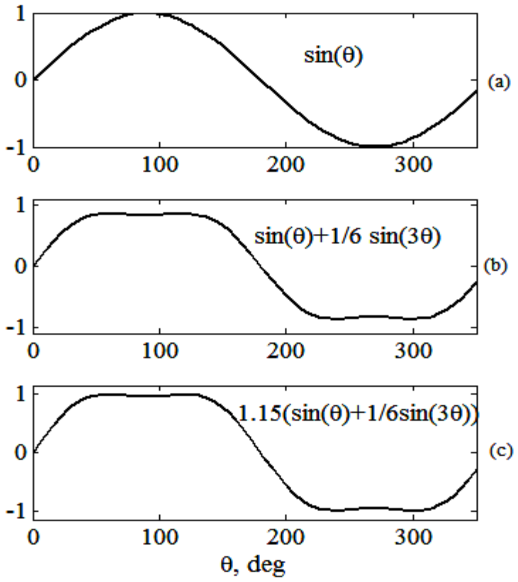


Fig. 4. Increasing fundamental output voltage by addition of third harmonic.

| | Third harmonic peak | Amplitude of fundamental | Peak value of Resultant wave |
|---|---|---|---|
| (a) | 0 | 1 | 1 |
| (b) | 1/6 | 1 | 0.866 |
| (c) | 1.15*(1/6) | 1.15 | 1 |

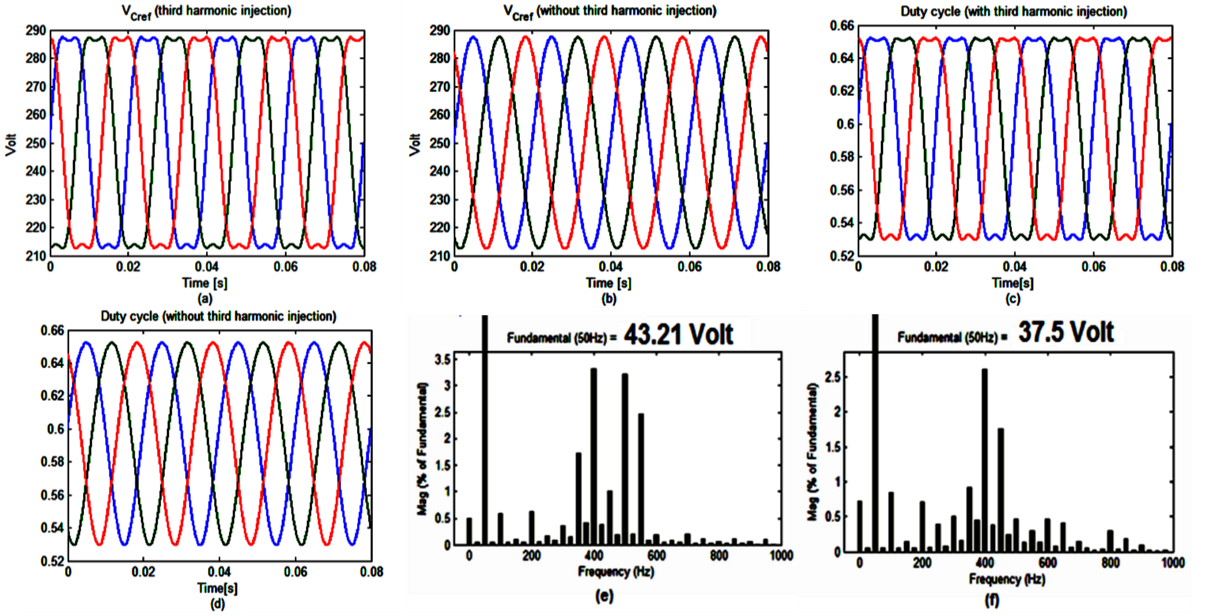


Fig. 5 Reference input is equal to 25% of maximum allowable voltage, (a) reference voltages of capacitors with third harmonic injection (b) reference voltages of capacitors without third harmonic injection (c) Duty cycle of inverter legs with third harmonic injection (d) Duty cycle of inverter legs without third harmonic injection (e)FFT of phase voltage with third harmonic injection and (f) FFT of phase voltage without third harmonic injection

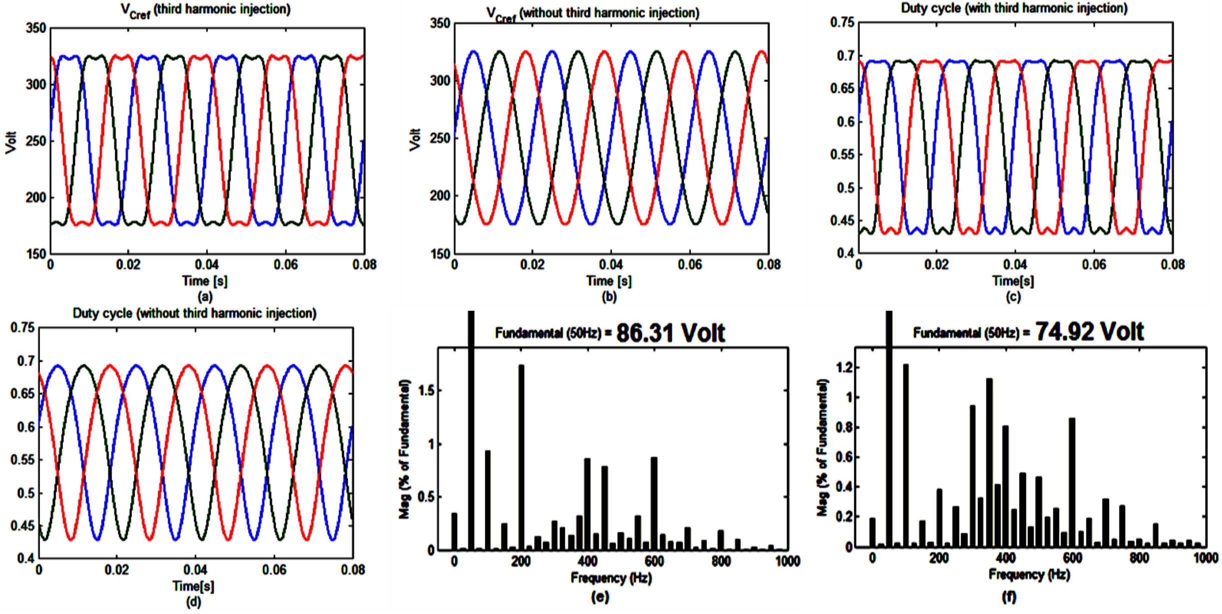


Fig. 6 Reference input is equal to 50% of maximum allowable voltage

Fig. 7 shows the block diagram of the grid-connected boost-inverter. $P_{ref}$ and $Q_{ref}$ are used to determine the desired current components ($i_{gd\ ref}$, $i_{gq\ ref}$) that govern the power flow. A saturation block is used to define the limited overload capability of the inverter. The maximum allowable current is adjusted to be 1.5 times the full load current as the inverter switches cannot be overloaded. Then, a current controller is used to obtain the AC component of capacitor reference voltage (PI current control in synchronous reference frame). Then, a suitable DC component is added to the AC component to obtain the inverter reference voltage. The DC component is selected to guarantee proper operation at unity modulation index (minimum THD), i.e. $K_{dc}=K_{ac}+V_{dc}$.The option of injecting third order harmonic component is shown in Fig.7 at the per-phase PWM generator sub-system.

A MATLAB model has been built with data shown in Table III. The performance of the grid-connected boost-inverter during normal as well as abnormal conditions is studied.

***Case1:*** This case studies the performance of the boost-inverter during normal/healthy conditions. Active and reactive power orders are adjusted to 4kW and 0 VAR respectively, the simulation results are shown in Fig. 8.

***Case 2:***in this case the performance of boost-inverter is tested during faulty condition, a remote fault is applied in the grid that leads to 50% voltage sag at t=0.05s and is cleared at t=0.1s. It is expected that the fault level increases at the specified fault location but due to the limited overload capability of the inverter, the reference voltage is decreased automatically to limit the fault current to 1.5 times the full load current. The simulation results for this case are shown in Fig. 9. The simulation results show the effectiveness of boost-inverterin grid connected applications. Since it has a boosting capability it will be suitable for integrating the renewable energy sources to the grid. In addition, it has a sinusoidal output voltage, i.e. the need of AC output filters is eliminated.

Table III. Grid-connoted boost-inverter parameters

| | |
|---|---|
| $V_{dc}$ | 100 V |
| $L_g$ | 0.3 mH |
| Inverter inductance | 1 mH |
| Inverter capacitance | 0.1 mF |
| Switching frequency | 3 kHz |
| Inverter full load current | 30 A (peak) |
| $P_{ref}$ ,$Q_{ref}$ | 4kW , zero VAR |
| $V_{grid}$(peak) | 100 V (phase) |

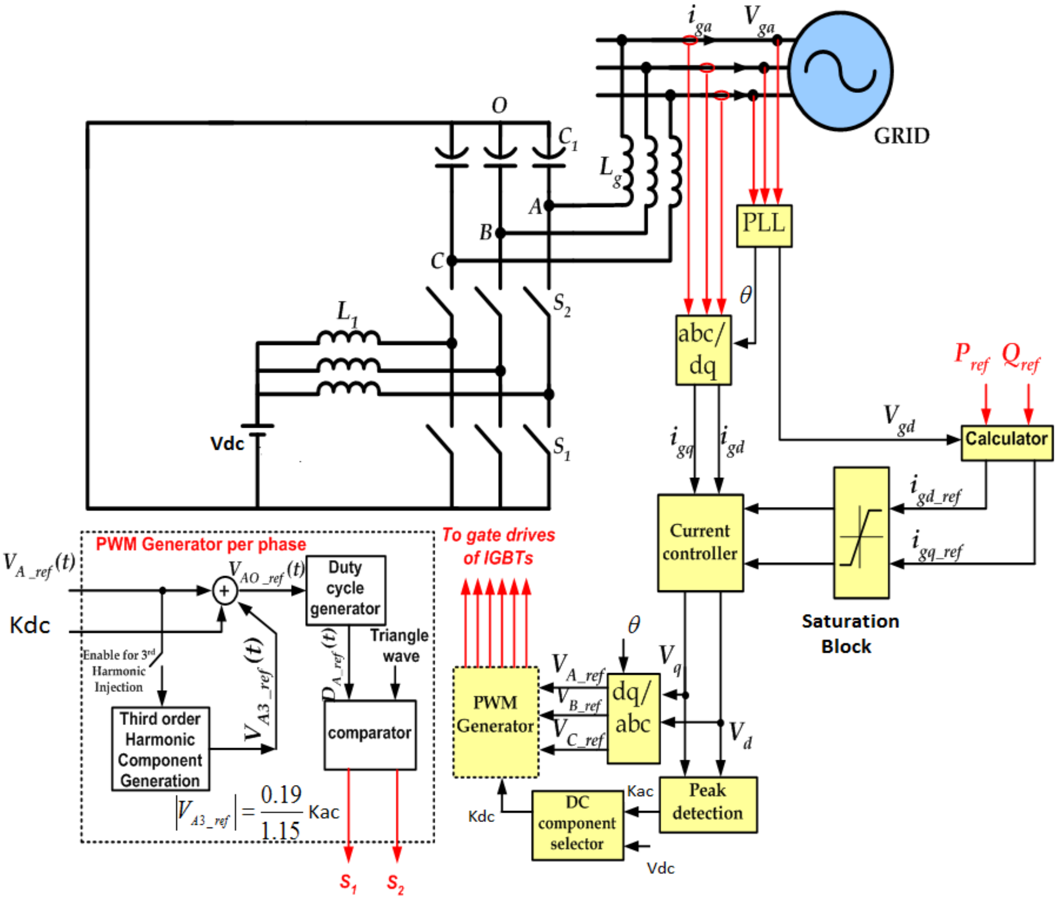
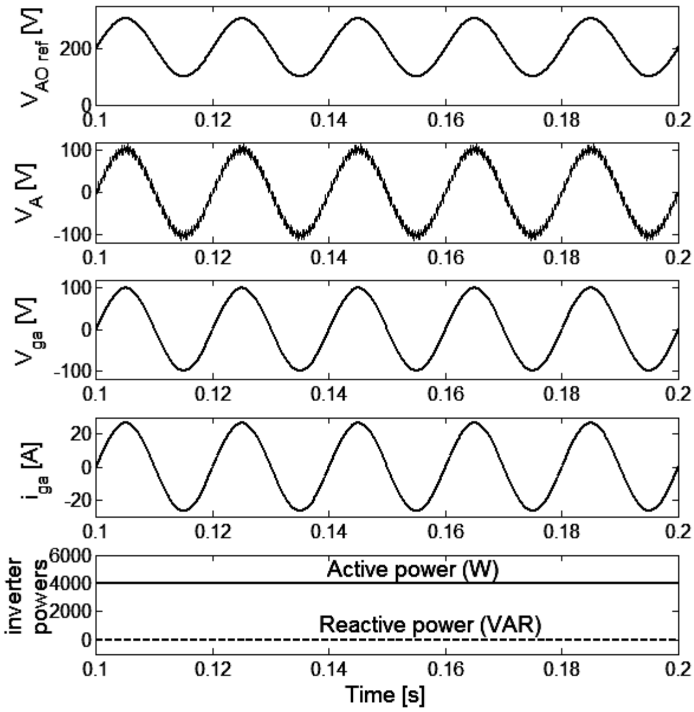


Fig. 7. Block diagram of grid-connected Boost-inverter



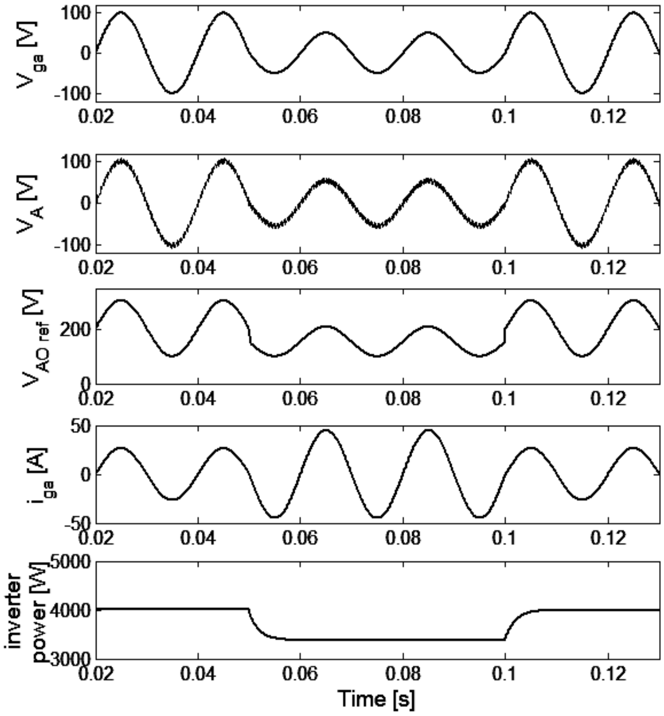


Fig. 8. Case1 simulation resultsFig. 9. Case2 simulation results

## V. EXPERIMENTAL SETUP

An experimental setup was built (Fig. 10) to:

- Validate the normal operation of boost-inverter and show its boosting capability in island mode.
- Exploring the effect of third harmonic injection on its range extension.
- Assess the performance of grid-connected boost-inverter during normal operating conditions.

The experimental setup consists of a three-phase inverter employing six IGBTs driven by a high voltage driver, three capacitors, three inductors, resistive load and DC supply. The firing pulses of 3 kHz switching frequency are generated from Texas Instrument DSP TMS320F28335 to obtain desired phase voltage.
Following tests are applied:

***Test I:*** To validate the normal operation of boost-inverter, parameters of the setup are adjusted as in table IV. The experimental results are shown in Fig. 11a and 11b. It is obvious that the experimental results validate the boost-inverter concept.

***Test II:*** An extended gain boost-inverter is tested by injecting third harmonic order to the AC component. The corresponding experimental results are shown in Fig. 11c. It is obvious that the Inverter gain was extended by 15% without distorting the output voltage.

***Test III:*** The performance of a grid-connected boost-inverter during normal operating conditions was also tested experimentally. In this mode, the boost-inverter was used to inject a certain amount of power (30W, 0VAR) to the grid. Fig. 11d shows the inverter output voltage which is coupled to the grid via an interface reactance. The grid supplied current is shown in Fig. 11e, it is obvious that the grid supplied current is negative with respect to its voltage, i.e. the power (30W) is injected to the grid.

TABLE IV. Experimental setup parameters

| | |
|---|---|
| $V_{dc}$, $K_{ac}$,$K_{dc}$ | 30V, 30V, 60V |
| Output frequency | 50 Hz |
| Switching frequency | 3kHz |
| Inverter capacitance, inverter inductance, Load | 0.04 mF, 1mH |
| AC Load | 25 Ω per phase |

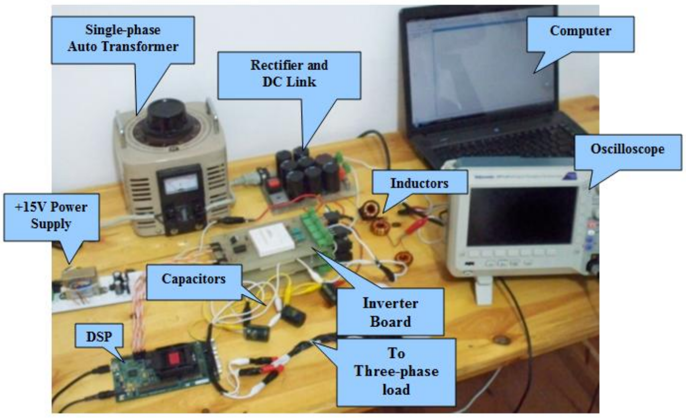
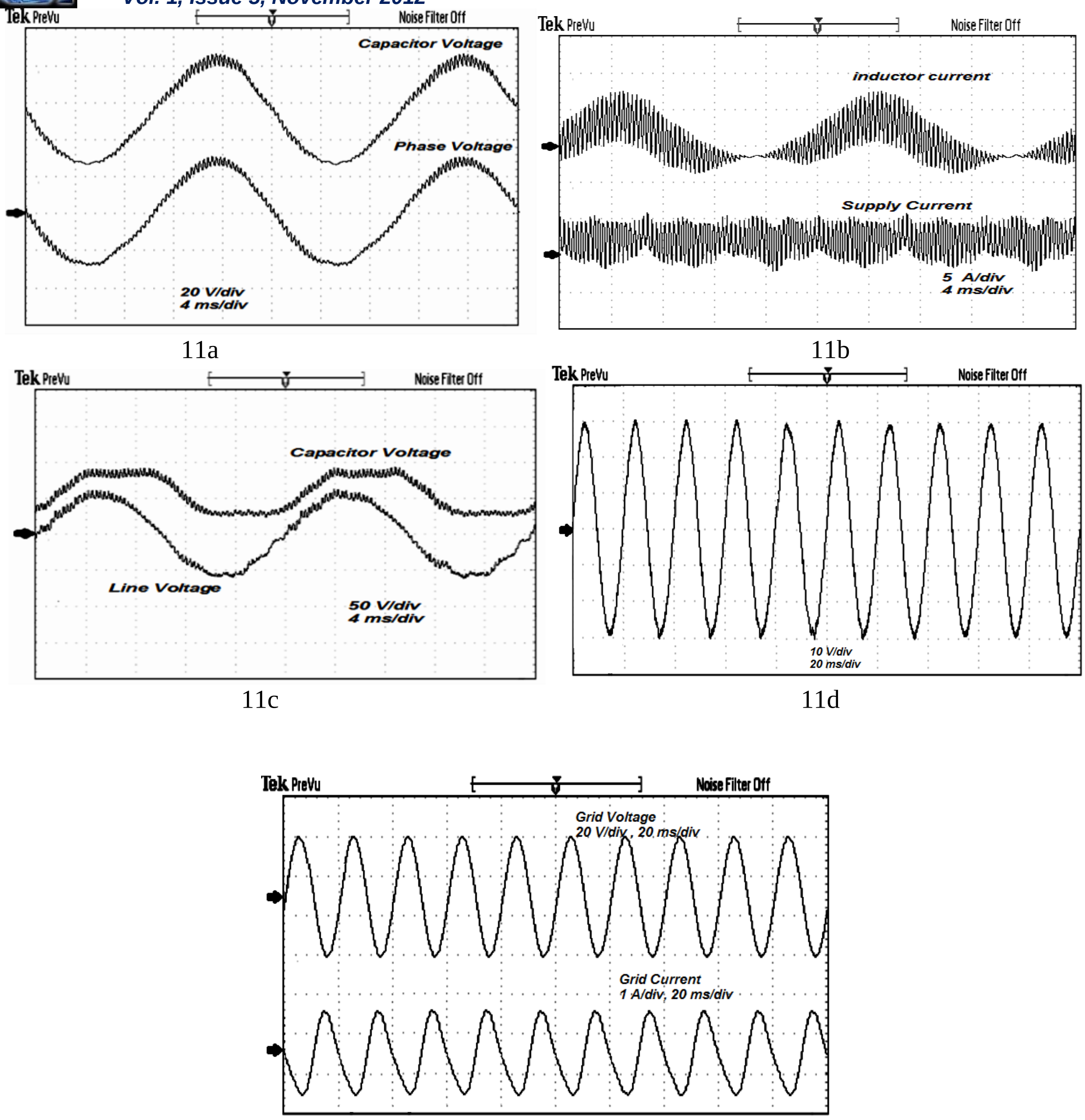


Fig. 10 Three phase boost-inverter Experimental setup



11a

11b

11c

11d

11e

Fig. 11 (a) *Test I:* capacitor and phase Voltage (b) *Test I:* inductor and supply currents, (c) *Test II:* capacitor and line voltage, (d) *Test III:* boost-inverter output voltage and (e) *Test III:* grid voltage and current.

## VI. CONCLUSION

This paper deals with three-phase boost-inverter which is suitable for transferring a specific amount of renewable power to AC loads (low cost distributed inverters). The main contributions of this paper are:

- Applying the third harmonic injection technique to increase the gain of boost-inverter by 15%.
- Studying its performance when connected to the grid.

Simulation and experimental results show the effectiveness of the grid connected boost-inverter during normal operating conditions (transfers renewable power to AC loads). It will be also effective during the abnormal conditions since it contributes with limited fault current due to the maximum current limit in its current controller.

## ACKNOWLEDGMENT

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## Biography

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**S. Ahmed**was born in Kuwait City, Kuwait, in July 1976. He received the B.Sc. degree in electrical engineering from Alexandria University, Alexandria, Egypt, in 1999, and the M.Sc. and Ph.D. degrees from the Department ofElectrical and Computer Engineering, Texas A&M University, College Station, TX, in 2000 and 2007, respectively.From 2001 to 2007, he was with Schlumberger Technology Corporation working on downhole mechatronic systems. He is currently an Assistant Professor with Texas A&M University at Qatar, Doha, Qatar. His research interests include mechatronics, solid-state power conversion, electric machines, and drives.