Improved Transformer-Based Full-Bridge Inverter

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Abstract-The paper presents a improved transformer-based full-bridge inverte. A capacitive full-bridge circuit is added to provide instant current under non-linear load condition and thereby reducing the harmonics significantly even under non-linear load condition. The redundant capacity, cost, size and weight of line frequency transformer can therefore be dramatically reduced. Moreover, a new integrated controller for inverter control is proposed to eliminate both DC current component and steady state error even under heavy load condition. The proposed integrated controller consists of a Fuzzy logic controller acts as voltage controller, DC offset canceller, an RMS compensator and non-linear load compensator. The results derived from a DSP-based inverter system and model was simulated using MATLAB/ SIMULINK software.Also the waveforms of voltage, current, harmonics, DC offset voltage are obtained.

Index Terms-Inverter, Line frequency transformer, Voltage harmonics, Fuzzy Logic Controller, Voltage Controller, DC Offset Canceller, RMS Compensator, Non Linear Load Compensator.

I. INTRODUCTION

In recent years, single phase inverter has been widely used in various applications such as renewable energy conversion UPS, power source, etc. The circuit structure of the single-phase inverter can be divided into half-bridge and full-bridge structures. The main function of the inverter is to provide an AC output voltage with less voltage distortion and harmonics (power quality) under both linear and non-linear loads. The inverter can be divided into transformer-based and transformer-less types to fulfill the requirement of safety standards and the field applications. Although the transformer-less inverter, without line-frequency transformer installed in front of load for isolation, provides the merits of compact size, lower cost, less voltage harmonics yielded by the saturation of line frequency transformer, and fast response, no galvanic isolation between power source and load.

Galvanic isolation between power source and load is one of the most important characteristics of the transformer-based inverter, which is with a line frequency transformer between inverter and load. For higher reliable and serve safety applications, such as medical installations and data center UPS systems which require isolation between the output neutral and power source, transformer-based inverters are heavy in demand. In addition, the transformer-based inverter can block DC voltage and filter out the high frequency noise generated by the inverter and thereby increasing the output voltage range. The harmonic currents of non-linear load may cause excessive losses and flux saturation of line frequency transformer for transformer based inverter. Although some researches on the single-phase Inverter or AC-DC converter with line frequency transformer which make its weight, size and cost to be reduced. single-phase inverter with line-frequency transformer has some advantages over its counterpart at the cost of bulky transformer. And it can be suitable for some applications, e.g. stationary power conversion applications.

The blocking of DC voltage is very important for the load contained magnetic components such as inductor and transformer. Some DC voltage components exist in the output of AC inverter which may cause saturation and increase power loss of the line frequency transformer. Although the implementation of digital-controlled inverter is popular, it is very difficult to eliminate the DC voltage component in output. The research takes the voltage feedback from transformer at the inverter output and uses a low-pass filter to extract DC voltage, and thereby reducing it by control method. In a direct control of current is provided to block DC current component for avoiding core saturation of the line frequency transformer connected at the output of single-phase inverter.

This paper proposes a new digital-controlled single-phase transformer-based inverter for non-linear load applications. A non-linear load compensating module with fast current response, which is constructed by a capacitor-powered full-bridge circuit, is added to load side to provide instant current for non-linear load. The output peak current of DC-AC inverter is limited to the rating of line frequency transformer. Hence, the redundant capacity of line frequency transformer can be significantly reduced and thereby reducing the cost, size and weight, etc. The total harmonic distortion (THD) of load voltage can be reduced under non-linear load condition. Moreover, a new integrated controller for inverter control is proposed to eliminate both DC current component and steady state error even under heavy load condition. The proposed integrated controller consists of a Fuzzy logic controller acting as voltage controller, DC offset canceller, an RMS compensator and non-linear load compensator.

II. PROBLEM DESCRIPTION

For a single-phase transformer-based inverter, the DC voltage is difficultly suppressed to zero at output. The resources of DC component may be yielded from the following mechanisms.

(1). DC offset in PWM circuit or finite data length effect for counter-based PWM circuit.
(2). DC offset voltage in feedback voltage signal
(3). Dead-time effect.
(4). Unmatched characteristics of power switches and its driving circuits.

As a consequence of the DC components may lead to flux saturation in transformer, the inverter may conduct unstable voltage control which may destroy the power switches of the inverter. Because the output current is affected by loaded conditions for the voltage control application, one may not use current regulator to avoid flux saturation.

It is difficult to design proper flux level to meet the requirement of flux in wide frequency range. To meet the requirement of both size and cost of transformer, we usually let the flux level be saturated in low frequency. And this design will cause more voltage harmonics at low frequency operation. In practice, to modulate high frequency signal using both finite carrier frequency and fixed-sampling rate by microprocessor will introduce voltage harmonics.

For line frequency transformer, flux saturation may occur contributed by large non-linear load current and DC component. One of the examples reported in [38] for single-phase rectifier, the total harmonic distortion of input current goes up to 136% and thereby resulting in saturation of transformer, which supplies power to the rectifier.

III. SINGLE PHASE TRANSFORMER-BASED INVERTER

Fig. 1 is the proposed circuit of the inverter. It mainly consists of a full-bridge DC-AC module, a line frequency transformer and a non-linear load compensating module. The structure is simple and generally leads to rather good voltage measurement at LC filter output. In order to reduce the loading effect on LC filter, a leakage inductance L_P of the transformer and a capacitor C installed at load side of the transformer are used to proposed inverter circuit. The voltage sensor is installed in load side of the transformer. The non-linear load compensating module connected in load side is constructed by a full-bridge circuit, an inductor L_O and a capacitor C_O which acts as energy buffer instead of a DC power source. Under non-linear load condition, the capacitor C_O releases energy to share part of the inrush current with the inverter, and supplements its energy from the inverter under constant DC-link voltage conditions.

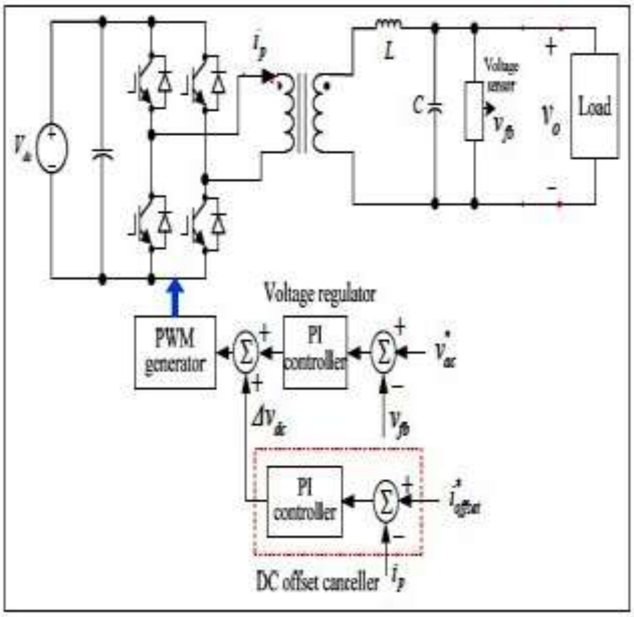

Fig.1 Proposed circuit of single-phase transformer-based inverter

The proposed integrated controller to cope with both linear and non-linear loads is drawn in Fig. 2. The voltage command for PWM generator is yielded from four control modules, namely fuzzy logic-type voltage controller, DC offset canceller, RMS compensator and non-linear load compensator. The Fuzzy logic-type voltage controller is used to generate the main voltage control force. DC offset canceller and RMS compensators are utilized to mitigate the effect of DC component generated by output voltage of the DC-AC module and reduce the steady-state error between voltage command and its feedback, respectively. For further improvement of load side voltage, a non-linear load compensator is added to generate instant current such that both the voltage harmonics and redundant capacity of transformer can be reduced for non-linear load application. A PIC Microcontroller is employed to realize the proposed integrated controller in software. The composite voltage command V_{acT}* shown in Fig.4 is arranged as:

$$v_{act}^*=v_{ac}^*+v_{il}^*=v_{ac1}+\Delta v_{dc\Delta}+v_{il} \qquad (1)$$

$$v_{ac1}=v_{acf}+F_Z(v_1^*-v_{fb}) \qquad (2)$$

$$\begin{aligned} v_1^* &= V_A^* \sin ø \\ &= (\Delta V_A+V^*)\sin ø = v^*+\Delta V_A \sin ø \end{aligned} \qquad (3)$$

where

v^* ($=V^* \sin ø$) : user’s setting voltage command.

v_{acT}^* : voltage command yielded by the proposed integrated controller.

v_{ac1} : voltage command yielded by voltage controller.

v_{iL}^* : voltage command from current limiter.

v_{acf} : voltage command from feedforward controller of voltage controller.

F_z : Fuzzy logic controller.

Δv_{dc} : compensated voltage generated from DC offset canceller.

ΔV_A : load compensating component yielded by RMS voltage compensator.

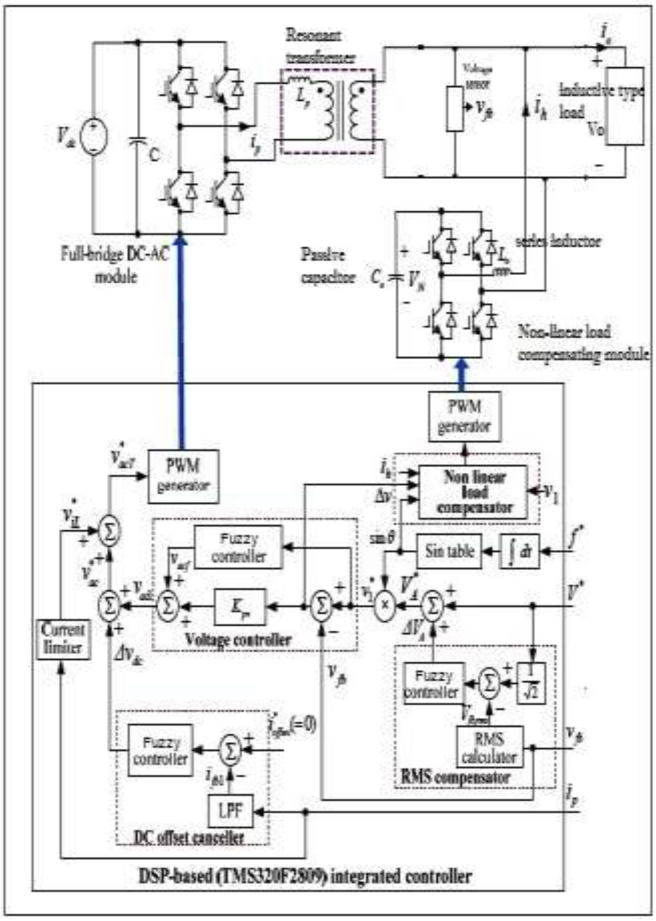

Fig. 2. Proposed integrated controller for non-linear load compensation

The proposed integrated controller is briefly described as follows:

(1) Voltage controller

This controller is in charge of preserving stability and regulating the voltage errors caused by load disturbance and imperfect tracking control. The controller is a composite of command feedforward component, v_{acf}, and amplified voltage tracking error, $F_Z(v_1{}^*\text{-}v_{fb})$. Due to the time delay of detected DC offset current, only proportional gain is used to keep the controlled voltage more stable. This type of voltage controller inevitably led to steady-state error which can be overcome by RMS compensator. Fuzzy logic plus feed-forward controller is used and it is designed with the specifications of bandwidth >400 Hz and phase margin > 30 degrees.

(2) RMS voltage compensator

It is used to mitigate the RMS voltage difference between command and output voltage which is yielded by Fuzzy logic-type voltage controller. The rms value of the feedback voltage v_{fb} is calculated on-line, and the value will be updated every cycle. Fuzzy logic controller is applied to RMS compensator. Due to the limitation of updated time of rms value, reasonable bandwidth of RMS compensator is set. In this paper the bandwidth is 7.5 Hz for line frequency applications.

(3) DC offset canceller

As the DC voltage occurs, the voltage generated by Fuzzy logic-type voltage controller and RMS compensator will be deteriorated without DC offset canceller mechanism. To improve this, a DC offset canceller is developed. From which, a DC current component is detected via the output current i_o by a second-order low pass filter with 5 Hz cut-off frequency. The canceller is arranged to let the DC current be reduced to zero by a Fuzzy logic type closed loop controller.

(4) Non-linear load compensator

Fig. 3 shows the proposed non-linear load compensator. As shown in Fig. 3, a current limiter and a current controller are provided to enhance the accuracy of output voltage under non-linear load condition. The current limiter restricts output current of the inverter to the peak value of rated current of the transformer, and the remaining current required for non-linear load is offered by the non-linear load compensating module. The non-linear load compensator consists of two voltage controllers for different operating modes and one current controller. All controllers are with Fuzzy logic control law. Fig.3 shows the control function block of the non-linear load compensator which provides both charging mode with PFC control and discharging mode with fast current response. The switch SW controlled by the control function of operating mode selection, is used to let the compensator operated between one of these two modes according to the voltage difference $|\Delta v|$ $(=|v_1{}^*\text{-}v_{fb}|)$, which is the difference between voltage command * 1 v and feedback voltage v_{fb} as shown in Fig. 4. According to the Fig. 5, their operations are described as follows:

(i) *Charging mode* $|\Delta v| \le \xi$

It implies that the DC-AC module can offer enough current to load. Hence the non-linear load compensator is operating in charging mode and lets the switch SW be connected in position "*A*". Thus the DC-link voltage V_N of the compensating module is fixed in constant value with active PFC control to reduce the current harmonics. The voltage ξ is a preset value which is adjusted according to the noise level and required response time of the inverter.

(ii) *Discharging mode* $|\Delta v| \ge \xi$

During this period, the DC-AC module can't provide enough current to non-linear load which is caused by the limitation of rating and slow response of the transformer. Hence the non-linear load compensator lets the switch SW be connected in position "B", discharging mode. Thus the compensating module sends out the extra current with fast speed to non linear load.

The parameter ξ is determined such that the output voltage can meet the IEEE-519-1992 standard; more details are as follows. Under the worst condition, the voltage difference Δv is represented by the square wave shown in Fig. 4. The related Fourier series for this square wave is:

$$\Delta v(t) = \frac{2V_M}{\pi}\left[\sin\omega_0 t + \frac{1}{3}\sin 3\omega_0 t + \frac{1}{5}\sin 5\omega_0 t + \ldots.\right]$$

Where w_o is fundamental angular frequency and V_m is peak value of square wave $\Delta v(t)$.

One can find the value of $V_{m.}$ In this paper, for considering resolution and accuracy of AD converter, influence of electric noise, and bandwidth of the proposed non-linear load compensator, the parameter ξ is set as 40~50% of V_m. In order to avoid oscillation between these two modes, a hysteresis band is added in the operating mode selection module.

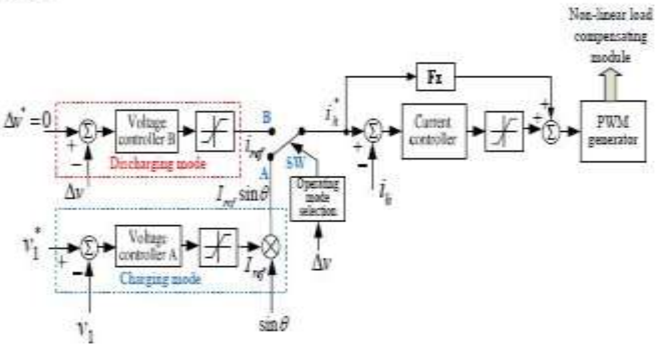

Fig. 3. Proposed non-linear load compensator

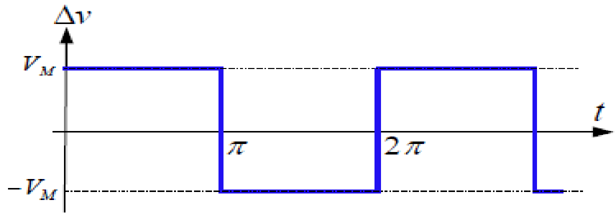

Fig 4. Voltage difference Δv under the worst condition

IV. SIMULATION AND EXPERIMENTS

A. Simulation Results

MATLAB SIMULINK simulated the proposed configuration before it was physically implemented in a prototype. The PWM switching patterns were generated by comparing reference signals against a triangular carrier signal. Subsequently, the comparing process produced PWM switching signals for switches S_1–S_6. One leg of the inverter operated at a high switching rate that was equivalent to the frequency of the carrier signal, while the other leg operated at the rate of the fundamental frequency. Switches S_5 and S_6 also operated at the rate of the carrier signal. The simulation result of inverter output voltage V_{inv}. The dc-bus voltage was set at 300. Therefore, operation is recommended to be between M_a = 0.66 and M_a = 1.0. V_{inv} . The output voltage As I_{grid} is almost a pure sinewave at unity power factor, the total harmonic distortion (THD) can be reduced compared with the THD. The simulation and experimental result of single-phase transformer-based inverter is shown in Fig. 5

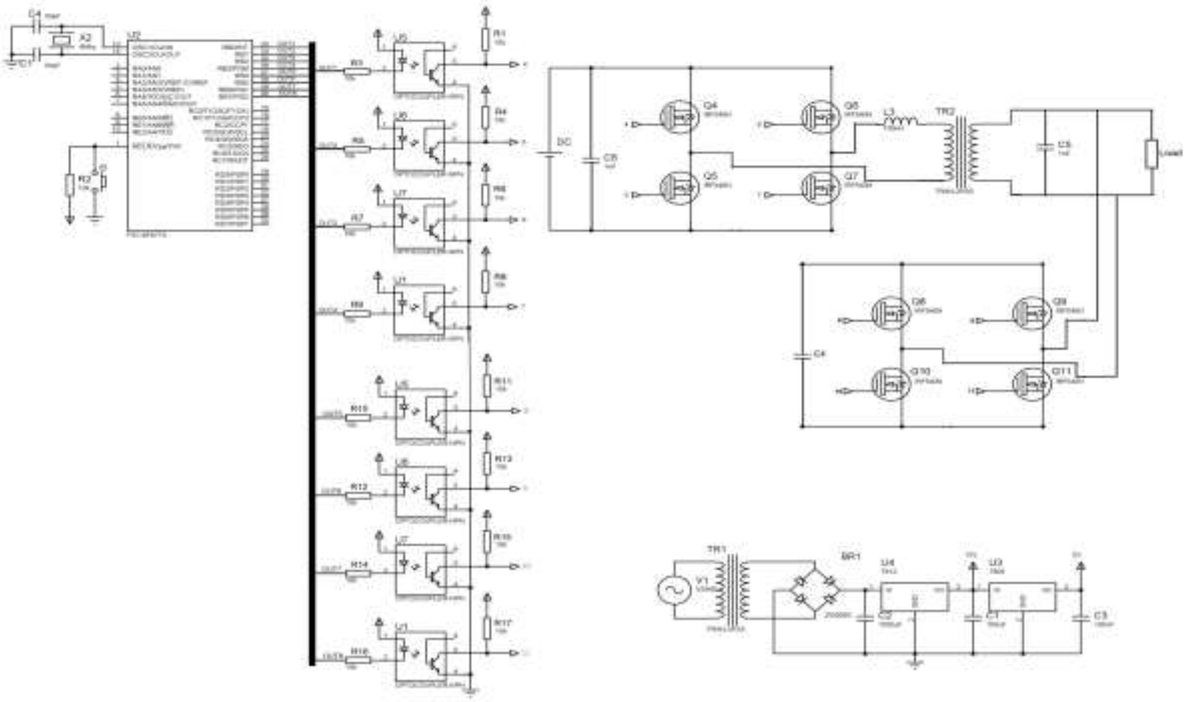

Fig.5 Simulation diagram of Improved Transformer based Full-Bridge Inverter

The key specifications of the proposed inverter and its components are listed as follows Simulations

- DC link voltage V_{dc} of the DC-AC inverter: 200V
- Output voltage v_o : 50 ~120Vrms
- Rated power: 1.5 kVA
- Rated current: 13.6Arms
- Output frequency: 45 ~ 400Hz
- Carrier frequency of the DC-AC inverter: 15.36 kHz
- Sampling rate of voltage and current: 30.72 kHz
- Output capacitor C : 9.4μF
- Leakage inductance of line frequency transformer Lp :1.68 mH
- Magnetized inductance of line frequency transformer :0.671H
- DC-link capacitor Co of the non-linear load compensating module: 3*650μF / 450V
- Output inductor Lo of the non-linear load compensating module: 1.2 mH
- DC link voltage V_N of the non-linear load compensating module: 210V

Simulations provide a safe environment to evaluate even the most extreme outputs, provided a simulation has been validated in hardware. Some commercial drives have error detection and isolation, which would not be helpful if the target is to observe drive performance under non linear load conditions, Simulations of single phase transformer based inverter for non linear load application.

The measured results for different types of control schemes under various operating conditions are provided as follows.

Case 1: voltage controller

The saturation effect of isolation transformer is first evaluated by letting ΔV_A and Δv_{dc} be zero. The measured results with only Fuzzy logic voltage controller, one can learn the following results:

(i) To explore the effect of DC-offset voltage on transformer, the very small gain is used which results in sluggish response and existence of steady state error between user's setting command v^* and feedback voltage v_{fb},

(ii) Duo to the DC offset voltage, the input current i_p of transformer is getting larger to meet the setting value of over current protection. The large current is mainly yielded by saturation effect of the line frequency transformer.

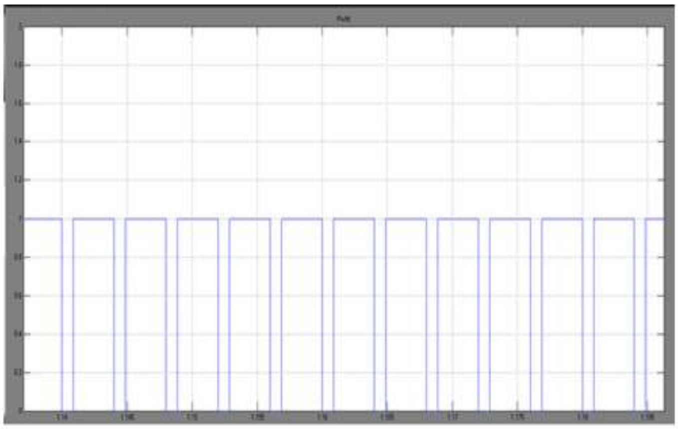

Fig.6 PWM Signal obtained by Fuzzy logic method

Case 2: DC offset canceller

Let the algorithm of the voltage controller of DC-AC inverter be zero, the measured results of proposed DC offset canceller is shown in Fig. 6. The DC offset current i_{fb1},

Case 3: RMS compensator

Fig. 7 shows the measured results with and without the RMS compensator under $110V_{rms}$ /60Hz/rated resistive load condition. There exists steady state voltage error between output voltage $V_{fb,\ rms}$ and its command $V^*/\sqrt{2}$ before starting the RMS compensator.

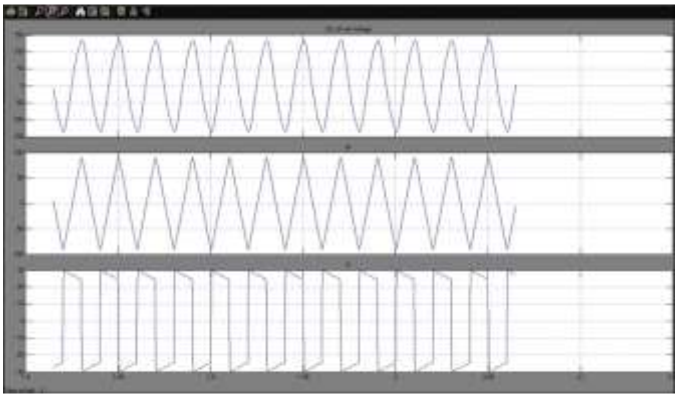

Fig.7 Simulation Waveform of Existing System

Case 4: Proposed inverter control under resistive load

In the performance evaluation for the proposed integrated controller, the steady-state capability is first observed. Fig. 8 show the measured voltage command, v*, input current of transformer, i_P, output voltage, v_o, and its feedback signal, v_{fb}, by the proposed scheme with rated resistive load. The total harmonic distortion of output voltage v_o at $110V_{rms}$ and rated resistive load is listed in Table 1, and the THD for various frequency conditions are all less than 3%.

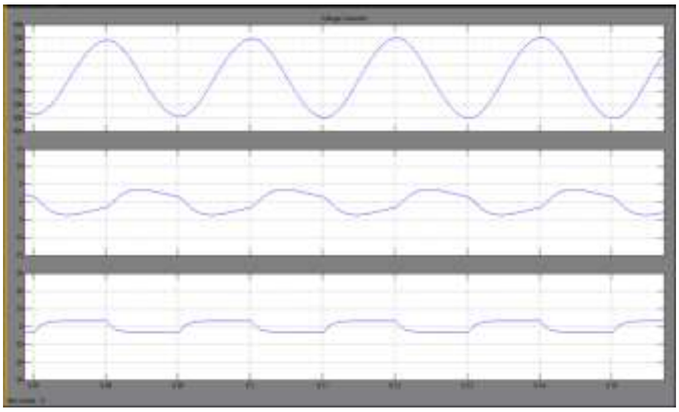

Fig.8 Simulation Waveform for Proposed System

Table1. Measured THD, proposed inverter under rated resistive load

Frequency of V_o	600HZ	200HZ	400HZ
THD of V_o	2.3%	2.4%	2.7%

The total harmonic distortion of output voltage v_o at $110V_{rms}$ and rated resistive load is listed in Table 1, and the THD for various frequency conditions.

Case 5: Proposed inverter control under non-linear load

Fig 11 and 12 are the measured results of the proposed inverter with and without non-linear load compensation under non-linear loading condition, respectively. The non-linear load is yielded by a rectifier circuit and its peak current is set to 30A. Fig. 13 is the measured results to verify the operating mode when the load changes from linear load to non-linear load.

Table 2 shows the measured voltage harmonics with/without non-linear load compensation at different loaded conditions. From these experimental results, the proposed non-linear load compensation can reduce THD of all tested conditions. Moreover, one can observe the peak input current i_P of line frequency transformer is effectively limited to the rated peak current (20A) of the inverter and the THD of output voltage v_o is reduced from 7.95% to 3.82% with non-linear load compensation to meet the IEEE-519-1992 standard. Moreover, the DC-link voltage of non-linear load compensating module powered by capacitor can be maintained at 210V under non-linear load condition.

B. Experimental Results

A TMS320F2812 DSP was used to verify the simulation results. PV arrays of 750 W were used as the inverter's input source. Table.2 shows the characteristics of the PV modules

Table2. PV Module Characteristics

Parameter	Value
Model	SEIMENS P75
Max Power	75W
Short Circuit Current, I_{SC}	4.8A
MPPT Current, I_{MPPT}	4.4A
Open Circuit Voltage, V_{OC}	21.7V
MPPT Voltage, V_{MPPT}	17.0V

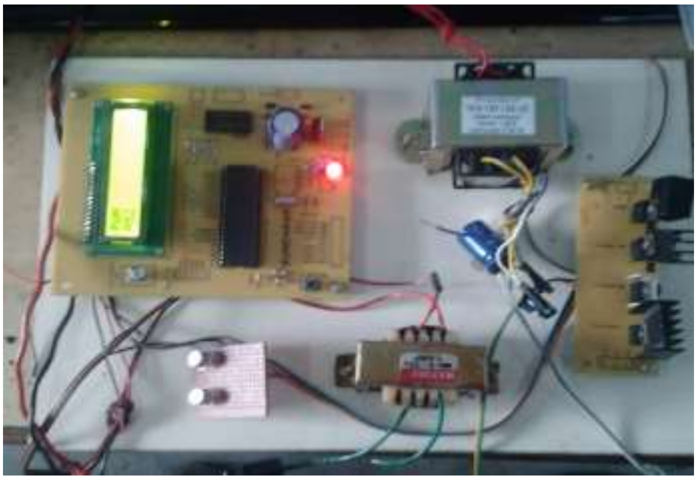

Fig.9 Experimental Setup for Proposed System

used in this paper. Ten modules of SIEMENS SP75 were connected in series to produce 750 W of peak power. Fig.9 shows the prototype of the full bridge inverter. By comparing the three reference signals with the triangular carrier signal in the DSP, the experimental result for Vinv and Igrid. Vinv consists of seven levels of output voltage, and Igrid had been filtered to resemble a pure sine wave. At this instant, the modulation index Ma was above 0.66. The dc-bus voltage was set at 300 V to inject current into the grid. Table.3 shows the experimental result for V_H, I_P and THD which illustrates that both the voltage and the current are in phase.

Table2. The measured voltage harmonics with/without non-linear load compensation

		i_p(peak value)	THD (v_o%)	Voltage harmonics %			
				3rd	5th	7th	9th
IEEE Std			5.0	3.0	3.0	3.0	3.0
750W	W/O	30A	7.95	6.32	4.37	2.06	0.30
	W	20A	3.82	2.97	1.94	0.94	0.70
350W	W/O	16A	5.68	4.09	3.27	2.00	0.69
	W	12A	2.27	1.19	1.30	1.11	0.60
175W	W/O	12A	5.08	3.57	2.95	1.81	0.70
	W	8A	2.19	1.16	1.28	0.99	0.61

FLUKE 43B power quality analyzer measured the THD and the power factor. The THD measurement of corresponds to the waveform. Comparing all three THD measurements, the seven-level inverter produced the lowest THD compared with the five- and three-level ones. This proves that, as the level increases, the THD reduces, which is an essential criterion for grid-connected PV systems.

V.CONCULUSION

Experimental results are carried out on a 1.5 kVA and 45~400Hz single-phase inverter with suitable controller Technique. The results show that the THD of output voltage can be reduced from 7.95% to 3.82% which meets the requirement of IEEE-519 standard under the same non-linear load conditions. The input peak current of the transformer is also decreased from 30A to 20A. Moreover, both DC current component and steady state error can be eliminated to confirm the topology and controller.

The contributions of this paper include:

- Proposal of a new transformer-based single-phase inverter which can significantly reduce the harmonic distortion to meet the related code even under non-linear load condition.
- Proposal of a new integrated controller to eliminate the DC component, steady state error and mitigate the inverter output distortion contributed by non-linear load.
- Presentation of digital-controlled transformer-based single-phase inverter to confirm the above-mentioned claims.

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