Comparative Studies of a Two-Stage Cascade Output Filter Single and Three-Phase PWM Inverters Feeding Rectifier-Types Non-linear Loads

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***Abstract*– Uninterruptible power supply is essential to drive certain sensitive and critical loads that cannot afford to experience unexpected power failure such as computers, some laboratory and hospital equipments among others. These loads, called rectifier-types nonlinear loads because of the presence of rectifier circuits at their front ends, generate harmonics in the power systems. Sinusoidal voltages and currents are distorted by the harmonics generated and create potential problems to the power industry. This paper investigates and compared the performances of the two-stage cascade output filter single and three-phase voltage source PWM inverters (VSIs), feeding rectifier-types nonlinear loads. Simulation was done in matlab/simulink and hardware implementations were successfully done. A voltage total harmonic distortion of 3.44% was obtained for two-stage cascade output filter three-phase PWM inverter and 4.82% for the single-phase PWM inverter respectively, when feeding rectifier-types nonlinear loads. This shows and confirms that a two-stage cascade output filter three-phase PWM inverter has better performance characteristics, such as handling voltage and current harmonics distortions than its single-phase PWM inverter counterpart.**

***Keywords*– Two-Stage Cascade Output Filter, Rectifier-Types Nonlinear Loads, Total Harmonics Distortions, and Uninterruptible Power Supply (UPS)**

I. INTRODUCTION

Uninterruptible power supply is essential to the smooth operation of some sensitive and critical electrical loads, such as computers, TV sets, Photocopiers and hospital and laboratory equipments such as the atomic absorption spectroscopy (AAS) among others. Critical loads such as computer systems, hospitals and airline reservation systems need UPS [3]. The power inverter thus, is an integral solution. These loads are nonlinear and they generate harmonics because of the presence of rectifier circuits at their front end. The prevalence of rectifier-types of such nonlinear loads and their negative effects on power systems makes it significantly important to design suitable power inverters that can deliver sinusoidal voltages and currents with low total harmonic distortions even when feeding nonlinear loads [4], [12]. The share of rectifier-types nonlinear loads is over 50% of present day global load composition [11]. The distortion of sinusoidal voltage and current waveforms caused by harmonics are among the major power quality concerns in the electric power industry [1], [2], [8].

Several research works have been carried out globally with tangible successes on simulation, designs and implementations of suitable power voltage source inverters (VSIs) for various applications. The VSIs are widely used in industries because they behave like natural source of voltage. Modern power inverters can deliver sinusoidal voltage and current even when feeding nonlinear loads. On the other hand, the nonlinear loads draw non-sinusoidal currents even when connected to sinusoidal voltage [5]. The voltage total harmonic distortions of modern inverters must be kept at minimum and according to the recommended limit of the IEEE standard 519-1992: has to be kept at less than 5%. The quality of the output of an inverter is determined by the content of harmonics present in it [10], and therefore should only have fundamental component at the desired frequency. The presence of harmonics could be detrimental to the power systems and other loads connected to it. They could cause electromagnetic interference (EMI) and resonances, increased losses, equipment heating, loss-of-life, and interference with Protection, Control, and Communication Circuits as well as customer loads [9]. In [6], the PWM inverter appears therefore to be the ideal source of voltage for supplying not only Resistance, Capacitance, and Diodes (RCD) type but also all receiver equipment which are generators of harmonic currents. Besides their qualities with respect to voltage and frequency stability, they are the best generators in the market for supplying electronic and micro-processor loads. The performances in terms of handling harmonic distortions and efficiency of a two-stage cascade output filter single and three-phase PWM inverters under rectifier-types nonlinear loads were studied in this work.

II. MATERIALS AND METHODS

The matlab/simulink software was used to simulate 1000VA single and three-phase two-stage cascade output filter PWM inverters feeding rectifier-types nonlinear loads. The fast fourier transforms of the simulated results were also carried out and the total harmonic distortions of currents and voltages were obtained for both inverters. The sinusoidal pulse width modulation (SPWM) technique was employed for the single-phase and space vector pulse width modulation (SVPWM) for the three-phase inverter. A sinusoidal reference wave of 50Hz was modulated with a carrier wave of frequency 4KHz to generate the switching pulses using the ATMEL AT89C51 microcontroller.

A) The Three-Phase Two-Stage Cascade Output PWM Inverter

For the 1000VA two-stage cascade output filter three-phase PWM inverter, another LC low pass filter is placed between the first LC low pass filter and the load. The second LC filter helps to remove some of those harmonics that successfully escaped through the first filter. The schematic of the design is shown in Fig.1. According to [5], the dynamic response of the UPS inverter is mainly determined by the elements of the filter. Therefore, the filters' rating is one of the most important considerations during the designs. The circuit diagram simulated in matlab/simulink is however shown in Fig. 2. The actual circuit design for implementation using the AT89C51 microcontroller was done using the proteus software. The microcontroller was used to generate the switching pulses using a controlled algorithm through a look-up table. The SVPWM technique was applied to the inverter in order to obtain a sinusoidal output voltage with minimal undesired harmonics.

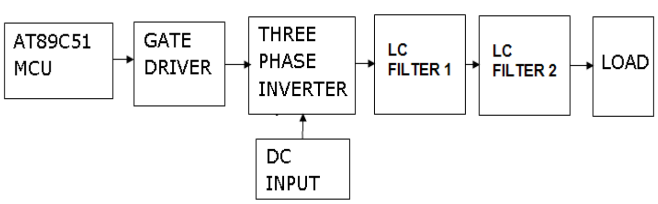

Fig. 1: Schematic of the MCU- 3Phase Inverter

B) The Single-Phase PWM Inverter

The 1000VA single-phase two-stage cascade output filter PWM inverter was also simulated using the matlab/simulink software. The sinusoidal pulse width modulation was used with a reference voltage of 50Hz and a carrier wave of 4KHz. The actual design with the AT89C51 microcontroller was achieved using the proteus software. The block diagram of the single-phase PWM design is given in Fig. 3 while the circuit diagram simulated in matlab/simulink software is given in Fig. 4.

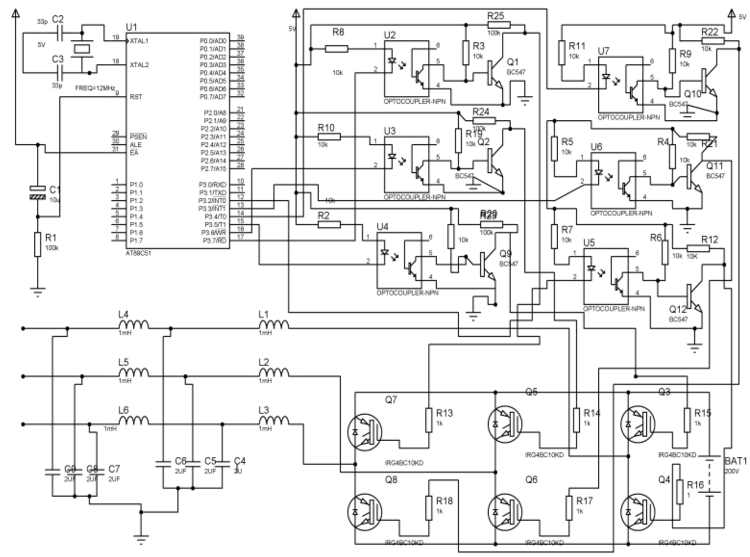

Fig. 2: Circuit Diagram of the Three-Phase Multiple-filter Inverter

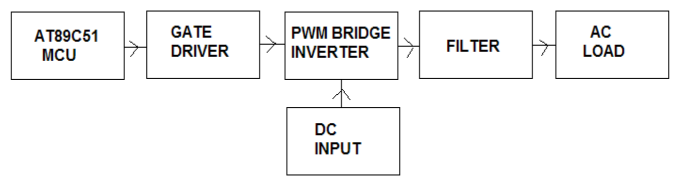

Fig. 3: Block Diagram of the 1-Phase PWM Inverter

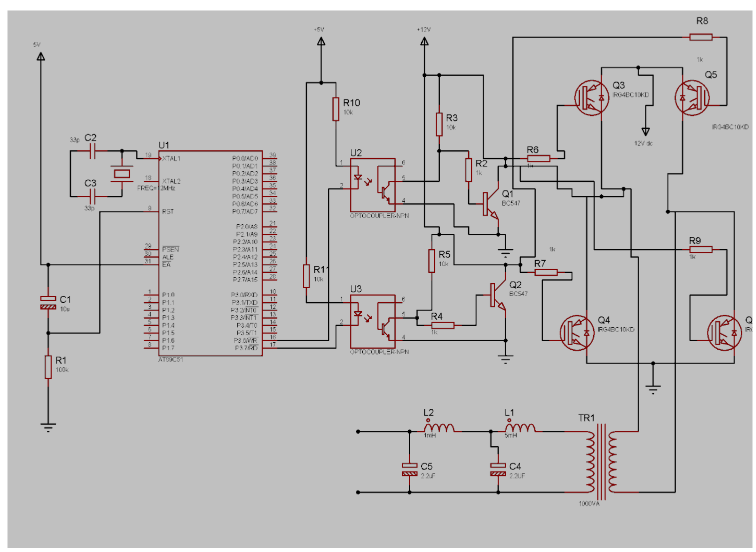

Fig. 4: Circuit Diagram of the Single-Phase PWM Inverter

The Fast Fourier transforms of the two-stage cascade output filter single and three-phase PWM inverters feeding rectifier-types nonlinear loads showing voltage and current total harmonic distortions are shown in Fig. 5 – Fig. 8.

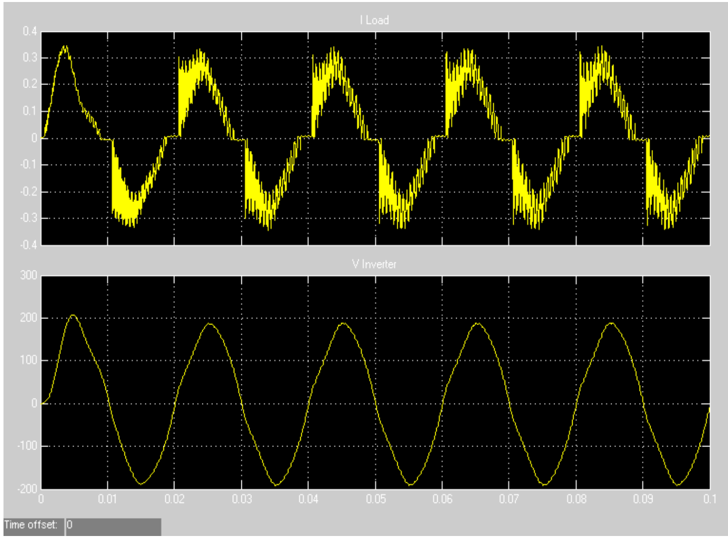

Fig. 5: FFT Analysis of the Single-Phase PWM Inverter's Load Current (ILoad) under Rectifier-type Load

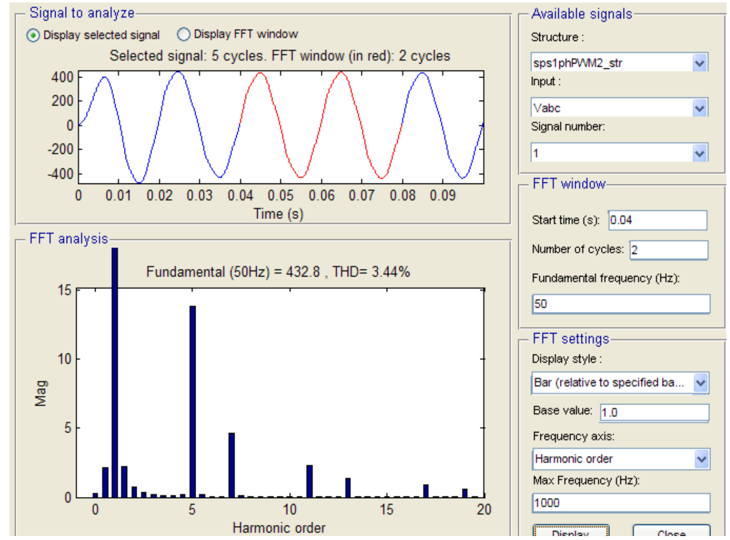

Fig. 7: FFT Analysis of the Three-Phase Inverter Output Line Voltage (V_{abc}) using Two-stage Cascade Output Filter under Rectifier-types load

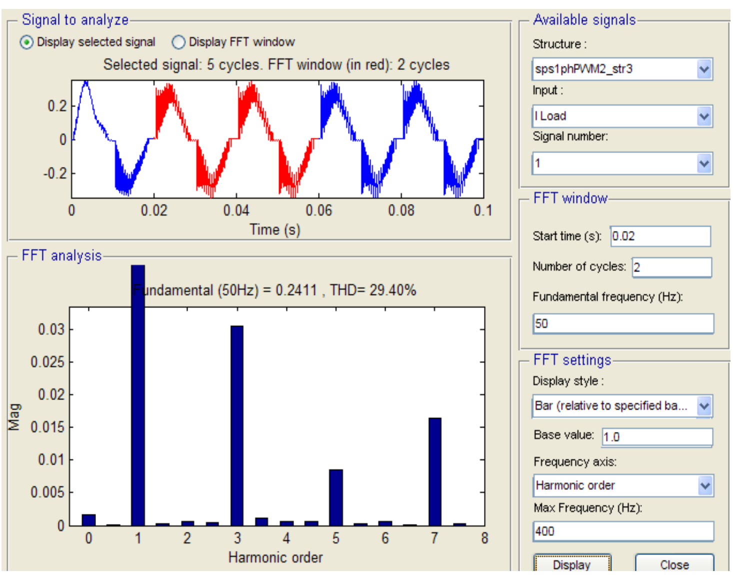

Fig. 6: FFT Analysis of the Single-Phase PWM Inverter's Output Voltage (V Inverter) under Rectifier-type Load

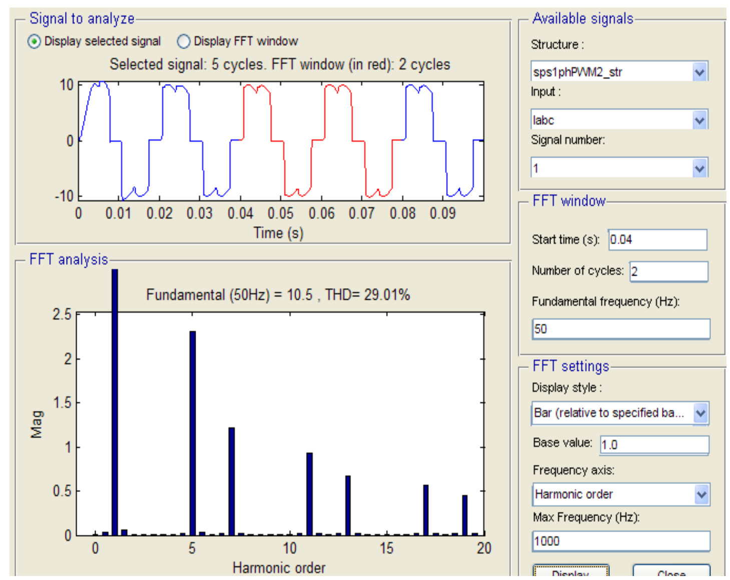

Fig. 8: FFT Analysis of the Three-Phase Inverter line current (I_{abc}) using Two-Stage Cascade Output Filter under Rectifier-types Load

C) Total Harmonic Distortions

The total harmonic distortion is a measure of the harmonic distortions to currents and voltages caused by harmonics in the system. It is prescribed as the ratio of the root mean square (rms) values of all harmonics components present in a signal to the rms value of the fundamental component [12]. Theoretically, the voltage total harmonic distortions (THD_V) and current total harmonic distortions (THD_I) can be determined using Eq. 1 and Eq. 2 respectively.

$$THD_V = \frac{1}{V_{01}} \sqrt{\sum_{n=2,3,..}^{\infty} V^2 on} \qquad (1)$$

$$THD_I = \frac{1}{I_{01}} \sqrt{\sum_{n=2,3,..}^{\infty} I^2 on} \qquad (2)$$

where

V_{on} = harmonics components of output line voltage

V_{01} = rms fundamental component of output line voltage

I_{on} = harmonic components of load current

I_{01} = rms fundamental component of load current

If the rms values of the peak output line voltage (V_m) and peak load current (I_m) are known, then the total harmonic distortions of output line voltage and load currents can be determined using Eq. (3) and Eq. (4) respectively.

$$THD_V\,(\%) = \frac{\sqrt{V_m^2 - V_{01}^2}}{V_{01}} \qquad (3)$$

$$THD_I(\%) = \frac{\sqrt{I_m^2 - I_{01}^2}}{I01} \quad (4)$$

The rms value of phase voltage is given in Eq. (5), the relationship between the rms value of output line voltage (V_L) and rms phase voltage (V_P) is given in eqtn (6), while the fundamental components of line output voltage and phase voltage are given in Eq. (7) and Eq. (8) respectively [7], [12].

$$V_{P,rms} = \frac{\sqrt{2}}{3} V_s \quad (5)$$

where V_s is the source dc voltage,

$$V_{L,rms} = \frac{V_{P,rms}}{\sqrt{3}} \quad (6)$$

$$V_{L1} = \sqrt{3}\, V_{P1} \quad (7)$$

$$V_{P1} = \frac{\sqrt{2}}{\Pi} V_s \quad (8)$$

III. RESULTS AND DISCUSSION

The simulated and experimental results obtained for the two-stage cascade output filter single and three-phase PWM inverters under rectifier-types (R=830Ω, C=2μF) nonlinear loads are given in Table 1 and Table 2 respectively. The simulated results showed that the output line voltage total harmonic distortions (THD_V) obtained for the two-stage cascade output filter three-phase inverter is 3.44%, which is less than 5% within the limit recommended by the IEEE standard: 519-1992. The simulated output voltage total harmonic distortions (THD_V) obtained for the two-stage cascade output filter single-phase PWM inverter under rectifier-types nonlinear loads gave 4.82%. The currents total harmonics distortions for the two-stage cascade output filter three-phase and the single-phase PWM inverters are 29.01% and 29.40% respectively as given in Table 1.

The experimental results obtained from the hardware implementations of the simulated works given in Table 2 showed the output voltages and input dc currents for both inverters. The output currents are of course dependent on the loads and its impedance. The inverters were also tested under RL (R=330Ω, L=0.5mH) linear loads with no appreciable voltage and current harmonic distortions.

IV. CONCLUSIONS

These results show that the harmonics generated by rectifier-types nonlinear loads are better handled with two-stage cascade or more output filter three-phase PWM inverter than using single-phase PWM inverters. Three-Phase PWM inverters are therefore superior to single-phase PWM inverters in terms of handling harmonics associated with non-linear loads.

Table 1: Comparison of FFT Analysis Results for the Two-Stage Cascade Output Filter Three-Phase Inverter and Single-Phase PWM Inverter Under Rectifier-types Non-linear Load

3-Phase				1-Phase	
S/No	Number of Filters	THD_I (%)	THD_V (%)	THD_I (%)	THD_V (%)
1	One Filter	29.10	7.53	65.46	8.63
2	Two Filters	29.01	3.44	29.40	4.82

Table 2: Experimentally measured parameters for the two-stage cascade output filter Three-Phase and Single-Phase PWM Inverters

Parameters	3-Phase	1-Phase
Input DC Voltage (Volts)	241	12.25
Output Line Voltage (Volts)	180	225
Output Phase Voltage (Volts)	104	------
Input Current (Amps)	6.1	3.89

REFERENCES

[1]. Duan, J., Czarkowski, D. and Zabar, Z. (2003), 'Estimation of Load Composition using Multi-layer Feed-forward Neural Networks', 35th North American Power Symposium, Rolla, Missouri, 618-623.

[2]. Duan, J., Czarkowski, D. and Zabar, Z. (2004), 'Neural Network Approach for Estimation of Load Composition', Proceedings of the 2004 International Symposium on Circuits and Systems ISCAS'04, Vancouver, Canada, 988-991.

[3]. Faiz, J. and Shahgholian, G. (2006), 'Uninterruptible Power Supply Systems – A review', International Journal of Electromotion, 13(4), 276-289.

[4]. Faiz, J., Shahgholian, G. and Ehsan, M. (2008), 'Stability Analysis and Simulation of a Single-Phase Voltage Source UPS Inverter with Two-stage Cascaded Output Filter', Euro. Trans. Electr. Power, 18, 29.

[5]. Faiz, J. and Shahgholian, G. (2009), 'Modelling and Simulation of A Three-Phase Inverter with Rectifier-Type Nonlinear Loads', Armenian Journal of Physics, 2(4), 307-316.

[6]. Fiorina, J. N. (1993), 'Inverters and Harmonics – Case Studies of Non-linear Loads', Cahier Technique Merlin Gerin, No. 159, pg. 4,12, 16.

[7]. Gastli, Adel (2014), 'PWM Inverters – Chapter 6', Advanced Power Electronics, retrieved 04 July, 2014, <ape.gastli.info/Chapter4/APE_CH4.pdf>, 3-22.

[8]. Hajagos, L.M. and Danai, B. (1998), 'Laboratory Measurement and Models of Modern Loads and their Effects on Voltage Stability Studies', IEEE Transactions on Power Systems, 13(2), 584-592.

[9]. Pandian, G. and Reddy, S.R. (2009),' Simulation and Analysis of Multilevel Inverter Fed Induction Motor Drive', Indian Journal of Science and Technology, 2, 67-69.

[10]. Qazalbash, A.A., Awais, A., Abdul, M. and Mahveen, K. (2009), 'Design and Implementation of Microcontroller based PWM technique for Sine wave Inverter', POWERENG 2009, IEEE, 163-167, March 18-20, 2009.

[11]. Shmilovitz, D., Duan, J., Czarkowski, D., Zabar, Z. and Lee, S. (2007), 'Characteristics of Modern Nonlinear Loads and their Influence on Systems with Distributed Generation', Int. J. Energy Technology and Policy, 5(2), 219-240.

[12]. Tharkur, N., & Rakesh Singh L. (2014), 'THD Analysis of Output Voltage for VSI fed Induction Motor Drives', International Journal of engineering and Management Research, 4(4), 130-133.

[13]. Zhu, P., Li, X., Kang, Y. and Cheng, J. (2004),'Three-Phase Series-Parallel Double Conversion UPS with Power Quality Conditioning Characteristics', the 4th International Power Electronics and Motion Control Conference, August 14-16, 2004, Xi'an, China, IEEE/IPEMC, 2, 960.