



*Full Length Research Paper*

# Selective Harmonic Elimination Control for AC-DC-AC Regulated Converter

Mona F. Moussa and Yasser G. Dessouky

Arab Academy for Science and Technology and Maritime Transport, Miami, P.O. Box: 1029, Alexandria, Egypt.

Abstract

Static power converters are used for many applications, such as general power supplies. This paper analyzes the performance of single phase AC-DC-AC converter, where the converter consists of two parts, an AC to DC controlled rectifier cascaded with a DC to AC multilevel inverter, so as to increase the number of voltage levels of the inverter to reduce the filter size of the output voltage of the DC-AC converter. Multilevel converter technology has recently emerged as an important alternative in the area of high-power applications. The topology configuration consists of multilevel three single-phase H-bridge inverters connected in series each of which is fed from an unequal DC voltage through a multi-limb output transformer via full controlled thyristor bridges, whose control signals are generated from a closed loop control circuit to maintain constant load voltage for different load conditions. In the literature, several modulation methods have been applied to multilevel inverters where higher switching frequency reduces filter size but increases switching losses. The Selective Harmonic Elimination, SHE modulation method is presented where additional notches are introduced in the multi-level output voltage. These notches eliminate harmonics at the low order/frequency and shifts it a higher order/frequency and hence the filter size is reduced without increasing the switching losses and cost of the system. The proposed modulation method is verified through simulation and also validated practically.

**Keywords:** Selective Harmonic Elimination; Staircase Modulation; Cascaded H-Bridge inverter, multilevel inverter, AC-DC-AC converter, and regulated power supply.

## INTRODUCTION

Today's advance of power semiconductors and digital signal processors with enhanced computational power make possible the development of highly advanced algorithms in order to provide clean power in the presence of highly distorting and unsymmetrical loads. Many advanced control strategies have been proposed so as to improve the performance of the power supply, (Uffe et al., 2000; Liviu, 2002). This paper focuses on the

selective harmonic control to improve the performance of the power supply. The system configuration, as shown in **Figure 1**, is made-up of three single-phase cascaded multilevel inverters.

Multilevel inverters have been drawing growing attention especially in the distributed generation where a number of batteries, fuel cells, solar cell, and micro-turbines can be connected through a multilevel inverter to feed a load or the AC grid without voltage balancing problems (Wu and Song, 2004). The multilevel voltage source inverter is popularly used in high power industrial applications such as AC power supplies, static VAR compensators, drive systems, frequency converters for

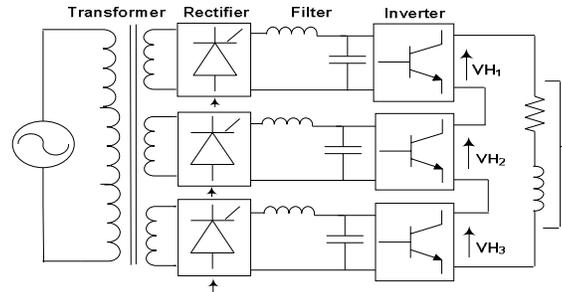


Figure 1. AC-DC-AC converter system.

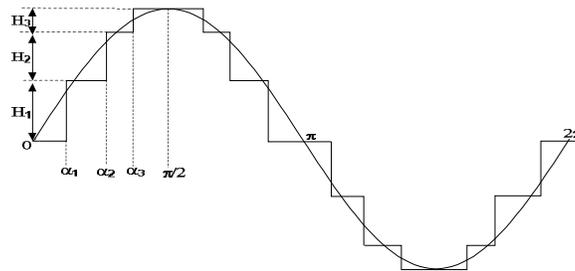


Figure 2. Output voltage waveform of a cascade multilevel inverter.

motors, uninterruptible power supplies and also with ground power units (GPU) for airplanes (Rodriguez et al., 2002). Multicell multilevel inverter systems have been known for medium-voltage/high-power applications in order to reduce the required blocking voltage of the power semiconductor devices. Multilevel inverter technology is based on the synthesis of the AC voltage from several voltage levels on the DC bus (Lezana et al., 2008; Lienhardt et al., 2007; Hosseini et al., 2009; Tianhao et al., 2006). The significant advantages of multilevel configuration is the harmonic reduction in the output waveform without increasing switching frequency and their switching frequency is lower than a traditional two-level inverter, which leads to reduced switching losses (Sule et al., 2007; Rodriguez et al., 2002; Leon et al., 1998; Lai and Peng, 2002; Koyama et al., 2001; Dell'Aquila et al., 2002). Numerous topologies and modulation strategies have been introduced and studied extensively for utility and drive application in recent literature (Massoud et al., 2007). Power electronics researchers have proposed many modulation techniques to reduce harmonics in the inverter output voltage (Bina, 2007; Holmes and Mcgrath, 2001; Muthuramalingam et al., 2006; Du et al., 2006; John et al., 2003). Selective Harmonic Elimination, SHE techniques were introduced in (Leon et al., 2002; Chiasson et al., 2005; Ray et al., 200; Li et al., 2000; Chiasson et al., 2004; JZhong et al., 2005; Chiasson et al., 2003; Filho et al., 2008; OZPINECI et al., 2004; Dahidah and Agelidis, 2008). In this paper, a single phase 220V, 50Hz supply is feeding a single

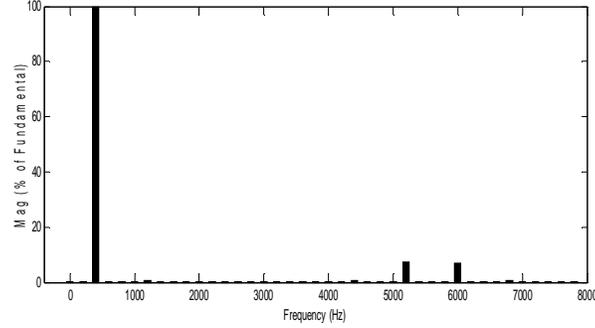
phase step up transformer which has three output windings with different turns ratio. Each winding is connected to a fully controlled thyristor bridge rectifier whose DC output is regulated by a DC link LC filter to feed a single phase H-bridge inverter at a 400Hz. The output voltages of the three inverters are cascade connected to supply a single phase 254V, 20kVA load with regulated voltage through a feedback signal from output load voltage to control the thyristor rectifiers. This power supply is suitable for submarine applications where navigation systems are fed by 400 Hz supply.

### Selective harmonic elimination in multilevel inverter

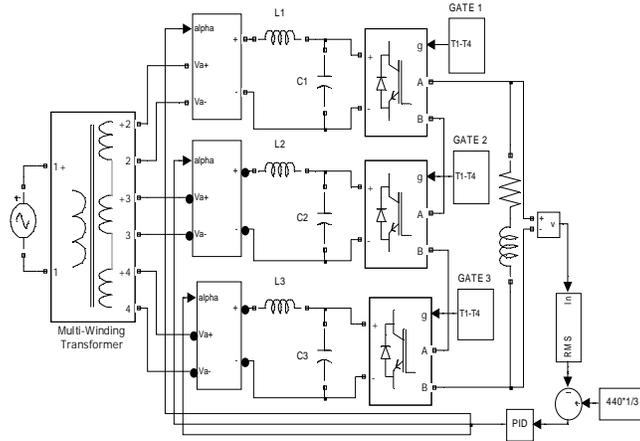
In this paper, a new modulation strategy is used where the turns ratio of the transformers ( $H_1$ ,  $H_2$  and  $H_3$ ) and the pulse width of the three H-bridge inverters are selected to eliminate  $3^{rd}$  to  $11^{th}$  harmonics, thus reducing size of the filter required to obtain pure sin output wave. The concept of the proposed SHE method is to introduce additional notches in the basic voltage waveform of the square wave inverter. The output voltage is chopped a number of times at angles to eliminate the selected harmonics. These angles are calculated in off-line correlating the selected harmonics to be eliminated in the inverter output voltage. This modified modulation method introduces additional notches in the stepped waveform of the inverter output voltages as shown in Figure 2. These notches with their angle are used to eliminate additional

**Table 1.**

$\alpha_1 = 12.86^\circ;$	$\alpha_2 = 38.57^\circ;$	$\alpha_3 = 64.29^\circ;$
$H_1 = 0.445;$	$H_2 = 0.357;$	$H_3 = 0.198;$



**Figure 3.** Spectrum analysis of single phase.



**Figure 4.** Simulink block diagram of single phase AC-DC-AC converter.

harmonics in the output voltage.

### Determination of output waveform shape

The output voltage waveform  $V(t)$  shown in Figure 2 can be expressed in Fourier series as:

$$V(t) = \sum_{n=1}^{\infty} V_n \sin n\alpha_n \quad (1)$$

The amplitude of the  $n^{\text{th}}$  harmonic is expressed only with the first quadrant switching angles  $\alpha_1, \alpha_2, \alpha_3$  as:-

$$V_n = \frac{4V_{dc}}{n\pi} [H_1(\cos n\alpha_1) + H_2(\cos n\alpha_2) + H_3(\cos n\alpha_3)] \quad (2)$$

Where  $0 < \alpha_1 < \alpha_2 < \alpha_3 < \frac{\pi}{2}$

In SHE,  $V_n$  is equated to zero for the harmonics to be eliminated [31], as follows:

$$V_3 = 0 = H_1(\cos 3\alpha_1) + H_2(\cos 3\alpha_2) + H_3(\cos 3\alpha_3) \quad (3)$$

$$V_5 = 0 = H_1(\cos 5\alpha_1) + H_2(\cos 5\alpha_2) + H_3(\cos 5\alpha_3) \quad (4)$$

$$V_7 = 0 = H_1(\cos 7\alpha_1) + H_2(\cos 7\alpha_2) + H_3(\cos 7\alpha_3) \quad (5)$$

$$V_9 = 0 = H_1(\cos 9\alpha_1) + H_2(\cos 9\alpha_2) + H_3(\cos 9\alpha_3) \quad (6)$$

$$V_{11} = 0 = H_1(\cos 11\alpha_1) + H_2(\cos 11\alpha_2) + H_3(\cos 11\alpha_3) \quad (7)$$

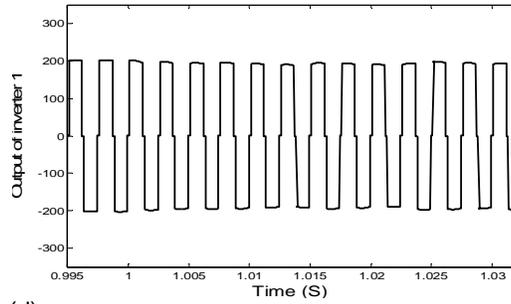
These are five equations and also:

$$H_1 + H_2 + H_3 = 1 \quad (8)$$

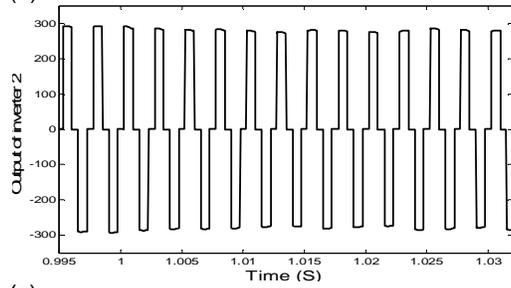
Solving these six equations together using MATHCAD software, the value of  $H_1, H_2, H_3, \alpha_1, \alpha_2,$  and  $\alpha_3$  can be obtained as shown in Table I. Having got the values of the angles  $\alpha$  and DC voltage heights  $H$ , the spectrum analysis using Fourier Transformation for the output voltage is shown in Figure 3 where the Total Harmonic Distortion, THD is 12.9% and the selected 3<sup>rd</sup> harmonic at 1200 Hz to the 11<sup>th</sup> harmonic at 4400 Hz are eliminated.

### Simulation

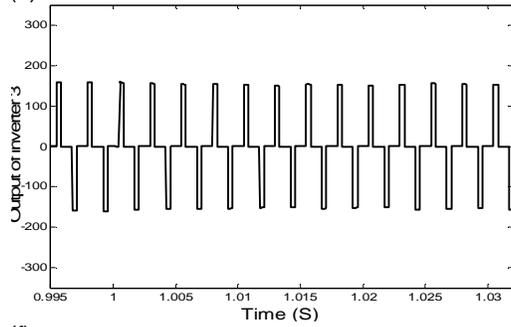
The stabilized AC-DC-AC power supply used is shown in Figure 4 which consists of a step up transformer with one



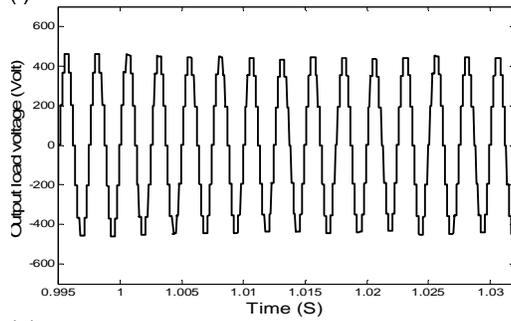
(d)



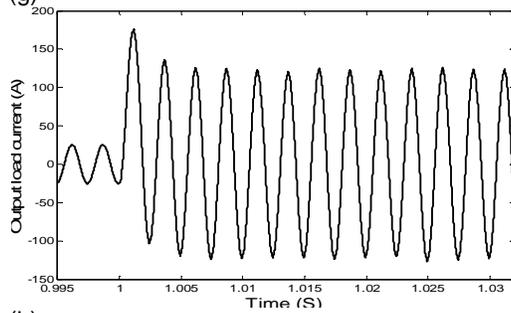
(e)



(f)

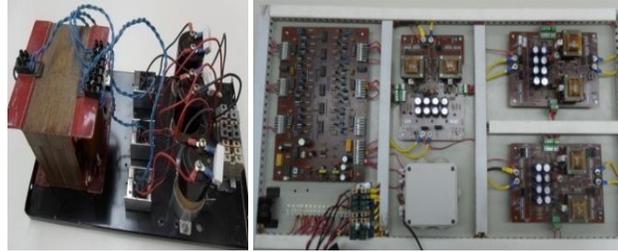


(g)

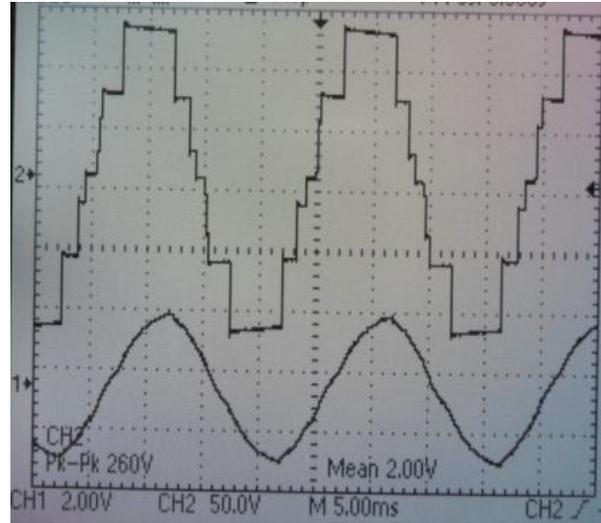


(h)

**Figure 5.** (a) RMS output volt, (b) 3-trans O/P voltages, (c) 3-rectifier O/P DC Volt, (d),(e),(f) 3-quazi inverter voltages, (g),(h) instantaneous O/P voltages and current.



**Figure 6.** Experimental rig.



**Figure 7.** Load [(upper) voltage, (down) current].

primary and three secondary and whose turns ratio are  $(0.8:H_1)$ ,  $(0.8:H_2)$ , and  $(0.8:H_3)$  to compensate for the voltage drop due to impedance of the components, followed by a controlled rectifier and then a low pass filter, therefore, three different DC voltages are obtained. Each DC voltage is feeding a quasi-single inverter whose angles are  $\alpha_1$ ,  $\alpha_2$ , and  $\alpha_3$  (given in table 1) which are cascaded to get the required wave form. This system consists of a load voltage feedback control signal in order to maintain the voltage of the load constant at 254 volt irrespective of the loads variations by controlling the DC voltage levels of through the controlled rectifiers. The inverters operate at 400Hz. The system has been tested from 20% to 110% of full load at time  $t = 1$ s. The transient response results are shown in Figure 5.

It should be noted that some power suppliers use the transformer after the DC to AC inverter to step up the voltage in the 400 Hz frequency level (Holmes and Lipo, 2003) while in this system the step up transformer is used before the AC to DC rectifier in the 50 Hz frequency level which has an advantage of lower iron core losses and less noise. The results of Figure 5 show that the effectiveness of this AC/DC/AC converter to supply a regulated AC voltage regardless of the load changes with low THD without even using a filter across the load.

### Practical implementation

An experimental rig with an open-loop uncontrolled AC/DC scaled-down prototype was built to validate the operation of the proposed power supply, as shown in Figure 6, where a single phase 200VA, 220V step-up transformer has one primary coil and three secondary coils which feed three uncontrolled, 5A, 220V single-phase bridge rectifiers, each of which is connected to a DC capacitor ( $100\mu\text{F}/380\text{V}$ ) to smooth the voltage to result in 200V, 180V, 70V, each of which is connected to an DC/AC semi-quazi H-bridge inverter which consists of four switches IRFP150N. MOSFET, whose gating signals are built on board with the inverter whose widths are  $152^\circ$ ,  $100^\circ$ ,  $50^\circ$ . To protect the MOSFET switches and the thyristor, a soft starting technique is used in the firing and control signals of both circuits. The three inverters are cascaded in series to result in an output voltage free of 3<sup>rd</sup>, 5<sup>th</sup>, 7<sup>th</sup>, 9<sup>th</sup> and 11<sup>th</sup> harmonics. Figure 7 shows the output load voltage and current for a lagging power factor loading while Figure 8 shows the input supply voltage and current. The result showed that the three-step output voltage resulted in an almost sinusoidal current with no need to use a filter. The scope of the work did not include the improvement of the supply current. However, the

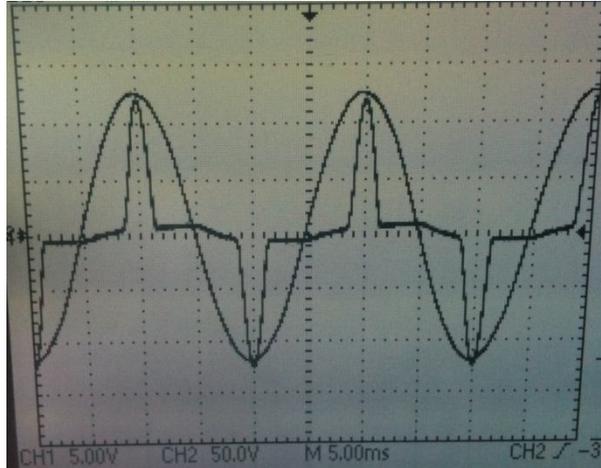


Figure 8. Supply (sin. voltage, current).

transformer could be designed to use multi-phase diodes to eliminate the harmonics in the input current as well. This would result in better performance and less saturation in the transformer core.

## CONCLUSION

A high performance static AC-DC-AC converter is designed. The controller has a good control property. The system topology adopts three single-phase H-bridge inverters such that the three H-bridge inverter is controlled independently in order to improve the performance under different load conditions. With the help of the developed algorithm, the switching angles are computed from the non-linear equation characterizing the Selective Harmonic Elimination problem to contribute minimum THD in the output voltage waveform. Therefore, lower order harmonics like 3<sup>rd</sup>, 5<sup>th</sup>, 7<sup>th</sup>, 9<sup>th</sup> and 11<sup>th</sup> are eliminated and higher-order harmonics are optimized in case of fundamental switching. The selected harmonic elimination is a popular issue in multilevel inverter design. The proposed selective harmonic elimination method has been validated in both simulation and experiment. The simulation and experimental results show that the proposed algorithm can be used to eliminate any number of specific lower order harmonics effectively and results in a dramatic decrease in the output voltage THD. In the proposed harmonic elimination method, the lower order harmonic distortion is largely reduced in fundamental switching. Also, experiments show its validity and feasibility.

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