JPE 16-2-7

http://dx.doi.org/10.6113/JPE.2016.16.2.464
ISSN(Print): 1598-2092 / ISSN(Online): 2093-4718

Selective Harmonic Elimination in Multi-level Inverters with Series-Connected Transformers with Equal Power Ratings

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Abstract

This study applies the selective harmonic elimination (SHE) technique to design and operate a regulated AC/DC/AC power supply suitable for maritime military applications and underground trains. The input is a single 50/60 Hz AC voltage, and the output is a 400 Hz regulated voltage. The switching angles for a multi-level inverter and transformer turns ratio are determined to operate with special connected transformers with equal power ratings and produce an almost sinusoidal current. As a result of its capability of directly controlling harmonics, the SHE technique is applicable to apparatus with congenital immunity to specific harmonics, such as series-connected transformers, which are specially designed to equally share the total load power. In the present work, a single-phase 50/60 Hz input source is rectified via a semi-controlled bridge rectifier to control DC voltage levels and thereby regulate the output load voltage at a constant level. The DC-rectified voltage then supplies six single-phase quazi-square H-bridge inverters, each of which supplies the primary of a single-phase transformer. The secondaries of the six transformers are connected in series. Through off-line calculation, the switching angles of the six inverters and the turns ratios of the six transformers are designed to ensure equal power distribution for the transformers. The SHE technique is also employed to eliminate the higher-order harmonics of the output voltage. A digital implementation is carried out to determine the switching angles. Theoretical results are demonstrated, and a scaled-down experimental 600 VA prototype is built to verify the validity of the proposed system.

Key words: AC to DC converter, DC to AC inverters, Power supply, Regulated power supply

I. INTRODUCTION

The technique of selective harmonic elimination (SHE) has been developed for more than 40 years [1], [2]. The current of linear loads is distorted when supplied from a non-sinusoidal voltage source because of voltage harmonics. If low frequency harmonics are selectively eliminated from a voltage waveform, the resulting current waveform is improved. Specifically, the elimination of a high amount of low frequency harmonics equates to the increased likelihood of the current waveform being sinusoidal. The primary advantages of SHE include providing low switching frequency and directly controlling harmonic components [3]-[8]. Depending on the different types of topologies and different goals of applications, various perspectives can be adopted to formulate SHE problems [9]-[11]. After the formulation of such problems, a set of nonlinear equations, which are traditionally generated from a Fourier series representation and the objective function based on the specific perspective, should be solved before obtaining the desired switching angles [12], [13]. Thus, most SHE applications use solutions obtained from off-line calculations to reduce system complications [14]-[19]. SHE techniques decrease the dependence on passive filters when eliminating low frequency components because filters become prone to losses resulting from the internal resistance among filter components [20]-[23].

Multi-level inverters are a developing technology [24]-[26]. They come in three types, namely, diode clamped, flying

Manuscript received Jun. 9, 2015; accepted Oct. 1, 2015
Recommended for publication by Associate Editor Liqiang Yuan.
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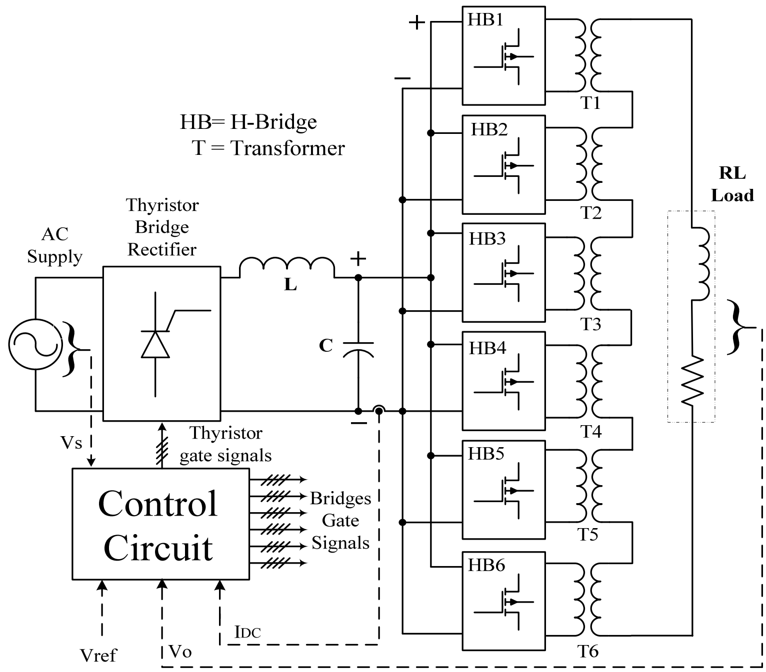


Fig. 1. AC/DC/AC converter using SHE and transformers with equal power ratings.

capacitor, and cascaded multi-level inverters. Compared with diode clamped and flying capacitor-type multi-level inverters, cascaded H-bridge multi-level inverters require the least number of components to achieve the same number of voltage levels. Moreover, an optimized circuit layout is possible for this type of multi-level inverter because each level features the same structure without additional clamping diodes or capacitors. However, as the number of voltage level m increases, the number of active switches of cascaded H-bridge multi-level inverters also increases according to 2×(m−1).

In some AC/DC/AC applications, output transformers are deployed to adapt the voltage level between primary and secondary sides and/or to meet isolation requirements. For example, a static converter provides AC power to communication equipment, such as gyros and radars for marine military ships, in which alternators rated at hundreds of kW and coupled to combustion engines provide 60 Hz, 440 V three-phase line voltages. These line voltages feed the loads of three-phase ships and create several 10 kVA, 60 Hz, 70 V single-phase sources through an open delta transformer to feed on-board single-phase loads. Each single-phase source feeds several communication equipment loads at the 400 Hz, 127 V level. Previously, motor generator sets were used to perform this power conversion at different voltage and frequency levels. However, static converters are now replacing motor generator sets because of their advantages.

Another typical industry application of static converters is the 7.5 kW static converter for the auxiliary systems of underground trains. For this converter, the input is 50 Hz, 220 V single-phase AC voltage, and the output is 400 Hz, 127 V single-phase regulated voltage used for the fans and lighting applications of underground trains, which feature an isolated and low DC voltage level of 48 V to protect passengers from the dangers of damaged equipment wiring.

This study introduces a single-phase AC/DC/AC regulated supply source (Fig. 1) whose input is 50 Hz, 220 V. This supply source is rectified through a semi-controlled bridge rectifier to produce a controlled DC voltage under different loading conditions via a feedback control signal from the output load voltage. The controlled DC voltage then feeds six single-phase quazi-square inverters, each of which supplies a single-phase transformer whose secondaries are connected in series to develop a 400 Hz, 127 V output voltage. Operating at an output frequency of 400 Hz reduces the size of the transformer in comparison with that at an output frequency of 50/60 Hz.

The transformer turns ratio and inverter switching angles are designed to achieve two objectives. The first objective is to achieve equal power ratings for the transformers. Such condition equates to equally sized transformers and thus yields a maximum utilization factor for all transformers that provide isolation between the power and communication systems on a ship. The second objective is to use the SHE technique to produce an output voltage with an almost sinusoidal output current with a power frequency inverter and without the use of a PWM technique and high carrier frequency, which causes bad interference on navigation equipment. The objective also involves not using an AC filter to cause the converter to generate a sinusoidal current and thereby demonstrate good efficiency. Regulating DC voltage levels through an inner feedback control loop from the DC link current and an outer feedback control loop from the load voltage ensures a stable and regulated power supply under different loading conditions.

The present work conducts a theoretical study of the system, as well as a scaled-down experimental system rated at 50 Hz, 220 V, 600 VA input AC supply with an output of 400 Hz, 127 V output voltage. This paper is organized as follows. Section I describes the proposed system and the characteristics of the series transformers. Section III explains the SHE strategies employed along with series transformers and presents a set of full-range solutions with respect to switching angles. Section IV shows a theoretical model of the proposed system using the MATLAB/SIMULINK software. Moreover, the section describes the transient performance and simulated results. Section V compares two supply sources: one with a transformer with an equal power rating implemented with the SHE technique to eliminate some low-order frequencies and another with a transformer with no equal power rating implemented to eliminated harmonics. Section VI shows the experimental results for a 600 VA AC/DC/AC test rig. Section IX summarizes the conclusions.

II. System Description

The system consists of two parts: an AC/DC converter and an AC/DC converter cascaded to a DC/AC converter. The first part involves a standard single-phase semi-controlled bridge rectifier that uses thyristor switches with an input of 50 Hz, 220 VRMS voltage. A second-order DC link filter is connected across the converter output to smoothen the DC voltage, which is kept controlled for different loading conditions to ensure a regulated output voltage. The firing signals of the two thyristors are generated through a two-stage control feedback. First, the outer feedback control loop, in which the error signal between a 127 V command signal and the feedback signal from the output load voltage of the DC/AC converter, is applied to the voltage PI controller. Second, the command signal of the second inner feedback control loop, which is the output of the voltage PI controller, is compared with the measured DC link current signal. Then, the error signal is applied to a second current PI controller to generate the thyristor firing signals. Controlling the DC link voltage consequently results in the regulation of the output voltage of the AC/DC/AC converter from a partial load to a full load.

The DC/AC converter consists of six quazi-square single-phase H-bridge inverters, each of which exhibits a different switching angle αi, where i = 1:6. The six inverters have the same DC input voltage generated from the AC/DC bridge rectifier converter, whereas the output of each H-bridge inverter is connected to a single-phase transformer whose turns ratio is $1:H_i$, where i = 1:6, and the sum of the six H's is adjusted to achieve any required voltage transformation ratio.

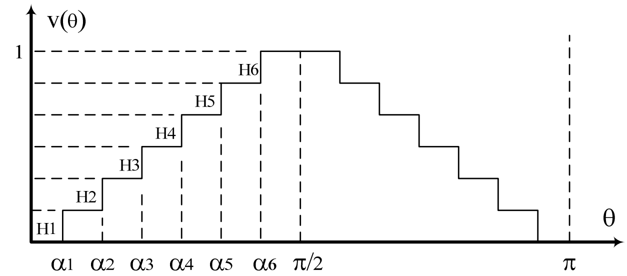


Fig. 2. Output voltage waveform of the DC/AC converter.

Connecting the outputs of the six transformers in series with a unity transformation ratio compensates for the voltage drop in the different parts of the AC/DC/AC converter.

III. Characteristics of Series Transformers and SHE Strategy

A. Transformers with Equal Power Ratings

Fig. 2 shows the output voltage waveform of the DC/AC converter. In this figure, the heights H_1:H_6 are determined by the turns ratios of the transformers, whereas the widths α_1:α_6 are determined by the switching angles of the H-bridge inverters. The 12 unknown values of H_1:H_6 and α_1:α_6 are determined to achieve certain criteria. The first criterion is to achieve equal apparent power ratings so as to obtain six transformers with equal sizes. Equally sized transformers equate to identical transformer core sizes and easy manufacturing even with different turns ratios. The transformer is not rated as active but features apparent power, which is the multiplication of RMS current and RMS voltage [27], [28] because iron losses depend on the voltage applied and copper losses depend on the current that flows through the winding. Given that six secondary windings of the transformers are connected in series, they have the same output RMS currents, which are assumed to be sinusoidal. Therefore, to achieve equal transformer power ratings, the RMS voltages of the six secondary windings should be equal.

Consider that the output voltage of each transformer is a quazi-square pulse. Then, the RMS voltage of any transformer secondary is given by

$$V_{RMS\_j} = \sqrt{\frac{\int_{\alpha_j}^{\pi-\alpha_j} (H_j V_{DC})^2 \, d\theta}{\pi}}; \text{ where j = 1:6} \quad (1)$$

$$V_{RMS\_j} = \frac{V_{DC}}{\sqrt{\pi}} \times H_j \sqrt{(\pi - 2\alpha_j)} \quad (2)$$

Therefore, to achieve the same RMS output voltage for the six secondary windings, equations $H_1^2(\pi - 2\alpha_1)$ to $H_6^2(\pi - 2\alpha_6)$ should be equal. This condition results in five simultaneous equations. Given the fact that the sum of the six H's is unity, a sixth equation is produced. In sum, six simultaneous equations are formed for the 12 unknown values of H_1:H_6 and α_1:α_6 to achieve equal power transformer ratings.

TABLE I
CALCULATED TRANSFORMER TURNS RATIOS AND INVERTER SWITCHING ANGLES FOR EQUAL POWER RATINGS

H_1	H_2	H_3	H_4	H_5	H_6
0.148	0.149	0.154	0.161	0.170	0.218
α_1	α_2	α_3	α_4	α_5	α_6
1.80	11.30	23.30	32.17	40.67	62.57

B. SHE Control of Output Voltage

The second criterion for determining the unknown H's and α's is to achieve SHE control and thereby obtain a stair voltage resulting in a sinusoidal current. Using Fourier analysis for the output waveform shown in Fig. 2, any harmonic component Bi is given by

$$B_i = \frac{4\times V_{DC}}{\pi\times i}\sum_{j=1}^{6}\left(H_j\ \cos(i\times\alpha_j)\right) \tag{3}$$

Eliminating the 3rd–13th harmonics by substituting their components in (3) with zero results in another set of six simultaneous equations for the 12 unknown values of H_1:H_6 and α_1:α_6.

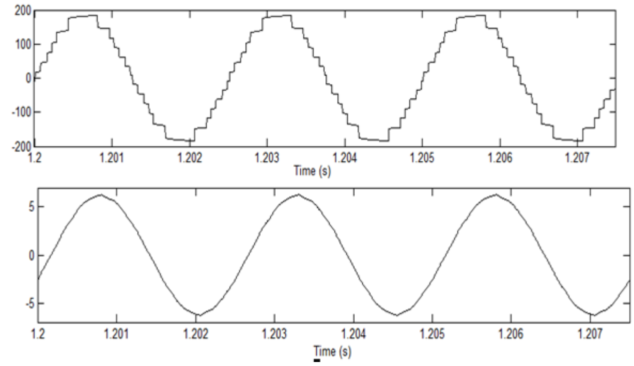
C. Performance Equations for Power Supply with SHE Control and Equal Transformer Power Ratings

A regulated power supply with equal power transformer ratings and an almost sinusoidal output current are achieved with six H-bridge inverters that feature quazi-square waveforms connected to six unequal turns ratio transformers. The design parameters of this power supply are six switching angles and six transformer turns ratios. Sections A and B explain how to derive these equations. The full set of the 12 equations is given in Appendix A.

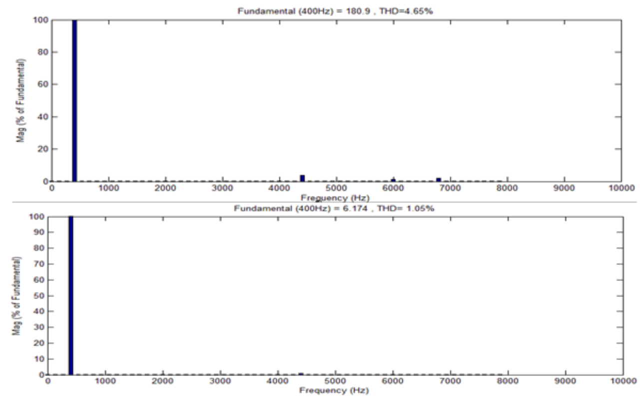
By performing an off-line calculation to solve the 12 equations using the MATH-CAD software, the 12 unknowns are determined (Table I).

IV. SIMULATIONS AND RESULTS

The system shown in Fig. 1 and described in Section II is modeled in MATLAB/SIMULINK. The input is 50 Hz, 220 VRMS single-phase supply voltage. The AC/DC converter is a semi-bridge rectifier. The DC second-order link filter includes an inductor and capacitor of 200 μH and 750 μF, respectively. The DC/AC converter comprises six H-bridge inverters and six transformers, whose switching angles and turns ratios are calculated accordingly (Table I). The full load is an RL single-phase load of 600 VA and 0.93 power factor fed at 400 Hz, 127 VRMS. A feedback signal is compared with a command value of 127 V, and the error is fed to an outer voltage PI controller whose output is cascaded to an inner current loop controller and then used to generate the firing angles of the two thyristors. The converter is initiated at zero time at zero initial condition, and then the load is changed at 9 s from a full load to a half load.



(a)



(b)

Fig. 3. (a) Steady-state wave. (b) Fourier spectrum for load voltage (upper) and current (lower).

Fig. 3(a) shows the steady-state full load voltage and current waveform while Fig. 3(b) shows the Fourier spectrum for the load voltage and current. The figure shows that the total harmonic distortion (THD) of the voltage is 4.6% and that the THD of the current is almost 1%. Fig. 4(a) shows the RMS voltage of each transformer while Fig. 4(b) shows the percentage VA power share of each transformer w.r.t. the total load power. The calculated values of the transformer turns ratios and the calculated switching angles result in equal RMS voltages and equal power ratings. The transient performance of the system when the load is changed from a full load to a half load is shown in Fig. 5 through the RMS command voltage with the actual measured value, output load current, and DC link voltage. The results prove the validity of the system in supplying load with a regulated output voltage under different loading conditions.

As shown in Fig. 3(b), the Fourier spectrum of the load voltage/current produced by the proposed SHE technique is designed to eliminate the 3rd–13th harmonics. However, according to the Fourier spectrum of load voltage, a small unwanted component exists at around 4.4 kHz; this component is the 11th harmonic. This unwanted component emerges because theoretically, the values of H's and α's are calculated using the MATH-CAD software to achieve equal transformer sizes and minimum harmonics with high precision fractions. However, when realizing these values, the three nearest digits are considered as they are practically

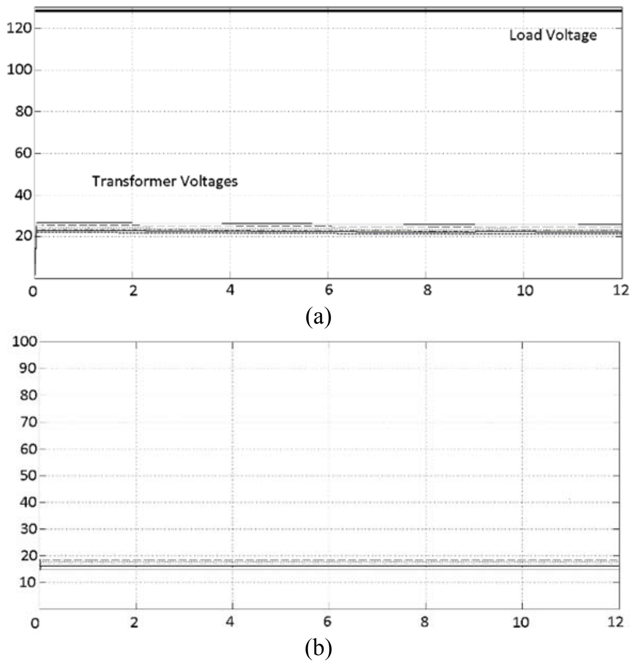


Fig. 4. (a) RMS voltage of each transformer. (b) Percentage VA power share of each transformer w.r.t. total load power.

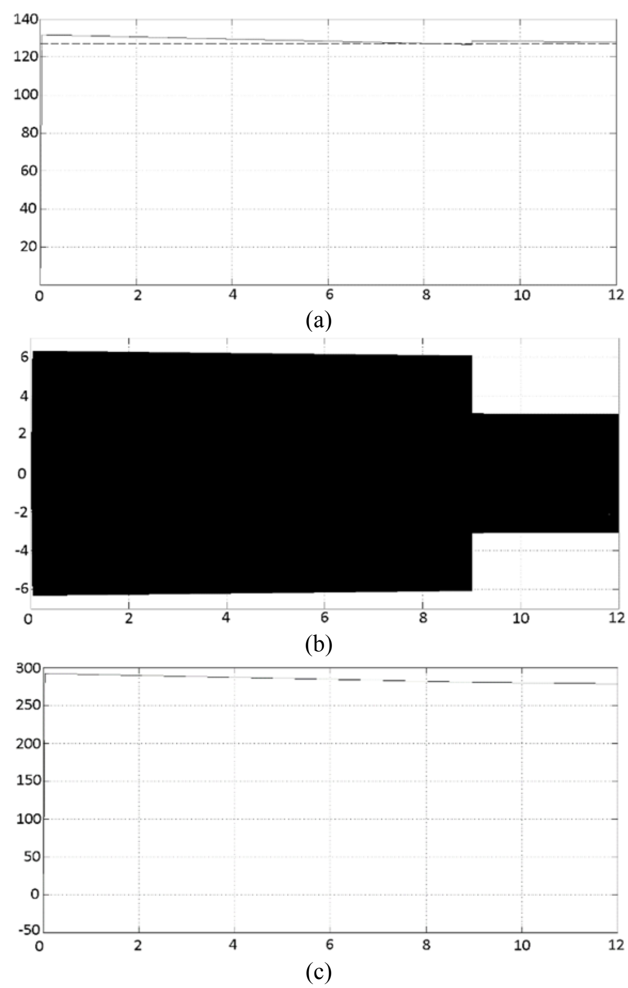


Fig. 5. (a) Command and actual RMS measured voltages. (b) Output load current. (c) DC link voltage.

TABLE II

CALCULATED TRANSFORMER TURNS RATIOS AND INVERTER SWITCHING ANGLES FOR UNEQUAL POWER RATINGS

H_1	H_2	H_3	H_4	H_5	H_6
0.200	0.220	0.211	0.176	0.126	0.067
α_1	α_2	α_3	α_4	α_5	α_6
5.61	18.00	31.74	46.07	60.63	75.30

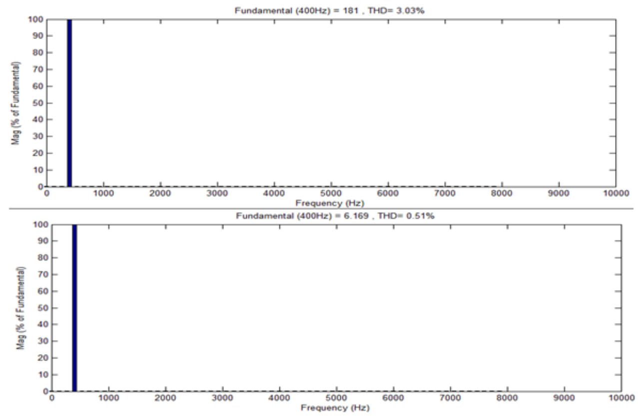


Fig. 6. Fourier spectrum of V_o (upper) and I_o (lower).

possible. Therefore, some small harmonics between the 3rd and 13th still exist but with very low values.

V. COMPARISON BETWEEN EQUAL AND UNEQUAL POWER TRANSFORMER RATINGS

The turns ratios of the transformers and the switching angles of the inverters are designed in Section III according to two criteria: to achieve equal power transformer ratings and to achieve SHE control.

One option is to focus on achieving SHE control to eliminate as much harmonics as possible. Then, the 12 equations to be solved to find the 12 unknown values of H_1:H_6 and α_1: α_6 are those that eliminate the 3rd–23rd harmonics by substituting their values with zero in (3); these equations are the first 11 equations, with the 12th equation being the sum of the six H's equals unity. The values of the 12 unknowns based on SHE control only are given in Table II.

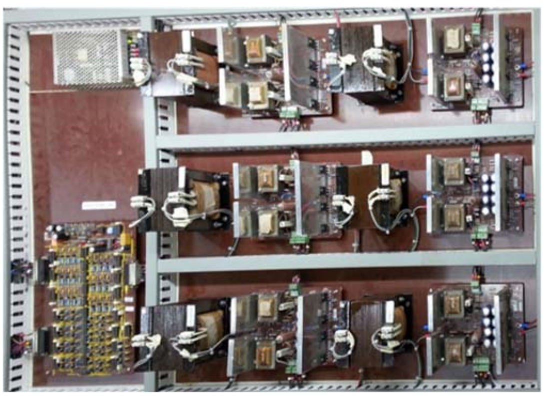
To compare the two designs, the same AC/DC/AC configuration is executed with the new calculated values for transformer turns ratios and inverter switching angles given in Table II. In this way, the system features the same conditions as the input supply and load conditions (Section IV) for regulating the output voltage at the same level. Fig. 6 shows the Fourier spectrum of the load voltage and current, and Table III shows the comparison of the results obtained from the calculations of the equal and unequal power transformer ratings. These results show that if the transformer turns ratios and inverter switching angles are designed to achieve equal power share and SHE control for certain harmonics, then the size of the transformers becomes equal, and the THDs of the voltage and current become satisfactory.

TABLE III

COMPARISON OF RESULTS OF EQUAL AND UNEQUAL POWER TRANSFORMER RATINGS

	Equal Power					
	T_1	T_2	T_3	T_4	T_5	T_6
Volt	21	22	23	23	24	26
Power Share	15	16	16.5	17	17.5	18
	Unequal Power					
	T_1	T_2	T_3	T_4	T_5	T_6
Volt	5	13	21	31	34	35
Power Share	3	7	16	22	25	27

(a)



(b)

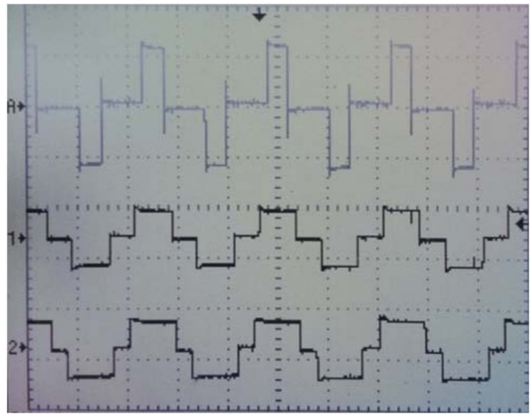
(c)

Fig. 7. AC/DC/AC converter: (a) (transformer/inverter/gate drive circuit) unit module. (b) DC/AC six-module converter and control signal generator. (c) AC/DC semi-controlled converter/second-order DC link filter/firing signal.

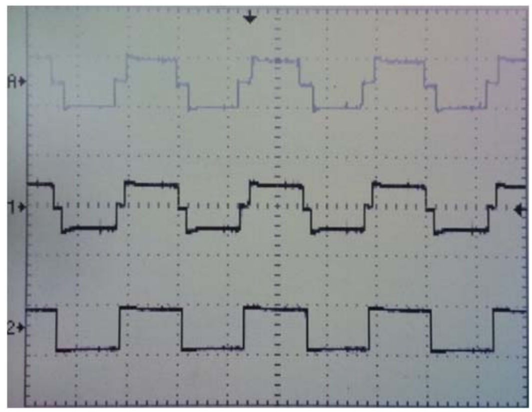
TABLE IV

SYSTEM INFORMATION

DC Link filter: C = 1,500 µF, L = 1.5 mH/10 A;
Inverter: Switch = IRFP450 and diodes = BYT12



(a)



(b)

Fig. 8. (a) Voltage of first, second, and third transformers. (b) Voltage of fourth, fifth, sixth transformers: 50 V/Div; 1 mSec/Div.

VI. EXPERIMENTAL RESULTS

The system shown in Fig. 1 and described in Section II is experimentally built for a 600 VA rig, as shown in Fig. 7. System information is given in Table VI. The inverters are run as phase shift inverters. Each switch is operated at 180°, and the two arms are shifted at an angle to obtain the resulting quazi pulse. This setting results in the equal utilization of the four switches. Fig. 8 shows the output voltage of the six transformers, and Fig. 9 shows the output load voltage and current at steady state. Fig. 10 shows the transient performance of the system through the load voltage and current and the DC capacitor voltage and current, with the load suddenly changed from a half load to a full load.

The load of the experimental results is a resistive load, which results in a current with the worst shape for testing. However, because of small line inductance, the current has a better shape than the voltage, as shown in Fig. 9(a), in which the phase shift appears small because of the nature of the

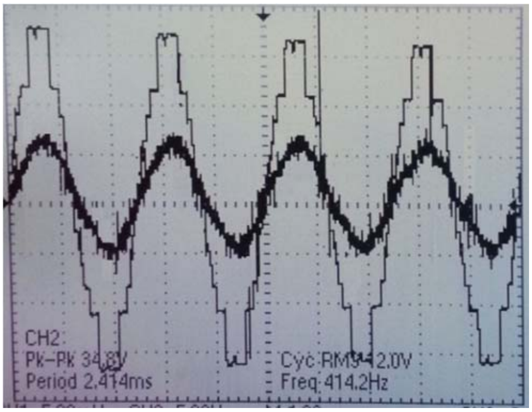
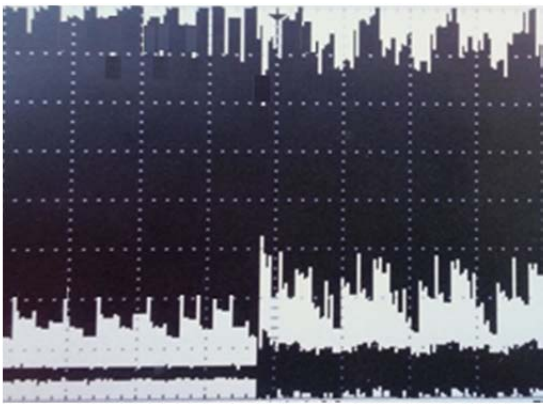
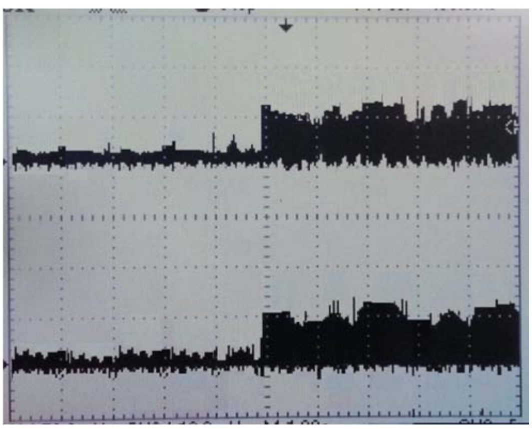


Fig. 9. Output load voltage and current: 1 mSec/Div; (upper) 50 V/Div; (lower) 5 A/Div.



(a)



(b)

Fig. 10. Transient analysis: (a) Load volt (upper) and current (lower). (b) DC capacitor volt (upper) and current (lower).

resistive load.

The THDs of the voltage and current from Fig. 9(a) obtained using the Tektronix digital scope are 8.4% and 3.2%, respectively, which are close to the theoretical values of 6.3% and 1%, respectively, which are obtained from the simulation shown in Fig. 3.

Fig. 10 shows that when the load current suddenly increases, the DC link current also increases to feed this power, and the feedback current and voltage signals succeed in regulating the load voltage by increasing the DC link voltage. The rig is left to operate continuously for two days, and the temperature of the six transformers and the heat sink of the inverters are measured (Table V).

TABLE V

TEMPERATURE (T) OF TRANSFORMERS AND INVERTER HEAT SINKS

	T_1	T_2	T_3	T_4	T_5	T_6
T (°C)	35	35	35.5	36	36.5	37
	S_1	S_2	S_3	S_4	S_5	S_6
T (°C)	40	40.5	40	41	40	41

The proposed technique is compared with another similar technique to understand their differences in terms of cost and efficiency. Section V explains the difference between the equal and unequal power transformer ratings. The comparison results indicate the satisfactory utilization and temperature performance of the proposed technique. The proposed technique is also compared with a similar technique from the inverter point of view. When the inverter employs the PWM technique, losses are expected to be high. In the case employing an alternative technique, the selection of equal switching angles leads to the output current having low frequency components instead of a sinusoidal current.

IX. CONCLUSIONS

An AC/DC/AC regulated static converter is presented. This converter is typically suitable for maritime applications supplying communication equipment loads, such as gyros and radars. It is also suitable for the lighting and fan applications of underground trains. The AC to DC converter consists of a semi-controlled bridge rectifier whose input is a 50 Hz, 200 V single-phase supply. The semi-controlled converter comprises only two diodes and two thyristor switches and is thus cheaper than the full-wave converter with little control circuit configuration. The firing signals of the two thyristors are generated through PI inner current and outer voltage controllers according to the error signal between a constant 127 V command signal and the actual output load voltage feedback. The result is a controlled DC voltage that depends on loading conditions. This DC voltage is then fed to six quazi-square H-bridge inverters whose outputs are connected to the primary coils of six transformers. The outputs of the six transformers are connected in series to produce a 127 V, 400 Hz regulated output voltage. The inverter switching angles and transformer turns ratios are calculated to achieve SHE control and series-connected transformers with equal power ratings. This system provides isolation between the input and the output sides and is thus suitable for transportation applications. The converter also provides a sinusoidal current at a multi-level regulated voltage and at a power frequency without PWM or high frequency. These characteristics make the converter suitable for maritime applications by avoiding interferences from the high frequency signals of navigation equipment. The number of levels could be increased to eliminate large amounts of harmonics, but the six-step voltage level achieves low THD that matches the IEEE standards.

APPENDIX [A]

The six equations for obtaining equal power transformer ratings are as follows:

$$H_1^2(\pi - 2\alpha_1) = H_2^2(\pi - 2\alpha_2) \tag{A1}$$

$$H_1^2(\pi - 2\alpha_1) = H_3^2(\pi - 2\alpha_3) \tag{A2}$$

$$H_1^2(\pi - 2\alpha_1) = H_4^2(\pi - 2\alpha_4) \tag{A3}$$

$$H_1^2(\pi - 2\alpha_1) = H_5^2(\pi - 2\alpha_5) \tag{A4}$$

$$H_1^2(\pi - 2\alpha_1) = H_6^2(\pi - 2\alpha_6) \tag{A5}$$

$$H_1 + H_2 + H_3 + H_4 + H_5 + H_6 = 1 \tag{A6}$$

The six equations for eliminating the 3rd–13th harmonics are as follows:

$$\sum_{j=1}^{6}\left(H_j \cos(3\alpha_j)\right) = 0 \tag{A7}$$

$$\sum_{j=1}^{6}\left(H_j \cos(5\alpha_j)\right) = 0 \tag{A8}$$

$$\sum_{j=1}^{6}\left(H_j \cos(7\alpha_j)\right) = 0 \tag{A9}$$

$$\sum_{j=1}^{6}\left(H_j \cos(9\alpha_j)\right) = 0 \tag{A10}$$

$$\sum_{j=1}^{6}\left(H_j \cos(11\alpha_j)\right) = 0 \tag{A11}$$

$$\sum_{j=1}^{6}\left(H_j \cos(13\alpha_j)\right) = 0 \tag{A12}$$

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