Regulated AC/DC/AC power supply using scott transformer

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Abstract

In today's industry, it is necessary to convert power for equipment used in environments where dissimilar voltages and frequencies are the norm. Static frequency converters or industrial power supplies are used for converting either 50Hz or 60Hz utility line power to 400Hz power. They are more efficient than motor-generator sets. In addition, they offer harmonic cancellation, power factor correction, phase conversion, voltage conversion with balanced, smooth, and controlled power output. Many varied applications in power electronics require sinusoidal outputs at frequency 400Hz. This paper describes the design, simulation and implementation of a power converter topology and control techniques for realizing sinusoidal output systems. A 150 KVA 3-phase power supply, whose line voltage and frequency are 440V and 60 Hz, is converted via a controlled rectifier to a dc voltage. Two center tapped transformer inverters shifted 90° in phase are used to convert the dc voltage to get two phase AC power supply which is converted via a Scott transformer to a three phase, whose line voltage and frequency are 440V and 400 Hz. A resonant filter is used to eliminate harmonics. Feedback signals from load voltage and dc link current are used to control the rectifier so as to maintain constant voltage at variable load conditions. The system is theoretically analyzed and experimentally verified.

Keywords: Static converters, Power supplies, Scott transformer, Resonant filter, Center tapped inverter.

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1. Introduction

Power supplies are among the most important components of any industrial application. Standard power supply is designed to optimize the power required, resulting in maximized efficiency, power factor and load regulation. Industrial power supplies are used for applications such as: aircraft power supplies, paper mill, laser power supplies, radar/sonar power supplies, battery charger, and marine propulsion systems [1-3]. In this paper, an industrial application is considered where the (6) MVA from the synchronous generator of a ship is used to supply different loads on board. A power converter is designed to supply 150 KVA of this total power to special loads such as Gyro system and other navigation equipments. The converter, shown in Figure 1, employs two stages of power conversion. In the first stage, the fixed frequency ac supply voltage is rectified to create the required dc bus by using thyristor phase controlled rectifier. In the second stage, the dc bus voltage is inverted at the required output frequency by using two half-bridge inverters 90º phases shifted. The Scott-transformer connection allowed 2-φ to 3-φ components to be interconnected, which adds an advantage to this power supply of having a relatively low cost because of using only two center tap inverters switched at power frequency with no PMW on the switches, meaning lower losses and voltage stresses where the DC link voltage is controlled using bridge rectifier.

2. System description

This static converter contains controlled rectifier, DC link filter, Scott transformer, single phase-inverter and series-parallel resonant filter. A description of these components is as follows:

2.1. Three phase fully controlled bridge converter

The phase controlled rectifier is obtained by six thyristors. Continuous control over the output dc voltage is obtained by controlling the conduction interval of each thyristor. The load harmonic voltage increases considerably as the average value goes down. The input current contains only odds harmonics of the input frequency other than the triplex harmonics. In this system, the three-phase supply, whose line voltage and frequency are 440V and 60Hz, is converted to dc voltage via controlled rectifier where the conduction interval to control the dc voltage from (425 V) to (510 V) from 10% to 120% of the full load respectively [4].

2.2. DC Link Filter

The function of the dc link filter is to attenuate the rectifier output voltage harmonics across the link inductor Lo and to sink the inverter input current harmonics into the link capacitor Co. However, attenuation of the rectifier output voltage harmonics across Lo creates additional ripple current into Co, while the sinking of the inverter input current harmonics into Co gives rise to additional ripple voltage across Lo. Therefore, both filter components (Lo and Co) are affected by both harmonic sources. The size and cost of this dc filter is determined by the rated system power, rated dc bus voltage, and the specified levels of THD in the link input current, and link output voltage. To smooth the dc voltage, a dc link filter is used whose parameters are designed to be (Lo = 5mH and Co= 22000μF) [5].

2.3. Scott transformer

A Scott-transformer, shown in Figure 2 is used to drive three phase current from a two phase source. It consists of a center tapped transformer T_1 and an 86.6% tapped transformer T_2 on the 3-φ side of the circuit. The primaries of both transformers are connected to the 2-φ voltages. One end of the T_2 86.6% secondary winding is a 3-φ output, the other end is connected to the T_1 secondary center tap. Both ends of the T_1 secondary are the other two 3-φ connections [6].

To compensate for the voltage drop in the internal impedance of the different parts of the system, the Scott transformer is a step up whose turns ratio is 1: 1.2 [7].

2.4. Single-phase centre-tapped transformer inverter

An alternating load voltage can be generated from a dc source by the use of a centre-tapped transformer as shown in Figure 3 [8]. Basically, by switching the two switches, the dc source is connected in alternative senses to the two halves of the transformer primary, so inducing a square wave voltage across the load in the transformer secondary [9].

For loads whose current is out of phase with the voltage, anti-parallel diodes feedback the stored load energy during those periods when the current reverses relative to the voltage. Two square wave center-tapped-transformer inverters are used whose output voltages are perpendicular (90° separation) which are the two phase voltage sources of the Scott transformer to get three-phase output voltages [10].

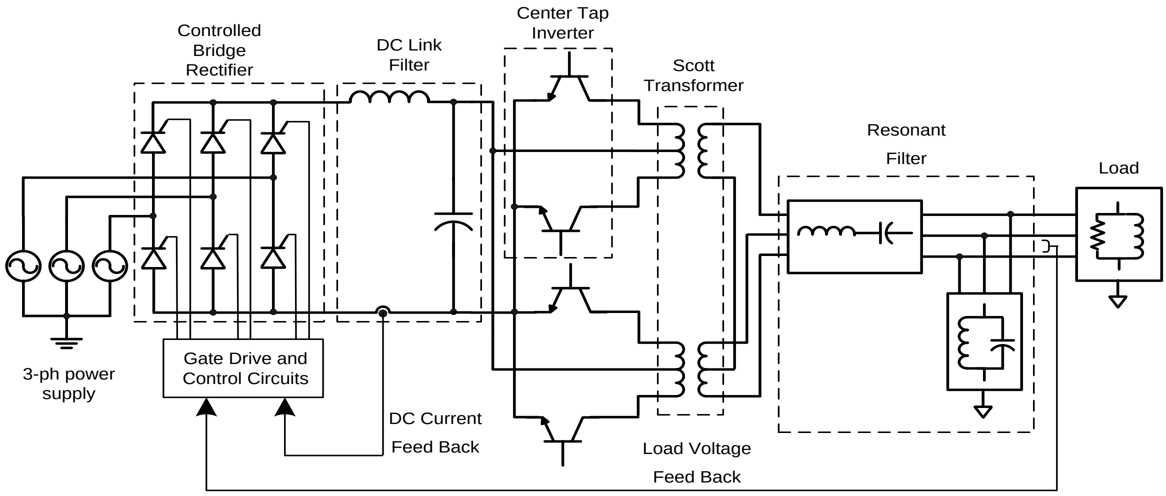


Fig. 1 AC/DC/AC Power supply.

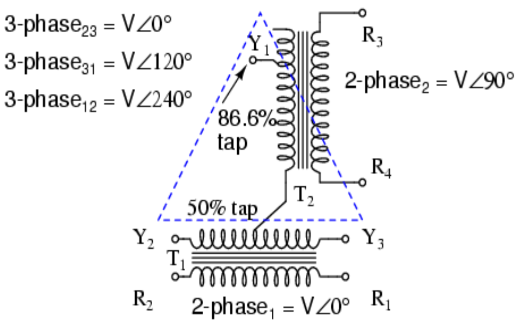


Fig. 2 Scott-transformer converts 2-φ to 3-φ.

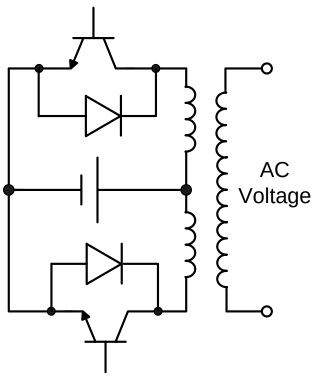


Fig. 3 Centre-tapped transformer inverter.

2.5. Harmonic and Filters

Harmonic distortion of voltages and currents in power systems are caused by the presence of non-linear loads in the system that produce distorted current. Using Fourier analysis, these distorted voltages and currents can be described in terms of harmonics. The harmonics in the lower frequency band are the most significant [11,13]. A few of the major effects of the harmonics are as follows: capacitor bank overloading, additional heating and losses in AC machines, increased probability of relay malfunctions, disturbances in solid-state and microprocessor based systems, interference with telecommunication systems [14]. The resonant arm filter, shown in Figure 4, is more appropriate to attenuate low order harmonics. Both the series arm L_1C_1 and the parallel arm L_2C_2 are tuned to the inverter output frequency. The series arm presents zero impedance to the fundamental frequency, but finite increasing impedance to higher frequencies [15]. The parallel arm presents infinite impedance at the fundamental frequency, but reducing impedance to higher frequencies. Taking the fundamental frequency

$$\omega_o = 2\pi f_o = \frac{1}{\sqrt{L_1C_1}} = \frac{1}{\sqrt{L_2C_2}} \qquad (1)$$

Making $C_1 = AC_2$ and $L_2 = AL_1$, and setting $\omega = n\omega_o$, where n is the order of the harmonic. The filter transfer function is then given by [16]:

$$\frac{V_o(n)}{V_i(n)} = \frac{1}{1 - \frac{1(n-\frac{1}{n})^2}{A}} \qquad (2)$$

The output voltage of the inverter, and then through the Scott transformer, is 400Hz, 180° conduction square wave whose major harmonic is the third (n=3) which equals to 33.3% of the fundamental [17]. If this value is to be attenuated to 4%, then the value of the gain (A) of (2) is determined to be 0.76.

The value of the reactance ($n\omega_oL_1$) is taken to be less than the load impedance (150KVA, 440 V_{line}, 0.8 PF) to avoid excessive load voltage changes when the load varies. Take $n\omega_oL_1 = 1.29\Omega$, then the filter parameters are given in Table 1

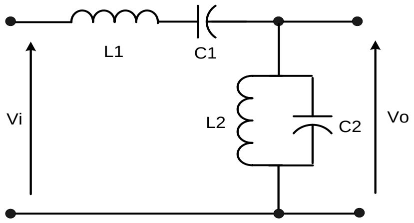


Fig. 4 Parallel-series resonant arm filter.

Table 1
Filter parameters

$C_1 = 380\mu F$	$C_2 = 500\mu F$
$L_1 = 0.41mH$	$L_2 = 0.31mH$

2.6. Feedback control system

The system has two PID controllers fed from the two feedback cascaded loop, namely, the outer loop from the load voltage and the inner loop from the current of the dc link filter. These controllers regulate the load voltage at constant level of 440V from almost no load to 120% full load.

3. Simulation

A prototype system is used to simulate the proposed system using MATLAB software as shown in Figure 5. The SIMULINK model starts at 10% full load till 0.8 sec when the full load is connected. Then at 1.2 sec, the supply is over-loaded by another 20% of full load. The results are shown in Fig. 6 to Fig. 10.

Fig. 6 and Fig. 7 show that the load is supplied by almost a sinusoidal current at almost constant and sinusoidal voltage at different load conditions. The resonant filter reduced the third harmonic in the voltage and in the current at almost 4% and 1% of the fundamental respectively, and reduced the THD in the voltage and current to (4.4 ± 0.7)% and (2.2 ± 0.4)% respectively. The third harmonic appeared, despite three-phase load nature, because the impact of two-phase connection in the Scott transformer. Fig. 8 and Fig. 9 show that the system has a good time response to regulate load voltage at sudden load change. However, the disadvantage of power converter is the harmonic input to the incoming source, this is shown in Fig. 10, where the fifth harmonic is more than 20% of the fundamental and the THD is greater than 25%. However, if the supply is critical, a method to improve supply power quality could be implemented.

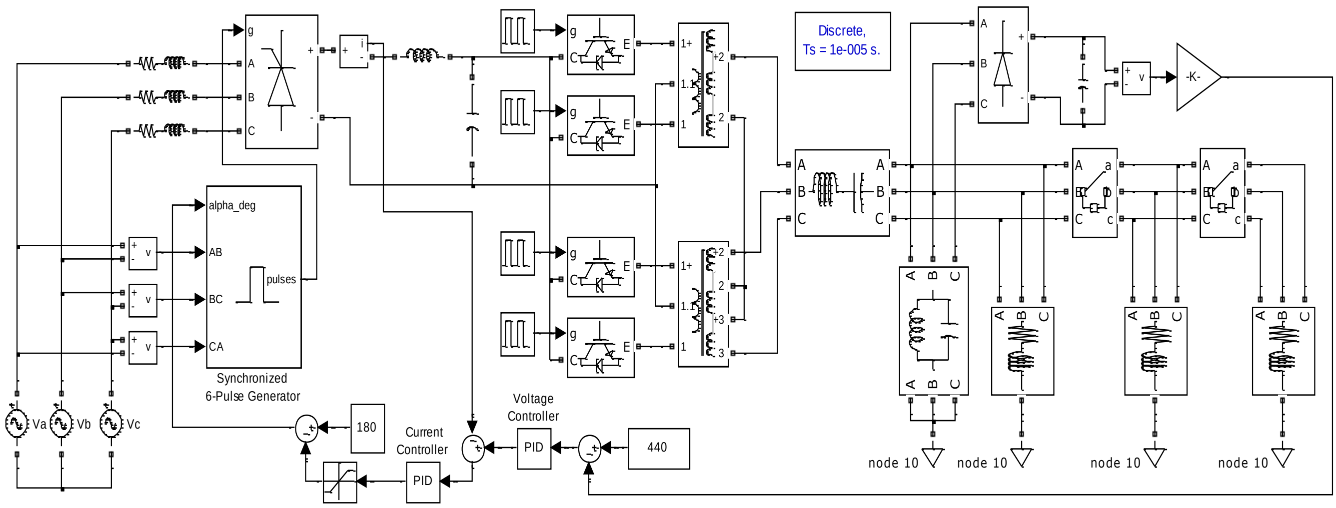
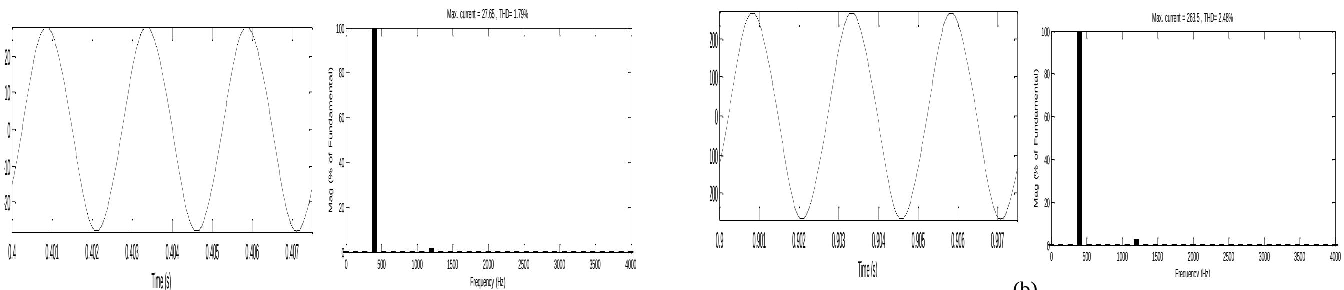
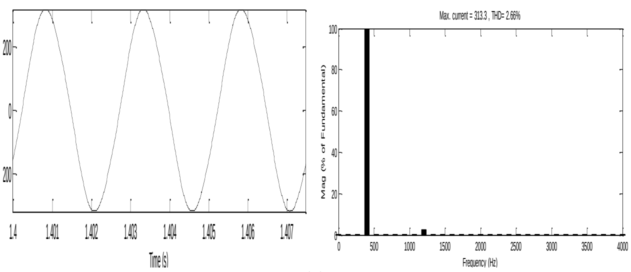


Fig. 5 Simulink Block Diagram of the overall system.



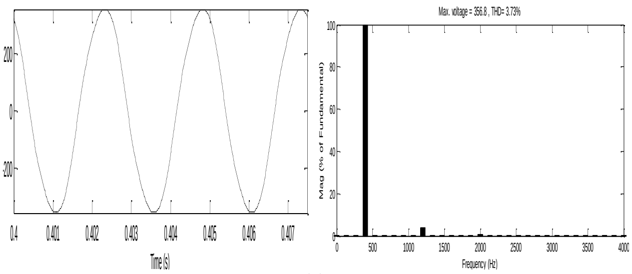
(a)

(b)

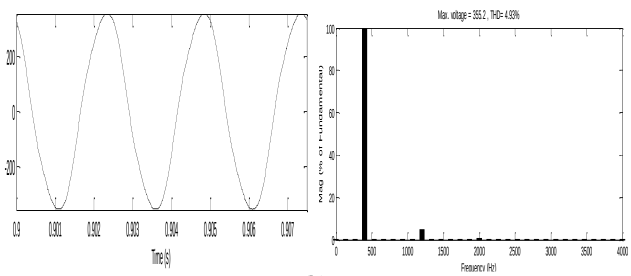


(c)

Fig. 6 Instantaneous output current waveform and FFT at: (a) 10% F.L, (b) 100% F.L, and (c) 120%F.L.



(a)



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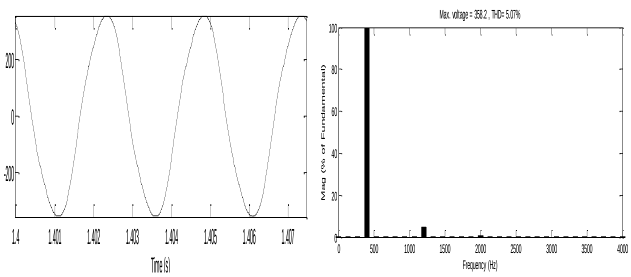
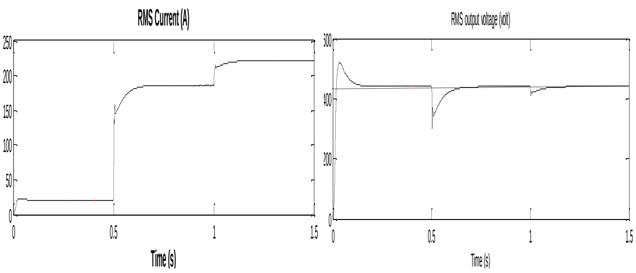


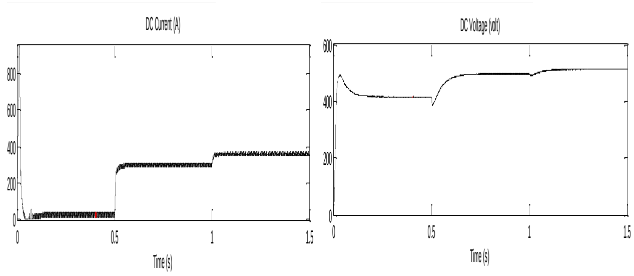
(c)

Fig. 7 Instantaneous output phase voltage waveform and FFT at: (a) 10% F.L, (b) 100% F.L, and (c) 120% F.L.



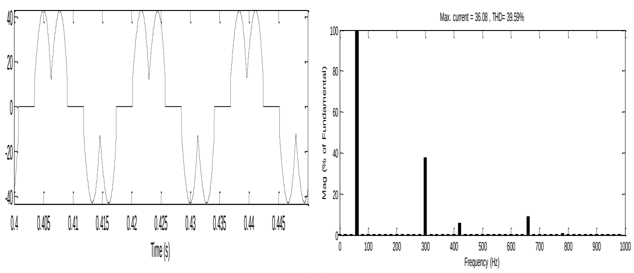
(a) (b)

Fig. 8 (a) RMS /load current, (b) RMS line voltage.

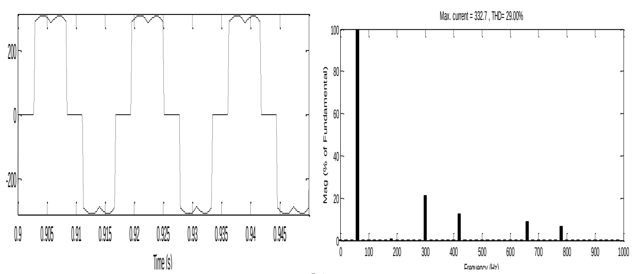


(a) (b)

Fig. 9 Instantaneous wave: (a) DC current, (b) DC voltage.



(a)



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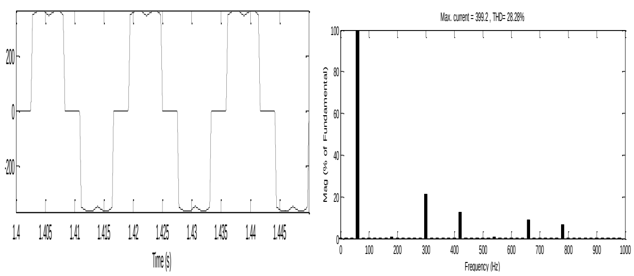

(c)

Fig. 10 Instantaneous input supply current waveform and FFT at: (a) 10% F.L, (b) 100% F.L, and (c) 120% F.L.

4. Experimental work

The system has been built in the lab as shown in Figure 11, with a scaled down rate of 1.5 kVA to verify the operation, where the 3-phase 44V, 50 Hz input supply is rectified using the CD43-40B Dual SCR Isolated POW-R-BLOK Module controlled rectifier. A 2nd order LC filter (L = 5mH, C = 1500µF/470V) smoothes the output DC which is the input to two single-phase perpendicular centre tap inverters (switches IRFP150N) to produce two-phase AC voltages which are converted to 3-phase voltages via the 120% step up Scott transformer, to make up for the voltage drop through the circuit. The load voltage harmonics are eliminated using the resonant filter (series branch: L = 11 mH, C = 15 µF/220V, and parallel branch: L = 3 mH, C = 45 µF/220V). The supply is loaded with a (44V/1.5KVA/400Hz) load. To regulate the load output voltage during loading, a three phase uncontrolled bridge with a small smoothing capacitor are used to measure the output load voltage which is fed back to the control circuit of the controlled rectifier to increase the DC average voltage through a PI controller. Also, a current limiter is used in this control circuit to protect the supply from access loading. To protect the MOSFET switches and the thyristor, a soft staring technique is used in the firing and control signals of both circuits. Fig. 12 to Fig. 16 show the experimental results, where Fig. 12 and Fig. 13, show the full load steady state line output voltage and current, respectively, which are sinusoidal. Fig. 14 and Fig. 15 show the voltage across primary of teaser winding of the Scott transformer and the supply current at steady state, respectively. Figure 16 shows the transient response of the DC link voltage when the supply is loaded suddenly from no load to full load, where the DC voltage is increased from 40 V to 51 V to regulate the output voltage at its nominal rated value. The experimental results show the validity of the supply to produce sinusoidal output voltage.

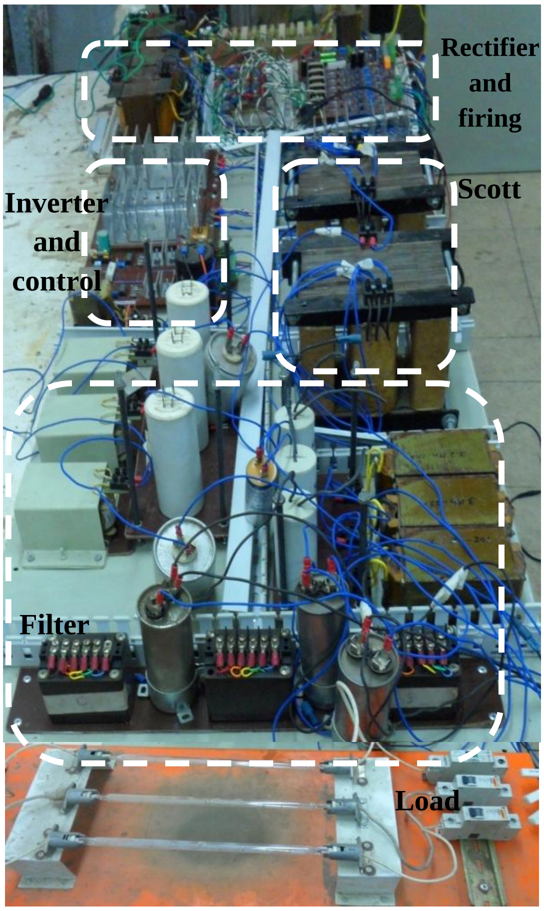

Fig. 11 Experimental rig.

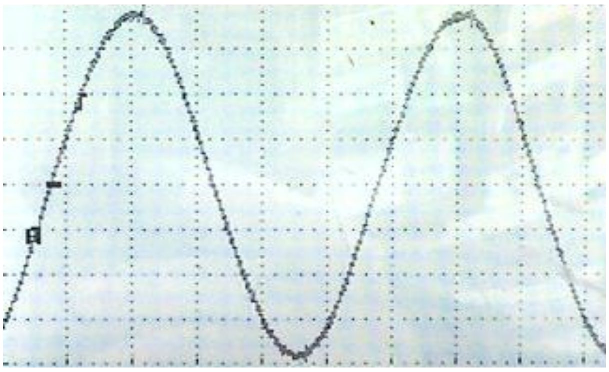

Fig. 12 Steady State Load Line Voltage.

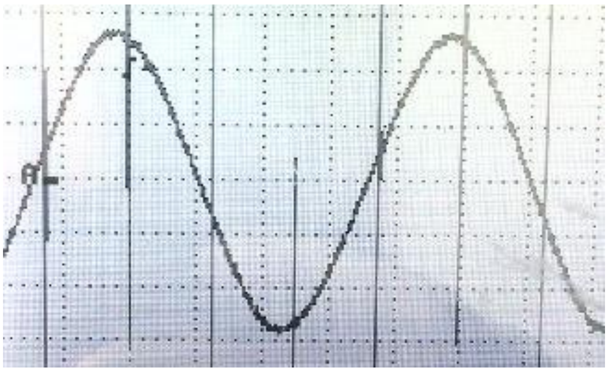

Fig. 13 Steady State Load Line Current.

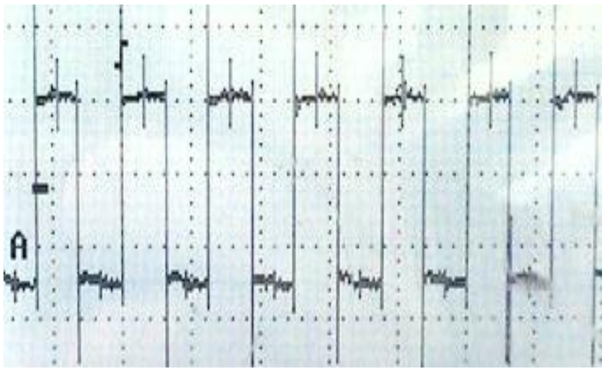

Fig. 14 Voltage across Primary of Teaser Transformer.

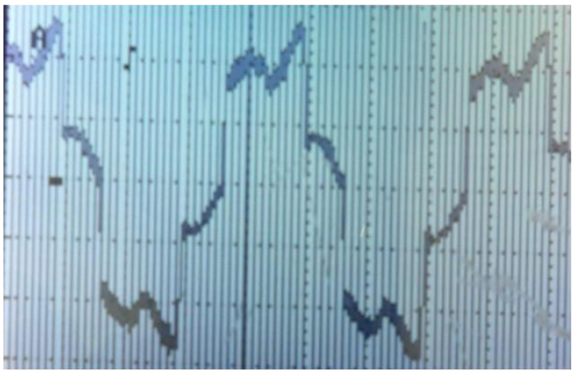

Fig. 15 Steady state Supply Current.

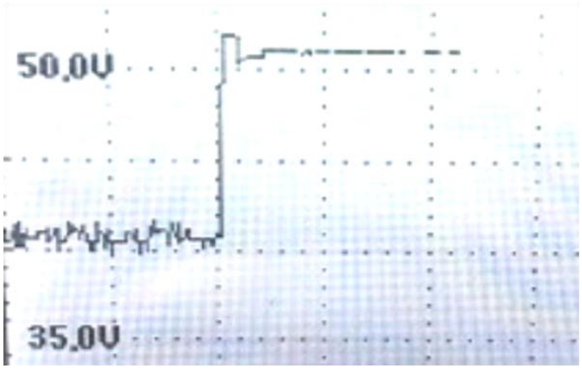

Fig. 16 DC Bus voltage.

5. Conclusion

This paper introduced the design, simulation and implementation of static power converter techniques for realizing sinusoidal output system. The converter is used to feed 150KVA, 440V, 400Hz critical loads on a ship from 440V, 60Hz three-phase supply. The controlled rectifier and dc link filter provide a dc voltage, controlled by feedback signals from load voltage and dc link current, which is then converted to three-phase via two centre tap inverters and a step up Scott transformer. A resonant filter is designed to eliminate 3^{rd} harmonics and higher. The system is experimentally verified at 15KVA, 44V. The simulated and experimental results have been presented to prove the validity of the system.

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