

Simulation of 40 kVA, 400 Hz Power Converter System

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Abstract— This paper discusses the design and simulation of Power converter System (PCS) of capacity 40 kVA for various applications such as defence, avionics, navy etc. The above simulation is based on double conversion and Sine Pulse width modulation (SPWM) technique. Solid state power converter uses high switching frequency devices like Insulated Gate Bipolar Transistor (IGBT). Simulation has been carried out using CASPOC software to determine the performance of the system. The several design aspects and number of iterations have been carried out to achieve optimum results and same have been presented.

Keywords— Power Converter; IGBT; double conversion technique; Sine Pulse width modulation; Switching frequency; Axial Flux Permanent Magnet Alternator;

I. INTRODUCTION

By seeing today's scenario for several applications, it is necessary to process electric power to suit various equipments used in environments where dissimilar voltages and frequencies are mandatory[1]. Solid state power or frequency converters are used for converting either 50 Hz or 60 Hz utility line power to 400 Hz 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 like aircraft, radar, communication equipments etc in power electronics requires sinusoidal outputs at frequency of 400 Hz. Major issue of using electrical power system operates at 400 Hz instead of conventional 50 Hz / 60 Hz is to make equipments smaller, lighter and efficient. Volume and weight are main constraints during design of electrical equipment for aero-grade applications, use of 400 Hz supply offers many advantages[2].

To fulfill this requirement, Power/frequency Converter plays a vital role to regulate and control the power quality (voltage and frequency) for proper operation of various loads like radar, communication equipments, missile launchers etc for defence applications to perform its intended function. Hence it is required to do design, analysis and simulation of Power Converter.

This paper describes the simulation of a power converter topology and control techniques for realizing sinusoidal output systems. Three-phase power supply, whose line voltage and frequency are 415V and 50 Hz, is converted via a un-controlled rectifier to generate a DC bus and further it is inverted using IGBT based inverter for 200 V, 400 Hz output.

From the basic circuit theory, design considerations, simulation of complete Power Converter at rated load, iterations on switching frequency and their results on CASPOC (Computer Aided Software for Power Converter) simulation software have been presented.

II. System Concept

Main aim of power converter system (PCS) is to provide constant and well-regulated ac voltage and frequency. It is connected between the ac voltage source from the three phase mains supply or very compact and high dense Axial Flux Permanent Magnet Alternator (AFPMA) based DG set. The variable voltage and frequency output of AFPMA can also be given as a input to Power Converter. This Power Converter unit works on sine triangle pulse width modulation (SPWM) IGBT based technique with inbuilt protections and control circuit.

Fig. 1 shows schematic of the PCS. Here, three phase mains of 415 V, 50 Hz has been taken for simulation purpose, further AFPM based Diesel Generator can be used to carry out simulation studies. Three phase uncontrolled rectifier converts the three phase AC signal from the mains to a constant regulated DC supply [3]. This DC is further given to 6 pulse IGBT based inverter. For battery backup, the DC link bus can be tapped if required.

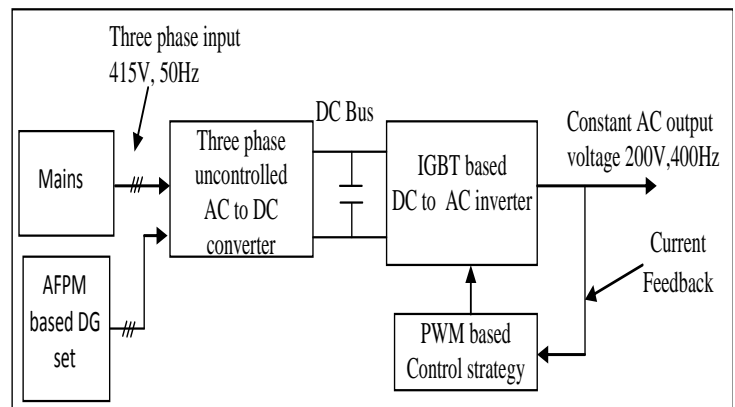


Fig. 1: Schematic of Power Converter

It converts DC voltage from the capacitor filter to a regulated ac supply. To achieve this, gates of IGBT's are triggered using a SPWM control technique [4]. If required output of the inverter can be further connected to transformer, which gives galvanic isolation between input and output also it will step down the voltage as per requirement. The input for the transformer is three phases and the output is three phase and neutral.

III. FORMULATION OF PWM CONTROL STRATEGY ON CASPOC

IGBT bridges are required to be effectively switched ON and OFF with PWM control technique for getting required AC output voltage. Using a pulse width modulation switching scheme the switches of the inverter are switched ON and OFF several times per half cycle. The duty cycle can be controlled by varying the on-time per switching period. The average output voltage can be maintained at the desired set point by controlling the duty cycle. To achieve this, the PWM control circuit has been designed as shown in Fig. 2 wherein the output of three phase signal (load current) is fed back to comparator which get compared with the reference signal. The output of this comparator is compared with triangular carrier signal to generate three prime phase shifted by 120 degree PWM signals. By using three NOT gates total 6 PWM signals are generated to drive the 6 IGBT's. The frequency of the carrier signal will determine the switching frequency. The pulse widths can be modified by changing the amplitude of the modulation signal. The ratio of the amplitude of the modulation and carrier signals is the modulation index.

$$M = V_m / V_c$$

The amplitude values of carrier and control signal for PWM generation are adjusted to achieve modulation index for optimum results. Where M is the modulation index, V_m is the amplitude of the control signal and V_c is the amplitude of the carrier signal. On the designed circuit various switching frequencies from 10 kHz to 20 kHz were tried and finally the optimum switching frequency is selected out of several iterations.

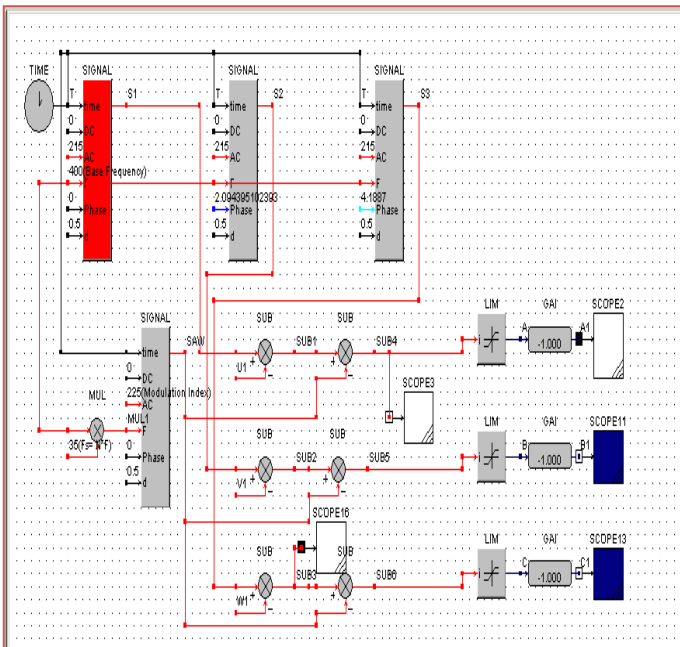


Fig. 2: PWM generation circuit

IV. SIMULATION CIRCUITS

In order to start the simulation of PC, initially the preliminary design calculations have been carried out to finalize the optimum values of components using standard formulas mentioned below: [5][6]

1] Load Calculations :

$$\text{Real Power} = \text{Reactive Power (P)} * \text{Power Factor} \quad (1)$$

$$P = \sqrt{3} V I \cos \phi \quad (2)$$

$$V_{ph} = \frac{V_L}{\sqrt{3}} \quad (3)$$

$$Z = \frac{V_{ph}}{I_{ph}} \quad (4)$$

$$R = Z \cos \phi \quad (5)$$

$$X_L = Z \sin \phi \quad (6)$$

Using above equations the optimum values of R and L are calculated and selected for 40 kVA capacity.

2] Six Pulse Diode Based Uncontrolled Rectifier :

For a three phase full bridge rectifier the average value of dc voltage can be obtained over a radian interval as shown in

Equation (10)

$$V_{dr} = \frac{1}{\pi} \int_{-\pi/6}^{\pi/6} \sqrt{2} V_{in} \cos \omega t d\omega t \quad (7)$$

$$V_{dc}(\text{avg}) = 1.35 V_{in} \quad (8)$$

$$V_{dr} = 1.654 V_m \quad (9)$$

$$V_L = 1.655 V_m \quad (10)$$

$$V_{pp} = V_{\text{positive}_p} - V_{\text{neg}_p}$$

3] Six Pulse IGBT Based DC to AC Converter (Inverter) :

$$\text{Amplitude modulation ratio (} m_a) = \frac{V_m}{V_c} = 1 \quad (11)$$

$$V_{LL} = \frac{\sqrt{3}}{\sqrt{2}} V_{AN} \quad (12)$$

$$V_{LL} = 0.612 m_a V_d \quad (m_a \leq 1-0) \quad (13)$$

$$\text{DC input voltage (} V_d) = \frac{V_{LL}}{0.612 * m_a} \quad (14)$$

Peak rating of switch

$$V_T = V_{dmax} \quad (15)$$

$$I_T = \sqrt{2} I_{o\text{max}} \quad (16)$$

DC side current (Drive input current) –

$$\text{Inverter id} = 3 * V_{LL} * \frac{I_o}{V_d * 0.8} \quad (17)$$

using above basic equations the circuit has been designed and its various parameters are given in Appendix.

A. Complete Circuit Simulation

After the design calculations, the components were selected and simulated model of power converter was build up in steps. Some of the off the shelf models which were readily available was taken as it is. Fig. 3 shows the simulated model of PCS which is based on double conversion technique [7]. In this circuit primarily the mains circuit block which was available in CASPOC is connected as input to uncontrolled rectifier. The output of rectifier is connected to filter capacitor bank to get ripple free DC output. Based on the amount of ripple contained in the rectified output the number of iterations have been performed to finalize the value of filter capacitors. This DC output is connected to IGBT based 3-phase inverter circuit. In order to obtain the distortion less three phase output of inverter

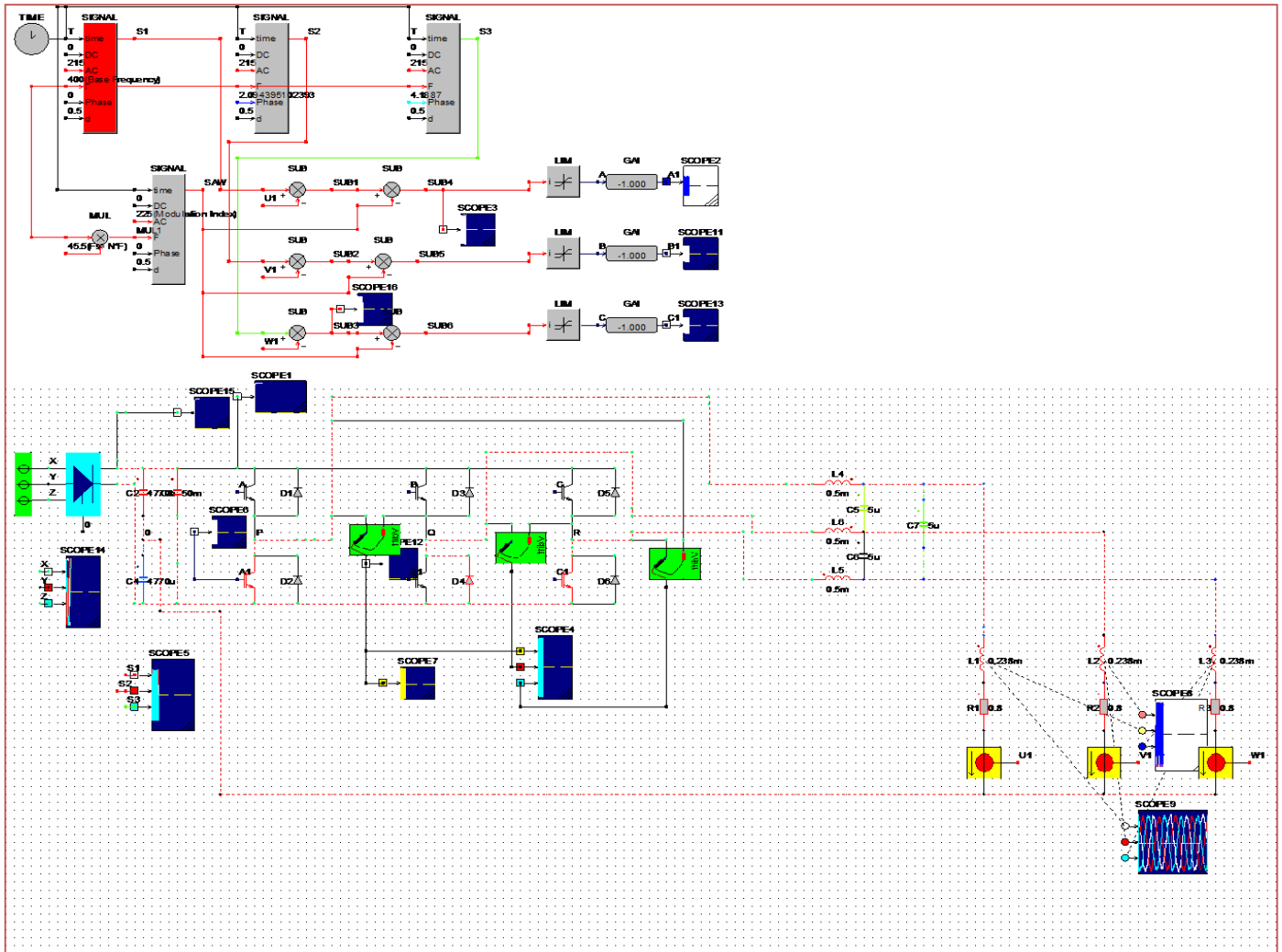


Fig. 3: Simulated circuit diagram in CASPOC simulation software

at desired frequency of 400 Hz, the LC filters are connected between each phase of inverter.

The values of LC filter was also finalized based on the various iterations and refined results obtained. Three phase inverter is loaded with the calculated values of R and L for getting load of 40 kVA.

B. PWM Generation Circuit

In order to trigger IGBT's of inverter circuit, fine PWM control is required. For the same the circuit was made as per Fig. 2. In this circuit load current of three phases was sensed through current transformer and compared with the three reference voltages. The generated six PWM signals were fed to gates of IGBT's which drives the power devices.

C. Load Connection in STAR connection

STAR connected loading arrangement is shown in Fig. 4. Load analysis was carried out for STAR connection. Accordingly the values of R and L was calculated and set for 1 kVA to 40 kVA load requirement.

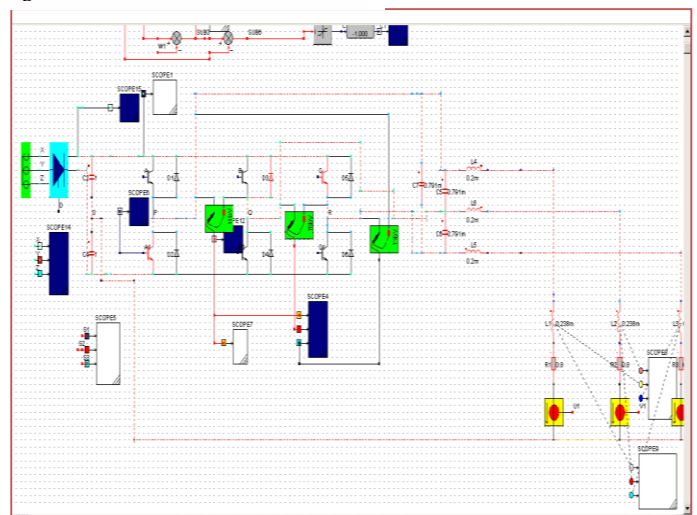


Fig. 4: Loading arrangement

The connections are made through CT from where the load current was sensed and fed back to the control circuit.

After checking all probe connections, the circuit simulation was started. The results are discussed in subsequent sections. [8]-[10]

V. SIMULATION RESULTS

A. Input signal to PC

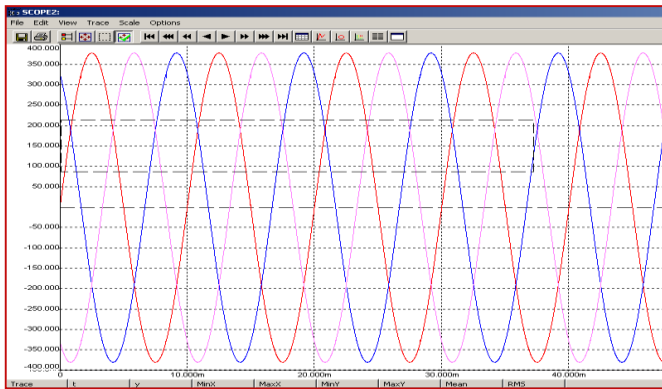


Fig.5: Three phase mains input

Three phase input of 415V, 50 Hz is shown in Fig. 5. This input is given to Power Conditioning System.

B. Rectified output

Fig. 6 shows output voltage of three phase uncontrolled rectifier w. r.t time along the high value of filter capacitor. This reduces ripple content to some extent from rectified output. Output voltage is fluctuating between 235 V to 240V.

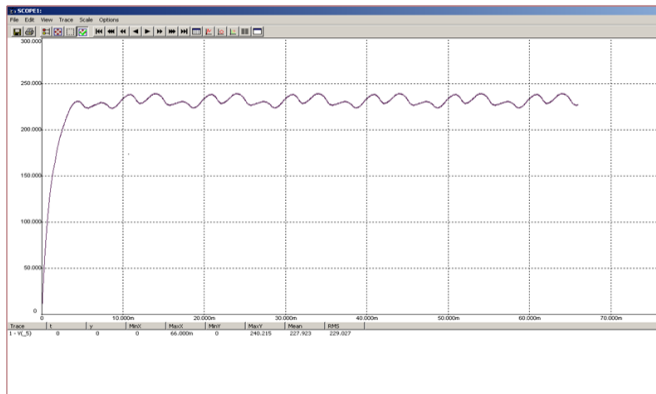


Fig.6: Rectified output signal

C. PWM Generation for driving gates of IGBT

In PWM generation circuit primarily three basic signals are PWM generated and same are inverted for driving six numbers of IGBTs. Fig. 7 shows the generated PWM output waveform. The circuit uses triangular modulation control technique which is explained in part III. For the same, the circuit simulation was carried out for various switching frequencies from 10 kHz to 20 kHz.

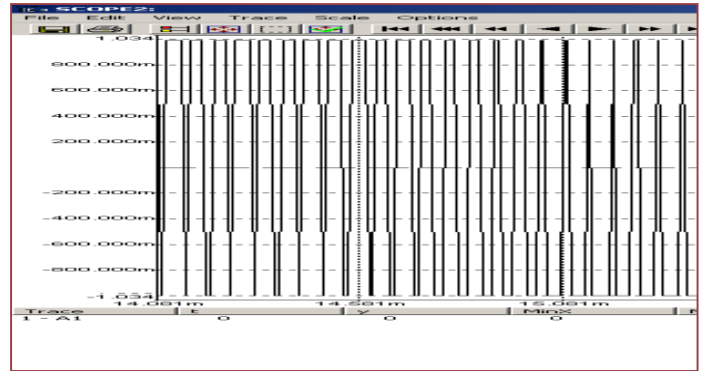


Fig.7: PWM output waveform

Figure 7 shows the PWM output wave at 17.6 kHz switching frequency.

VI. OPTIMIZATION OF SWITCHING FREQUENCIES

On simulated model in CASPOC, various switching frequencies (from 10 kHz to 20 kHz) were tried out on rated capacity to optimize the switching frequency which gives symmetrical undistorted load current waveforms[11]. The most optimistic results at different switching frequencies are shown in Fig. 8(A) to 8(D) and the inference of all iterations at various switching frequencies are also given below. At around 17.6 kHz the result is more optimistic.

A. Output current waveform

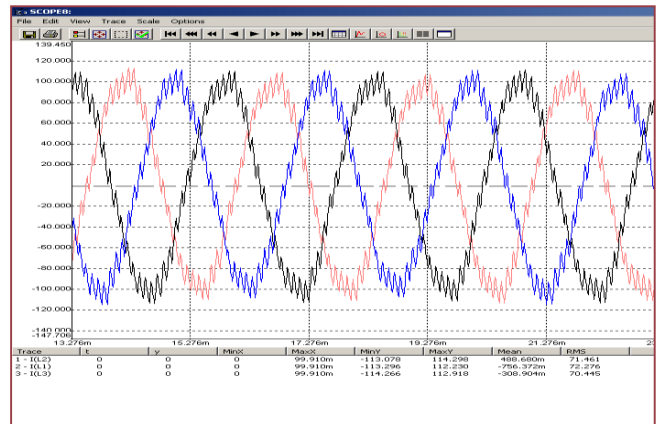


Fig.8(A):. Output Current @ SF=10kHz

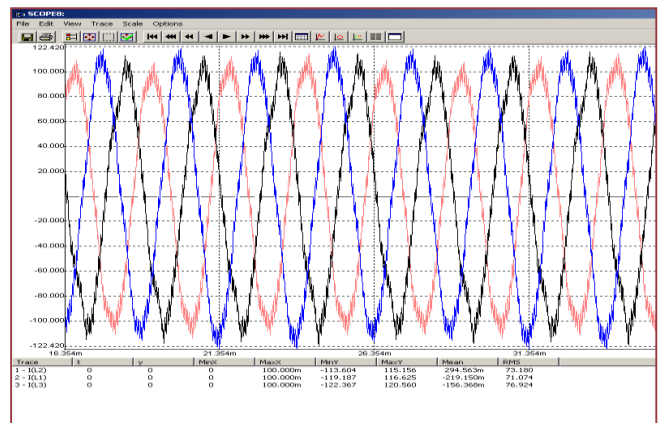


Fig.8(B). Output Current @ SF=15kHz

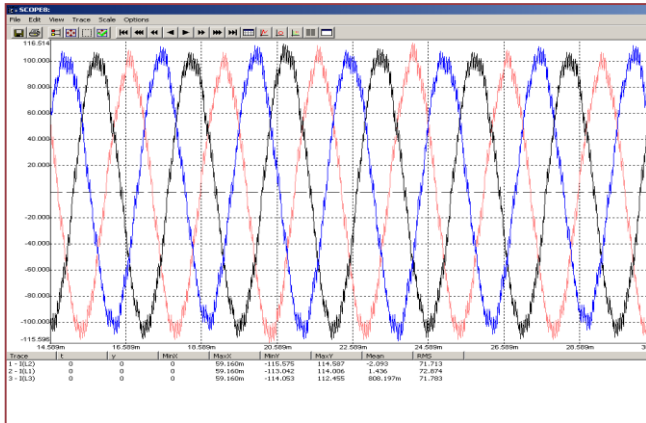


Fig.8(C): Output Current @ SF=17.6kHz

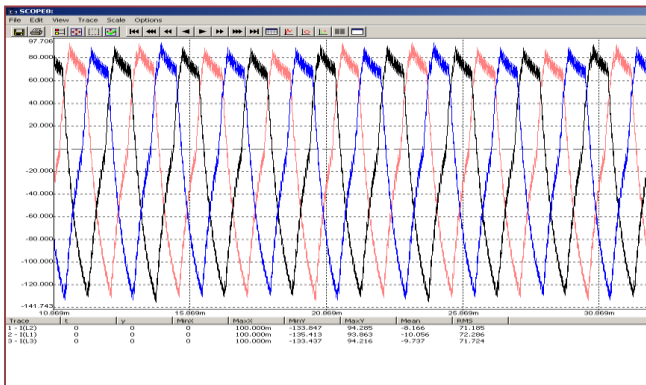


Fig.8(D): Output Current @ SF=20kHz

After carrying out the various iterations of SF, it is observed that, at 10 kHz the entire current waveform is distorted and at 20 kHz the waveform peaks are flattened at upper side for more duration whereas at lower side it is sharp in nature.

VII. OUTPUT RESULT WAVEFORMS

A. OUTPUT Current waveform

The simulated circuit model is loaded partially at various switching frequencies. After confirming the performance of the circuit at full load i.e. 40 kVA @ 17.6 kHz switching frequency, captured load current waveform w.r.t time is presented in Fig. 9.

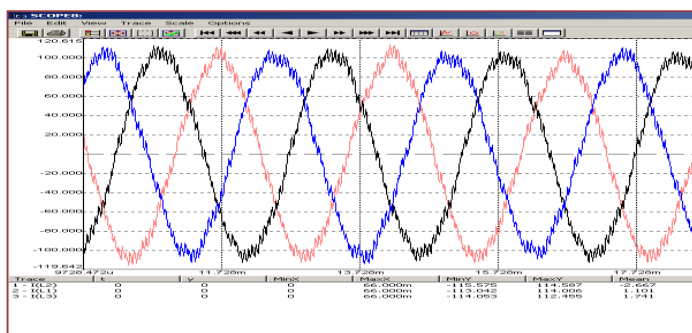


Fig.9: Three-phase load current waveforms

B. OUTPUT Voltage waveform

Voltage waveform was also captured at rated capacity and is as shown in Fig. 10.

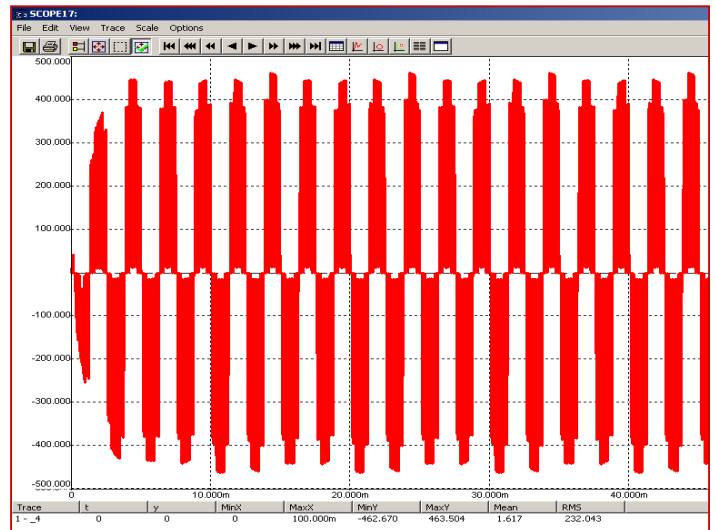


Fig.10: Output voltage waveform

C. DFT Analysis

After doing the simulation at various SF's, Discrete Fourier Transform (DFT) is also carried out at each SF's to study the harmonic spectrum. It is observed that between 15 kHz to 18 kHz range of SF, harmonic spectrum is optimal for selected filter values. The graph of DFT for voltage and current is as shown in Fig. 11 and 12 respectively.

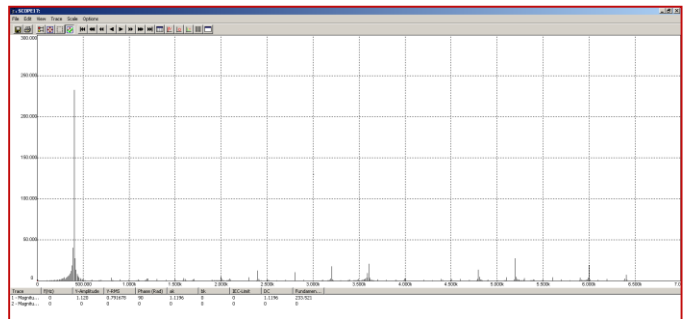


Fig.11: Voltage harmonic spectrum @ 17.6 kHz

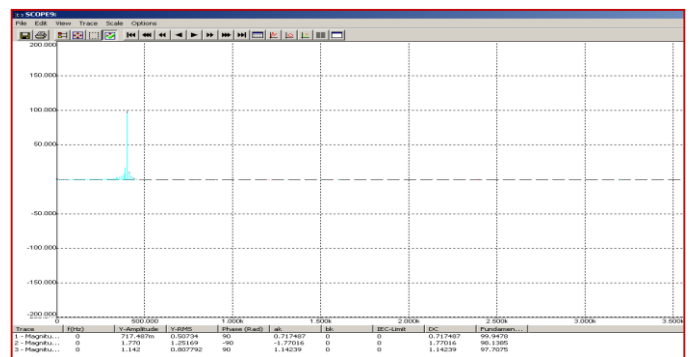


Fig.12: Current harmonic spectrum @ 17.6 kHz

After finalization of switching frequency, the simulation circuit was loaded in steps from 1 kVA to 40 kVA. The results are tabulated as given in Table 1. It is observed that the calculated and measured electrical load currents were matching approximately. Further isolated three phase step down transformer is required at the output side of the inverter for getting 200 V at the load [12].

TABLE I LOADING ANALYSIS

Load (kVA)	Readings at 17.6 kHz SF						
	Calculated	Measured output					
	I(A)	V1(V)	I1(A)	V2(V)	I2(A)	V3(V)	I3(A)
1	2.88	309.4	5.84	306.0	6.06	310.91	5.92
5	14.43	290.1	26.63	293.5	25.03	291.77	25.21
8	23.09	287.2	39.11	288.7	37.74	288.51	38.23
10	28.86	280.0	46.63	277.6	47.46	278.09	46.57
20	57.73	253.6	77.52	249.2	72.51	254.32	76.50
30	86.60	238.7	95.14	236.4	96.79	240.07	99.11
40	115.47	228.0	114.58	229.7	114	229.14	112.4

VIII. CONCLUSION

Design and simulation of 40 kVA, 200V, 400 Hz Power Converter using double conversion technique has been successfully completed in Computer Aided Software for Power Converter (CASPOC) simulation software. The exhaustive analysis was carried out by changing electrical parameters like modulation index, switching frequency, loads etc. The system was also simulated and studied with the STAR load configuration [13].

Theoretical and simulation results are compared with step load at the optimum switching frequency. The overall effect on load current waveform is observed and studied. For pure sine wave outputs of 40 kVA, 200 V, 400 Hz further fine tuning of output filter values are required to be done.

Based on this simulation study, the hardware realization is under development for several strategic application.

APPENDIX TABLE II
 The major design parameters

Type	Power Conditioning system
Power output	40 KVA, 400 Hz
Input	Three phase, 415 V, 50 Hz from mains
Uncontrolled rectifier module	1200V, 200A
Filter capacitor for rectifier	4700uF and 50mF
IGBT for Inverter	1200 V, 400 Amps Ron : 100 μΩ Roff: 100 kΩ Vth on: 1.2 V Vth off : 0 V
Freewheeling diode specs	Ron : 10 mΩ Roff: 1 MΩ Vth on: 1.2 V Vth off : 0 V
Output Filter (L&C) for each phase	0.5 mH & 5 uF
Connection	Star connected (RL) load
Load (R & L)	0.238mH & 0.8 Ω

IX. ACKNOWLEDGMENT

The authors wish to thank Shri. V. V. Parlikar Director, Research and Development Establishment (Engrs.), Alandi Road, Dighi, Pune-411015 for constant encouragement and valuable guidance to publish this paper in International Journal of Engineering Research and Technology (IJERT). Thanks to the entire design team for their valuable suggestions and support.

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