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CASE STUDY ON 175-320V DC TO AC 230V, 3Ph, 400Hz, 50KW ROTARY FREQUENCY CONVERTER & DESIGN OF EQUIVALENT STATIC FREQUENCY CONVERTER

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1 Abstract
Control Systems have been installed onboard marine platforms to operate and monitor the essential parameters of systems, viz., Power Generation & Distribution Systems, Main Propulsion Plant Control Systems, General Ship System Control Systems, Central Coordination Control System, etc.
The Control Systems are very essential and are designed to operate at 400Hz network. It works on three tier reliability viz., Main, Reserve and Emergency for ensuring availability of power supply in all regimes of operation.
The project covers a practical case study on DC to AC Rotary Electrical Converter fitted onboard marine platforms along with its interfacing with other systems and design of an equivalent Static DC to AC Frequency Converter.

2 Introduction

DC (175-320V) to AC (230V, 3Ph, 400Hz, 50KW) Rotary Frequency Converter consists of DC Compound Motor and AC Generator installed on common shaft. It is a heavy rotary machine and having difficulty for shipping-in, alignment and its installation. Further, it is also create heavy rotational noise and frequent maintenance issues viz., repairs on excitation circuit, cleaning of Commutator, slip-rings, carbon brushes, bearings, etc. Therefore, development of Static Frequency Converter by using power electronics is the best option for replacement of Rotary Frequency Converter due to its various advantages.

Static Frequency Converter is an ideal solution for providing desired frequency and voltage by using static technology, without any moving masses. Static frequency converter is used to supply voltage without any considerable load variations. The output frequency is entirely depending on the control of the ON/OFF static devices of frequency converters. It is totally independent of fluctuations in the input DC voltage and also works independent of load variations. Static frequency converter being proposed have low installation costs, they don’t require any heavy machinery and accurate alignment. It occupies less space and offers low noise compared to mechanical converters with heavy machinery.

3 Static Frequency Converter (SFC)

The SFC shall be a static solid-state type converter for giving true sinusoidal, regulated phase/voltage relationship output. It shall provide the required voltage and frequency output, while also providing sufficient protection to the SFC system itself, as well as, any downstream power systems. The SFC shall consist of modular construction solid-state components for 400Hz conversion and ancillary control devices. The SFC is consisting of following main stages as shown in Connectivity diagram given below and mainly consists of Power Section and Control Section.

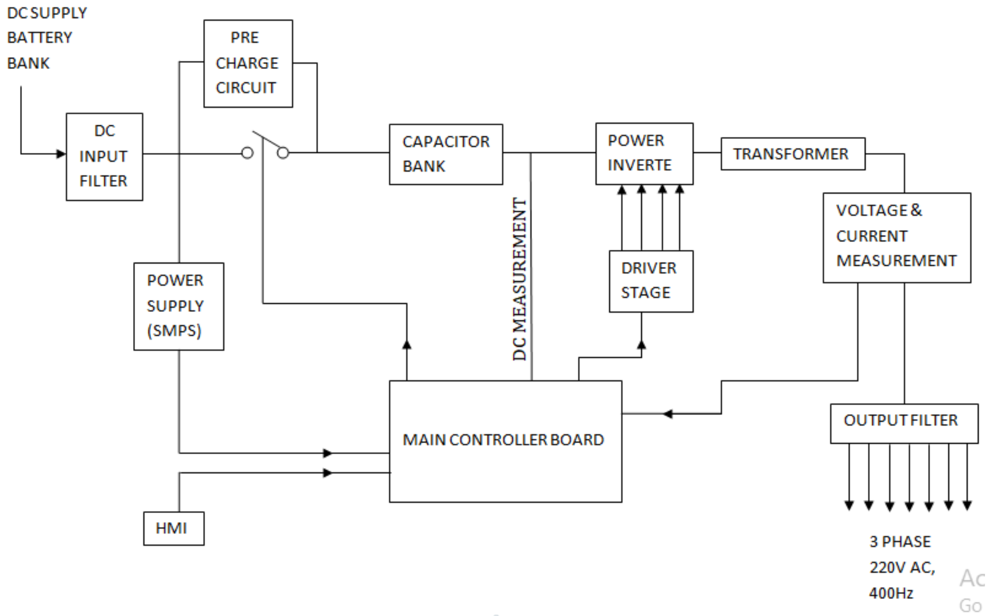


Fig.1: Connectivity Diagram of SFC

3.1 SFC Power Section. The Power Section of SFC mainly consist of input feed through capacitors, input filter for EMI protection and pre-charge power section, DC link capacitors for power reserve, power bridge or frequency converter circuit, Isolation Transformer and output filter.

3.2 Input Filter and Pre-charge section. The Input to the SFC is DC voltage. Input side consists of an EMI filter having common mode and differential mode filters and a pre-charge circuit. The input filters take care of the conducted noise on the lines.

When switching on, in order to prevent an excessive inrush current due the DC bus capacitors, the pre-charge circuit is used. The pre-charge circuit limits the input current (di/dt) by a power resistor. Once the bridge capacitors re-charged, this resistor is shunted by a contactor, which remains closed until the converter is switched OFF.

3.3 DC link. The power section after the pre-charge circuit is called the DC link section. This section consists of DC link capacitor bank which stores the energy and to provide the power reserve during inrush current requirement.

3.4 Power Bridge. The power bridge mainly consists of IGBT modules controlled through a PWM circuit for required output voltage and frequency. The power bridge consists of 6-pulse configuration for generation of 3-phase output. This is the frequency converter block where IGBTs are fired as per the PWM waveform generated by the control circuit. The IGBTs are mounted on heat sinks with forced cooling arrangement. The temperature of heat sink blocks are monitored by the control circuit for effectiveness of cooling and protection of the IGBTs under overheat condition. Filter block is provided at the output side of the power bridge operating at the same PWM frequency as the IGBTs allowing the 400Hz frequency to pass. The filter block is the combination of LC filter.

3.5 Output Transformer. The output transformer is provided for the following:-

(a) It acts as an isolation transformer to provide isolation between input DC power side and output AC power side.
(b) Transformer is designed as step-up transformer to provide the rated voltage of 230V AC at the lower range of DC battery input voltage (i.e. in the range of 175 to 190V DC).
(c) The transformer is provided with forced cooling arrangement.

3.6 SFC Control Section. The SFC Control Circuit consists of mainly following control section: -

(a) Microprocessor based Controller circuit and HCMI (Human Controlled Machinery Interface).
(b) Auxiliary Power Supply.
(c) Firing Control section with PWM and IGBT Driver circuit.
(d) Signal conditioning circuit for Sensor Signals like Current Sensors, Temperature sensors and voltage sensing circuits.

The Controlled circuit and HMI (Human Machine Interface) is provided with required application software for control and monitoring of SFC. The HMI screen provide the parameter readings for various parameters of SFC like Input/Output voltages and currents and temperatures, control commands outputs. It also provides the facility to display alarms & safeties built into the SFC and operator interface for setting of parameters and start/stop function. The controller circuit and HMI will be rugged and suitable for extended temperature operation.

The auxiliary power supply required for the control circuit is generated in auxiliary power supply section and the control circuit will be suitable for +24V DC and +/-15V DC operation. Other control supplies required for the control circuit will be generated locally on the control circuit.

The firing control section consists of: -

(a) PID section for the generation of voltage command based on the input output voltage, current and frequency feedback.
(b) PWM section to generate PWM waveform for the control of the IGBTs.
(c) IGBT Driver section for the firing of the IGBTs as per PWM control signal.

Signal conditioning section. It consists of voltage, current, frequency and temperature signal conditioning circuitry to give feedback to the controller and firing control section. Isolations are provided in the section for all power signals.

3.7 Control Panel for Operation of SFC. Following operating and indication elements will be catered on SFC front panel in addition to HMI for monitoring and control of SFC: -

(a) Local/Remote Selector Switch
(b) Input Supply Voltage On lamp (for presence of voltage)

(c) Output On/OFF lamp
(d) Common alarm indication lamp
(e) Input supply low indication
(f) SFC Start PB with indication
(g) SFC Stop PB with indication
(h) SFC Emergency stops PB.

The SFC can start up in following modes: -

(a) Local from the SFC panel.
(b) Remote from the remote location

3.8 Technical Specifications of SFC

Inputs:

Voltage	DC 175-320V

Output:

Voltage	3 phase 230V AC
Rated current	157 Amp
Rated frequency	400Hz
Overall efficiency	Better than 85%
Output power	50kW
Power factor	0.8 (cosΦ)
Frequency deviation	+/- 1%
Overload capacity	110% continuous
Overall current limit	110% continuous
Static Regulation 0-100% load	+/- 2%
Dynamic regulation 100%	5%, recovering to 2% within 100ms
Overload capacity (IGBTs)	110% continuous

Table 1: input and output parameters

3.9 Protection. Short circuit protection by electric current limiting and shutdown

4. Design of SFC.

4.1 DC-DC Converters. DC-DC power converters are employed in a variety of applications, including power supplies for personal computers, office equipment, spacecraft power systems, laptop computers, and telecommunications equipment, battery chargers as well as dc motor drives. The input to a DC-DC converter is an unregulated DC voltage, Vg. The converter produces a regulated output voltage V, having a magnitude (and possibly polarity) that differs from Vg. The ideal DC-DC converter exhibits 100% efficiency; in practice, efficiencies of 70% to 95% are typically obtained. This is achieved using switched-mode, or chopper, circuits whose elements dissipate negligible power. Pulse-width modulation (PWM) allows control and regulation of the total output voltage. This approach is also employed in applications involving alternating current, including high-efficiency DC-AC power converters (inverters and power amplifiers), AC-AC power converters, and some AC-DC power converters (low harmonic rectifiers).

4.2 Buck-Boost Converter. The buck–boost converter is a type of DC-to-DC converter (also known as a chopper) that has an output voltage magnitude that is either greater than or less than the input voltage magnitude. It is used to “step up” the DC voltage, similar to a transformer for AC circuits. It is equivalent to a fly-back converter using a single inductor instead of a transformer. Two different topologies are called buck-boost converter. DC-DC converters are also known as choppers.

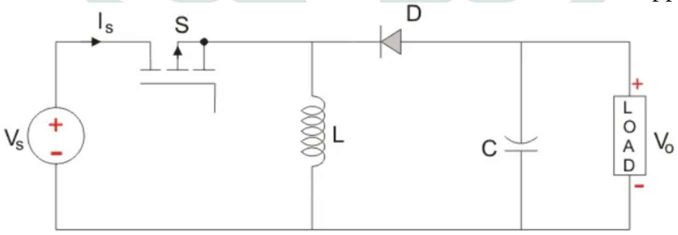


Fig.2:Buck-Boost_converter

The input voltage source is connected to a solid-state device. The second switch used is a diode. The diode is connected, in reverse to the direction of power flow from source, to a capacitor and the load and the two are connected in parallel as shown in the figure above. The controlled switch is turned on and off by using Pulse Width Modulation (PWM). PWM can be time based or frequency based.

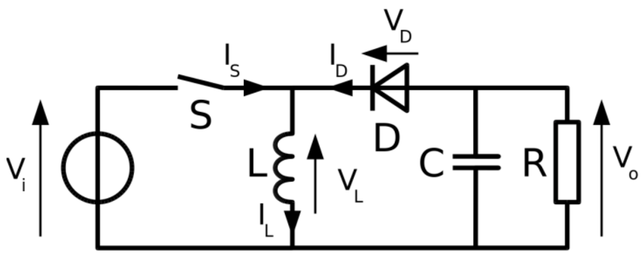


Fig.3: Schematic diagram of buck-boost converter

Design parameters of buck boost converter: -

Let us consider, Voltage output = V_o; Source voltage = V_s; Switching frequency = f_{sw}; Duty cycle = ; Resistance = R

Steps to obtain design parameters for buck boost converter are given below,

Step 1: To determine the duty cycle ratio: $D = \frac{\frac{V_o}{V_s}}{\frac{V_o}{V_s} - 1}$ (3.1)

Step 2: To determine the inductance value: $L_{min} = \frac{(1-D)^2 R}{2 f_{sw}}$ (3.2)

For continuous inductor current, the inductance should be 25% of L_{min} i.e. $L = 0.25 * L_{min}$

Step 3: To determine the capacitor value: $C = \frac{D}{R(\frac{\Delta V_o}{V_o}) f_{sw}}$ (3.3)

Note: Assuming ripple $(\frac{\Delta V_o}{V_o})$ to be less than 5%, The values arrived post calculation:

Input voltage (V_{in})	175V-320V
Output voltage (V_{out})	400V
Inductance	10μH
Capacitance	40mF
Resistance	100Ω

Table 2: Design parameters of Buck-Boost parameters.

Simulation Model of Buck-Boost Converter. The connectivity diagram in MATLAB is shown below: -

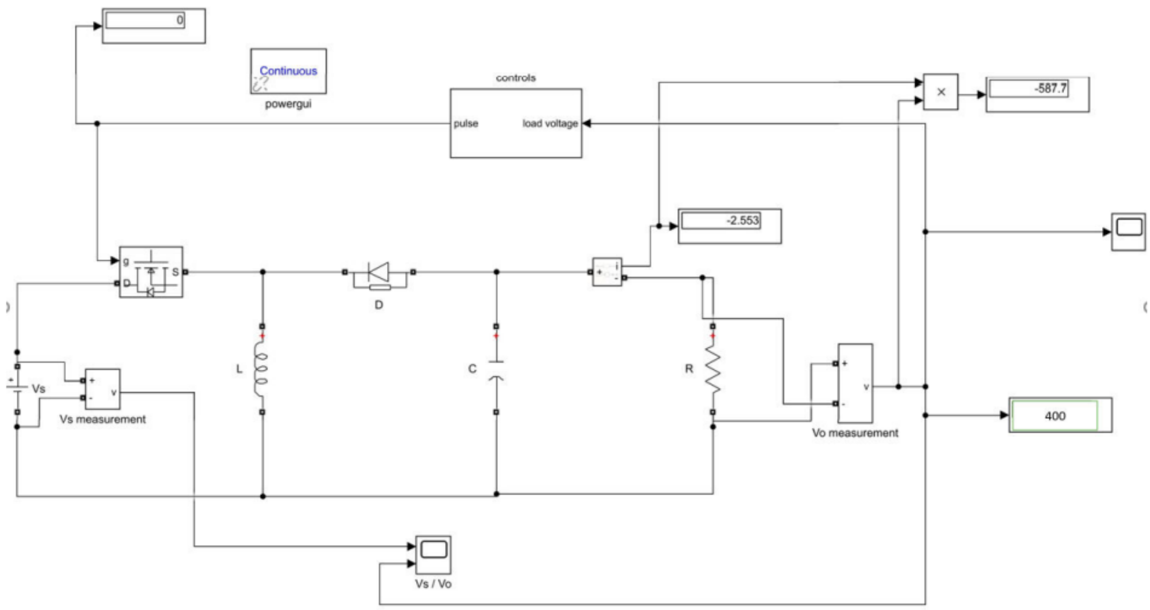


Fig.3: Simulink block of Buck-Boost converter.

Simulation Results:

At Input 175V and 320V DC, the output achieved is 400V DC and waveforms obtained from MATLAB are shown below.

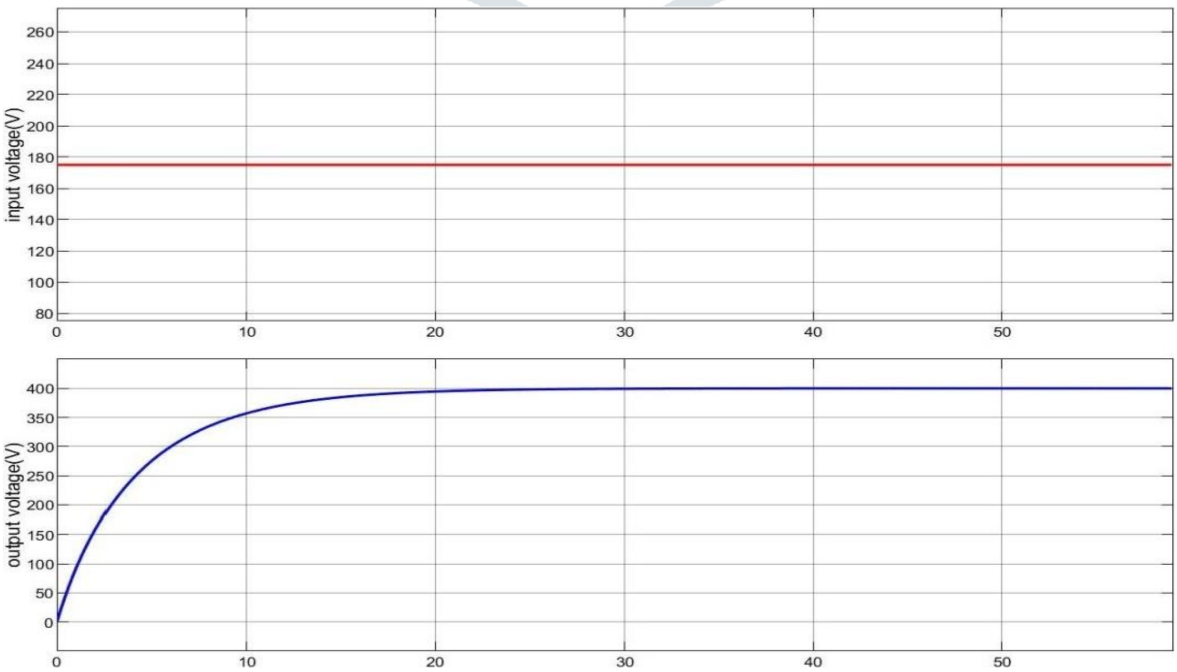


Fig.4: Waveforms Obtained from MATLAB At Input 175V and the Output is 400V

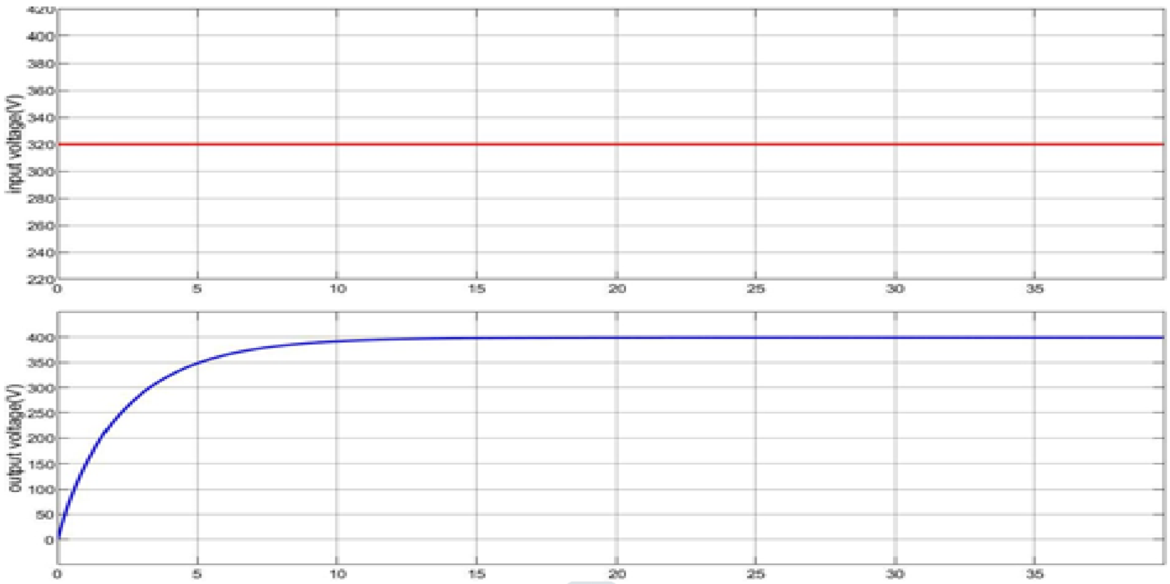


Fig.5: Waveforms Obtained from MATLAB At Input 320V and the Output is 400V

4.3 Three Phase Inverter. The dc-ac converter, also known as the inverter, converts dc power to ac power at desired output voltage and frequency. The dc power input to the inverter is obtained from an existing power supply network or from a rotating alternator through a rectifier or a battery, fuel cell, photovoltaic array or magneto hydrodynamic generator. The filter capacitor across the input terminals of the inverter provides a constant dc link voltage. The inverter therefore is an adjustable-frequency voltage source. The configuration of ac to dc converter and dc to ac inverter is called a dc link converter.
Inverters can be broadly classified into two types, voltage source and current source inverters. A voltage–fed inverter (VFI) or more generally a voltage–source inverter (VSI) is one in which the dc source has small or negligible impedance. The voltage at the input terminals is constant. A current–source inverter (CSI) is fed with adjustable current from the dc source of high impedance that is from a constant dc source. A voltage source inverter employing thyristors as switches, some type of forced commutation is required, while the VSIs made up of using GTOs, power transistors, power MOSFETs or IGBTs, self-commutation with base or gate drive signals for their controlled turn-on and turn-off.

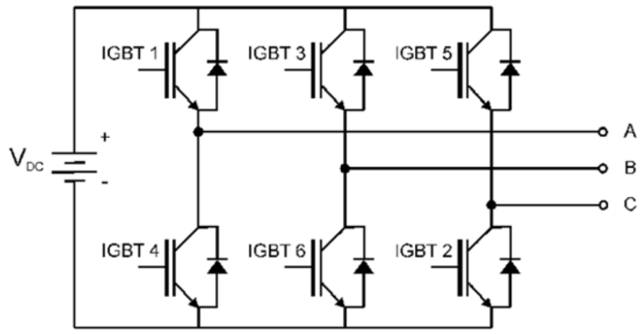


Fig.6: 3 Phase IGBT inverter circuit

4.4 Pulse width modulation inverter technology.

(a) **PWM fundamentals**. Pulse width modulation inverter circuit Definition: to control the output voltage by changing the pulse width, to control the output frequency of the circuit by changing the modulation cycle.

(b) **Pulse width modulation classification**. To modulate the pulse polarity can be divided into unipolar and bipolar modulation two kinds; To the carrier frequency signal and the reference signal relationship between the frequency can be divided into two kinds of asynchronous and synchronous modulation.

(c) **PWM inverter circuit features.** We can get quite close to the sine wave output voltage and current, it is also known sinusoidal pulse width modulation SPWM (Sinusoidal PWM).

(d) **SPWM control**. that is to control the inverter circuit switching device on and off so that the output to give a series of equal amplitude and pulse width ranging, from using these pulses to instead of sinusoidal waveform required. According to certain rules of each pulse width modulated, it can change the size of the output voltage of the inverter circuit and the output frequency may also be varied.

Modulation mode of PWM control circuit

(a) Carrier ratio is defined: In the 3-phase PWM power inverter circuit, the ratio of the carrier frequency fc and the modulated signal fs called the carrier frequency ratio, that is, N=fc/fs.

(b) 3-phase PWM inverter circuit control mode: According to whether the carrier wave and the modulation signal are synchronized has asynchronous and synchronous modulation two control mode. Asynchronous modulation control: When the entire carrier ratio is not a multiple of 3, carrier wave with the modulation signal is not synchronized modulation. Synchronous modulation control: In the three-phase inverter circuit when the carrier ratio is an integer multiple of 3, the carrier modulation signal modulation wave can be synchronized.

Sinusoidal Pulse Width Modulation Technique

(a) SPWM techniques are characterized by constant amplitude pulses with different duty cycles for each period. The width of these pulses are modulated to obtain inverter output voltage control and to reduce its harmonic content. Sinusoidal pulse width modulation is the mostly used method in motor control and inverter application. In SPWM technique three sine waves and a high frequency triangular carrier wave are used to generate PWM signal. Generally, three sinusoidal waves are used for three phase inverter. The sinusoidal waves are called reference signal and they have 1200 phase difference with each other. The frequency of these sinusoidal waves is chosen based on the required inverter output frequency (400 Hz). The carrier triangular wave is usually a high frequency (in several KHz) wave. The switching signal is generated by comparing the sinusoidal waves with the triangular wave. The comparator gives out a pulse when sine voltage is greater than the triangular voltage and this pulse is used to trigger the respective inverter switches. In order to avoid undefined switching states and undefined AC output line voltages in the VSI, the switches of any leg in the inverter cannot be switched off simultaneously. The phase outputs are mutually phase shifted by 1200 angles. The ratio between the triangular wave & sine wave must be an integer N, the number of voltage pulses per half-cycle, such that, 2N= fc /fs.

Amplitude Modulation, $M_a = \frac{A_s}{A_c}$; Frequency Modulation, $M_f = \frac{f_s}{f_c}$

% of individual harmonics, $\% \frac{rms(n)}{V_{DC}} = 100 \left(\frac{4}{n\Pi\sqrt{2}} \sum_{p=1}^{M_f} (-1)^{i+1} \cos n\alpha_i \right)$, Where, n=nth harmonics. (4.1)

% of total RMS of the output, when M_f is even, $\%V_n = 100 * \sqrt{\left[\frac{2}{\Pi} \sum_{P=1}^{\frac{M_f}{2}} (\alpha_{2P} - \alpha_{2P-1}) + \frac{\Pi}{2} - \alpha_{M_f} \right]}$ (4.2)

Total harmonics distortion, $THD = \frac{V_h}{V_1}$; (4.3)

Where, $V_h = \sqrt{\sum_{n=2,3,\ldots\ldots}^{\infty} V_n^2}$ or, $V_h = \sqrt{V_{out}^2 - V_1^2}$; V_1 = Fundamental component.

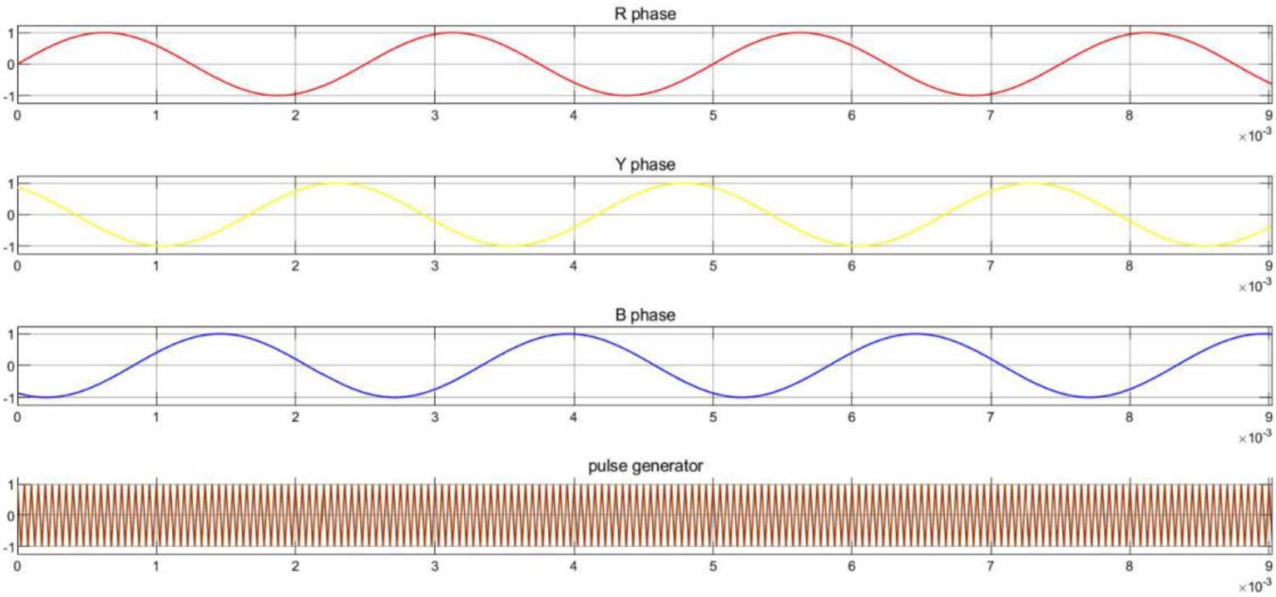


Fig.7: Waveform-MATLAB at Input RYB Sinusoidal &Pulse Generator for PWM technique

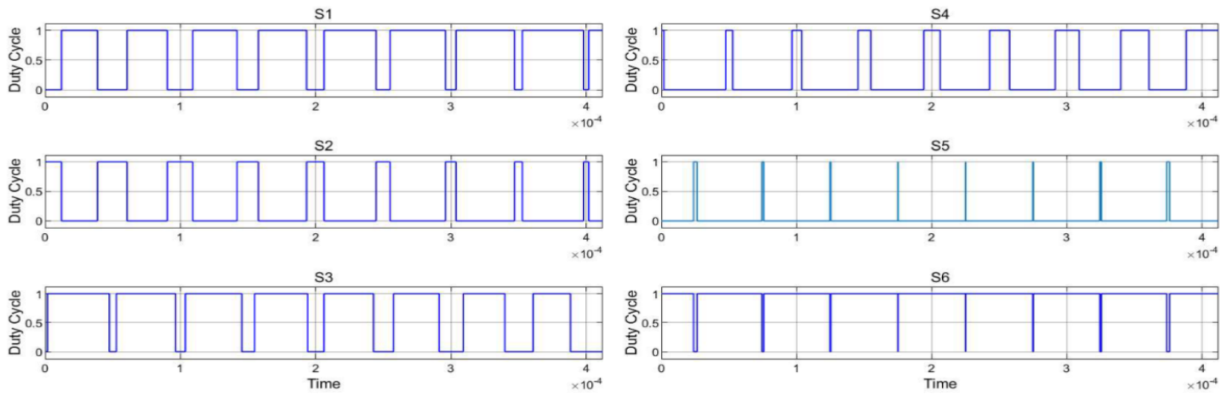
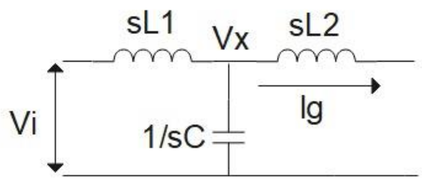


Fig.8: Waveforms from MATLAB for Duty cycle

4.5 LCL Filter. LCL filters are specially designed to reduce harmonics of current absorbed by power converters, with a rectifier input stage. (Frequency converters for motors, UPS, etc.). Mainly, they are made of a parallel-series combination of reactors and capacitors adapted to reduce the THD (I) of rectifiers.

Mathematical modelling for Filter. Let, consider inductors towards inverter as L1 and inductors towards load as L2, capacitors connected as C; Current passing through load as Ig; Voltage across load as Vg

Transfer function between Ig and Vi. Phase equivalent circuit of LCL filter in S-domain



From KCL,

$$\frac{V_i - V_x}{sL1} = I_g + \frac{V_x}{\frac{1}{sC}} \quad (4.5)$$

$$V_x = I_g sL2$$

From solving of above equations, $\frac{I_g}{V_i} = \frac{1}{S^3 L1L2C + s(L1+L2)}$ Let, $L1 + L2 = L$ & $L_p = \frac{L1L2}{L1+L2}$ (4.6)

Final transfer function equation is given below: $\frac{I_g}{V_i} = \frac{1}{sL(1+S^2 CL_p)}$ (4.7)

From the above equation the resonance frequency is expressed as shown below $\omega_{res} = \frac{1}{\sqrt{CL_p}}$

Filter values design

(a) **Step 1**: Selection of switching frequency, F_{sw} = 10KHz (4.8)

(b) **Step 2**: Selection of resonant frequency, $f_{res} = \frac{F_{sw}}{10}$ = 1000Hz (4.9)

(c) **Step 3**: Finding the value of capacitance, $C = \frac{0.05*S}{V^2*2*pi*f} = 6.23*10^{-6}$F (Note: S = rated power) (4.10)

(d) **Step 4**: Finding the value of inductance

(e) From final transfer function ($\frac{I_g}{V_i}$) and resonance frequency (ω_{res}),

$$\frac{I_g}{V_i} = \frac{1}{sL(1+\frac{s^2}{\omega_{res}^2})} \quad (4.11)$$

Replace, $s = j\omega_{sw}$, (4.12)

$$\frac{I_g(sw)}{V_i(sw)} = \frac{1}{j\omega_{sw}L(1+\frac{(j\omega_{sw})^2}{\omega_{res}^2})} \quad (4.13)$$

$$\left|\frac{I_g(sw)}{V_i(sw)}\right| = \frac{1}{\omega_{sw}L(1-\frac{\omega_{sw}^2}{\omega_{res}^2})} \quad (4.14)$$

From above equation the value of inductor is given as,

$$L = \left|\frac{1}{\omega_{sw}\frac{I_g(sw)(1-\frac{\omega_{sw}^2}{\omega_{res}^2})}{V_i(sw)}}\right| \quad (4.15)$$

Minimum value of required inductance is given as L1=L2=L/2

Maximum value of inductance is calculated based on voltage drop across inductor

Note: voltage drop = 20% of output voltage, $L_{max} = \frac{0.2*V_{output}}{2*pi*400*I}$, Then $L1 = L2 = \frac{L_{max}}{2} = 4.35*10^{-3}$H (4.16)

5 Static Frequency Converter. The block diagram of complete system is shown below. The connectivity diagram has been simplified to facilitate detailed simulation study through MATLAB software. In this circuit DC variable Voltage is feeding as input to MOSFET Chopper circuit and the AC 400Hz consumers are feeding from output of 3Ph IGBT converter.

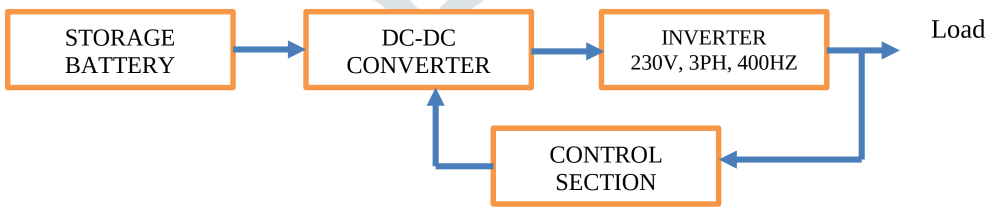


Fig.9: Block Diagram of Static Frequency Converter

Normal operating regime i.e. Inverter mode; Variable DC Source 175-320V from Storage Battery feeding DC-DC Converter; the output of DC-DC converter V=400V is feeding to 3Ph IGBT Inverter; and the output of inverter V=230V, 3Ph, 400Hz is connected to load).

Simulink model. The complete Model of MATLAB Simulink of Static Frequency Converter with variable DC Voltage input and constant output AC Voltage and Frequency of 3Ph is shown below.

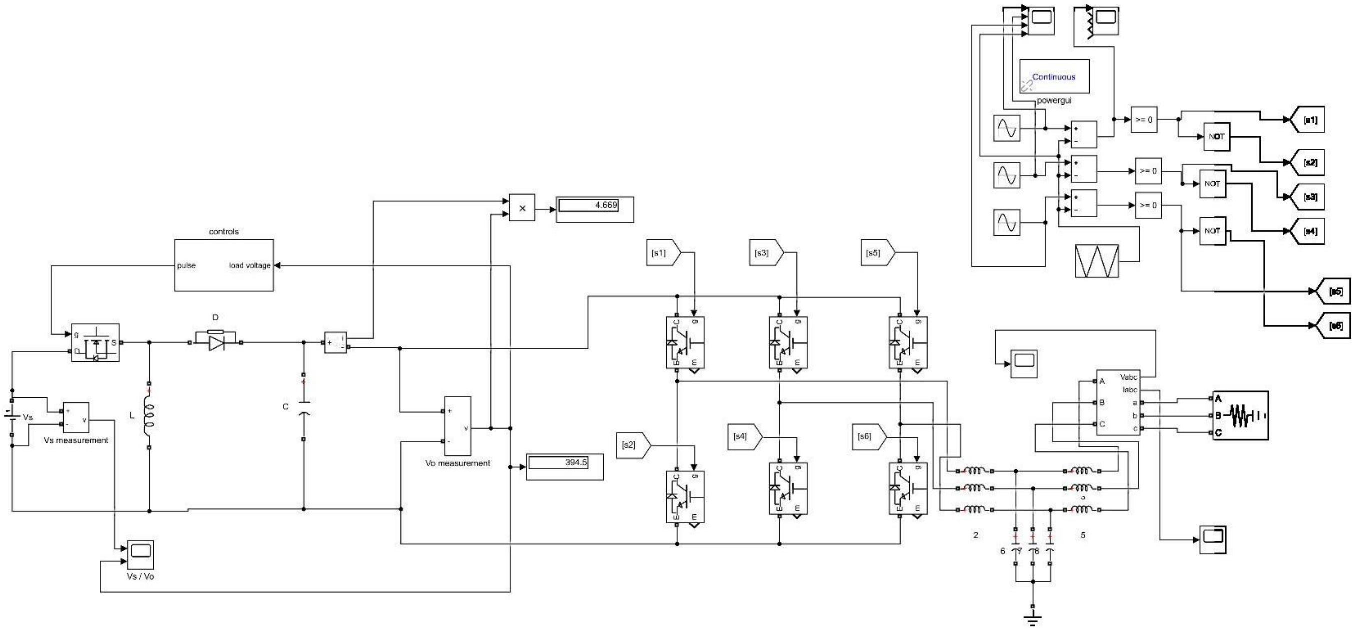


Fig.10: MATLAB Simulation of Complete System

Simulation Results. At the Input of 175V & 320V, the output obtained is 230V, 3Ph, 400Hz .

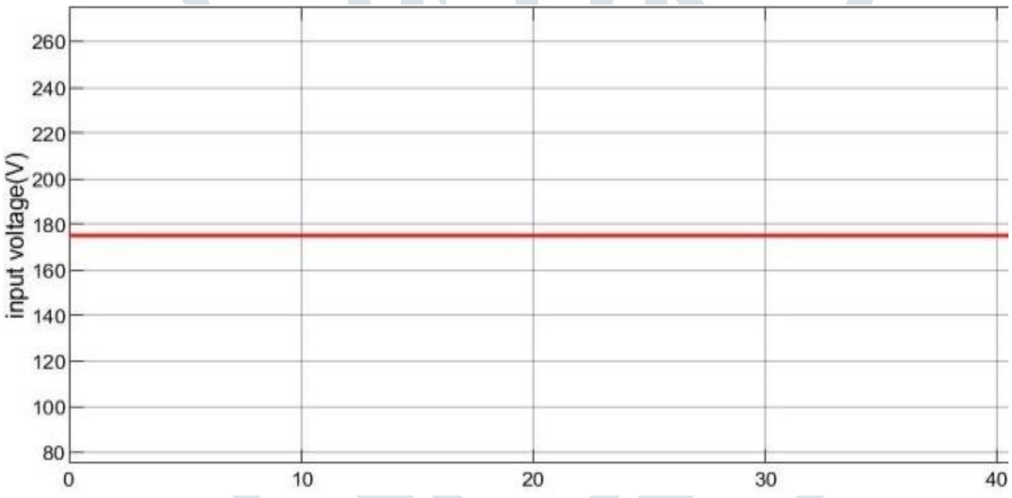


Fig.11: Input Wave forms at 175V

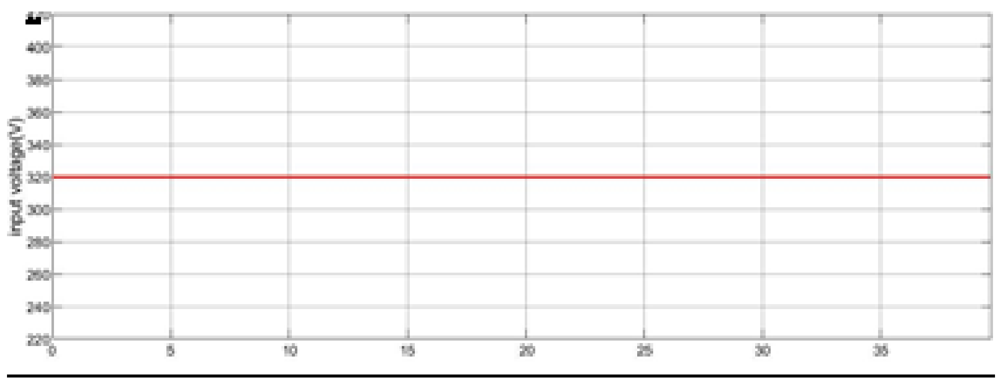


Fig.12: Input Wave forms at 320V

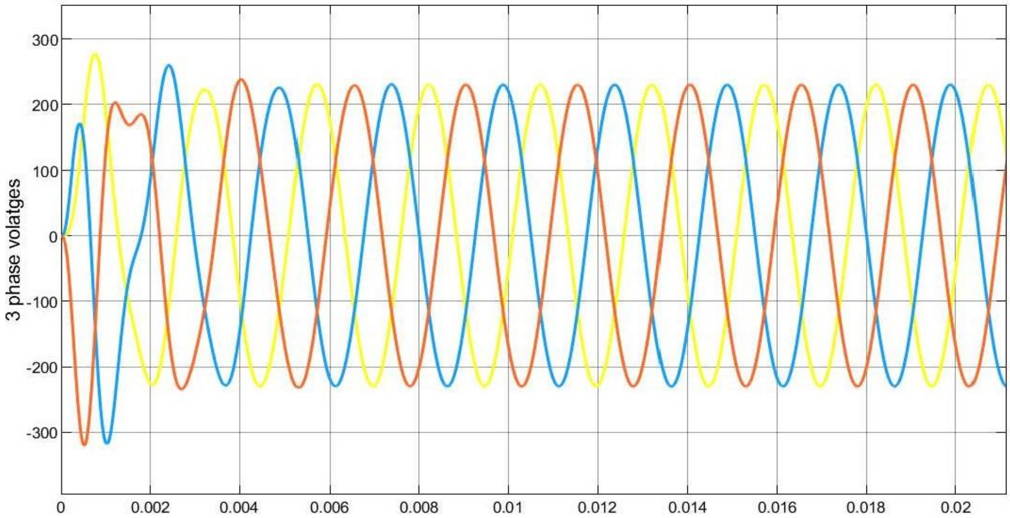


Fig.13: Waveforms from MATLAB at an Input of 175V and 320V, Output is 230V, 3Ph, 400Hz

Calculation of Frequency

Frequency, f=1/t, Where, f = Frequency, t = Time period

By Considering the Yellow phase wave form in the above Fig, it takes 04 cycles during a time period of 0.01 Sec.

Frequency, f = 4*1/t = 4*1/0.01= 400Hz.

6. Conclusion. Case Study on DC-AC 400Hz Rotary Converter installed onboard marine platforms, gave an opportunity to understand its installation and maintenance aspects of rotatory machines. During study, the various defects observed have been completely analyzed and addressed with a suitable solution. Accordingly, an equivalent Static Frequency Converter has been designed and the same was simulated in MATLAB with variable DC input voltage of 175-320V and a constant output of 230V, 3Ph, 400Hz has been obtained.

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