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Control and Modeling of Shaft Generator with PWM Voltage Source Inverter for ship

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Abstract** - This papers deals with well – based mathematical modeling of variable speed alternator (Shaft Generator) with PWM voltage source inverter used in ship.* *Detailed knowledge of electromagnetic characteristics of shaft generator is necessary for design complex ship's power system. Such knowledge is obtainable only by numerical simulations.* ***The dynamic behavior of shaft generators, SPWM voltage source inverter and their controllers during load variations are also discussed with the help of MATLAB/SIMULINK. Elimination of harmonic contents using sinusoidal pulse width modulation also discussed here.

***Index Terms** –PWM – Pulse width modulation, Shaft Generator, VSI – Voltage Source Inverter.*

I. INTRODUCTION

During the last decades, electrical power demand for ship use has increased heavily, mostly due to the increment of electrical facilities in ships [1]. And fuel consumption has also increased continuously. In order to save fuel consumption, a practical method is to apply main shaft generators to ships [2].Main shaft generator are a kind of electrical power supply device whose prime mover is the shaft of main engine. The efficiency of the operation of main engine is rather high, and the fuel it consumes is very cheap, mainly heavy oil. These factors make the running of main shaft generator economical. For this reason, more and more main shaft generators have been applied to ocean ships to optimize fuel consumption to lower the power production costs. Nowadays, SCR shaft generator, also called shaft generator of converter type, is the most popular kind of shaft generators for marine use. Fig.1 shows schematic diagram of shaft generator system used in ship for electrical power generation and distribution.

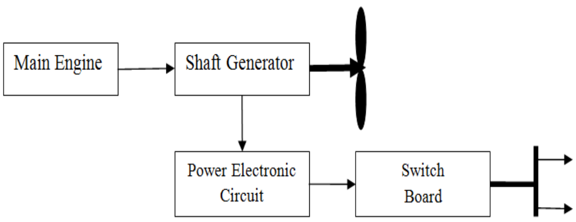

Figure 1Power Generation using shaft generator

II. CONSTITUTION AND MODELING OF POWER GENERATION SYTEM

Figure 2 gives in one hand a preview on the structure of the system and on the other hand the input and output of different subsystems. In case of shaft generator, which is driven by main engine, the speed of the former may vary at different situations like ship sailing in traffic water and crossing canals, resulting in variation in voltage and frequency of shaft generator.

The frequency of the shaft generator is proportional to shaft speed; the shaft is variable according to sea climate. Shaft generator always produces voltage with some frequency deviation from the rated value. Output of shaft generator is rectified by 3 – phase uncontrolled rectifier circuit, no need of generating firing pulses for rectifier circuit. Rectified output is fed to intermediate circuit which produces stabilized DC output and fed to 3 – phase pulse width modulated voltage source inverter and which gives fixed voltage and frequency as a output. Control and regulation circuit will correct the variation in output according user desired level. Review Stage Submit your manuscript electronically for review.

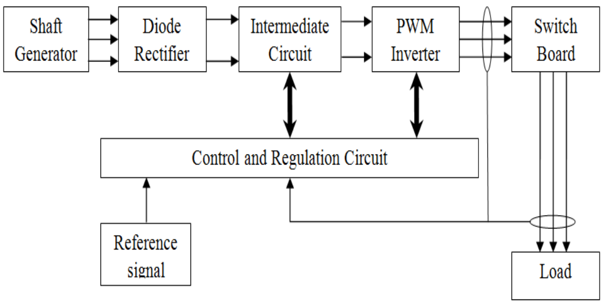

Figure 2 Power Generation and Control Circuit

A. Modeling of shaft generator

The equations (1) represent the governing equations for the synchronous machines in the reference d-q. In order to simplify calculations and to facilitate the interpretation of the results one used a unit system to standardize all the electric quantities [3],[4], [5],

$$u_d = r_s i_d + \frac{1}{\omega_n}\frac{d\psi_d}{dt} - \omega_m \psi_q$$

$$u_q = r_s i_q + \frac{1}{\omega_n}\frac{d\psi_q}{dt} + \omega_m \psi_d$$

$$0 = r_D i_D + \frac{1}{\omega_n}\frac{d\psi_D}{dt}$$

$$0 = r_Q i_Q + \frac{1}{\omega_n}\frac{d\psi_Q}{dt}$$

$$u_f = r_f i_f + \frac{1}{\omega_n}\frac{d\psi_f}{dt} \qquad (1)$$

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Where is ω_n the reference pulsation (rd/s)
ω_m is the mechanical pulsation in p.u.

The significance of flux is as follows:
- According to the direct axis:
Ψad = principal flux coupled by three rolling up,
ψσd, ψσD, ψσf = flux of escaping rolling up d, D and f
ψσDd = exclusive mutual flux between stator and shock absorbers,
ψσDf = exclusive mutual flux between shock absorbers and excitation.

Exclusive mutual flux between the excitation and the stator is supposed to be null.

- According to the transverse axis:

Ψaq = principal flux coupled with two rolling up,
ψσq, ψσQ = flux of escape of rolling up q and Q,
For these fluxes correspond the following respective inductances in p.u
lad, lσd, lσD, lσf, lσDd, lσQf, laq, lσq, lσQ

The flux Equations in p.u are given by (2):

$$\psi_d = l_{ad} i_d + l_{\sigma d} i_d + l_{ad} i_D + l_{ad} i_f$$
$$\psi_q = l_{ad} i_q + l_{\sigma q} i_q + l_{aq} i_Q$$
$$\psi_D = l_{ad} i_d + l_{ad} i_D + l_{ad} i_f$$
$$\psi_Q = l_{aq}(i_d + i_Q) + l_{\sigma Q} i_Q$$
$$\psi_f = l_{ad}(i_d + i_D + i_f) + l_{\sigma Df}\left(i_D + i_f\right) + l_{\sigma f} i_f \quad (2)$$

The flux can be written as

$$\psi = Ai \Rightarrow i = A^{-1}\psi \quad (3)$$

$$\begin{bmatrix} \psi_d \\ \psi_q \\ \psi_D \\ \psi_Q \\ \psi_f \end{bmatrix} = \begin{bmatrix} l_{ad}+l_{\sigma d} & 0 & l_{ad} & 0 & l_{ad} \\ 0 & l_{aq}+l_{\sigma q} & 0 & l_{aq} & 0 \\ l_{ad} & 0 & l_{ad}+l_{\sigma Df}+l_{\sigma D} & 0 & l_{ad}+l_{\sigma Df} \\ 0 & l_{aq} & 0 & l_{aq}+l_{\sigma Q} & 0 \\ l_{ad} & 0 & l_{ad}+l_{\sigma Df} & 0 & l_{ad}+l_{\sigma Df}+l_{\sigma f} \end{bmatrix} \times \begin{bmatrix} i_d \\ i_q \\ i_D \\ i_Q \\ i_f \end{bmatrix}$$

The electromagnetic torque equation is:

$$C_e = \psi_d i_q - \psi_q i_d \quad (4)$$

The load mechanical equation is:

$$\omega_m = \frac{1}{T_a}\left(C_e - Q_{prop}\right) \quad (5)$$

Using equation (1) and (2), the system can be written as

$$\dot{\psi} = K(\omega_m)\psi + Ri + Eu_g + bu_f \quad (6)$$

Using the system (6) and equation (3), the system can be written as (7):

$$\dot{\psi} = \left(K(\omega_m) + RA^{-1}\right)\psi + Eu_g + bu_f \quad (7)$$

Where:

$$\dot{\psi} = \begin{bmatrix} \dot{\psi}_d & \dot{\psi}_q & \dot{\psi}_D & \dot{\psi}_Q & \dot{\psi}_f \end{bmatrix}^T$$
$$i = \begin{bmatrix} i_d & i_q & i_D & i_Q & i_f \end{bmatrix}^T,$$
$$\psi = \begin{bmatrix} \psi_d & \psi_q & \psi_D & \psi_Q & \psi_f \end{bmatrix}^T,$$
$$u_g = \begin{bmatrix} u_d & u_q \end{bmatrix}^T.$$

The system (1) is given by (8):

$$\begin{bmatrix} \dot{\psi}_d \\ \dot{\psi}_q \\ \dot{\psi}_D \\ \dot{\psi}_Q \\ \dot{\psi}_f \end{bmatrix} = \begin{bmatrix} 0 & -\omega_n\omega_m & 0 & 0 & 0 \\ \omega_n\omega_m & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} \psi_d \\ \psi_q \\ \psi_D \\ \psi_Q \\ \psi_f \end{bmatrix} + \begin{bmatrix} -\omega_n r_s & 0 & 0 & 0 & 0 \\ 0 & -\omega_n r_s & 0 & 0 & 0 \\ 0 & 0 & -\omega_n r_D & 0 & 0 \\ 0 & 0 & 0 & -\omega_n r_Q & 0 \\ 0 & 0 & 0 & 0 & -\omega_n r_f \end{bmatrix} \begin{bmatrix} i_d \\ i_q \\ i_D \\ i_q \\ i_f \end{bmatrix} + \begin{bmatrix} \omega_n & 0 \\ 0 & \omega_n \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} u_d \\ u_q \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ \omega_n \end{bmatrix} \begin{bmatrix} u_f \end{bmatrix}$$

B. Voltage Source Inverter

The standard three-phase VSI topology is shown in Fig. 3 and the eight valid switch states are given in Table 1. of the eight valid states, two of them (7 and 8 in Table 1) produce zero ac line voltages. In this case, the ac line currents freewheel through either the upper or lower components. The remaining states (1 to 6 in Table 1) produce nonzero ac output voltages. In order to generate a given voltage waveform, the inverter moves from one state to another. Thus the resulting ac output line voltages consist of discrete values of voltages that are V_i, 0, and $-V_i$ for the topology shown in Fig. 3. The selection of the states in order to generate the given waveform is done by the modulating technique that should ensure the use of only the valid states.

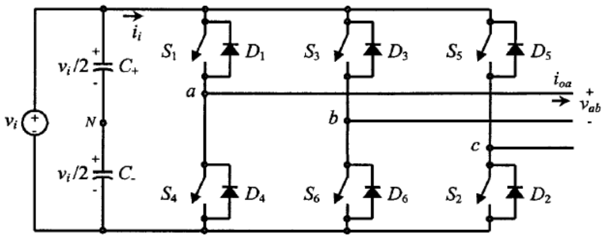

Figure 3 Three Phase VSI topology

State	State	v_{ab}	v_b	v_a
1, 2, and 6 are on and 4, 5, and 3 are off	1	v	0	$-v$
2, 3, and 1 are on and 5, 6, and 4 are off	2	0	v	$-v$
3, 4, and 2 are on and 6, 1, and 5 are off	3	$-v$	v	0
4, 5, and 3 are on and 1, 2, and 6 are off	4	$-v$	0	v
5, 6, and 4 are on and 2, 3, and 1 are off	5	0	$-v$	v
6, 1, and 5 are on and 3, 4, and 2 are off	6	v	$-v$	0
1, 3, and 5 are on and 4, 6, and 2 are off	7	0	0	0
4, 6, and 2 are on and 1, 3, and 5 are off	8	0	0	0

Table 1 Switching Sequence

The model of the inverter output voltage is given by

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \left\{ \begin{bmatrix} S_1 \\ S_3 \\ S_5 \end{bmatrix} \frac{V_i}{2} - \begin{bmatrix} S_4 \\ S_6 \\ S_2 \end{bmatrix} \frac{V_i}{2} \right\} \quad (9)$$

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III. SINUSOIDAL PULSE WIDTH MODULATION

Three-phase reference voltages of variable amplitude and frequency are compared in three separate comparators with a common triangular carrier wave of fixed amplitude and frequency. As shown in figure 4, a saw-tooth- or triangular-shaped carrier wave, determining the fixed PWM frequency, is simultaneously used for all three phases. This modulation technique, also known as PWM with natural sampling, is called sinusoidal PWM because the pulse width is a sinusoidal function of the angular position in the reference signal. The maximum value of ac fundamental line voltage is given by

$$V_{ab} = m_a \frac{\sqrt{3}}{2} v_i \quad (10)$$

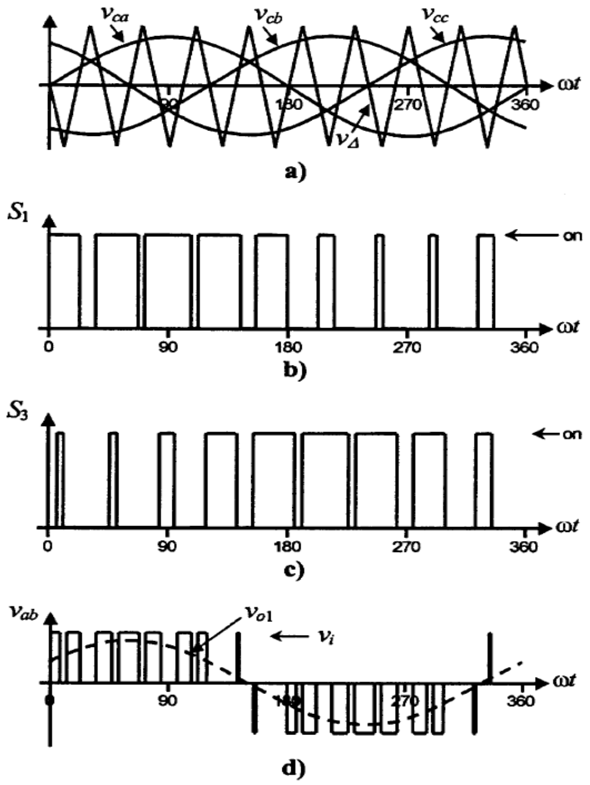

Figure 4 Sinusoidal Pulse Width Modulation Output

IV. ELIMINATION OF HARMOCIS USING SPWM

Although the SPWM waveform has harmonics of several orders in the phase voltage waveform, the dominant ones other than the fundamental are of order n and n±2 where n = fc/fm. This is evident for the spectrum for n=15 and m = 0.8 shown in Fig.5. Note that if the other two phases are identically generated but 120^0 apart in phase, the line-line voltage will not have any triple harmonics. Hence it is advisable to choose $\frac{f_c}{f_m} = 3k, (k \in N)$, as then the dominant harmonic will be eliminated. It is evident from Fig 5b, that the dominant 15th harmonic in Fig. 5a is effectively eliminated in the line voltage. Choosing a multiple of 3 is also convenient as then the same triangular waveform can be used as the carrier in all three phases, leading to some simplification in hardware.

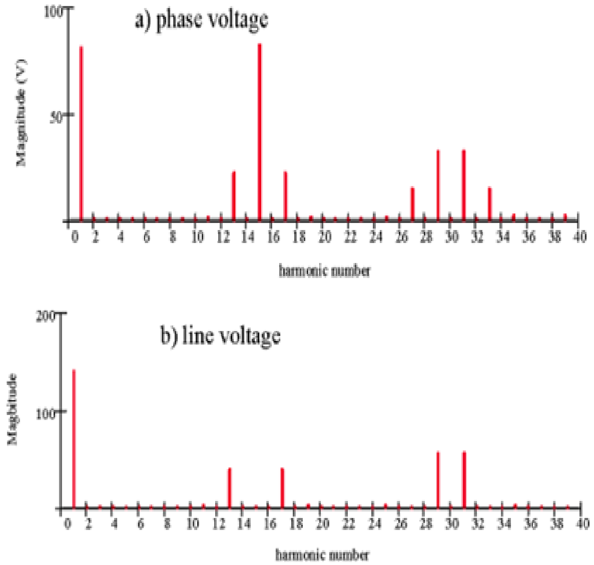

Figure 5 Harmonic Contents for phase and line voltage

IV. VOLTAGE REGULATOR

Fig 6. Shows the implementation of voltage regulator in MATLAB/SIMULINK. The duty of voltage regulator is to compare the output voltage with reference voltage and to produce the modulating signal for SPWM generator. If there is any change in output or reference, according to it changes the modulating signal value with the help of PI controller.

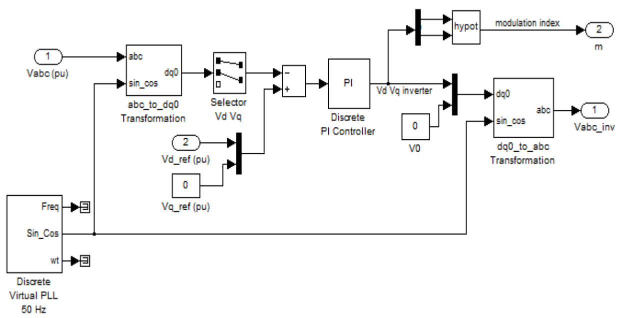

Figure 6 Implementation of Voltage Regulator using Matlab.

V.SIMULATION TEST AND RESULTS

To check the validity of the model described above a set of simulation tests have been carried out to analyses the system under steady state and transient conditions using MATLAB. Computer simulation is carried out using the system parameters given by: f = 50 Hz, ω = 2πf, V_L = 340 V, 2500 KVA, 460 V and 1800 rpm.

Based on the linear model described above and using root locus technique the parameters of the controller are found to be [15]. Kp = 0.4, Ki = 500. A Fig. 7 show the inverter output is constant voltage with frequency, with variable voltage and variable frequency input.

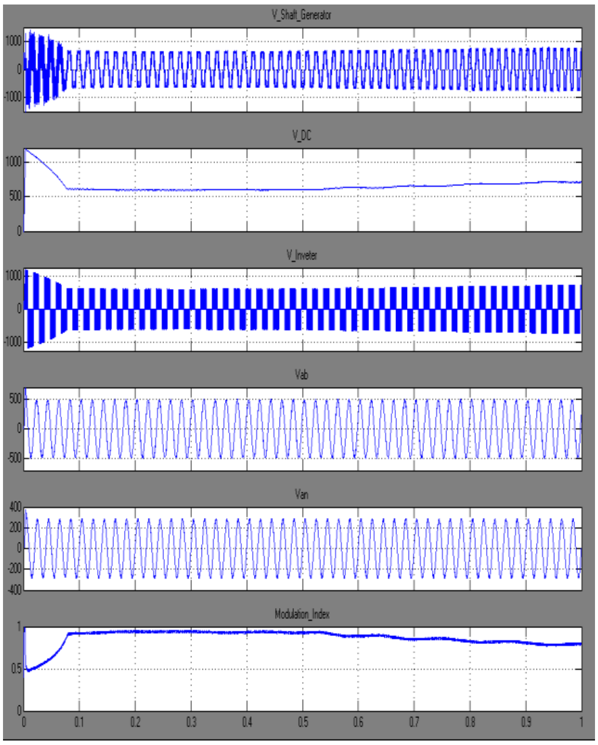

Figure 7 Output of entire system

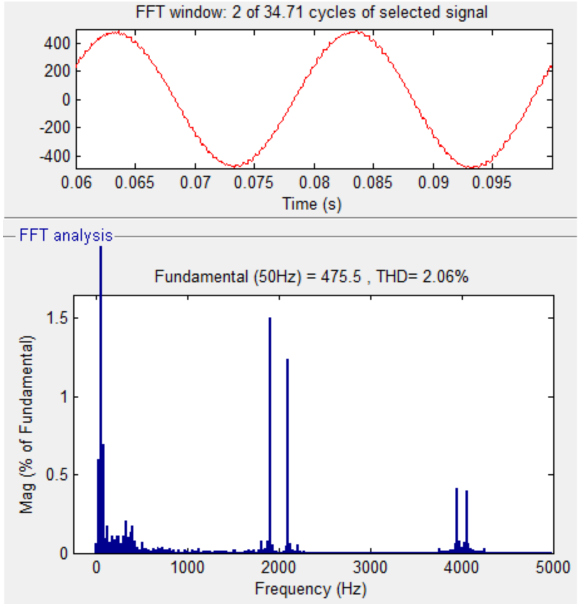

Figure 8 Harmonic Spectrum of Load Voltage

VI. CONCLUSION

This paper shows the complete system to working as a whole with controls to control the output voltage on MATLAB Simulink. The shafts generator response differs when subjected to variable mechanical power and variable speed. But with the help of voltage regulator in PWM inverter the load voltage remains constant.

A PI controller is used in voltage regulator as the steady state error is needed to be corrected, on the other hand not affecting the transient. It is also more flexible to use a PI controller instead.

The total harmonic content present in the load voltage and current is also reduced to reasonable values.

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