A

Dissertation Report

On

Modelling and Analysis of linear electrical generator

Submitted in fulfillment of

the requirements for the award of the degree

of

MASTER OF TECHNOLOGY

in

Electrical Engineering

(With Specialization in Power Electronics and Drives)

Submitted By

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CANDIDATE DECLARATION

I herein accept that the work that is being presented in this **DISSERTATION REPORT**, having title "**Modelling and Analysis of linear electrical generator** " to fulfil the criterial of mandatory needs for the award of the Master of Technology in electrical drives and power electronics(EDPE), submitted to the Department of Electrical Engineering of the Indian Institute of Technology Roorkee, India, is an authentic record of my work carried out under the guidance of Dr. Sajjan pal Singh, Professor, Electrical Engineering, IIT Roorkee The matter embodied in this has not been submitted for the award of any other degree.

Place: Roorkee **Sanjay Singh**

Date: EnrollmentNo.**14115104**

CERTIFICATE

This is to certify that the above mentioned statement made by the candidate is correct to the best of my knowledge.

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Abstract

As we moving further there is increase in demand for sources but unfortunately sources decreasing at alarming rate. Techniques involved in renewable energy are now coming forward as time passes. This not just because scarcity but also due to dangerous after effects of their uses like pollution, greenhouse effect and so many countless adverse impacts of ecology. Thus we need to take support of renewable energy available in tremendous amount. The energy content of oceanic waves is heavy source of potential for society now. Fortunately, technologies related to this also improved a lot.

Extraction of wave potential and its techniques are coming and have great interest throughout the world to extract energy from eco-friendly sources like ocean waves. But problem is that now we are having availability of rotational devices to convert energy but in ocean waves flow is back and forth. So we need device that can directly convert energy and provide us the output. Thus here we are working on permanent magnet linear generator(PMLG). Here this technology is called as direct drive technology.

Here modelling and analysis of permanent magnet linear generator (PMLG) and also MATLAB simulinking of (PMLG) is being presented. Study of different parameters and how they affect output of (PMLG) in terms of current and voltage.

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INTRODUCTION

Introduction

To begin with first, we will present the need of having upgradation to PMLG (permanent magnet linear generator). And how to proceed step by step so that we can very practical voltage level and power. Thus below are details how i proceeded.

1.1 Background

Wave energy conversion, now a days growing rapidly to help society worldwide by providing potential on harnessing predictable, sustainable, and almost unlimited source of energy. As compare to air, water is much higher in density thus the energy converting devices needed takes place very less in amount space getting compared that of wind turbines. When uneven heating of earth emanates wind and wind in turn creates waves, which is a source of energy now for whole world. The waves gather energy throughout the sea stretches and thus gives tremendous amount of wave energy on coastal shores. The wave energy system takes use of motion of waves in vertical direction. Hence the output power can be modulated at the available frequency of waves, approximately 4 to 11 seconds. Thus we need to condition and regulate the coming power for connection to a utility grid. Advancements in technology of power electronics has made possible to avail power production of power with max efficiency and max extraction of potential from oceanic wave.

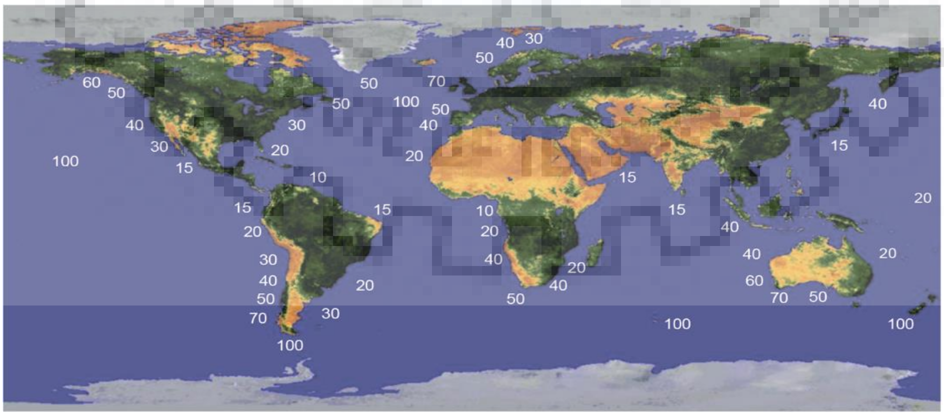


Fig. 1.1 -Water potential throughout world

1.2 **Wave Energy main oriented source**

Conversion of oceanic energy uses ocean waves, ocean tides and ocean currents like a potential to extract energy in form of electrical energy. Numerous mechanical devices are available currently deployed in conversion of oceanic energy into electrical energy. The devices can be similar to power supplying pelamis wave potential converter and ocean power based on technology of power buoy. But these devices more over translate oceanic wave motion to electrical energy mechanically through mechanical system and then to rotating generator. Here it must have intermediate step that is mechanical components which add to system losses and maintenance on account of various rotating and moving parts. The energy system groups at Oregon state university primarily focusing on wave energy converters which can eliminate mechanical to rotating devices. This thesis wholly and solely focuses on direct drive technology like linear electrical machines.

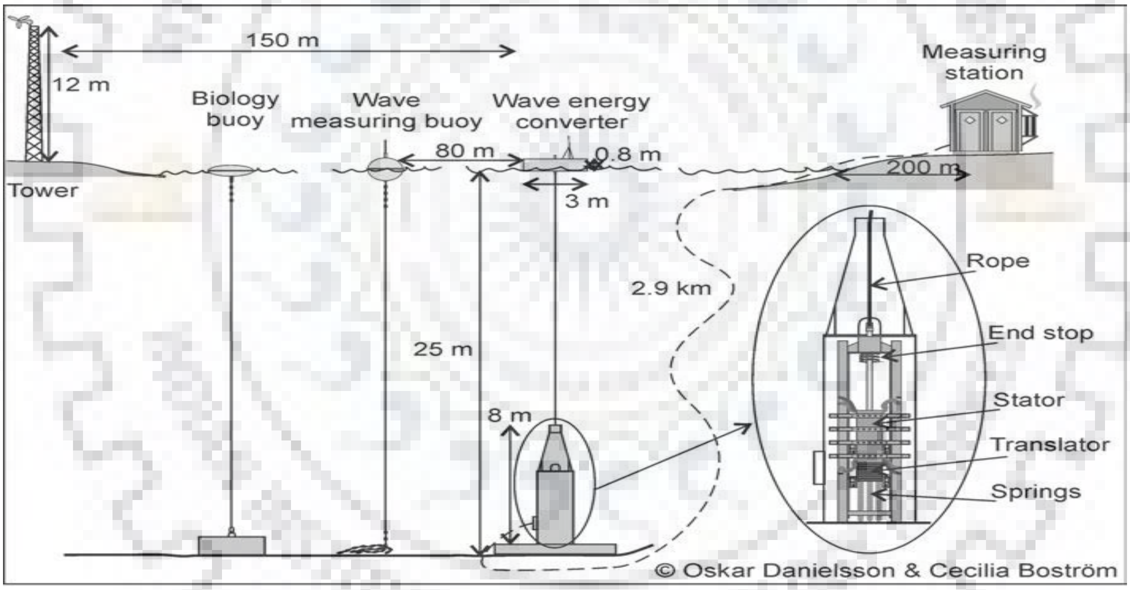


Fig. 1.2 -Model for direct drive to extract energy from waves

Such devices convert kinetic energy into linear motion from force excited by oceanic wave. Buoy moves vertically along the spar due to this force, which creates relative motion between moving parts and stationary parts of PMLG. As spar is moored to floor of ocean thus make it still.

The buoy movement linearly by excitation force causes relative motion between coils of generator and permanent magnets and provides electrical energy. According to faradays law we know how change in magnetic field relative to coils generates emf across winding. The direct drive linear generator having relative motion of permanent magnets and coils is basis for generation of electrical energy. The generated magnetic according to lenz's law by coils happens to be in opposite direction of varying magnetic force. Thus constant magnetic field within the active region is produced and which in turn produces an opposing generator force. Often direct drive linear generator are constructed to produce high voltage so that current through coils can be reduced to safe level.

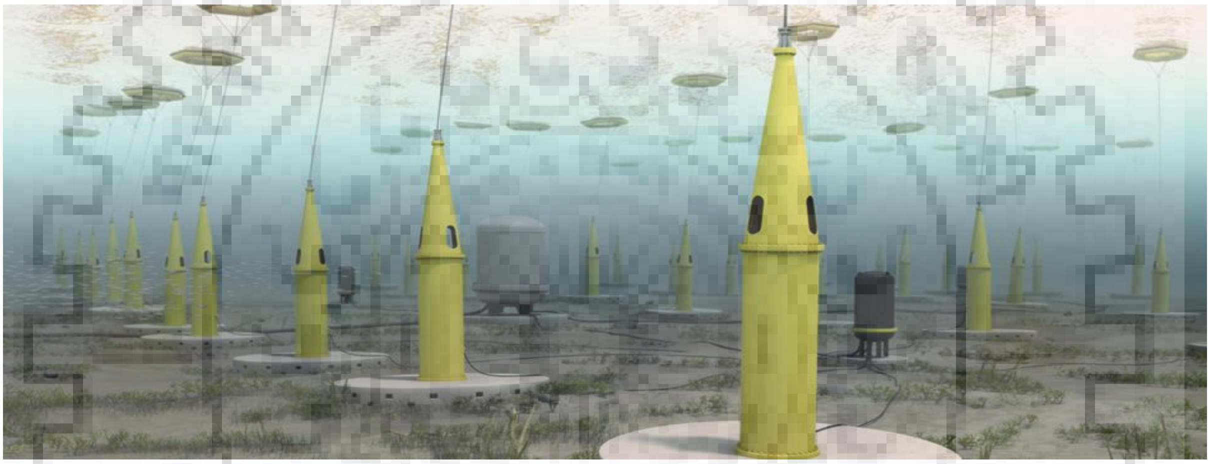
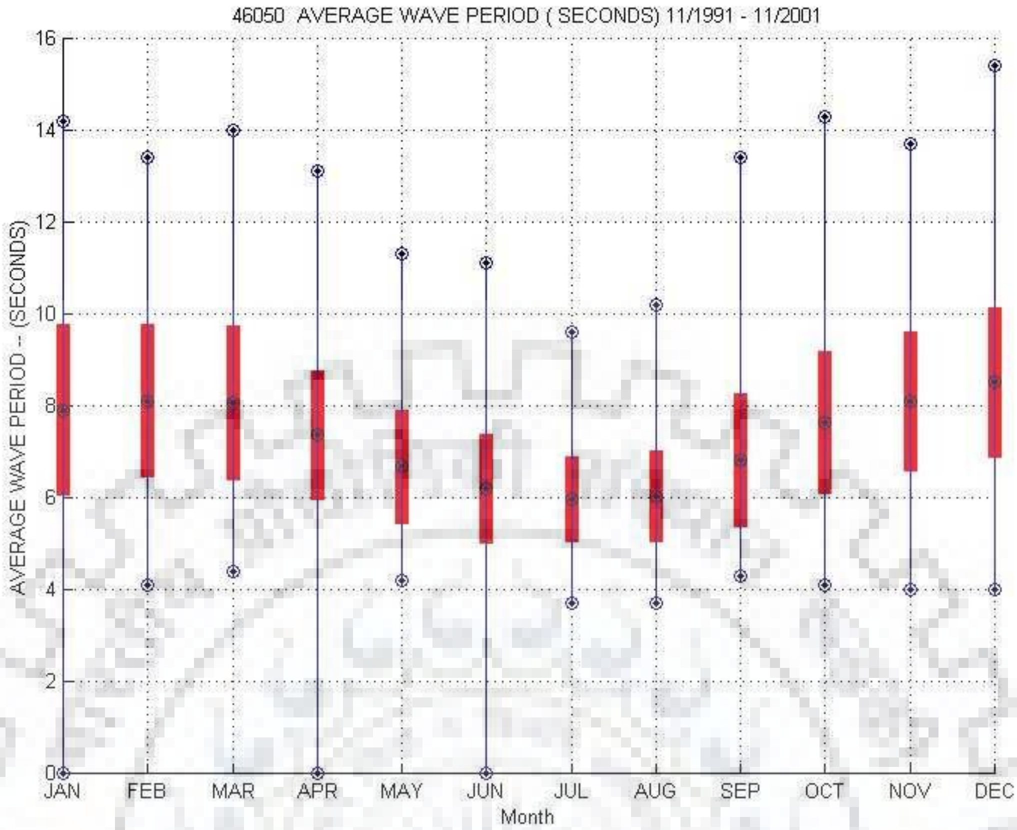


Fig 1.3- picture of plant installed so far

oceanic waves have changing wave periods and height can be determined by winds and distance traverse since the wave is created. We can define height of wave as the distance between crest (peak) and trough (low point). And similarly we can define period of wave as distance form crest to crest or trough to trough. Data analysis done so far by NOAA (National Oceanographic and atmospheric association) buoys shows a kind of sinusoidal trend as shown in given figure below.



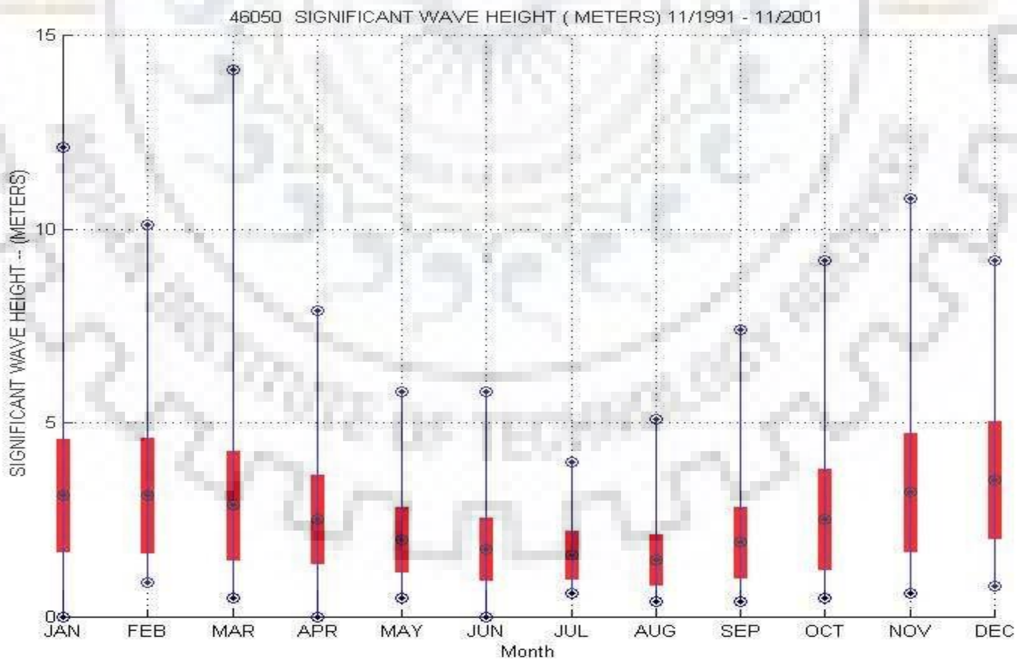


Fig 1.4 – ideal variations of oceanic waves

For computer simulations of power electronics with generator (generator and buoy system) interface, change in vertical velocity will produce variable voltage levels. The max output voltage will be determined by maximum vertical velocity and thus to regulate this varying voltage we need the power electronics.

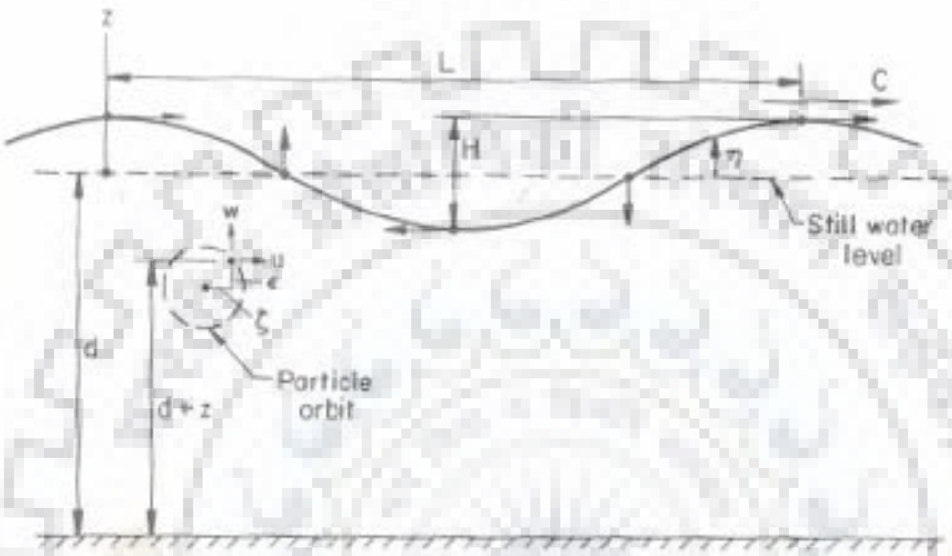


Fig 1.8 -Progressive surface wave parameters

In given figure, progressive wave surface parameters of a monochromatic wave progressing at a phase velocity, C. Remaining defining parameters are wave length, L in meters, wave height, H in meters and wave depth, d in meters. Velocity of wave can be defined wave length, L and wave period, T.

$$C = \frac{L}{T} \qquad (1.1)$$

Incoming wave front forces the surface particle to experience an upward vertical velocity. Which is represented by above equation. And as an assumption generator can be taken as a particle on the wave surface, where lateral motion and damping or phase shifting can be neglected. Hence it can be taken as wave follower. Vertical velocity of particle is given as

$$W_s = \frac{\pi H}{T} e^{kz} \sin(kx - \sigma t) \qquad (1.2)$$

$$k = \frac{2pi}{L} \qquad (1.3)$$

$$\sigma = \frac{2pi}{T} \qquad (1.4)$$

wave number is shown by equation 1.3 and equation 1.4 shows angular frequency. For investigation purpose we can assume generator velocity to be maximum at z=0. Thus vertical velocity ca be given as

$$W_c = \frac{\pi H}{T} \sin(kx - \sigma t) \qquad (1.5)$$

For an arbitrary position, x=0, particles velocity profile on wave surface is shown below in figure. Height of wave is taken up to be H= 1m and wave period T = 6 sec, depth of water as 45m.

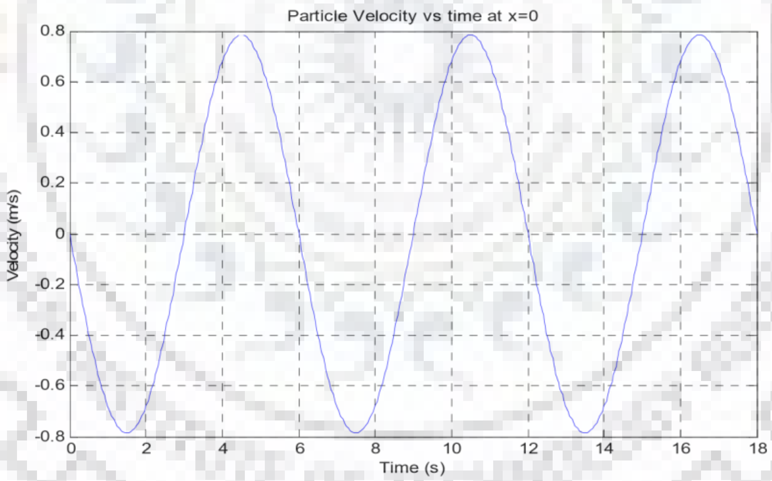


Fig 1.6 – movement of particle of tip of wave

For calculation, we may take height ranging from 1m to 3m. and max distance buoy travel 1m for 1kw generator, but by time velocity of buoy will change according to height. 91 meters will be fixed for wavelength that can be taken as wavelength. And we can get the peak velocity using wave height and wave period using equation 1.6.

$$w_c = \frac{\pi H}{T} \qquad (1.6)$$

1.3 Power Electronics Converter

The field electronics has rapidly and alarming expanding for making coming up devices. New technology and production methods availing facility for higher frequency, high voltage, increased current and higher capabilities. For competitive devices against fast switching FET (Field Effect Transistor) devices, we have high powered IGBTs (Insulated Gate Bipolar Transistors) now for easier and quick switching frequencies. IGBT provides higher power switching topologies, but FET do not allow us for high power handling facility.

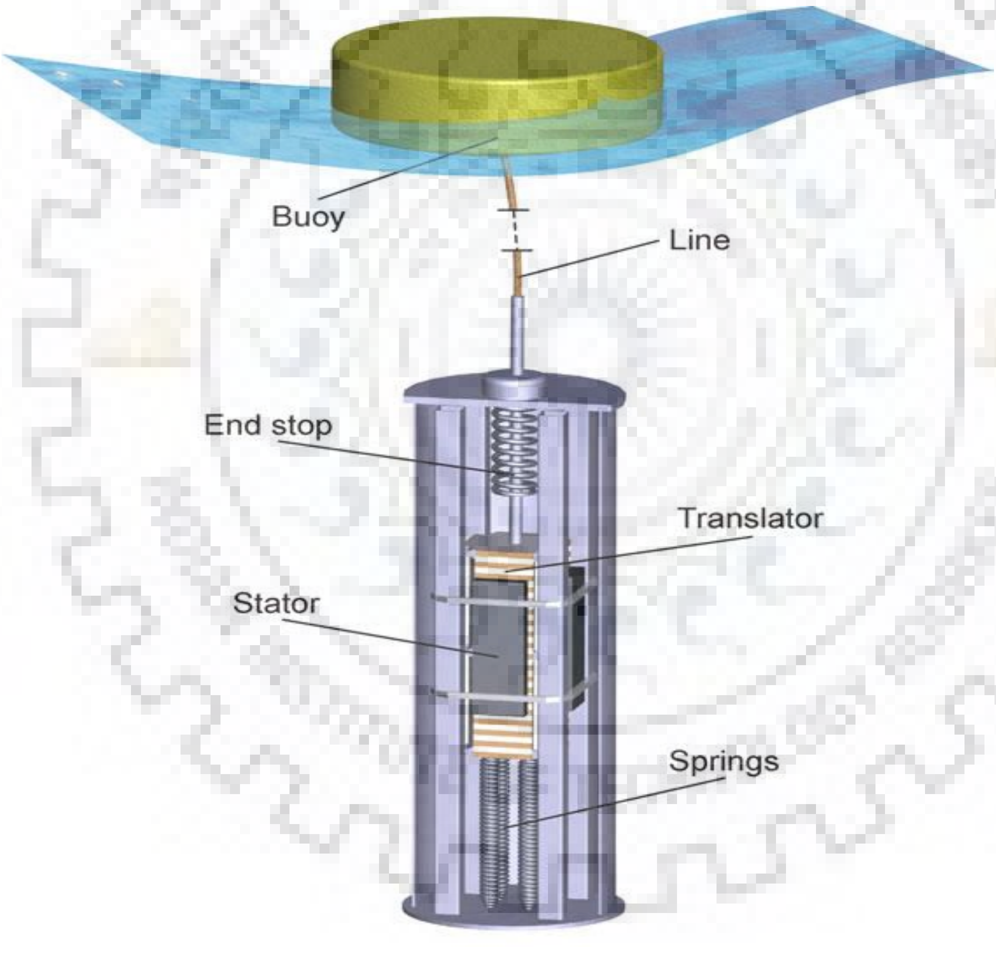
To control real and reactive power flow in and out of a generator with different active rectifier front end topologies. Variable frequency and variable voltage gives pulsed power and that cannot be used since low frequency excitation. For example, if any bulb is on operation then on and off kind of flash will be visible with twice the electrical frequency. In this thesis we will interface between terminals of generator and dc-dc converter.

CHAPTER-2

MODELLING OF PMLG

2.1 GENERATOR MODELLING

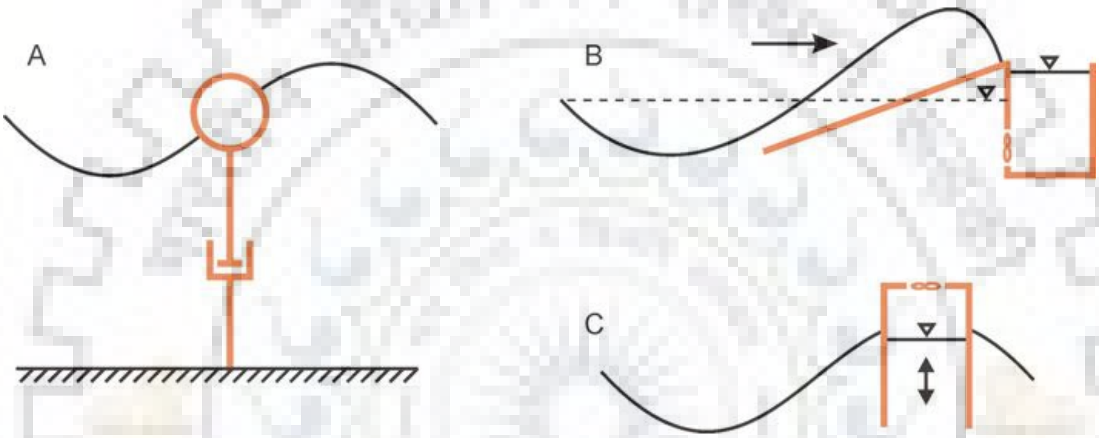
The model of generator can interface controls and power electronics components for ideal and dynamic system simulations. Ideal model of wave will be interfacing blocks of SimPowerSystem in MATLAB/Simulink as well as average model of power electronics. And in case of dynamic generator model will be interfacing ideal wave model and average model of the power electronics.



Model For PMLG Fig - (2.1)

2.2 Ideal Model

The permanent magnet linear generator (PMLG) is constructed to have maximum vertical displacement to be 1 meter and limited active magnetic area with a speed ranging from 0 to 3m/s. and for the construction of a MATLAB/Simulink, these parameters will be getting in use for ideal wave source and for testing all power electronic topologies. The monochromatic wave is used as baseline for ideal wave model. The variables required for ideal wave model can be changed in wave period and changes in output voltages.



Wave model and its effects on buoy   Fig-(2.2)

Derivation of ideal source will be mathematically basis on electrical and magnetic properties, as well as wave mechanically properties. But vertical displacements of generator depending on the maximum range associating for a specific generator distance, d in equation 2.1. PMLG can go for max distance travelling is 1m and displacement of generator will be due to wave excitation. In ideal conditions, force will be sinusoidal. The vertical displacement, y(t), is shown in equation 2.2, and the ocean wave frequency W_m in rad/sec and the maximum distance generator travel, d, in meters.

$$y(t) = \frac{d}{2}\sin(w_m t) \qquad (2.1)$$

$$\omega_m = 2\pi f_m = \frac{2\pi}{T_m} \qquad (2.2)$$

The flux crossed by coils within spar, respect to time (taking initial conditions zero) is given below in equation 2.2. the varying Φ is the peak flux produced using permanent magnets in tesla and magnetic wavelength λ in meters. Linear generators pole pitch is half the magnetic wavelength.

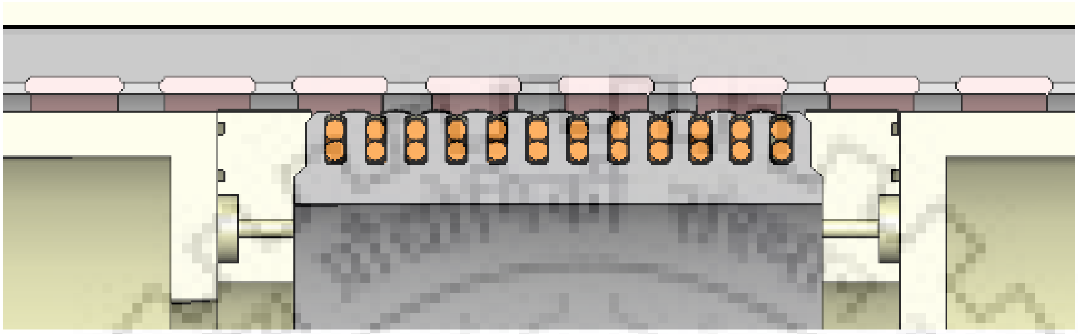


Fig-(2.3) - PMLG cross-sectional area

According to Faradays law, voltage induction within coils can be given by equation 2.3 and where N the no. of turns per coil and the flux change will give us voltage. After differentiation of flux linked, one may get voltage induced by equation 2.4. and this is voltage per phase. V is taken up as peak volt. Since PMLG is 3 phase machine so we will get voltage phasors shifted electrically by 120 degrees as shown below.

$$\phi(\mathrm{t}) = \Phi \sin(\frac{2\pi}{\lambda} y(t)) \tag{2.2}$$

$$v(\mathrm{t}) = N \frac{d\varphi}{dt} \tag{2.3}$$

$$v(\mathrm{t}) = \hat{V} \cos(\omega_m t) \cos(\frac{\pi d}{\lambda} \sin(\omega_m t) + \upsilon) \tag{2.4}$$

υ = 0, +/- (2pi/3)

$$\mathrm{v_a}(\mathrm{t}) = \hat{V}\cos(\omega_m t)\cos(\frac{\pi d}{\lambda}\sin(\omega_m t)) \qquad \textbf{(2.5)}$$

$$\mathrm{v_b}(\mathrm{t}) = \hat{V}\cos(\omega_m t)\cos(\frac{\pi d}{\lambda}\sin(\omega_m t) - \frac{2\pi}{3}) \qquad \textbf{(2.6)}$$

$$\mathrm{v_c}(\mathrm{t}) = \hat{V}\cos(\omega_m t)\cos(\frac{\pi d}{\lambda}\sin(\omega_m t) + \frac{2\pi}{3}) \qquad \textbf{(2.7)}$$

The amplitude of electrical frequency can be calculated as shown below using translators speed and magnetic wavelength. Where λ in meters is the magnetic wavelength. Here we can see that by increasing speed of translator, we can change frequency.

$$\omega_e = \frac{2\pi}{\lambda}\left(\frac{dx}{dt}\right) \qquad (2.8)$$

$$f_e = \frac{velocity_{pk}}{\lambda} \qquad (2.9)$$

The following parameters are taken for ideal wave source to assemble in matlab Simulink.

d =1m

λ=144mm=0.144m

ω_m=2π (f_m)

CHAPTER-3
SIMULINKING MODELS AND FIGURES

3.1Simulinking model for PMLG voltage

Here we will be taking as reference the ideal voltage simulinking model for our future reference. As it presents the expected form of voltage that is predicted theoretically so that our result has some accountability and perfection according set standards. Here maximum translator movement is taken to be 1m. and magnetic wavelength is 0.144m, specially here max voltage of waveform is kept to be 228 volts. First we develop single phase simulinking model then after that convert them into three phase form and it is simply after having mathematically calculation of flux, and then voltage. As we know translator movement would be ideally sinusoidal and flux will depend on translator position so we will get flux of type like distorted sinusoidal waveform. and after that on differentiation of flux we get single phase voltage that would be opposite to the change that caused it.

3.1 SIMULINK MODEL

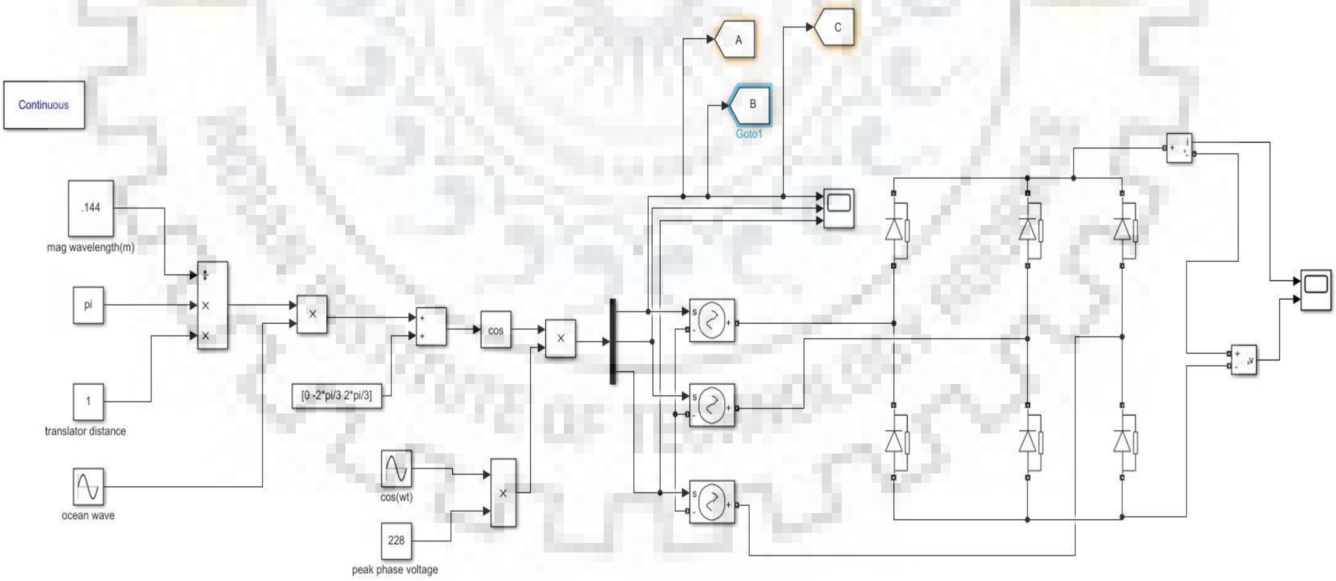


Fig 2.4 -The ideal voltage waveform simulinking model

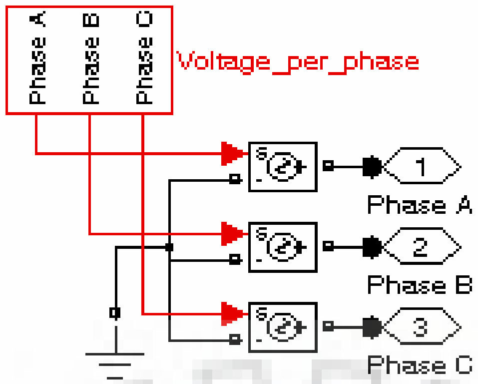


Fig 2.5-Per Phase Voltage to sim power system interface

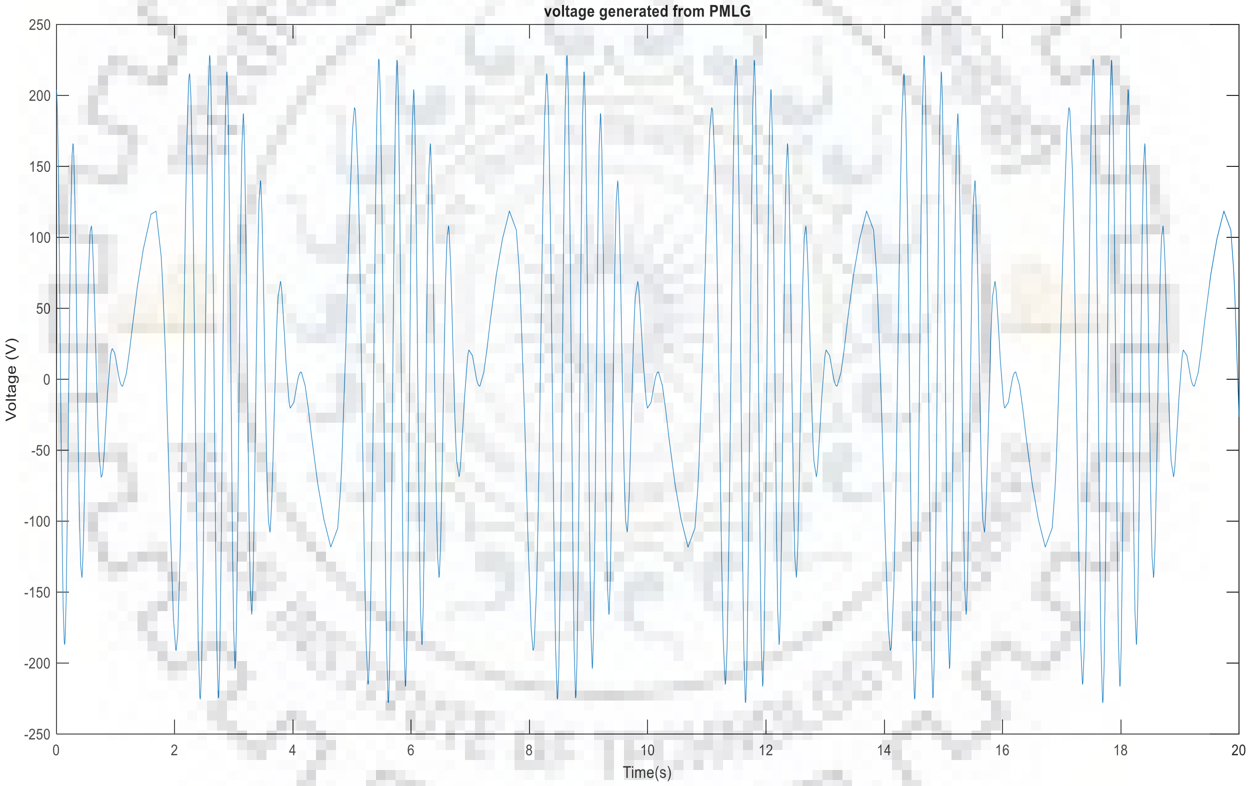


Fig 2.6 - Voltage waveform of above ideal simulinking model

the above figures have advantage for simulinking as it allows everything to be simulated and here sim power system which is voltage dependent and that too interfaced with monochromatic wave. As it presents the expected form of voltage that is predicted theoretically so that our result has some accountability and perfection according set standards. Here maximum translator movement is taken to be 1m. and magnetic wavelength is 0.144m, specially here max voltage of waveform is kept to be 228 volts. First we develop single phase simulinking model then after that convert them into three phase form and it is simply after having mathematically calculation of flux, and then voltage.Here in this system, sim power system boxes are exactly like circuit simulation display where system voltages and current could be found out. As Dynamic PMLG equations are likely to that of rotatory permanent synchronously running generator that is taken to develop controlling system. But equations do differ somewhat since the torque and force computation. The mechanical angle in rotatory machine depends on angular velocity but mechanical angle for PMLG can be taken dependent on linear translation velocity. they are used to output the voltage which is correlated with input reference.

CHAPTER-4

DQ MODEL

4 DQ CONTROL

4.1 dq Overview

Here we can take advantage of theory of d-q frame where we would dissolve the three phase in to 2 phase that is d-q model for ease of calculation and both d-q phase are orthogonal to each other. Later one makes direct axis (d-axis) and quadrature axis (q-axis) completely independent and allows us to fully have independent control of both powers that is reactive as well as active power and control of real torque. The PMLG d-axis is in direction of the north axis according to magnetic meridian and the q-axis will be perpendicular to the magnetic flux. As Dynamic PMLG equations are likely to that of rotatory permanent synchronously running generator that is taken to develop controlling system. But equations do differ somewhat since the torque and force computation. The mechanical angle in rotatory machine depends on angular velocity but mechanical angle for PMLG can be taken dependent on linear translation velocity. As it presents the expected form of voltage that is predicted theoretically so that our result has some accountability and perfection according set standards. Here maximum translator movement is taken to be 1m. and magnetic wavelength is 0.144m, specially here max voltage of waveform is kept to be 228 volts. First we develop single phase simulinking model then after that convert them into three phase form and it is simply after having mathematically calculation of flux, and then voltage. This system allows us to have controls of current with the q-axis and reactive power with the d-axis. Figure 3.1 describes the components of two axes. In equations below i_s is along direct axis that is total sum of all individual currents($i_a . i_b, i_c$). using complex no. The theory, we devise a method to convert all individual currents to net current along direct axis. But we need to convert three phase system to two systems. Here we will resolve every current along direct axis and quadrature axis. Here i_s^d *is dq* state space current. And that can be find out as shown below.

$$i_s = i_a(t) + i_b(t)e^{f2\pi/3} + i_c(t)e^{-f2\pi/3} \qquad (4.1)$$

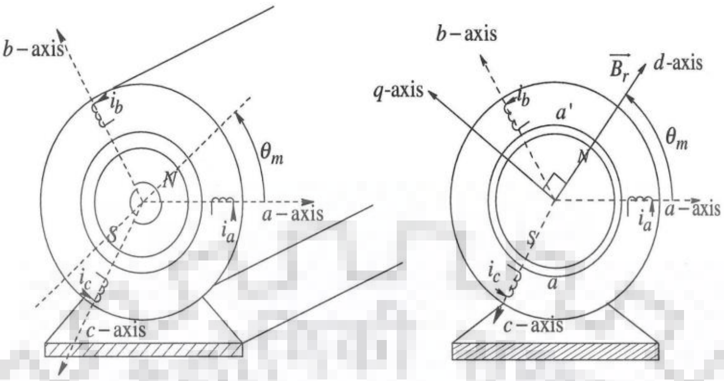


Fig. 4.1 – Three-phase to two-phase projection

$$\frac{\sqrt{\frac{3}{2}}N_s}{p}\left(i_{sd} + ji_{sq}\right) = \frac{N_s}{p}\,i_s^{\,d} \qquad (4.2)$$

$$\left(i_{sd} + ji_{sq}\right) = \sqrt{\frac{2}{3}}\,\bar{i}_s^{\,d}$$

Where i_{sd} *is* current resolved into state space vector along the direct axes. And i_{sq} is the current resolved onto space vectors along quadrature axes.

Where Ns, number of stator turns

P, number of pole pairs

Whenever projection occurs the scaling of d- axis and q-axis current automatically on their respective axis. And this is clear from above displaying of equations. The terms that are square root of turns and current makes sure the equal distribution of MMF like three phase equivalent.

As we can see that flux linked is completely zero across orthogonal windings thus it makes the completely decoupled magnetically. we can take advantage of theory of d-q frame where we would dissolve the three phase in to 2 phase that is d-q model for ease of calculation and both d-q phase are orthogonal to each other. As it presents the expected form of voltage that is predicted theoretically so that our result has some accountability and perfection according set standards. Here maximum translator movement is taken to be 1m. and magnetic wavelength is 0.144m, specially here max voltage of waveform is kept to be 228 volts. First we develop single phase simulinking model then after that convert them into three phase form and it is simply after having mathematically calculation of flux, and then voltage. As Dynamic PMLG equations are likely to that of rotatory permanent synchronously running generator that is taken to develop controlling system. But equations do differ somewhat since the torque and force computation. The mechanical angle in rotatory machine depends on angular velocity but mechanical angle for PMLG can be taken dependent on linear translation velocity. Later one makes direct axis (d-axis) and quadrature axis (q-axis) completely independent and allows us to fully have independent control of both powers that is reactive as well as active power and control of real torque. The PMLG d-axis is in direction of the north axis according to magnetic meridian and the q-axis will be perpendicular to the magnetic flux. This system allows us to have controls of current with the q-axis and reactive power with the d-axis. Figure 3.1 describes the components of two axes. As according to definition inductance is equal to proportional no. of turns taking square of inductance of magnetization is same like 3 phase equivalence.

$$L_{m-dq} = \left(\sqrt{\frac{3}{2}}\right)^2 * L_{m-1,phase}$$

$$L_{m-dq} = \left(\tfrac{3}{2}\right) * L_{m-1,phase} \qquad (4.3)$$

$$L_{m-dq} = L_m$$

From above equations we can very easily calculate using d-axis and q-axis inductance in equation 3.4.

$$L_{sd} = L_{m-dq} + L_{ls}$$

$$L_{sq} = L_{m-dq} + L_{ls} \qquad (4.4)$$

From these given equation magnetizing inductance and self-inductance, each and every one d-q windings will have inductance equal as before and also self-inductance to every phase of 3 phase system. As Dynamic PMLG equations are likely to that of rotatory permanent synchronously running generator that is taken to develop controlling system. But equations do differ somewhat since the torque and force computation. The mechanical angle in rotatory machine depends on angular velocity but mechanical angle for PMLG can be taken dependent on linear translation velocity. Here scaling would not be needed. As it presents the expected form of voltage that is predicted theoretically so that our result has some accountability and perfection according set standards. Here maximum translator movement is taken to be 1m. and magnetic wavelength is 0.144m, specially here max voltage of waveform is kept to be 228 volts. First we develop single phase simulinking model then after that convert them into three phase form and it is simply after having mathematically calculation of flux, and then voltage.

As we need to have same MMF in both frames that is three phase and dq windings thus accordingly we have to find correlation between two to find out MMF that would equivalent in both. So with the help of space vectors i_s it is possible to have representation of machine space-vector i_s as given in eq. 3.5, thus θ ds will the angle in case of stator current and space vector and space vector of dq-space.

$$\vec{i}_s^{\,d} = \vec{i}_s^{\,a} e^{-j\theta_{da}} \qquad (4.5)$$

In a three-phase system:

$$\vec{i}_s^{\,a} = i_a(t) + i_b(t) + i_c(t) \qquad (4.6)$$

Where $i_a(t)$ is a phase current

$i_b(t)$ is b phase current

$i_c(t)$ is c phase current

Using equation 3.5 we may get 3.7:

$$\vec{i}_s^{\,d} = i_a(t)e^{-j\theta_{da}} + i_b(t)e^{-j(\theta_{da}-2\pi/3)} + i_c(t)e^{-j(\theta_{da}+2\pi/3)} \qquad (4.7)$$

On separation the real and imaginary terms in equation 3.7, results in the very practical change in equation (3.8).

$$\begin{bmatrix} i_{sd}(t) \\ i_{sq}(t) \end{bmatrix} = \sqrt{\frac{2}{3}\begin{bmatrix} \cos(\theta_{da}) & \cos(\theta_{da} - \frac{2\pi}{3}) & \cos(\theta_{da} + \frac{2\pi}{3}) \\ -\sin(\theta_{da}) & -\sin(\theta_{da} - \frac{2\pi}{3}) & -\sin(\theta_{da} + \frac{2\pi}{3}) \end{bmatrix}} \begin{bmatrix} i_a(t) \\ i_b(t) \\ i_c(t) \end{bmatrix}$$

The Simulink model for the (PMLG) permanent magnet linear machine is shown in figure

4.2 Dynamic Model

In regard to ideal wave model, it was having to ease to get any desired amount of current according to voltage produced by ideal wave model generator. Here dynamic model is capable to allow quicker simulation as switching model could be sensed analytically using average model. But problem in ideal model is that we had no feedback facility to wave model thus PMLG system. But with help of dynamic model of PMLG, tis very easy to analyse this wave model with the hardware system as it done earlier so we can have reliable testing of given PMLG model. But here we are not going to control any parameter but just simply studying the impact of one on to others. So here below is the analysis that how the nature of force developed by PMLG will be and accordingly we need to take design and construction parameters.

As Dynamic PMLG equations are likely to that of rotatory permanent synchronously running generator that is taken to develop controlling system. But equations do differ somewhat since the torque and force computation. The mechanical angle in rotatory machine depends on angular velocity but mechanical angle for PMLG can be taken dependent on linear translation velocity.

The direct and quadrature (dq) axis equations of PMLG linear generator are show below, where R_s is coil resistance and electrical frequency is w_m , q axis current is i_q , d axis current is i_d and λ_{fd} is excitation flux linkage of stator due magnetic flux in PMLG.

As Dynamic PMLG equations are likely to that of rotatory permanent synchronously running generator that is taken to develop controlling system. But equations do differ somewhat since the torque and force computation. The mechanical angle in rotatory machine depends on angular velocity but mechanical angle for PMLG can be taken dependent on linear translation velocity. Also, V_d is the axis voltage of direct axis and V_q taken as q-axis voltage.

$$V_{sd} = R_s i_{sd} + \frac{d}{dt}\lambda_{sd} - \omega_m \lambda_{sq} \tag{4.7}$$

$$V_{sq} = R_s i_{sq} + \frac{d}{dt}\lambda_{sq} - \omega_m \lambda_{sd} \tag{4.8}$$

$$\lambda_{sd} = L_s i_{sd} + \lambda_{fd} \tag{4.9}$$

$$\lambda_{sq} = L_s i_{sq} \tag{4.10}$$

$$L_s = L_{ls} + L_m$$

Using both equations 4.7, 4.8, 4.9 and 4.10, results in the cross coupled dq- axis voltage equations.

$$\mathrm{V}_{sd} = R_s i_{sd} + \frac{d}{dt}\left(L_s i_{sd} + \lambda_{fd}\right) - \omega_m L_s i_{sq} \tag{4.11}$$

$$\mathrm{V}_{sq} = R_s i_{sq} + \frac{d}{dt}\left(L_s i_{sq} + \lambda_{fd}\right) - \omega_m L_s i_{sd}$$

$$\omega_m = \frac{p}{2}\omega_{mech} \tag{4.12}$$

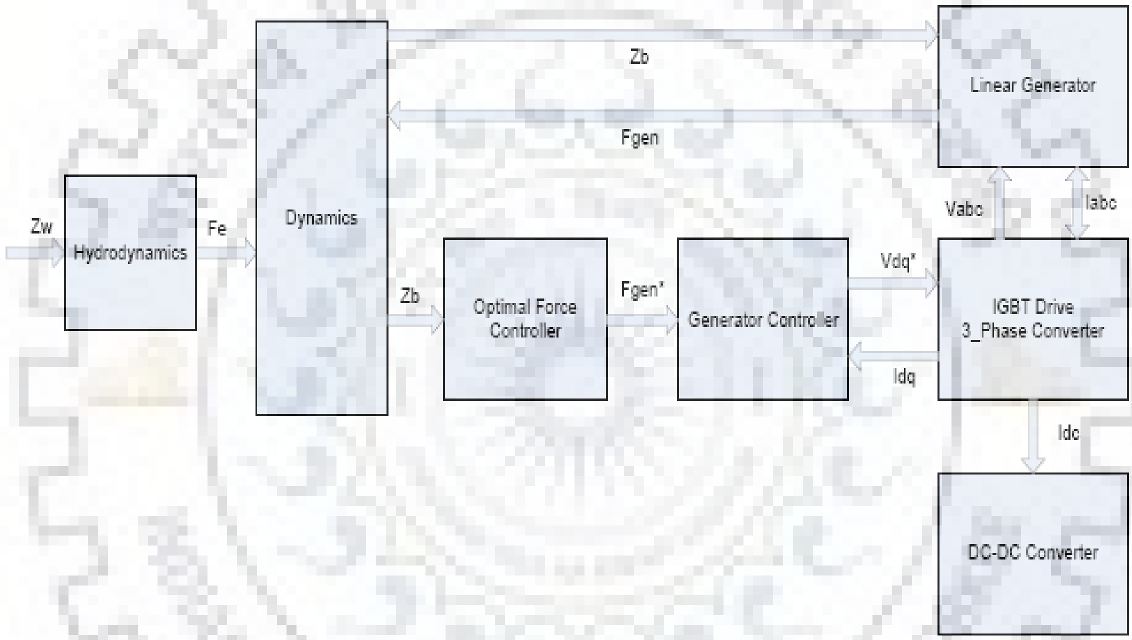
Below in eq. 4.12, mechanical that too rotational frequency can be taken in consideration with electrical frequency, both in rad/sec, divided by present no. of poles in machine.

$$T_{em} = \frac{p}{2}\left(\lambda_{sd} i_{sq} - \lambda_{sq} i_{sq}\right) \tag{4.13}$$

using equation 4.8 and substituting the dq- flux linked, gives out equation 4.13 As Dynamic PMLG equations are likely to that of rotatory permanent synchronously running generator that is taken to develop controlling system. But equations do differ somewhat since the torque and force computation. The mechanical angle in rotatory machine depends on angular velocity but mechanical angle for PMLG can be taken dependent on linear translation velocity. Also, V_d is the axis voltage of direct axis and V_q taken as q-axis voltage.

producing load torque getting connected to current by quadrature axis and magnetic linked and excited flux.

$$T_{em} = \frac{p}{2}\left(\left(L_s i_{sd} + \lambda_{fd}\right) i_{sq} - L_s i_{sq} i_{sd}\right) = \frac{p}{2}\lambda_{fd} i_{sq} \qquad (4.14)$$



` Fig 4.2 -Dynamic generator/buoy model

In above figure the dynamic model is shown. Dynamic model and hydrodynamic model need to develop forces generated in oceanic waves. As Dynamic PMLG equations are likely to that of rotatory permanent synchronously running generator that is taken to develop controlling system. But equations do differ somewhat since the torque and force computation. The mechanical angle in rotatory machine depends on angular velocity but mechanical angle for PMLG can be taken dependent on linear translation velocity. Also, V_d is the axis voltage of direct axis and V_q taken as q-axis voltage.

To compute generator load optimally intelligently we need optimal force controller block. Excitation of wave force will be exerting force on the buoy and it would be prescribing force to exert on the wave. The current output will be determining the developing PMLG force.

The quadrature current substitute in eq. 4.11 to result developed torque. We know that torque is force multiply by radius of PMLG device. Equation of length of stator for PMLG is given by equation 4.13 and that is also taken as pole pitch, τ and that is multiplied by given number of poles. The synchronous rotatory generator shown in equation4.13, where r can be taken as average radius of machine rotor.

The Current in q-axis put into equation 4.11 results in torque. As Dynamic PMLG equations are likely to that of rotatory permanent synchronously running generator that is taken to develop controlling system. But equations do differ somewhat since the torque and force computation. The mechanical angle in rotatory machine depends on angular velocity but mechanical angle for PMLG can be taken dependent on linear translation velocity. Also, V_d is the axis voltage of direct axis and V_q taken as q-axis voltage.

Force multiplied by radius of PMLG is torque and equation 4.13 represents stator length for PMLG and this is the pole pitch τ multiplied biy given poles. Rotary synchronous generators circumference could be find out in equation 4.3, here r will be average radius.

$$l = \tau \text{ p phases} = 3\tau \text{ p} \qquad (4.13)$$

$$c = 2\pi r \qquad (4.14)$$

Substitution in equation 2.13 into given eq. 2.14 where the distance and circumference are equal:

$$r = \frac{3\tau p}{2\pi} \qquad (4.15)$$

Assuming a machine having two poles, 1 pole pair, then machine radius would be equal to:

$$r = \frac{3\tau}{\pi} \tag{4.16}$$

For a rotating machine of two poles, the torque developed would be equal to:

$$T_{em} = \lambda_{fd} i_{sq} \tag{4.17}$$

Here according to definition torque would be multiplication of force and radius thus will give relation between torque and force:

$$F = \frac{T_{em}}{r} = \frac{\pi}{3\tau} \lambda_{fd} i_{sq} \tag{4.18}$$

From here we can see that linear synchronous machine has force output in case of multiple pole pairs, certainly increase with no. of pairs of poles similar to rotating machine having pole pairs linearly increasing the torque. Thus general equation of developed force will be eq. 4.19

$$F = \frac{p\pi}{6\tau} \lambda_{fd} i_{sq} \tag{4.19}$$

4.3 SIMULINK MODEL FOR FORCE PERFORMANCE

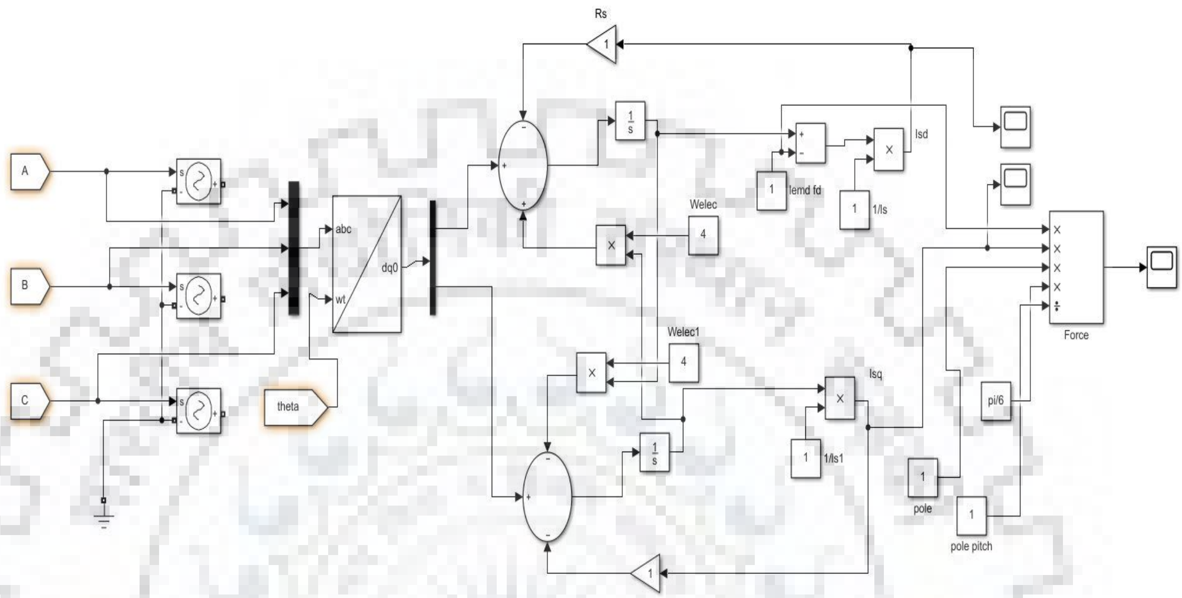


Fig 4.3 - Dynamic Simulinking model of PMLG

Here in this dynamic model, we can separately see the how quadrature current and direct axis current decides the variations in force developed by PMLG.

The force varies on changing the following parameters, like pole pitch, per phase voltage, translator distance, and no of magnets, etc. this we analysed in reverse but vice versa is also true. Given below are the concluded results.

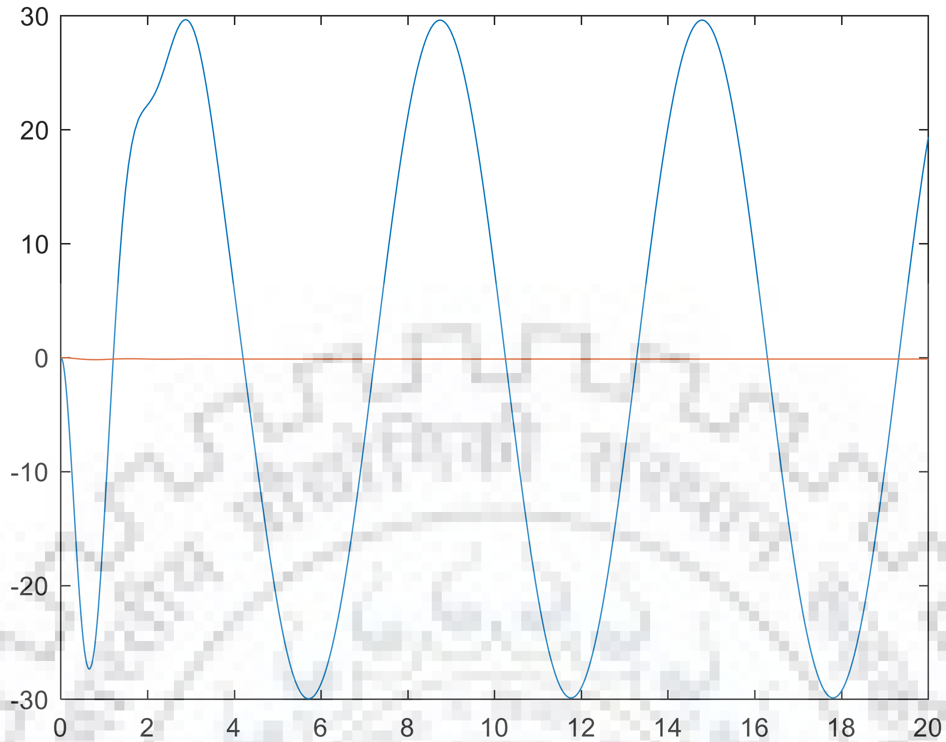


Fig 4.3 -Variations of force developed PMLG

Here y axes is force in newton and x axes is time is second

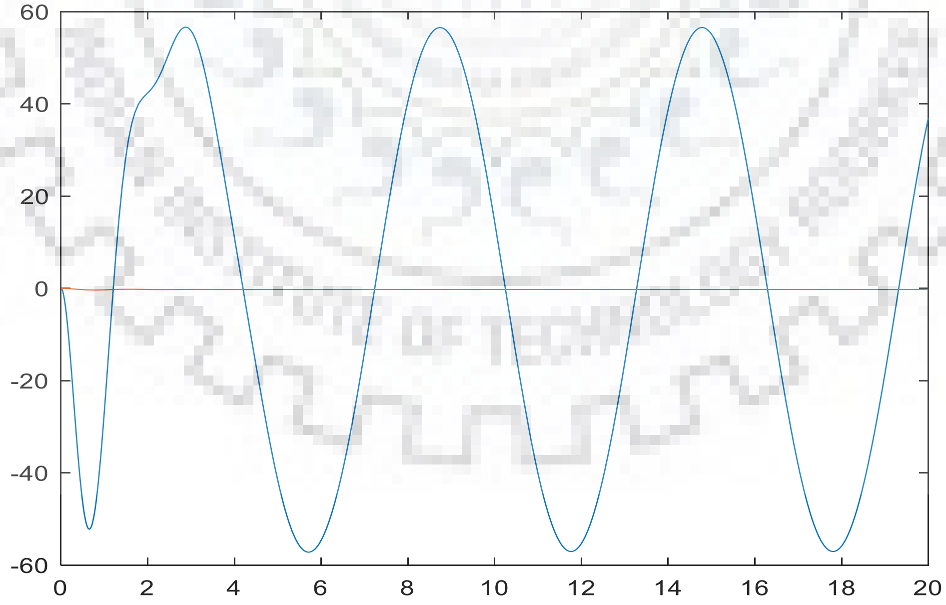


Fig 4.5 - Quadrature current of PMLG

Here y axes is quadrature current in ampere and x axes is time in second

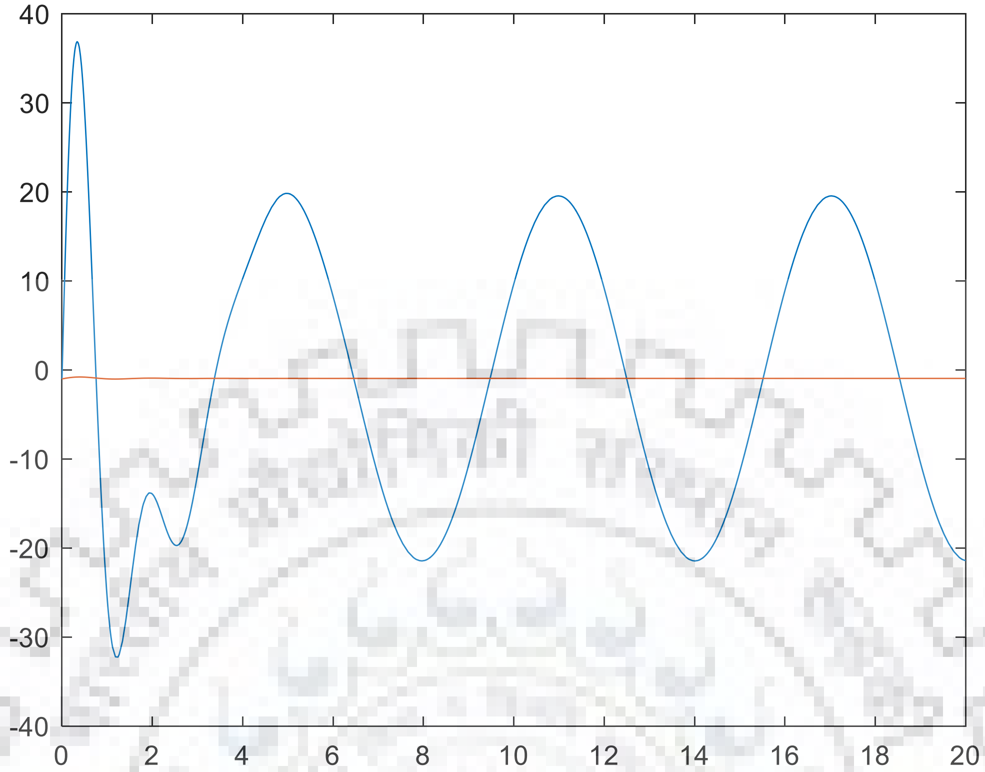


Fig 4.6 -Direct axis current of PMLG

Here y axes is direct axes current and x axes current

4.4 SIMULINK MODEL FOR AVERAGE POWER

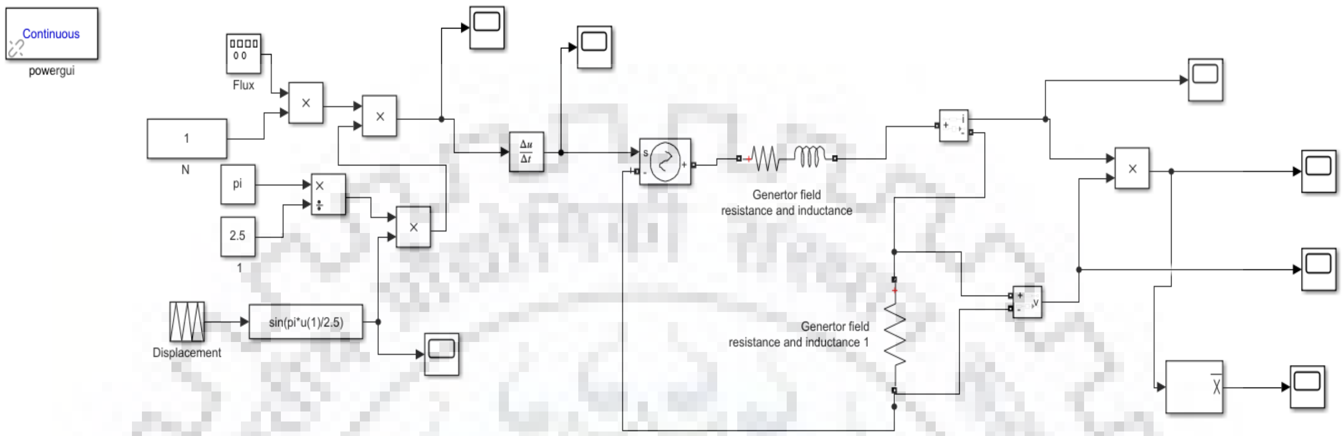


Fig 4.6 -Simulinking model to analyse power developed by PMLG

Here we can see power is fluctuating so we need to rectify the per phase voltage. Then only we can use PMLG for practical purpose. After Rectification we get voltage almost of constant magnitude which is very practical for use. Below are the variations of parameters shown in figures.

Here peak flux is taken to be 0.5 weber

Number of magnets to be 4

Peak voltage in volts 25 volts

And on these given parameters average power is 40 watts

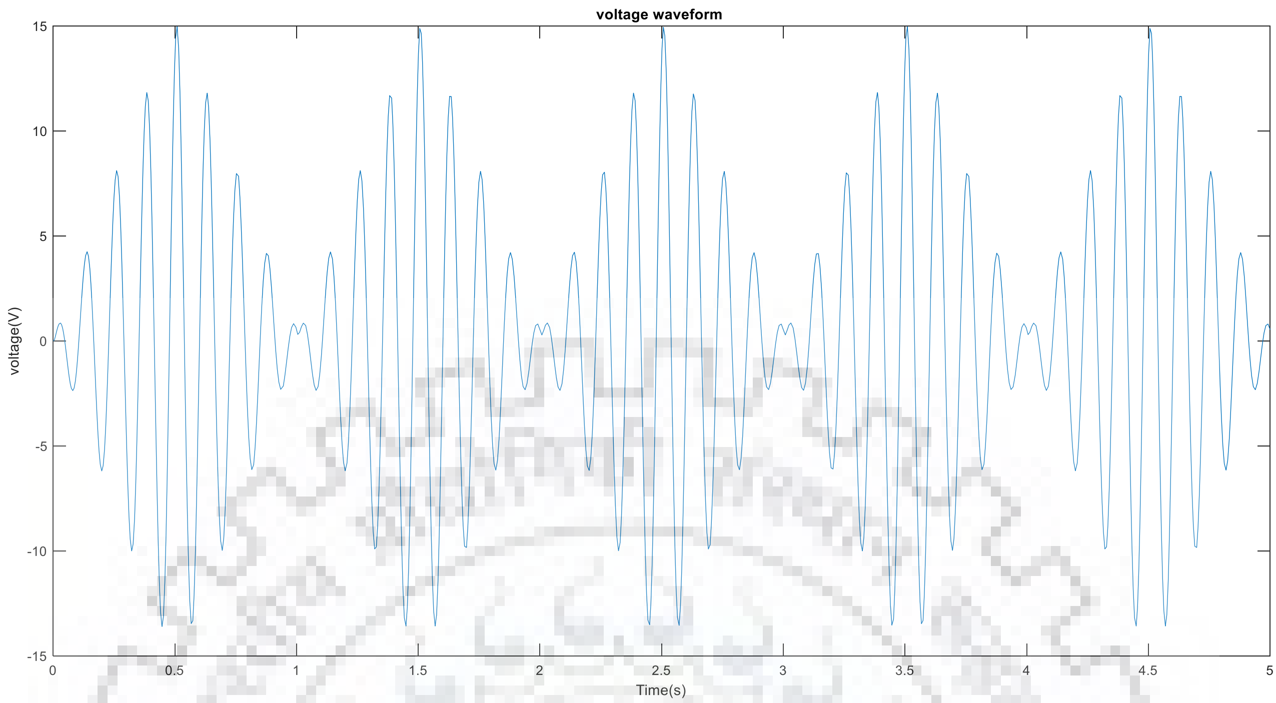


Fig 4.8 - voltage waveform

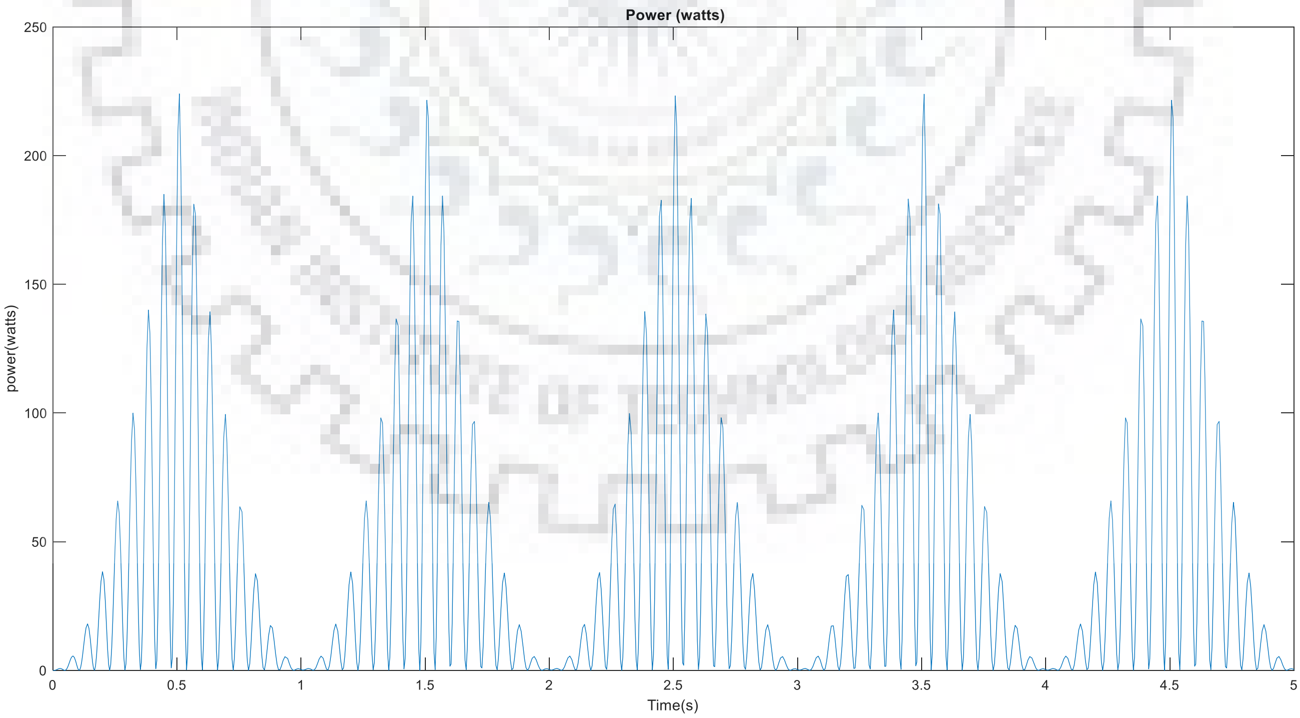


Fig 4.9 -The power developed by PMLG

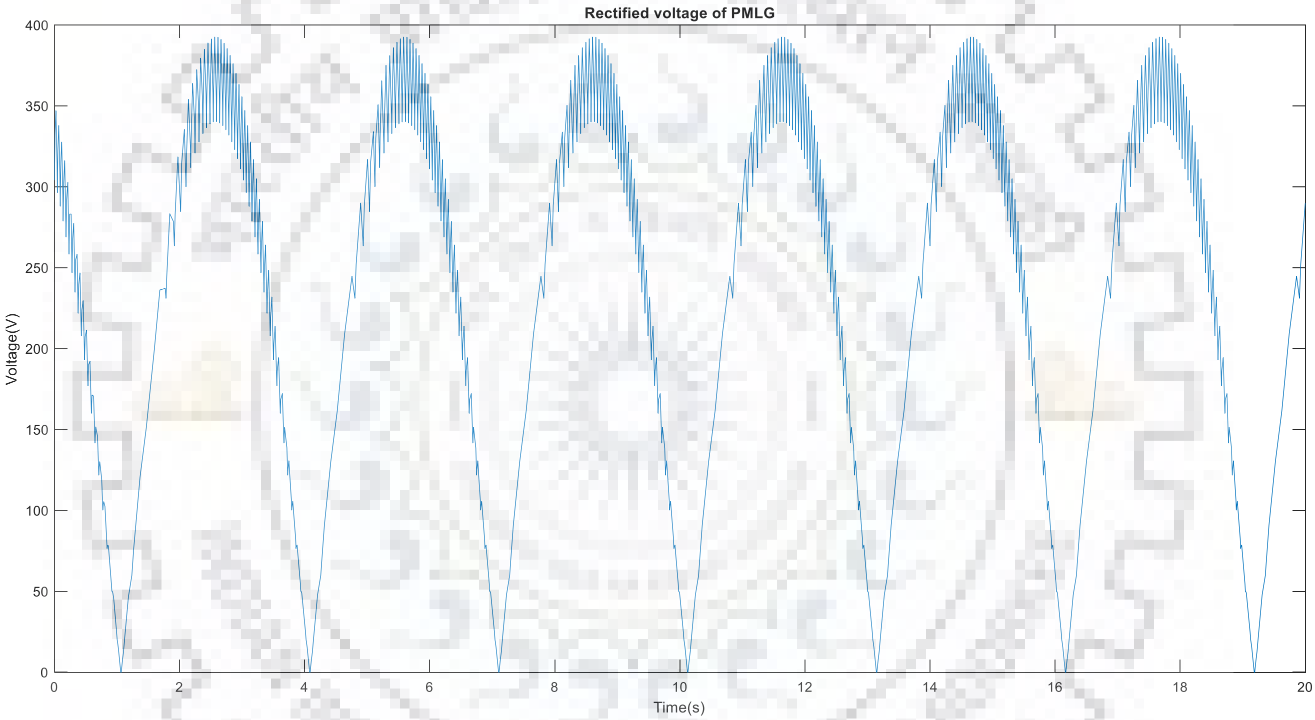


Fig 4.10 - Rectified voltage of PMLG

From above diagrams we can conclude that voltage repulse are reduced a lot and now voltage is capable to be used practically. Here for study purpose we unity load and here we can see that average power given by PMLG is around 25 watts. Though it is very less for practical uses even then it is quite appreciable and for lighting tube light of 25 watts can be used.

4.5 SIMULINKING MODEL OF PMLG HAVING CAPACITIVE RECTIFICATION

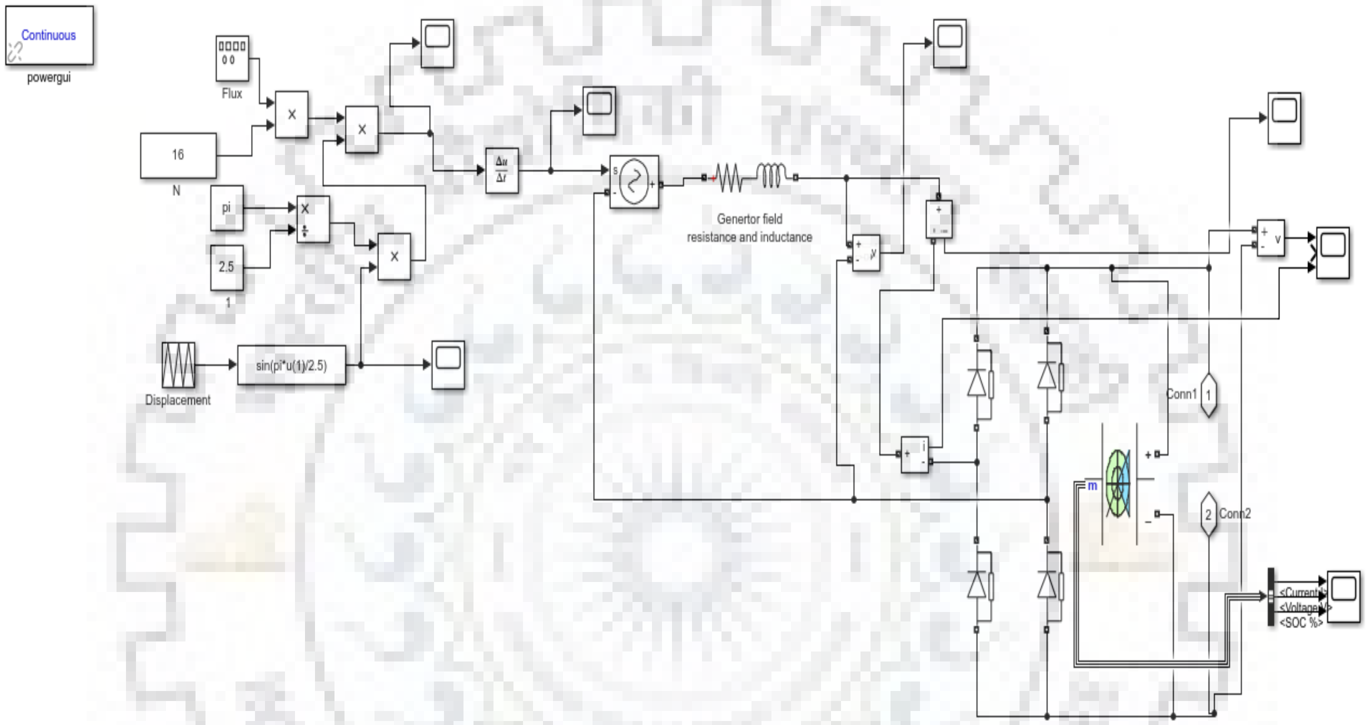


Fig 4.11 Simulink model to analyse effect of number of magnets and also of frequency on voltage output.

4.4 Now shown below figures presents the variation of output voltage

4.4.1 if number of magnets are four and thus frequency is 8.

Then below are the voltage and flux diagram to show impacts on them.

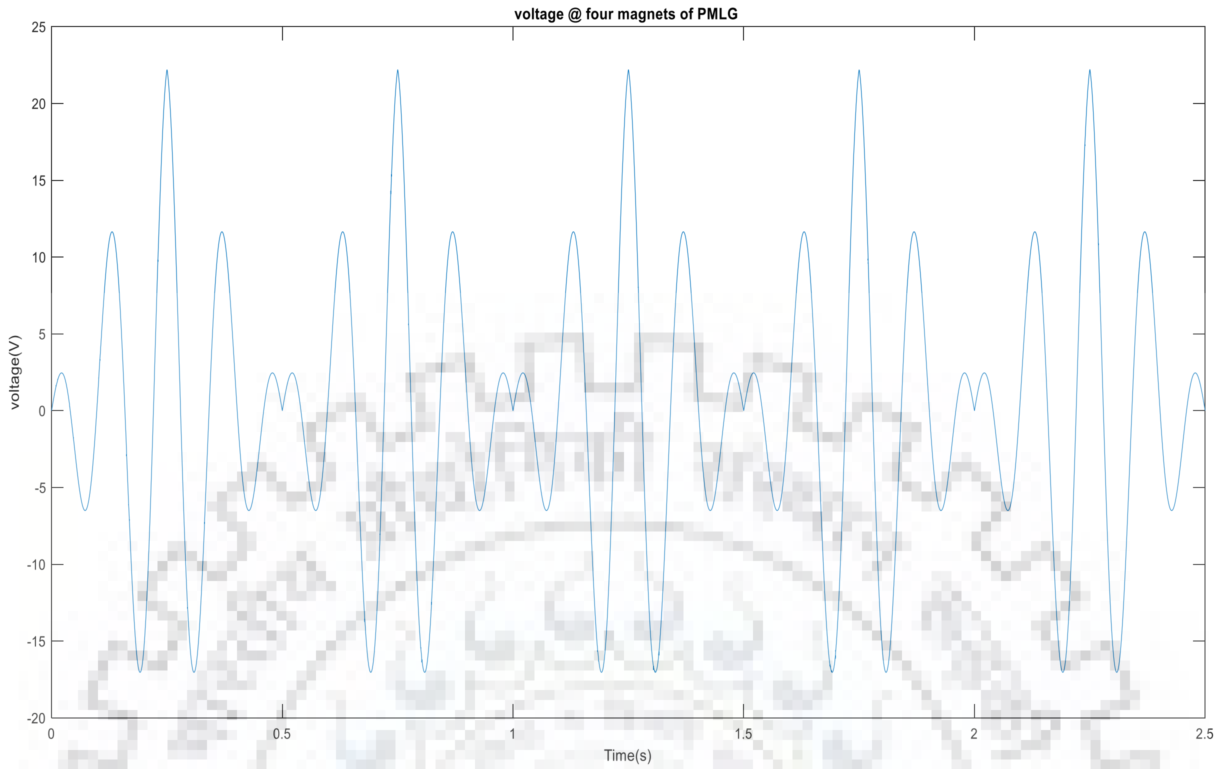


Fig 4.12- voltage waveform

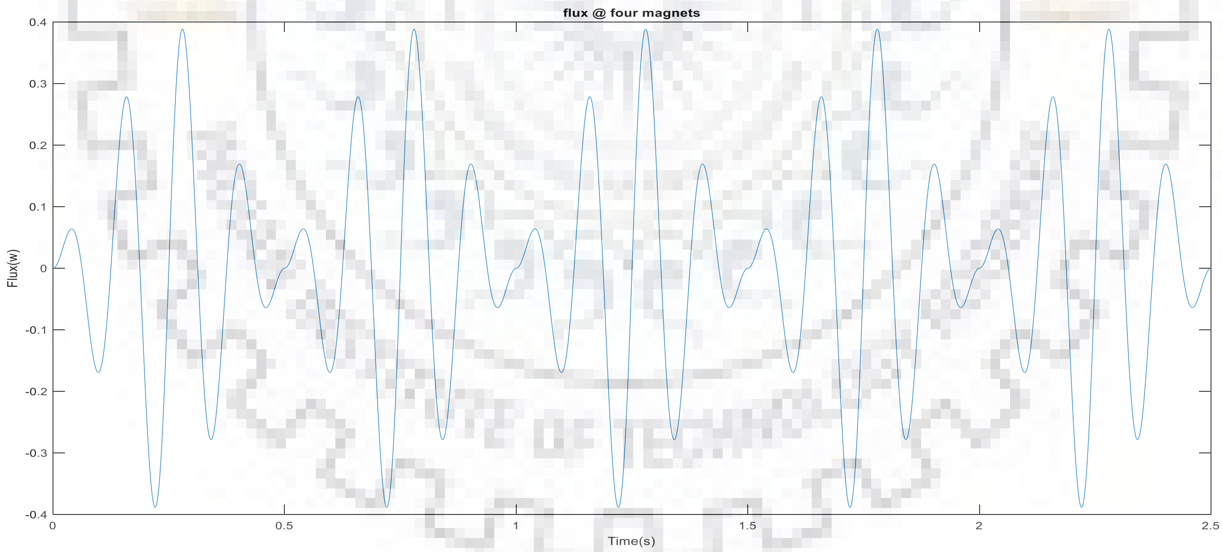


Fig 4.13- Flux waveform @ four magnets

4.4 IF NUMBER OF MAGNETS ARE SIX

Then below are the following figures to show how voltage and flux varies accordingly.

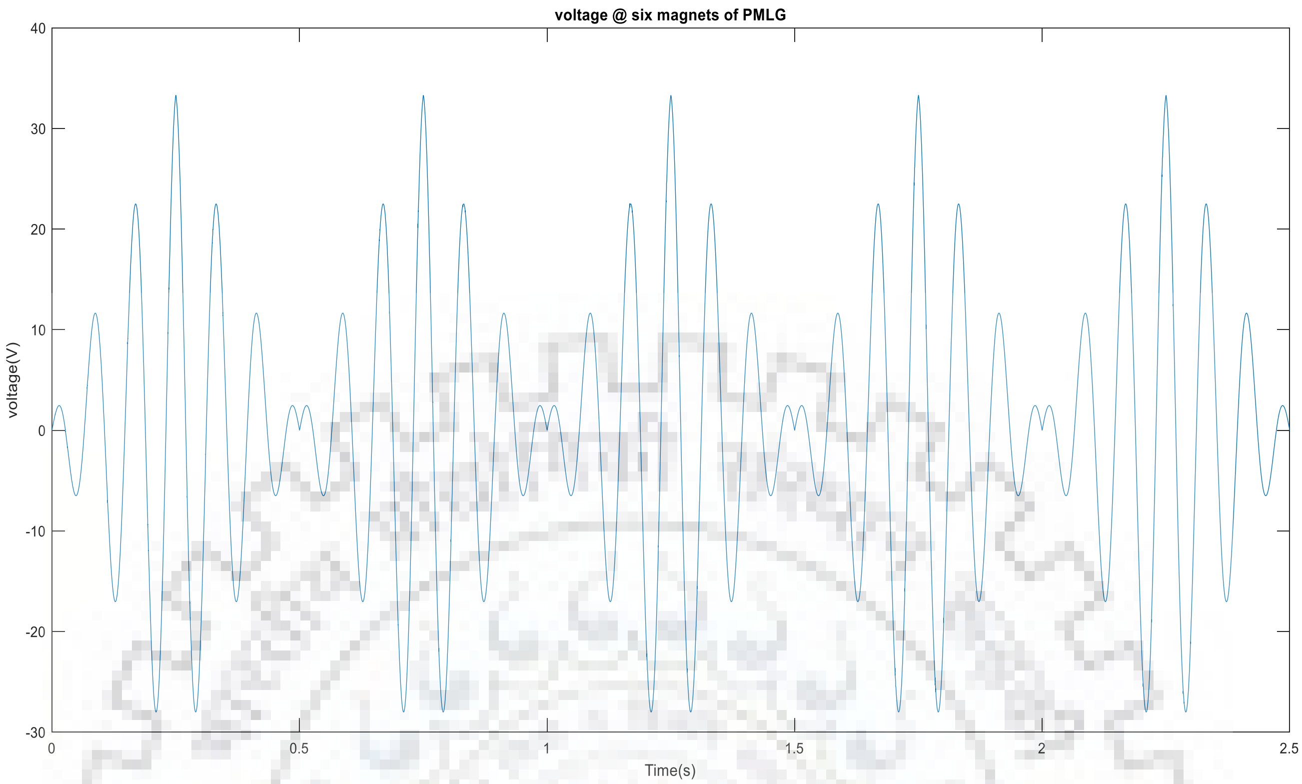


Fig 4.14- voltage waveform @ six magnets

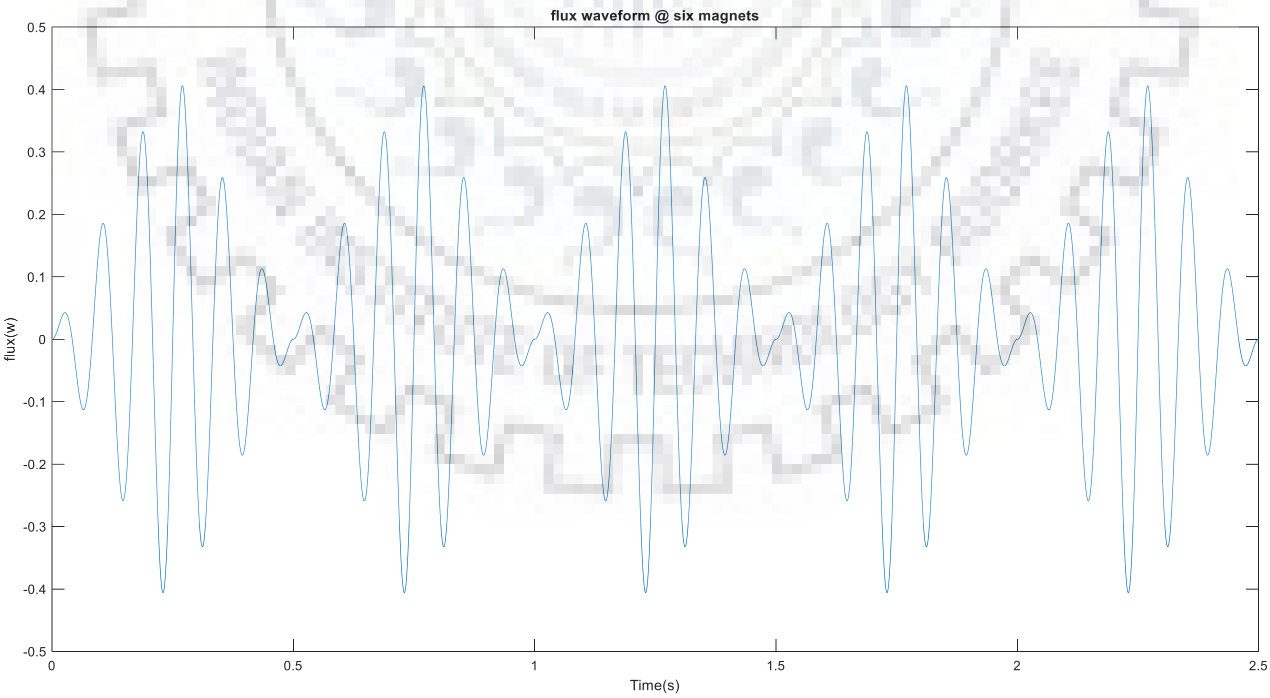


Fig 4.15- flux waveform @ six magnets

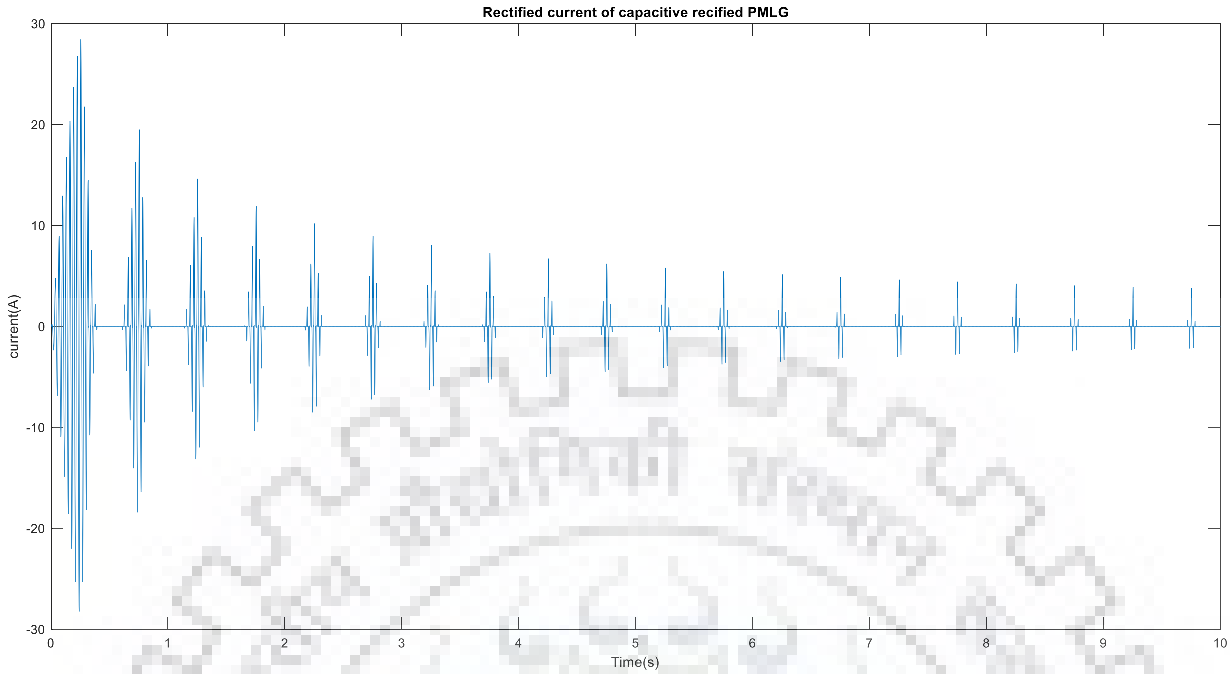


Fig 4.16 – Capacitive rectification of PMLG parameters and current diagram

4.5 The variation of average output voltage on changing no. of magnets

Here we can see that average voltage is somewhat increasing on increasing the flux frequency or we can say on increasing the number of magnets. Shown below is the table how average output voltage varies.

Number of magnets	**Average output voltage**
• **Four**	• **18 volts**
• **Six**	• **25 volts**
• **Eight**	• **32 volts**
• **Ten**	• **40 volts**
• **Twelve**	• **46 volts**
• **Fourteen**	• **55 volts**
• **Sixteen**	• **66 volts**

Table 4.1 variation of voltage according to number of magnets

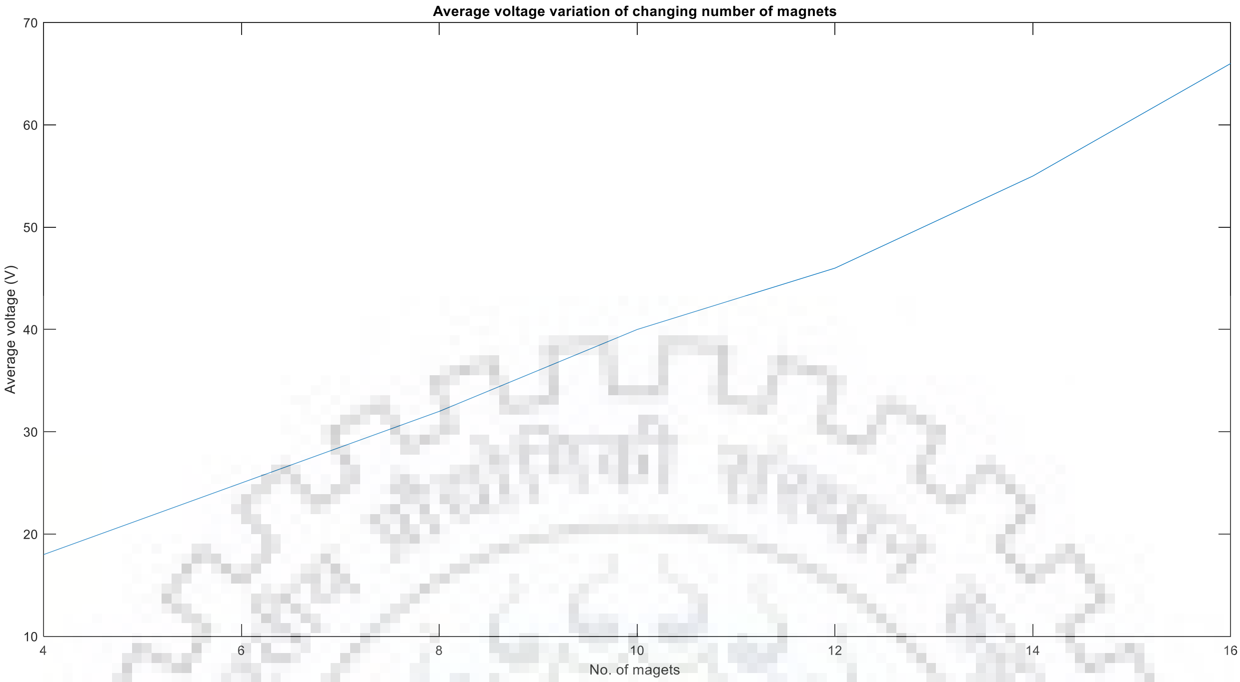


Fig 4.17 variation of voltage on changing number of magnets or frequency

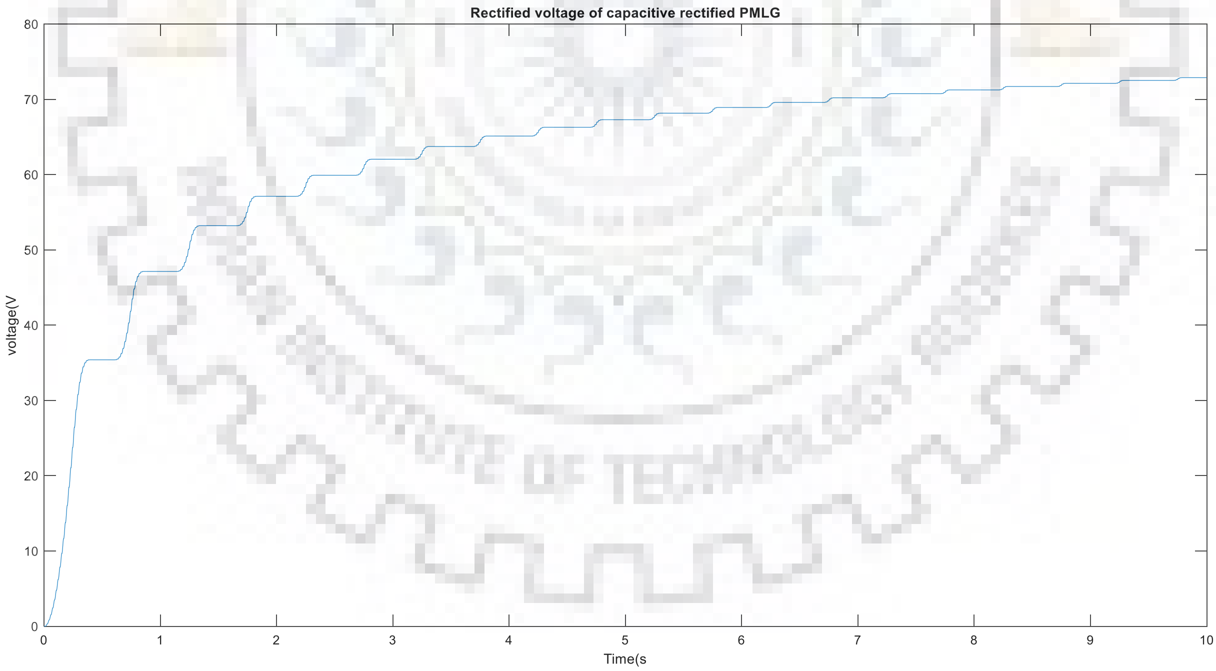


Fig 4.18 -Rectified voltage

4.5 The variation of average output power on changing no. of magnets

Here we can see that average power is somewhat increasing on increasing the flux frequency or we can say on increasing the number of magnets but later on it almost saturates. Shown below is the table how average power voltage varies.

Number of magnets	Average output power(watts)
• Four	• 40
• Six	• 77
• Eight	• 114
• Ten	• 145
• Twelve	• 165
• Fourteen	• 180
• Sixteen	• 182

Table shows variation of average output power of changing no. of magnets

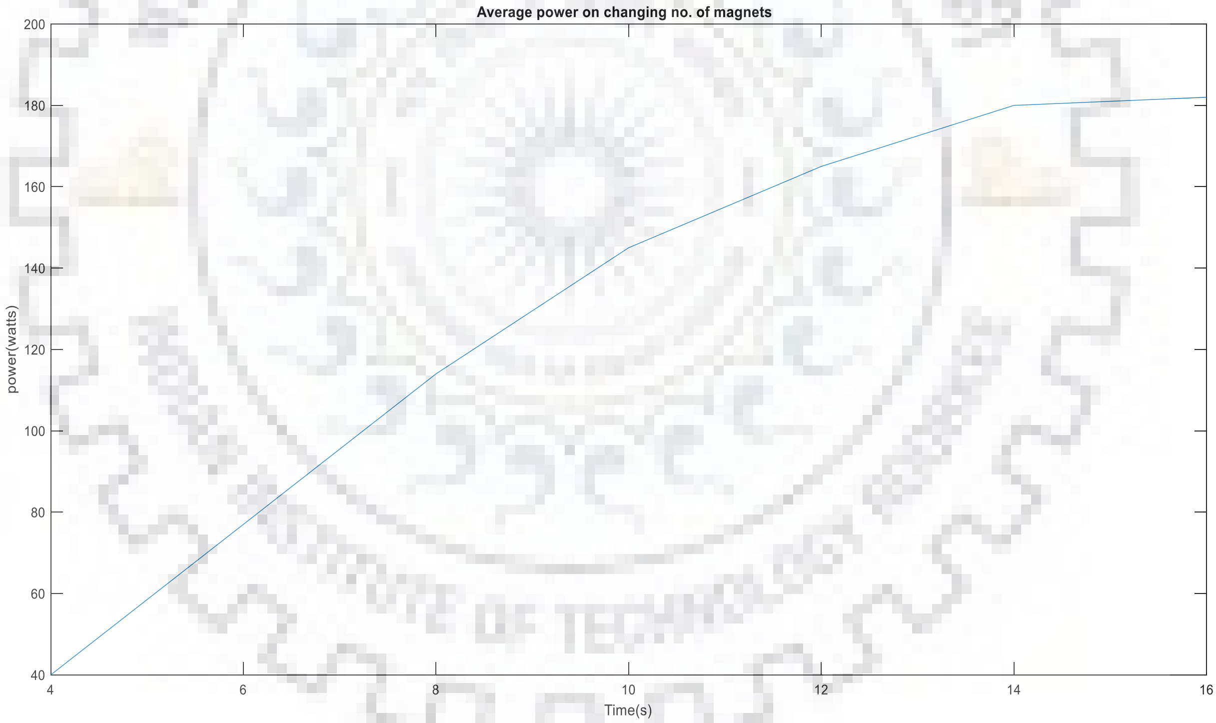


Fig 4.19- Average output power on variation of magnets or frequency

CHAPTER-5

CONCLUSIONS AND APPLICATIONS

5.1 CONCLUSION

First ideal model of generator was taken up to provide baseline for simulation comparisons. Here modelling of permanent magnet linear generator is carried on using d-q current, voltage and flux equations and then simulated in Simulink. A three phase active rectifier is designed to have practical form of voltage and power output. Numerous simulations are done for idea and dynamic and average model to verify our system according to practical need.

The nature of force developed by PMLG is studied so that we can expect the nature of output voltage. Here we could analyse that the power developed is sufficient to light up the tube light.

5.2 APPLICATIONS

1. To be used to extract wave energy
2. To be used for sensing vibrations but not with so much accuracy
3. Can be used for device having back and forth motion like vibrator

CHAPTER-6
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