# Linear Generator Models in Simulink Block

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***Abstract-*** **This paper introduces the model of linear generator in 3 phase analysis and in dq transformation. The linear generator is used to compare the synchronous generator because the source of the input is changing from torqueto the force. As known, force flows along the direction of the moving object. This linear generator model will use speed as the moving source to generate electricity at the output terminal. The model of the linear generator has been modeled in a simulink block diagram in MATLAB. Matlab program has been used because of its simplicity and it is easy to assemble the model. The output can be change from un-control to control source by connecting the power electronics devices such as dc-dc converter, rectifier and inverter after the linear generator model. At the end of this paper it shows the results for both models that can be used to understand more about the linear generator generation.**

**Keywords- Linear machine, Matlab, Simulink**

## I. Introduction

Electric generation from a renewable energy has become one of the demand sources for future. It is to reduce the carbon emission in the air. Currently the generation is based on the synchronous generator machine, which is connected to the wind turbine or at the hydroelectric damn. Synchronous generator is suitable for torque application and when the source is changed to the force the linear generator can be used. As been known, torque is a rotating element while force has a direction. Due to this different input to the generator, synchronous generator can be changed to linear generator by change the stator and rotor into flat mode.

The linear generator is a device that drives a linear motion load without using gears, screws or crankshafts; where it can overcome the problems with the stiffness, mass friction and backlash. The linear generator is shown in Fig. 1. Linear synchronous generator is used to generate current and voltage when the force applies on the rotor while the stator creates an electromagnetic field. When the rotor moving along the stator the electromagnetic field generates the voltage. Linear generator has a different topology with the rotary machine but has similar working principle. The concept of linear motors is base on the travelling magnetic field [1, 2]. This travelling magnetic field generates when the rotor moves horizontal while the stator current flowing in the armature. Due to the advantage of the horizontal move, the source of the rotor is the force where it proportional to the speed. As the result the speed will be proportional to the outputs of the linear generator.

Figure 1. Linear Machine

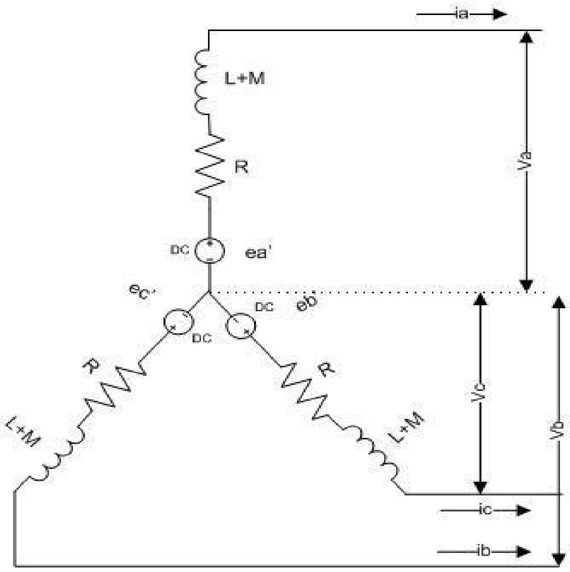


Figure 2. Armature Equivalent Circuit

Due to this concept, the energy recovery from the linear generator can be observed independently or in other meaning, the kinetic energy from moving object can be changed to the electric output using this linear generator. To understand more clearly about the linear generator, the concept of synchronous generator has been implemented. The analysis of linear generator is same with the synchronous generator where the linear dimension and displacements are replaced the angle and force replaced the torque [1]. Due to this statement, the model of the linear generator can be modeled in two models where,

- 3 Phase Analysis System
- dq transformation (Vector Oriented Method)

Both models are used to determine the outputs generate using linear generator during braking. The dq model of the synchronous machine is introduced as the reference for the dq linear generator in reduces the complexity of the three phase analysis of the system. In this paper the linear generator has been modeled in both methods to understand the ability to change the energy from the speed, which is the force to the electrical energy.

## II. Linear Generator Models

### A. Linear Generator- 3 Phase Analysis

As known, the linear generator can be modeled as a synchronous generator [7]. All the parameters are the same but the difference is only to the phase angle ($\theta$). In a synchronous generator the ($\theta$) is based on the torque in the rotating part while for the linear movement the ($\theta$) is based on the horizontal moves of the linear generator. Consider the system is in a balanced condition. Fig. 2 shows the armature equivalent circuit in a balanced system.

After several simplifications and modifications, Eq. 1 shows the flux linkage of the components, one is for field current $i_f$ and the other is due to armature current $i_a$ ,

$$\begin{aligned} \lambda_a &= (L+M)i_a + L_{af} i_f \\ \lambda_b &= (L+M)i_b + L_{bf} i_f \end{aligned} \quad (1)$$

and the mutual inductance between the field coil $M_f$ and the position $\theta_w$ is given by,

$$\begin{aligned} L_{af} &= M_f \cos(\theta_w) \\ L_{bf} &= M_f \cos(\theta_w - 120^0) \\ L_{cf} &= M_f \cos(\theta_w + 120^0) \end{aligned}$$

For the complete system, Eq. 2 shows the voltages at the terminal $V_{abc}$ with the internal impedance R+L of the machine and it given by,

$$\begin{aligned} V_a &= -Ri_a - (L+M)\frac{\delta}{\delta t} i_a + \omega M_f I_f \sin(\theta_w) \\ V_b &= -Ri_b - (L+M)\frac{\delta}{\delta t} i_b + \omega M_f I_f \sin(\theta_w - 120^0) \quad (2) \\ V_c &= -Ri_c - (L+M)\frac{\delta}{\delta t} i_c + \omega M_f I_f \sin(\theta_w + 120^0) \end{aligned}$$

where,
$L_{af}$, $L_{bf}$, $L_{cf}$ are inductance at field winding,
$\theta_w$ is a phase shift,
L is inductance at stator,
M is the mutual inductance for the stator and rotor.

From Eq. 2, it shows the outputs are included the $\omega$ (rotation speed) and $\theta_w$ (phase angle). The equation related to these parameters is shown in Eq.3

$$\theta_w = \frac{2\pi z}{\beta} = \omega t \quad (3)$$

where; z =distance and $\beta$ =wavelength. By simplify Eq. 3, the $\omega$ can be written as,

$$\begin{aligned} \theta_w &= \omega t \\ \frac{2\pi z}{\beta} &= \omega t \\ \frac{2\pi z}{\beta t} &= \omega \\ \frac{2\pi V}{\beta} &= \omega \end{aligned} \quad (4)$$

where,
z =distance
$\beta$ =wavelength.
V=speed of the moving linear machine.

Eq. 4 shows the relationship between the torque in synchronous generator to the speed in linear generator. It indicates, the model of the synchronous model can be used for the linear model. By apply Eq. (2,3,4) the model of the linear generator can be modeled using Simulink Block Diagram in the MATLAB and it is shown in Fig. 3.

Fig. 3 shows the outputs of the linear motor ($V_{abc}$). This $V_{abc}$ is proportional to the $\omega$ and relates to the speed of the machine. To understand these outputs practically, the synchronous generator can be connected to the flywheel in order to behave likes the linear generator where the flywheel operates as a speed input. The power generates from the machine can be calculated by $P_{gen} = V_{abc} I_{abc}$ in generator or by $P_{gen} = F_e V$ in linear generator. From Eq. 2, if the losses of the R and (L+M) is small and can be ignored, the power equation can be written as,

$$\left[ -Ri_{abc} - (L+M)\frac{\delta}{\delta t} i_{abc} + \omega M_f i_f \sin(\theta_w)_{abc} \right] I_{abc} = F_e V$$

$$[\omega M_f i_f \sin(\theta_w)_{abc}] I_{abc} = F_e V$$

$F_e$ represents the 3 phase force shown in Eq. 5

$$F_e = \frac{\omega}{V} M_f i_f \begin{bmatrix} \sin(\theta_w) \\ \sin(\theta_w - 120^0) \\ \sin(\theta_w + 120^0) \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \quad (5)$$

Eq. 5 is used to model the block diagram of the force generation in the 3 phase analysis. This force is proportional to the current generates at the terminal and it is not proportional to the speed. From this relationship, it explains that, the current at the terminal is higher when the speed is zero. This explains that the current and the speed cannot be controlled but the control parameter is the force. The force has a vice verse concept with the speed, the force will be maximum when the speed is zero. It proves this during the braking, the vehicle tries to stop high force need to be used.

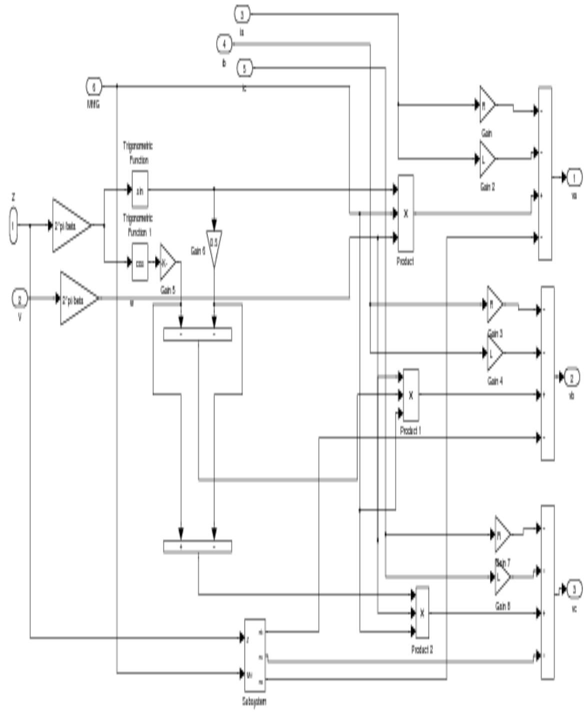

Figure 3. Linear Motor Simulink block diagram

As been explained, the force will be used as the input for the linear generator to determine the electric output and also to determine the speed of the input. Eq. 6 shows the relationship between the force and the speed.

$$F = ma = m\frac{\delta V}{\delta t} \qquad (6)$$

where,
m is the mass of the vehicle
a is the acceleration

Eq. 6 can be modeled in simulink block to represent the force structure. In here the outputs can be selected as speed, distance or acceleration. The outputs will be the parameters to the input of the linear machine model for 3 phase analysis and dq transformation.

*B. Linear Generatorr - Dq Transformation*

The model of the linear synchronous generator has also been designed using dq transformation for having faster simulation time. The dq model is based on [8]. Dq transformation is used for three phase converter analysis and for controller design where the rotating frame has the same angular frequency of the fundamental frequency of the linear generator ($\theta_w$). This concept is much easier to analyse and develop because all the time-varying state variables become dc time invariant and only one operating point needs to be defined and considered [8]. In 3 phase analysis, by writing the circuit equation in the three phase reference frame it caused the time varying parameters of the inductance ( L) and mutual inductance (M) to be considered. In other words, the simulation of sinusoidal waveforms requires a very small integration step even in the steady state operation, which could create computational problems (long simulation time and insufficient memory for storing simulation history in the workspace).

The linear generator is modelled in a dq reference frame where the relationship between a set of dq and the corresponding set of three phase abc variables is provided by equation below,

$$\begin{bmatrix} d \\ q \end{bmatrix} = \frac{2}{3}\begin{bmatrix} \cos(\omega t) & -\sin(\omega t) \\ \cos(\omega t - 120^0) & -\sin(\omega t - 120^0) \\ \cos(\omega t + 120^0) & -\sin(\omega t + 120^0) \end{bmatrix}^T \qquad (7)$$

$$[X_{dq}] = T[X_{abc}]$$

and the inverse transform of Eq 7 is given by,

$$\begin{bmatrix} a \\ b \\ c \end{bmatrix} = \begin{bmatrix} \cos(\omega t) & -\sin(\omega t) \\ \cos(\omega t - 120^0) & -\sin(\omega t - 120^0) \\ \cos(\omega t + 120^0) & -\sin(\omega t + 120^0) \end{bmatrix}\begin{bmatrix} d \\ q \end{bmatrix} \qquad (8)$$

$$[X_{abc}] = T^{-1}[X_{dq}]$$

Assume there is loss less and the equation can be simplify to ,

$$V_{abc} = M_f i_f \frac{\delta}{\delta t}\begin{bmatrix} \cos(\omega t) \\ \cos(\omega t - 120^0) \\ \cos(\omega t + 120^0) \end{bmatrix} \qquad (9)$$

In Eq 7 and 8, the synchronous machine in dq coordinate frame can be establish in the following equation,

$$\left[ T^{-1}\begin{bmatrix} V_d \\ V_d \end{bmatrix} = M_f i_f \frac{\delta}{\delta t}\begin{bmatrix} \cos(\theta_w) \\ \cos(\theta_w - 120^0) \\ \cos(\theta_w + 120^0) \end{bmatrix} \right]^T \qquad (10)$$

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = M_f i_f \frac{\delta}{\delta t}\begin{bmatrix} \cos(\theta_w) \\ \cos(\theta_w - 120^0) \\ \cos(\theta_w + 120^0) \end{bmatrix}^T$$

where,

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = M_f i_f \begin{bmatrix} -\omega\sin(\omega t) \\ -\omega\sin(\omega t - 120^0) \\ -\omega\sin(\omega t + 120^0) \end{bmatrix}\begin{bmatrix} d \\ q \end{bmatrix}$$

$$= M_f i_f \omega\begin{bmatrix} 1.5\sin(\omega t - \omega t) \\ -1.5\sin(\omega t - \omega t) \end{bmatrix}\begin{bmatrix} d \\ q \end{bmatrix}$$

$$\left[\frac{\delta}{\delta t} T^{-1}\begin{bmatrix} i_d \\ i_q \end{bmatrix}\right] T = T\frac{\delta T^{-1}}{\delta t}\begin{bmatrix} i_d \\ i_q \end{bmatrix} + \frac{\delta}{\delta t}\begin{bmatrix} i_d \\ i_q \end{bmatrix}$$

$$= \begin{bmatrix} 0 & -\omega \\ \omega & 0 \end{bmatrix}\begin{bmatrix} i_d \\ i_q \end{bmatrix} + \frac{\delta}{\delta t}\begin{bmatrix} i_d \\ i_q \end{bmatrix}$$

R- armature phase resistance;
L+M- self and mutual impedance;
$\omega$ -linear speed;
$V_{dq}$-armature d and q axis of terminal voltage;
$I_{dq}$-armature d and q axis of terminal current;
$i_f$- field winding terminal current

After several manipulations in Eq.10, the final equation can be written a ,

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = -M_f i_f \omega \begin{bmatrix} 1.5\sin(\omega t - \omega t) \\ -1.5\sin(\omega t - \omega t) \end{bmatrix} \begin{bmatrix} d \\ q \end{bmatrix} \quad (11)$$

Eq. 11 shows the outputs of the terminal linear generators are consist of $V_d$ and $V_q$. As seen, both of these outputs are proportional to the $\omega$ where the equation contain of speed refer to Eq 4. For the maximum power output, it is easy to ignore the self and mutual inductance, the full power to the terminal voltage of the linear generator can be written as,

$$\begin{aligned} V_d &= -Ri_d = 0 \\ V_q &= -Ri_q + 1.5\omega M_f i_f \end{aligned} \quad (12)$$

where R is resistance in the linear generator

To model the block diagram of the dq model, the dq transformation function needs to be considered. This is because, it changes the three phase components value to the dc components with the rotating angle follow the speed of the force generated in the machine. In this paper the dq model has been developed in a MATLAB simulink environment. The power for dq components also can be calculated by referring to Eq. 13 where it consists of speed and current information. The power equation is shown as below,

$$\begin{aligned} P &= V_d i_d + V_q i_q \\ &= \frac{3}{2}\left[-Ri_d^2 - Ri_q^2 + 1.5\omega M_f i_f\right] \end{aligned} \quad (13)$$

Eq. 14 shows the force is generated by the machine in dq analysis. It shows that the force is related to $i_q$ component where it is proportional to the magnitude of the input in the dq imaginary frame.

$$F_e = \frac{9}{4}\frac{\omega M_f i_f}{V} i_q \quad (14)$$

*C. Power Electronics System*

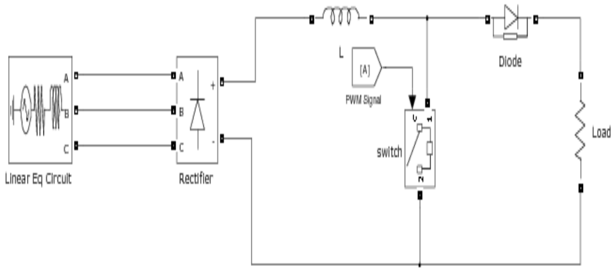


Figure 4. Power Electronics Component

The power electronics models are used to change the kinetic energy produces by the speed to the electrical energy at the terminal of the linear generator. The electrical power is generated at the terminal of the linear generator is meaningless if no further connection has been implemented. To make sure the output can be modified and used, several power electronics components can be used where connects directly to the terminal output of the linear generator. The output can be control when applying the uncontrolled rectifier, dc-dc converter such as boost converter and the inverter.

The uncontrolled rectifier is the most effective and easiest solution for ac-dc conversion compares to 3 phase controllable IGBT rectifier [4] in-term cost reducing. This will make the power factor correction able to permit the amount of the harmonics injection if connected to the utility grid [6]. This rectifier does need the controller where it provides a stable contribution energy [3]. The power can only flow from the generator to the load. Because of the uncontrollable action at the rectifier, so the controllable action has to be designed at the dc-dc converter.

Boost converter has been selected to control the output with varying input. This can be achieved by maintain the boost output. By maintain the boost output voltage at a certain level refer to the reference value hopefully this reference can be used for low voltage or high voltage supply. By adding the storage elements also will help in capture this energy. In other applications, this converter can act as maximum power tracking which act as a changer or vibrator to change the instantaneous power for the linear generator to the constant power from in the dc link. Fig. 4 shows power electronics parts with the rectifier and boost converter as a medium conversion.

## III. Simulation Results

*Linear Generator Results - 3 Phase Analysis and dq Transformation*

In this section, the results for both models will be explained to determine the effectiveness of the models. For the first simulation result, it shows that the outputs from the 3 phase model and dq model are consist of velocity, distance, force, terminal voltage and current at the linear generator terminal.

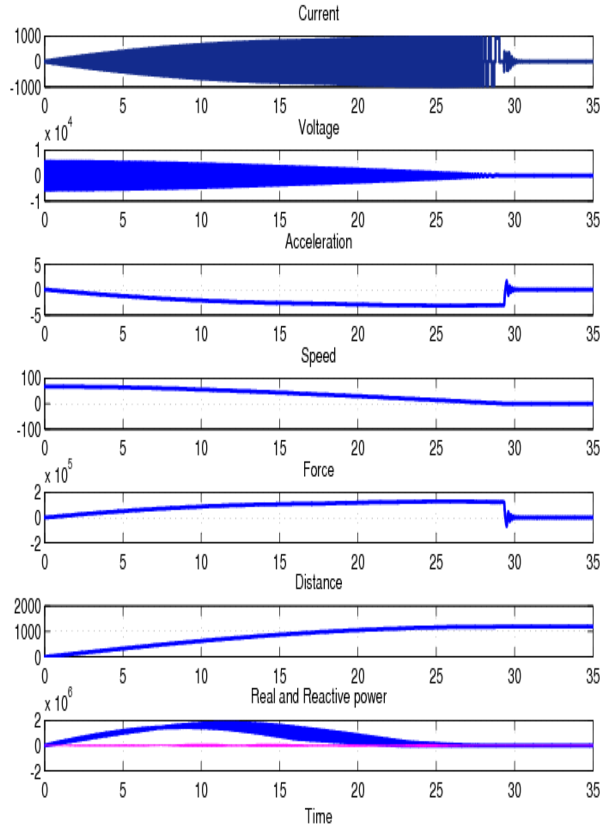


Figure 5. 3-Phase Linear Machine Model Output

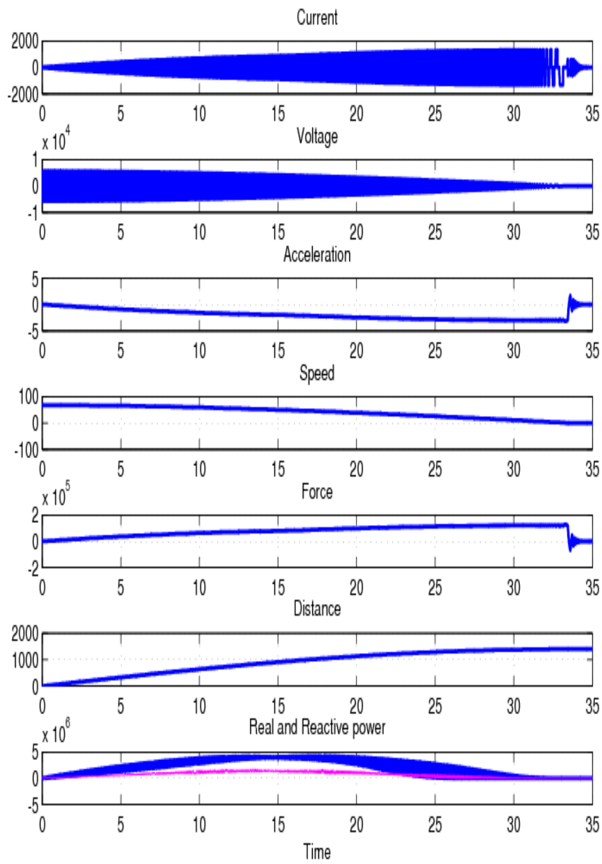


Figure 6. Dq Linear Machibe Model Output

Fig. 5 shows the output of the linear generator in a 3 phase model. The simulation was run for about 35 seconds. The first two graphs, represent the current and voltage waveform where it is different from each other. When the current is maximum the voltage is minimum. This is due to the effect of the load which is shown in Fig.4. The acceleration graph shows the negative sign because, the linear generator is slowing down from high speed to zero speed. This has been proven by the speed and acceleration waveforms. For the real and reactive power the generation only involves the real power (blue) because only the resistive load has been used as a dummy load. For the real and reactive power outputs, the total time to capture the power is less then 30 seconds or less then 20% of the speed. The peak power can be captured when the acceleration is started to give constant deceleration. By applying the speed controller on the linear machine the output generation can be maximize.

Fig. 6 shows the simulation result of the same linear machine but in dq model design. This model has been developed in dq transformation. For dq transformation the total time to complete the simulation just takes less then a minute compared to the 3 phase analysis model which is more then 10 minutes.

From both results the linear generator can be applied during braking. For example the distance needs to be covered to reduce the speed of the linear machine from 67m/s to zero is about 2km. It means that, the linear generator with 2km long is required to capture the energy when the vehicle starts to brake on this speed. The peak power can be captured when the acceleration is started to give constant deceleration. The simulation can run for more or less then 35 seconds, by change the load at the terminal voltage of the linear generator.

As a conclusion for this first simulation, the linear generator is one prominent device that able to collect the energy from the vehicle braking and transfer it to the electrical energy. It proves that by transform the 3 phase system to dq system the result can be collected in a shorter time without giving any effects to the outputs. The main contribution form this is the power from the speed can be changed to electrical output by using several power electronics devices with proper modeling of the linear machine.

For the second part of the simulation results, the results show that the current and voltage that are generated can be controlled to the desired value. This will be explained in the next paper. Fig. 7 and 8 show the output with different control topologies at the boost converter. Fig.7 is when the PI controller is used to generate the PWM signal for the switching process at the boost converter. This result shows that after 5 seconds the voltage is increased dramatically and tries to follow the desired output before the controller stabilize and is continued to generate the output after the output for the terminal voltage has been stopped at 30 seconds. The dc voltage is maintain at 2700V where this is the reference value of the dc reference.

For Fig.8, it uses a current voltage controller to control the voltage and current. By compare from Fig.7

the output increases from 0 until 20s. After 20s the output is maintained at the desired value where it same with Fig. 7. After that, the output will be maintained at the reference value until the simulation is stopped.

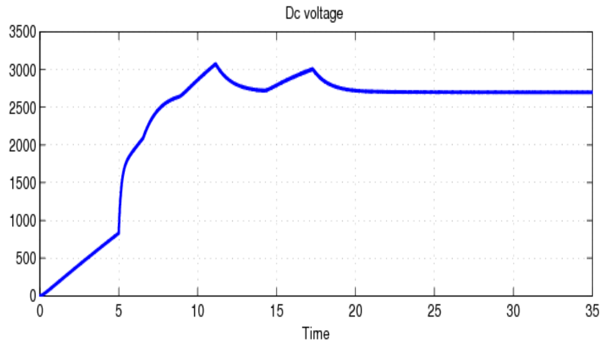

Figure 7. Boost with PI control

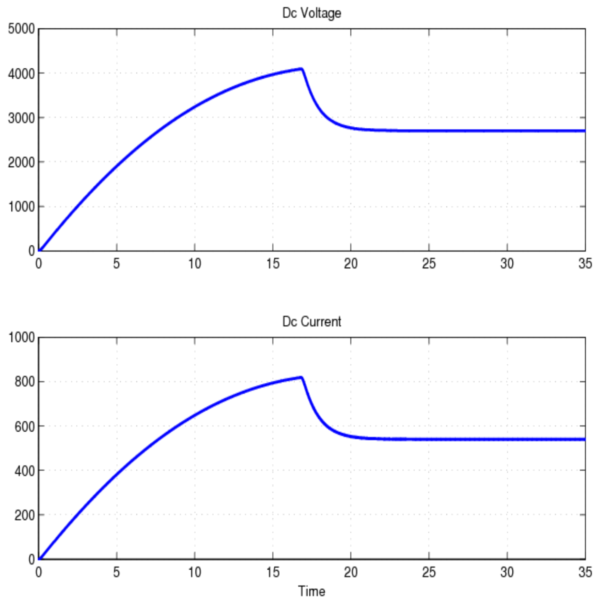

Figure 8. Boost with Current Voltage Control

## IV. Conclusion

For the conclusion, the linear generator can be modeled in both techniques and connect to the power electronics modules to change form kinetic energy to electric energy. Both techniques give the same results at the terminal voltage but in different time to finish the simulation. By using the dq transformation or dc component analysis the time taken for the simulation to finish is less then the three phase model. It is concluded that by reducing the number of phases for analysis, faster time simulation can be achieved.

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