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Improved Closed Loop Controlled PFC Boost Converter Fed Dc Drive with Reduced Harmonics and Unity Power Factor

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Abstract-

Single-phase switch mode ac-dc converters are being used as front end rectifiers for a variety of applications due to advantages of high efficiency and efficiency and power density. However, these classical converters draw non-sinusoidal input ac currents which lead to low input power factors and injections of harmonics into the utility lines. But higher efficiency can be achieved if we use the boost converters with PFC. This paper proves this by doing the simulation of boost PFC converter having load of DC drive in matlab software. The Boost converter circuit is analyzed and simulated with dc motor load in order to check that the circuit can has advantages like reduced harmonics and improved power factor. Also, tried to get near unity power factor by using boost PFC converter with EMI filter.

Keywords- Boost Converter, Electro Magnetic Interference, Harmonic Distortion, Power Factor Correction.

NOTATIONS

$V_{in\,(norm)}$	Normal value of input voltage
$V_{in(Min)}$	Minimum value of input voltage
Vin(peak)	Maximum value of input voltage
f_s	Switching Frequency
f_{line}	Line frequency
P_o	Output Power
$T_{ambient}$	Surrounding temperature
S	Power MOSFET
C_x	Input Capacitor of EMI Filter
C_y	Output Capacitor of EMI Filter
L_c	Inductor for Common Mode Noise
L_d	Inductor for Differential Mode Noise
L_b	Boost Inductor
D_p	Power Diode
C_o	Output capacitor
EMI	Electro Magnetic Interference
PFC	Power Factor Correction

I. INTRODUCTION

With the onset of industrial growth and development in the country, there has been a multifold rise in the power requirement. Thus efficient utilization of power has become extremely critical. Power Factor is an important concept concerning power and energy management. It is a measure of how efficiently, or inefficiently, a customer uses electrical power. Inductive loads such as transformers, electric motors and high-intensity discharge lighting generally cause a low power factor. Customers who do not use electrical power efficiently end up paying additional fees for inefficient use of power by their electric utility company. The benefits of employing a power factor correction device are many. Reduction of heating losses in transformers and distribution equipment, longer equipment life, stabilized voltage levels, increased capacity of your existing system and equipment, improved profitability and lowered expenses are some advantages.

Also, Electromagnetic pollution of the power line introduced by power electronic systems include harmonic distortion due to non-linear loads typically, rectifiers. It results in poor Power Factor which not only reduces the efficiency but also increases the cost of electricity. More importantly, many devices suffer from harmonically rich waveforms. This is because more and more electronics loads are connected to the grid whose front-end stage usually being a diode or thyristor rectifier. The high distortion of the current absorbed by these loads causes a non-sinusoidal voltage drop across the line impedance, resulting in considerable voltage distortion. Due to these harmonics, severe damages can be caused like, motors can overheat as a result of harmonics. In case of three phase motors, these harmonics can result in significant neutral current which can also result in overheating and ultimately in motor failure. So, various types of single phase PFC converter circuits to improve the AC current waveform have been developed and used.

An ideal power factor corrector (PFC) should emulate a resistor on the supply side while maintaining a fairly regulated output voltage. In the case of sinusoidal line voltage, this means that the converter must draw a sinusoidal current from the utility; in order to do that, a suitable sinusoidal reference is generally needed and the control objective is to force the input current to follow, as close as possible, this current reference.

There are two types of PFCs- Active and Passive. The preferable type of PFC is active PFC since it makes the load behave like a pure resistor, leading to near-unity load power factor and generating negligible harmonics in the input line current. Active PFC utilizes electronics to force the input current to look like a reflection of the input voltage(i.e. resistive). The result of this type of correction typically results in Power Factor of greater than 0.98 and harmonic distortion of less than 3%. An example of Active PFC is the boost chopper circuit which constructs the PFC converter with a switching device in the DC side of the diode bridge rectifier circuit. Good characteristics such as a sinusoidal current waveform in phase with the AC line voltage and the constant DC voltage can be obtained from the PFC converter. But, these conventional PFC boost converter suffers from the high conduction loss in the input rectifier-bridge.

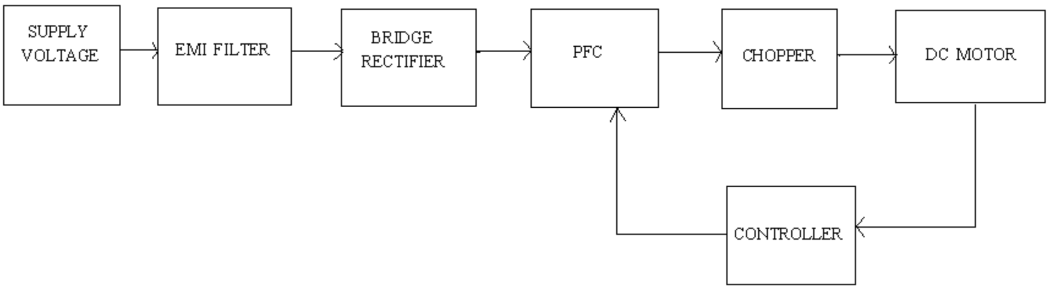

Figure 1 Bock Diagram of Close-Loop controlled DC Motor.

Power factor correction is particularly important for dc drives because phasing back of the SCRs results in relatively poor power factor, especially when the motor is at reduced speeds. Additional transformer capacity is required to handle the poor power factor conditions (and the harmonics) and more utilities are charging a power factor penalty that can significantly impact the total bill for the facility.

There is also another problem occurs in power circuits and it is of Electro Magnetic Interference. This is related with the disturbance caused due to electromagnetic waves to the operation of any electronic circuit. Because of rapid change in voltages and currents within a switching converter, power electronic equipment is a source of electromagnetic interference with other equipment as well as with its own proper operation. So, Electro Magnetic Interference Filter (EMI Filter) has to be used at the input of PFC converter. An EMI filter is needed to reduce the differential mode and common mode noise. The filter comprises of inductors and capacitors connected in differential and common mode configuration. Thus, in this project a new circuit is proposed which consists of three parts, EMI Filter circuit to filter out electromagnetic interference; PFC Boost Converter circuit to improve power factor and the close loop control circuit for controlling the PFC Boost Converter. The main final block diagram for the whole work is given in Fig. 1.
Hence, this new control scheme for PFC not only remove the EMI effect but also improve the power factor.

II. BOOST PFC CONVERTER

A boost converter (step-up converter) is a power converter with an output DC voltage greater than its input DC voltage. It is a class of switching-mode power supply (SMPS) containing at least two semiconductor switches (a diode and a transistor) and at least one energy storage element. Filters made of capacitors (sometimes in combination with inductors) are normally added to the output of the converter to reduce output voltage ripple.

The boost converter is operated under DCM of the inductor current mode to achieve a sinusoidal input current shaping. This circuit uses only one active switch with no active control of the current. The addition of a switch and an inductor to a diode-capacitor rectifier allows an extension of the entire line period. The resulting behavior reduces considerably the harmonic pollution and characterizes the load as a class A equipment. The drawbacks of the simple converter are excessive output voltage and the presence of fifth harmonics in the line current. This kind of converter removes these problems and is commonly used in industrial and commercial applications requiring a high input power factor because their input-current waveform automatically follows the input-voltage waveform. Also, the circuit has an extremely high efficiency.

The full-bridge rectifier can be combined with a boost converter to form a unity power factor circuit as shown in Fig 2. By controlling the current of the boost inductor with the aid of feedback control technique, the input current of the rectifier can be made sinusoidal and in phase with the input voltage, thereby having an input Power Factor of approximate unity. This is done because there is a distortion in the input voltage caused by the distorted current when the system is operated as an uncontrolled diode bridge rectifier. Harmonic current interacting with the source impedance primarily due to utility lines and transformers, causes this distortion. This distortion is corrected by triggering the power factor controller and wave shaping the input current into desired sinusoid.

The thyristor for PFC converter with different firing angles will give less output power, more harmonics and less power factor as compared with Diode rectifier. Hence, the diode rectifier is used as a dc input source to the Boost Converter as shown in Fig. 2. The boost converter has V_d as the input voltage and V_o as the output voltage. Here, output voltage is greater than the input voltage. Thus, boost converter is also known as a step-up converter. A large inductor L in series with the source voltage is essential. When the switch is on, the input current flows through the inductor and switch and the inductor stores the energy during this period. When the switch is off, the inductor current cannot die down instantaneously. This current is forced to flow through the diode and load during this off-period. As the current tends to decrease, polarity of the emf induced in L is reversed. As a result, a voltage across the load is the sum of supply voltage and inductor voltage and it is greater than the supply voltage.

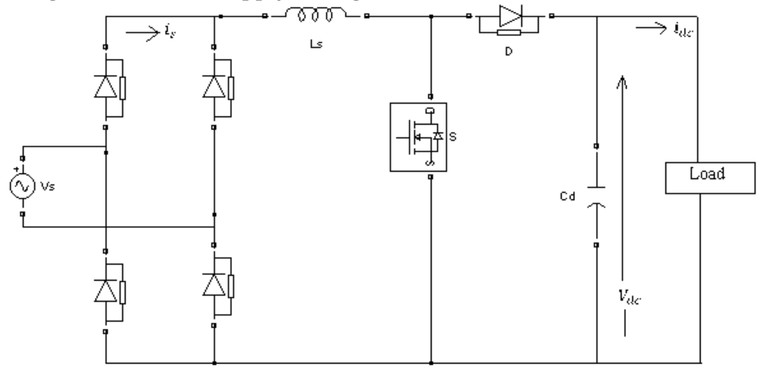

Figure 2 Unity PF Boost Converter

The voltage impressed across the inductor during on-period is V_d. During this period, the current rises linearly from a minimum level I_1 to a maximum level I_2. Therefore, the voltage across inductor is

$$V_L = V_d \quad (1)$$

Also,

$$V_L = \frac{L(I_2 - I_1)}{T_{on}} = \frac{L(\Delta I)}{T_{on}} \quad (2)$$

From eq. (1) and (2)

$$T_{on} = \frac{L(\Delta I)}{V_d} \quad (3)$$

The voltage impressed across the inductor during off period is $(V_o - V_d)$ and the current drops linearly from the maximum level I_2 to the minimum level I_1. Therefore, the voltage across the inductor is,

$$V_L = (V_o - V_d) \quad (4)$$

Also,

$$V_L - \frac{L(I_2 - I_1)}{T_{off}} = \frac{L(\Delta I)}{T_{off}} \quad (5)$$

From eq. (4) and (5),

$$T_{off} = \frac{L(\Delta I)}{V_o - V_d} \quad (6)$$

From eq. (3),

$$L(\Delta I) = T_{on} * V_d \quad (7)$$

From eq. (6),

$$L(\Delta I) = T_{off} * (V_o - V_d) \quad (8)$$

From eq. (7) and (8),

$$T_{on} * V_d = T_{off} * (V_o - V_d)$$

Or,

$$V_o = (T_{on} + T_{off}) * \frac{V_d}{T_{off}}$$

Or,

$$V_o = T * \frac{V_d}{T_{off}}$$

Or,

$$V_o = \frac{V_d}{1 - \propto} \quad (9)$$

where α = delay angle of the boost converter. As firing angle increases from 0 to 1, the output voltage ideally increases from V_d to infinity. Hence, the output voltage is boosted.

A Boost PFC Converter consists typically of a diode rectifier, a boost inductor, switching device and a boost capacitor. Thus, there are two modes of operation- discontinuous mode and continuous mode.

Discontinuous mode is when the boost converter's MOSFET is turned on, when the inductor current reaches zero and turned off when the inductor meets the desired input reference voltage. In this way, the input current follows that of the input voltage. Thus, attaining a power factor of one(1).

In the continuous mode, the boost converter's MOSFET does not switch on, when the inductor is at zero current. Instead, the current in the energy transfer inductor never reaches zero during switching cycle. Thus, losses are minimal.

III. PFC CONTROL SCHEME

The main objective of the PFC control scheme of the boost converters is to regulate the power flow while ensuring tight output voltage regulation as well as unity input power factor. The control scheme shown in Fig. 3 is the most extensively used control scheme for these converters.

In this scheme, the output of voltage regulator is first limited to a safe value which then forms the amplitude of input reference current. After that, this reference amplitude is multiplied to a template of input voltage for synchronizing the reference with input voltage which is required for unity power factor operation. Then, the inductor current is forced to track its reference current using current controller, which generates appropriate gating signals for the active device(s). The explanation of the various components of this control scheme are as follows.

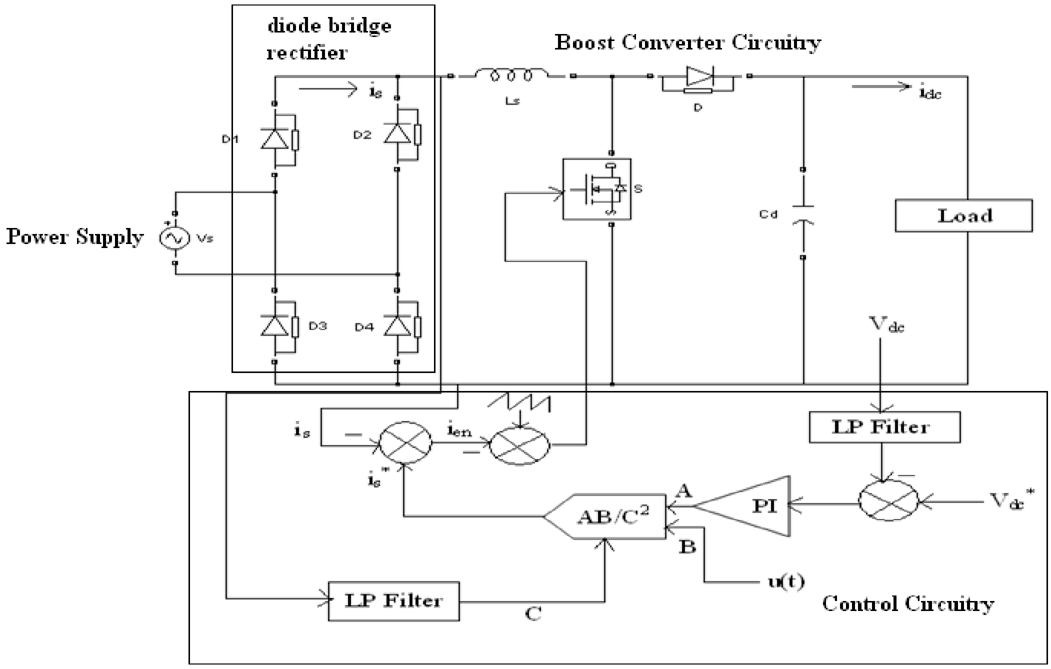

Figure 3 Control scheme of PFC Converter

1. Supply System

Under normal operating conditions the supply system can be taken as a sinusoidal voltage source coming out from EMI filter of amplitude V_m and frequency f_s. The instantaneous voltage is given as:

$$v_s(t) = V_m \sin \omega t \qquad (10)$$

where $\omega = 2\pi f_s t$ electrical rad/s and t is instantaneous time.

From the sensed supply voltage, a template $u(t)$ is estimated as

$$u(t) = \frac{v_s(t)}{V_m} \qquad (11)$$

2. DC Voltage Controller

In this, a proportional integral (PI) voltage controller is selected for tight regulation of the output voltage in voltage loop. The dc voltage v_{dc} is sensed and compared with set reference voltage v_{dc}^*. Thus, the resulting voltage error $v_{e(n)}$ at nth sampling instant is:

$$v_{e(n)} = v_{dc}^* - v_{dc(n)} \qquad (12)$$

$$v_{O(n-1)} = v_{O(n-1)} + K_P\left(v_{e(n)} - v_{e(n-1)}\right) K_i v_{e(n)} \qquad (13)$$

where K_P and K_i are the proportional and integral gain constants. $v_{e(n-1)}$ is the error at the $(n-1)$th sampling instant. The output of the controller $v_{O(n)}$ after limiting to a safe permissible value is taken as amplitude of reference supply current A.

3. PWM Current Regulator

Current regulation loop is required for active wave shaping of input current to achieve unity input power factor and reduced harmonics.

4. Reference Supply Current Generation

For this, the input voltage template B obtained from sensed supply voltage, is multiplied with the amplitude of reference source current A in the multiplier-divider circuit. Also, a component of input voltage feed-forward C is added to improve the dynamic response of the converter system to line disturbances. The resulting signal forms the reference for the input current. The instantaneous value of the reference current is given as:

$$i_s^2 = AB/C^2 \qquad (14)$$

5. Active Wave-shaping of Input Current

The inductor current error is the difference of reference supply current and inductor current ($i_{en} = i_s^* - i_s$). The error signal is amplified and compared to fixed frequency carrier wave to generate gating signals for power devices of the converter.

IV. ELECTROMAGNETIC INTERFERENCE FILTER

Power electronic circuits switch on and off large amounts of current at high voltages and thus can generate unwanted electrical signals, which effect other electronic systems. These unwanted signals occur at higher frequencies and give rise to EMI, also known as radio frequency interference (RFI). The signals can be transmitted to the other electronic systems by radiation through space or by conduction along cable. Thus, the Electro Magnetic Interference is transmitted in two forms: radiated and conducted. The switching converters supplied by the power lines generate conducted noise into the power lines that is usually several orders of magnitude higher than the radiated noise into free space. Metal cabinets used for housing power converters reduce the radiated component of the electromagnetic interference. Conducted noise consists of two categories commonly known as the differential mode and the common mode. The differential mode noise is a current or a voltage measured between the lines of the source, that is line to line voltage. The common mode noise is a voltage or a current measured between the power lines and ground, that is line to ground voltage.

The low-level gate control circuit of the power converter can also be effected by EMI generated by its own high-power circuitry. When this occurs, the system is said to possess susceptibility to EMI. Any system that does not emit EMI above a given level, and is not effected by EMI, is said to have electromagnetic compatibility (EMC).

An EMI filter is needed to reduce the differential mode and common mode noises. The filter comprises of inductors and capacitors as shown in Fig. 4(a).

V. MODELLING OF DC MOTOR

For dc motor, the torque T is related to the armature current i, by a constant factor K_t: $T = K_t i_a$. For the separately excited DC motor, the back emf e, is related to the rotational velocity by: $e = K_b \omega_r$. In SI units, K_t (armature constant) is equal to K_b (motor constant).

The DC motor equations based on Newton's law combined with Kirchhoff's law:

$$J\frac{d\omega}{dt} + B\omega = K_t i_a - T_L \qquad (15)$$

$$L_a \frac{di_a}{dt} + R_a i_a = V_a - K_b \omega_r \qquad (16)$$

where J is the moment of inertia, B is damping ratio of the mechanical system, R_a is the electrical resistance of the armature circuit, and L_a is the electrical inductance of the armature circuit. In the state-space form, the equations above can be expressed by choosing the rotational speed and electric current as the state variables and the voltage as an input. The output is chosen to be the rotational speed.

$$\frac{d}{dt}\begin{bmatrix}\omega_r \\ i_a\end{bmatrix} = \begin{bmatrix} -\frac{B}{J} & \frac{K}{J} \\ -\frac{K}{L_a} & -\frac{R_a}{L_a}\end{bmatrix}\begin{bmatrix}\omega_r \\ i_a\end{bmatrix} + \begin{bmatrix}0 \\ \frac{1}{L_a}\end{bmatrix} V_a \qquad (17)$$

$$\omega_r = \begin{bmatrix}1 & 0\end{bmatrix}\begin{bmatrix}\omega_r \\ i_a\end{bmatrix} \qquad (18)$$

VI. SIMULATION RESULTS

The boost converter system is simulated using Matlab simulink. The A.C. source with EMI filter is shown in Fig.4(a). Noise is injected by using an additional source of higher frequency connected in series. Distorted input voltage is shown in Fig.4(b). The voltage waveform after EMI filter is shown in Fig.4(c). The circuit diagram of open loop system with disturbance is shown in Fig.5(a). Rotor speed curve is shown in Fig.5(b). The circuit of closed loop system is shown in Fig.6(a). Driving pulses for the MOSFET are shown in Fig.6(b). Error signal is shown in Fig.6(c). From the response of closed loop system, it can be seen that the speed reaches the set value.

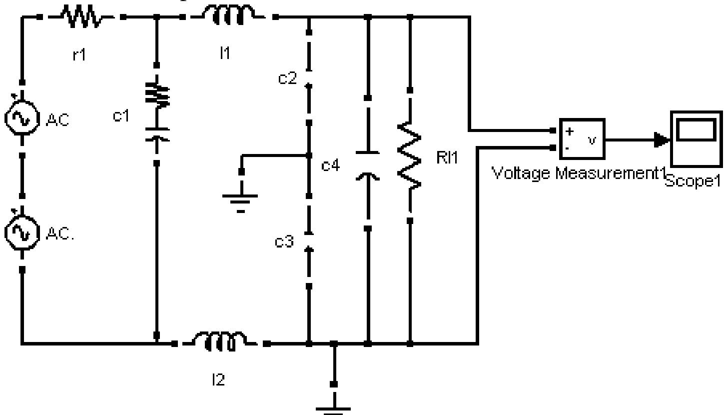

Figure 4(a). EMI filter circuit

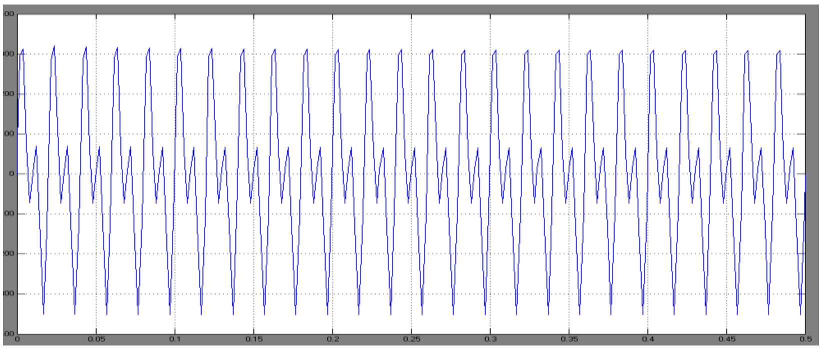

Figure 4(b). Input Voltage before EMI filter

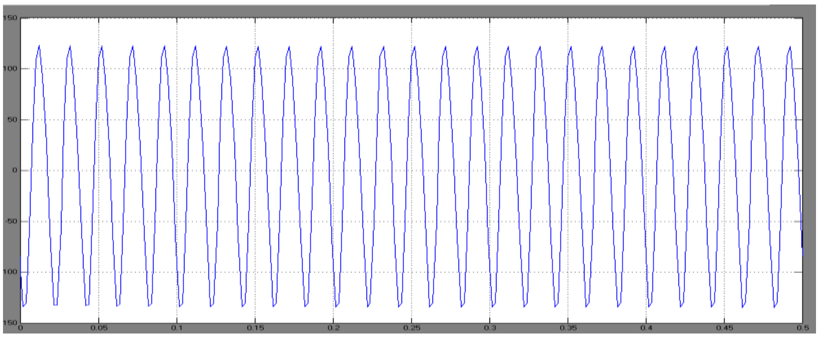

Figure 4(c). Voltage after EMI filter

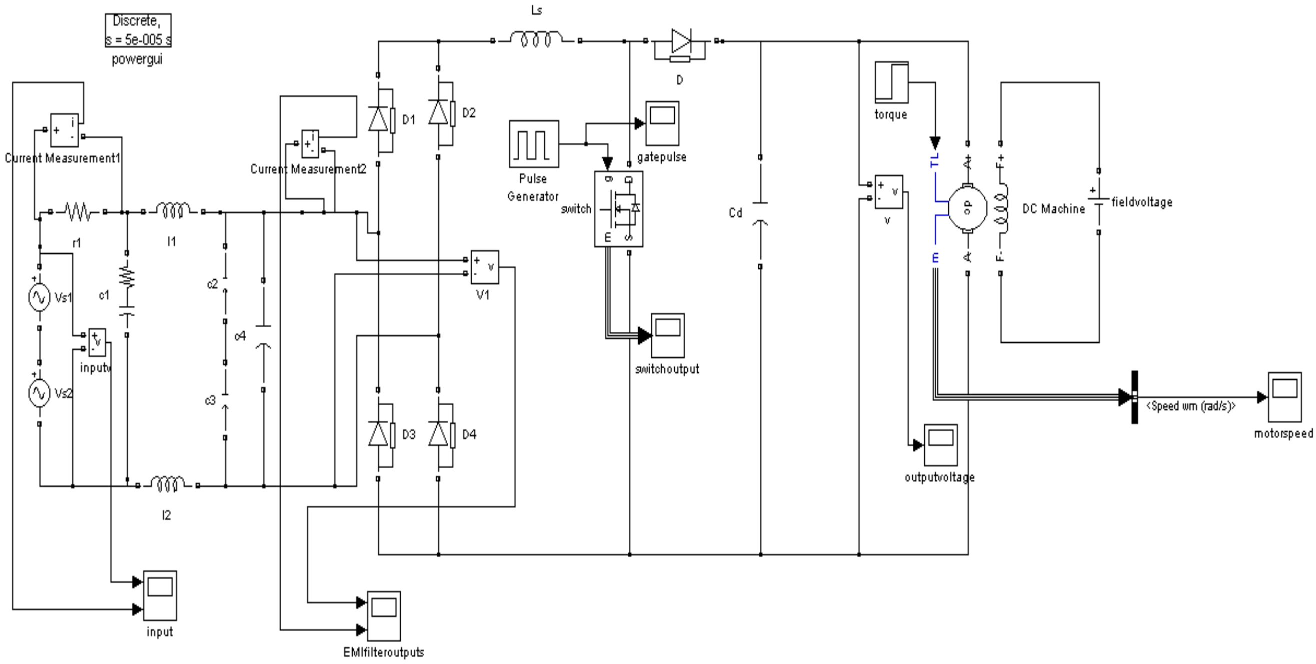

Figure 5(a). Simulation circuit of open loop system

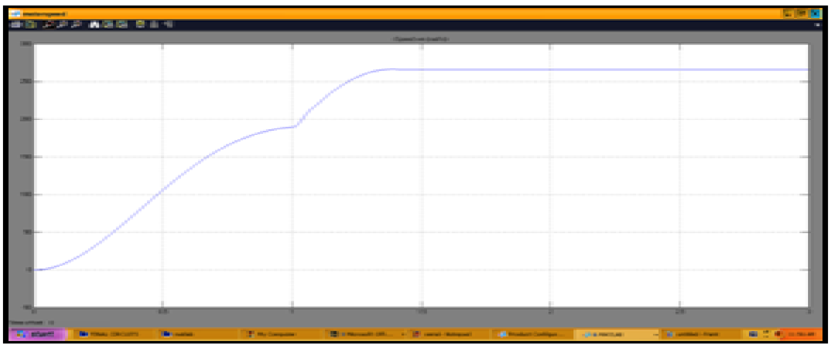

Figure 5(b). Rotor speed (Rad/Sec) with disturbance in open loop system

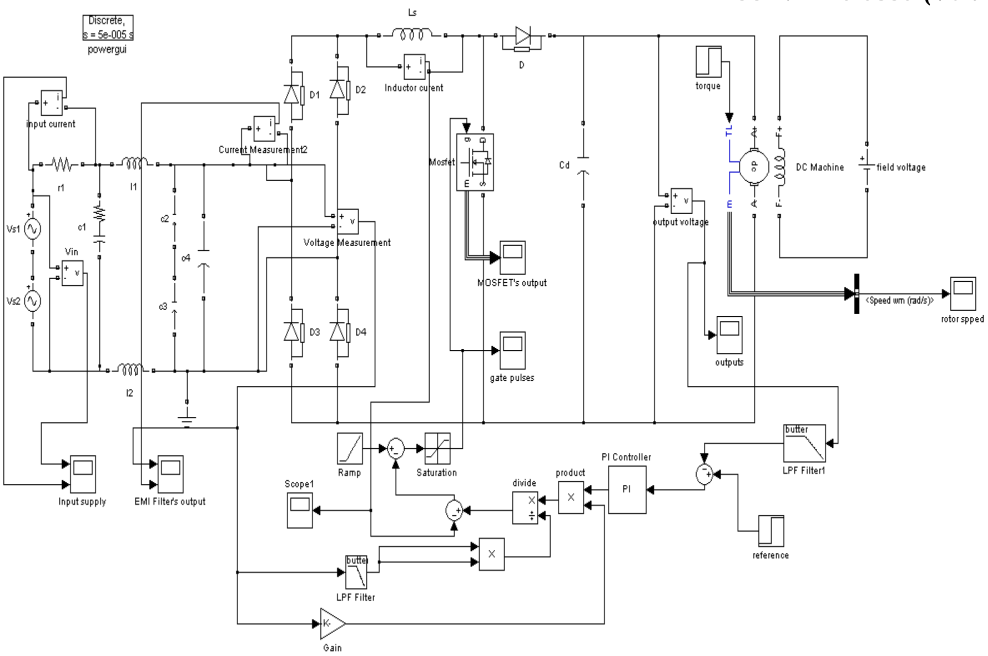

Figure 6(a). Circuit diagram for closed loop system

Figure 6(b). Output pulses

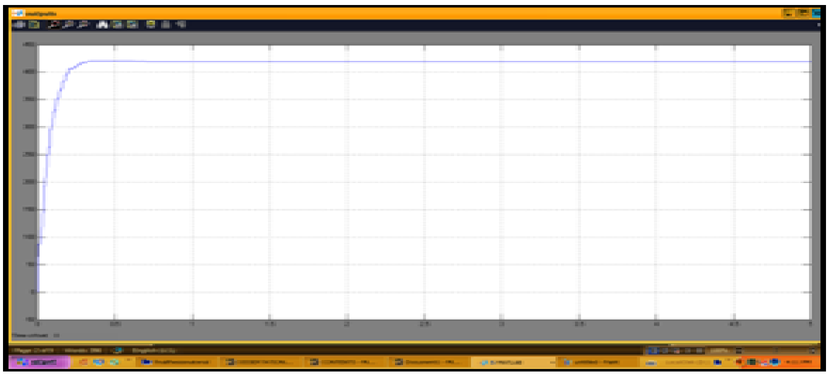

Figure 6(c). Rotor Speed (Rad/Sec) with Disturbance in Closed Loop System

VII. CONCLUSION

This circuit has advantages like reduced hardware, high performance and improved power factor. The simulation results are in line with the predictions. This work has covered the simulation of open loop and closed loop controlled PFC converter. The hardware implementation will be done in future.

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