Proceedings of the Pakistan Academy of Sciences 51 (3): 201–208 (2014)

ISSN: 0377 - 2969 (print), 2306 - 1448 (online)

Pakistan Academy of Sciences

Research Article

Performance of Six-Pulse Line-Commutated Converter in DC Motor Drive Application

Syed Riaz ul Hassnain[1], Haider Zaman[1], Zunaib Ali[1], Muqadsa Iftikhar[1], and Tariqullah Jan[2]*

[1]University of Engineering & Technology Peshawar, Abbottabad Campus, Pakistan
[2]University of Engineering & Technology, Peshawar, Pakistan

Abstract: This paper presents the speed control of DC motor using six pulse controlled rectifier. The conventional Proportional Integral (PI) control is used for firing angle control. The armature current is fed back and compared with reference current representing desired speed values. The proposed system is simulated using SimPowerSystem and Control System Matlab toolbox. The time domain plot of reference and actual armature current are shown in results section. The results are satisfactory with deleterious effect on input current. The frequency plot of input current is provided to show the harmonic contents, generated as a result of control operation.

Keywords: Silicon control rectifier (SCR), DC motor, proportional integral control, harmonics, displacement factor and distortion factor, line-commutated converter (LCC)

1. INTRODUCTION

The continuous popularity of DC motors is due to their efficient performance and control advantages over ac motors. The scope of DC motor varies from high speed automation to electric vehicles. The dc motors are increasingly used in applications where speed or torque needs to be varied and controlled with high accuracy. The most commonly used DC motors for variable speed are series and separately excited [1], but generally DC series motor is used for traction purposes.

With the development of high power solid state switches, the DC motor control applications started to grow almost exponentially. Today, broadly two methods are employed (based on switches controllability) to set the applied voltage as a variable parameter. In the first method applied voltage can be made variable by using controlled rectifiers which provide variable DC from a fixed ac shown in Fig. 1(a) whereas in the second method uncontrolled rectifiers are used to produce a fixed DC from a fixed ac and at the output of rectifier a DC chopper circuit is used which provide variable DC just by changing the duty cycle shown in Fig. 1(b) [2].

In this paper our major focus is to discuss the use of SCR based converters for speed regulation i.e. to get variable DC voltage from a fixed ac voltage. The use of SCR allows simple voltage variability just by varying the firing angle and thereby the speed of the motor. For the speed regulation of DC motor, the speed needs to be monitored as the speed of DC motor changes with load torque [3]. The control circuit corrects the firing angle of SCR, which in-turn changes the armature voltage, thereby regulating the speed. The control circuit used here consists of PI current controller, which takes current as feedback, compares it to the reference and then generates firing angle of SCRs to minimize the error and regulate the speed [4-5]. The benefits of feedback network (which is also called closed loop control system) are of high level of accuracy, compensation of load variations and system nonlinearities, fast response and continuous monitoring of process [6]. The block diagram of DC motor fed with closed loop controlled rectifier is shown on Fig. 2.

First, the mathematical model of DC motor is developed in section 2. Working principle of six

Received, July 2014; Accepted, August 2014
*Corresponding Author: Tariqullah Jan, Email: tariqullahjan@nwfpuet.edu.pk

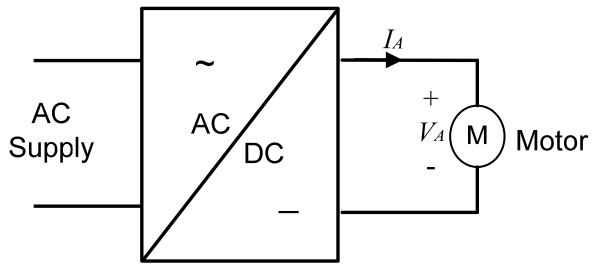

Fig. 1(a). Controlled rectifier fed motor.

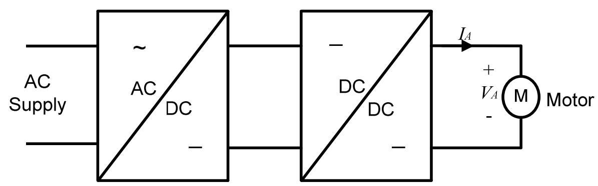

Fig. 1(b). Uncontrolled rectifier followed by DC-DC converter.

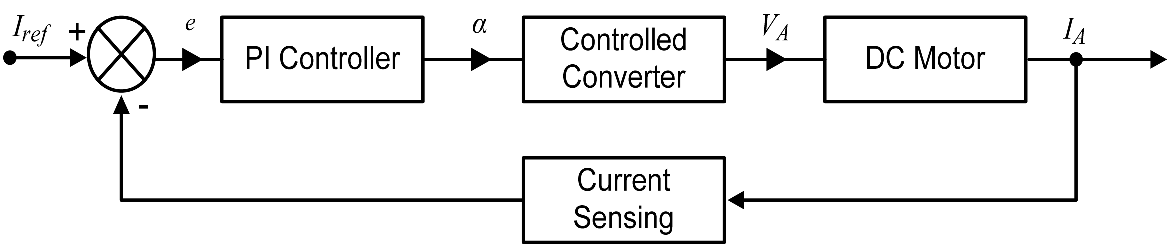

Fig. 2. Block diagram of DC motor fed with closed loop controlled rectifier.

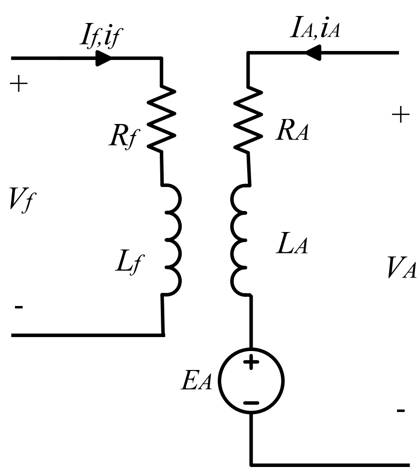

Fig. 3. Separetly excited DC motor.

pulse line-commutated converter is described in section 3. The section 4 presents the complete system responses under a transient condition, followed by a conclusion.

2. DC MOTOR MODELING

The equivalent circuit of commonly used DC motor i.e. separately excited DC motor is shown in Fig. 3. In case of separately excited DC motor the armature circuit and field circuit is independent of each other. When the armature current i_A is passed through the armature circuit placed in a magnetic field produced by field current $i_f$passing through the field circuit, the motor produces a back electromotive force E_A and induced torque τ_{ind} , which balance the load torque at a particular speed. For separately excited DC motor, the current passing through the field windings is independent of the current passing through armature windings. The transient and steady state analysis of separately excited DC motor is derived using Fig. 3.

Transient Analysis

The instantaneous field current is given by differential equation:

$$V_f = i_f R_f + L_f \frac{di_f}{dt} \tag{1}$$

The instantaneous armature current can be calculated from:

$$V_A = i_A R_A + L_A \frac{di_A}{dt} + E_A \tag{2}$$

Where E_A is back emf of the motor and is given by

$$E_A K \omega i_f \tag{3}$$

The torque induced by the motor τ_{ind} is:

$$\tau_{ind} = K i_f i_A \tag{4}$$

The induced torque in terms of load torque is:

$$\tau_{ind} = J \frac{d\omega}{dt} + B\omega + \tau_{load} \tag{5}$$

Where,

ω = angular speed (rad/s)

B = constant of viscous friction $\left(\mathrm{N.}\frac{\mathrm{m}}{\mathrm{rad/s}}\right)$

K = voltage constant (V/A − rad/s)

L_A = armature circuit inductance (H)

L_f = field circuit inductance (H)

R_A = armature circuit resistance (Ω)

R_f = field circuit resistance (Ω)

τ_{load} = load torque (N. m)

J = Moment of inertia

Steady-state Analysis

For the steady state analysis all the derivatives with respect to time are put to zero. The resulting steady state average quantities are:

$$V_f = I_f R_f \tag{6}$$

$$\begin{aligned} V_A &= I_A R_A + E_A \\ &= I_A R_A + K\omega I_f \end{aligned} \tag{7}$$

$$\begin{aligned} \tau_{ind} &= K I_f I_A \\ &= B\omega + \tau_{load} \end{aligned} \tag{8}$$

The power induced or developed is:

$$P_{ind} = \tau_{ind}\omega \tag{9}$$

In modeling of DC motor, the main concern is to find the relationship between speed of DC motor and armature voltage. The speed of the separately excited DC motor in terms of armature voltage can be derived using $Eq. (7)$, i.e.:

$$\omega = \frac{V_A - I_A R_A}{K I_f} \tag{10}$$

Using $Eq. (6)$,$I_f = V_f/R_f$

$$\omega = \frac{V_A - I_A R_A}{K V_f/R_f} \tag{11}$$

From $Eq. (11)$ it is cleared that the speed of motor is directly related to armature voltage V_A, larger the armature voltage greater will be the speed and vice versa[6]. The type of control in which the controlling parameter is voltage, is called voltage control. In practice, the armature and filed currents are kept constant to fulfill the demand of torque while armature voltage is made variable to control the speed. So, in this study a DC motor is fed with the output of a three phase SCR bridge.

3. WORKING PRINCIPLE OF SIX PULSE CONVERTER

The circuit diagram for 3-phase six pulse controlled rectifier is shown in the Fig. 4.The circuit consist of six thyristors, i.e.,

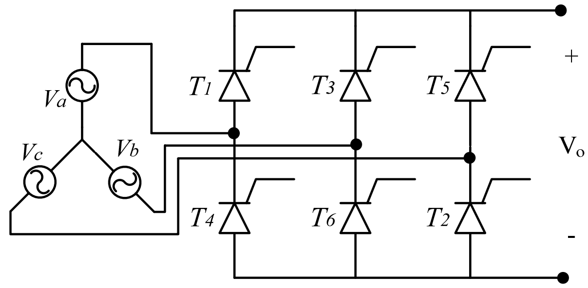

Fig. 4. Six pulse controlled rectifier.

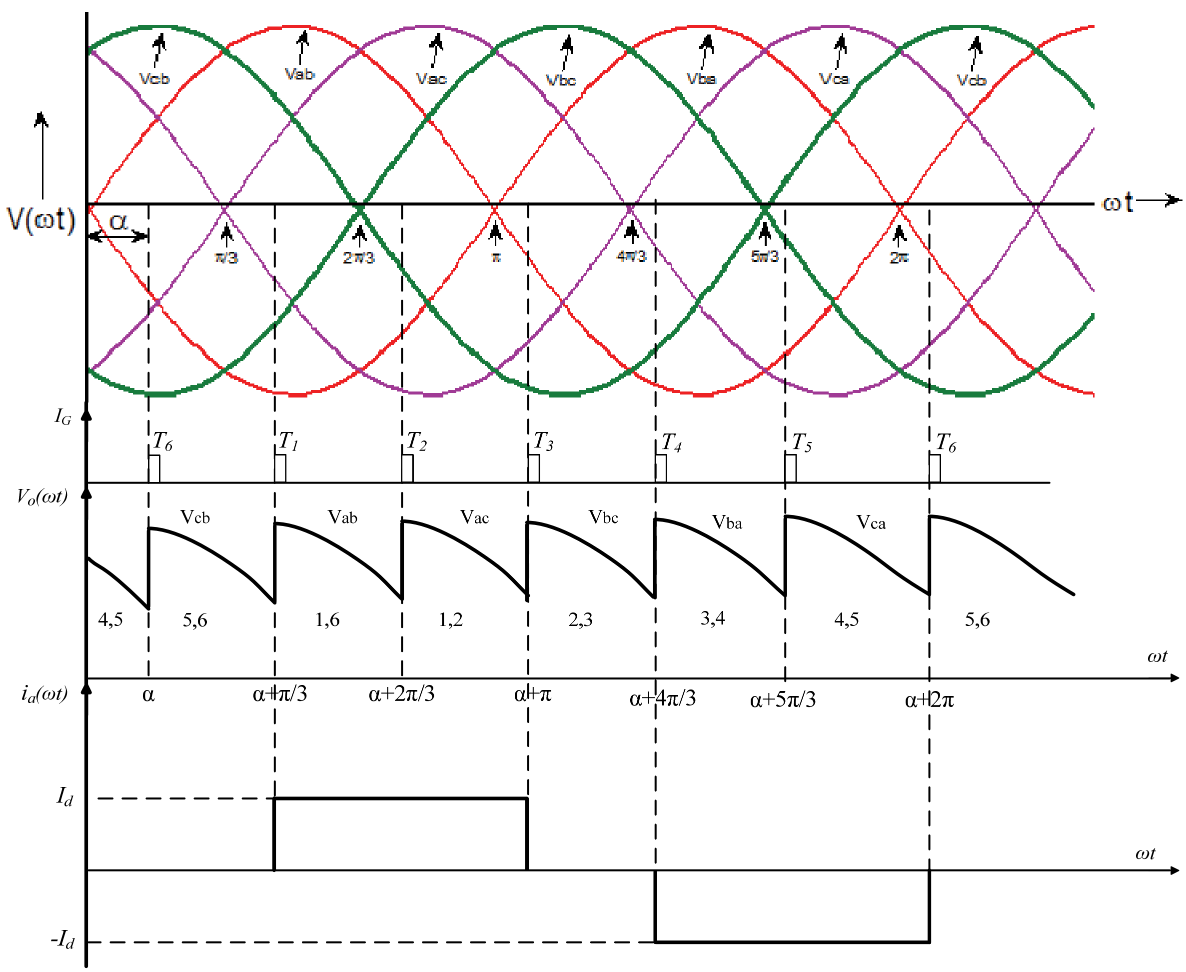

Fig. 5. The $\mathbf{3\emptyset}$ line to line voltage waveform $\boldsymbol{V(\omega t)}$, converter output voltage waveform $\boldsymbol{V_o(\omega t)}$, phase "$\boldsymbol{a}$" current waveform $\boldsymbol{i_a(\omega t)}$.

T_1,T_2,T_3,T_4,$T_5$and T_6 for rectification purpose. Three phase system consist of three sinusoidal input voltages ($V_a, V_b \& V_c$) with same frequency and magnitudes i.e. ($f_a = f_b = f_c = f$) & ($V_{ma} = V_{mb} = V_{mc} = V_m$) but shifted 120° from each other. The operating principle of the circuit is that, the pair of SCR connected between the lines havinghighest amount of line-to-line voltage will conduct provided that the gate signal is applied to SCRs at that instant. i.e. SCR needs gate signal in addition to $V_{AK} > 0$. The input and output voltage wavefroms and input current waveform for phase "a" are shown in Fig. 5.

Between $0 \leq \omega t \leq \pi/3$ the highest line-to-line voltage is V_{cb}, with $T_4 \& T_5$ intially conducting. By firing T_6 at delay angle of α,results V_{cb}at load. It should be noted is that V_{cb}apperas across load till $\pi/3 + \alpha$. Although beyond the point $\pi/3$ the line-to-line voltage V_{ab} has the highest value but until T_1 is not fired, it will not appear across the load and the maximum voltage across load is still V_{cb}.As T_1 is fired, T_5 turns off and now current passes through $T_1 \& T_6$ i.e. V_{ab} appears across the load. Another impotant conclusion is that, only one SCR needed to be fired at a time except for the first cycle. Because first SCR of the pair already conducts due to phase sequence.

From Fig. 5 it can be seen that frequency of output pulsating voltage is $6f$ and in this way the harmonic components are shifted to higher frequencyAs compare to three pulse converter, it reduces the need of filtering at the output[7-8].The output DC voltage of a controlled rectifier is a function of the firing angle α and it can be calculated from Fig. 5. The relation is:

$$V_{dc} = \frac{1}{\pi/3} \int_{\alpha+\pi/3}^{\alpha+2\pi/3} \sqrt{3} V_m \sin(\omega t)\, d(\omega t) \tag{12}$$

$$V_{dc} = \frac{3\sqrt{3}V_m}{\pi} \int_{\alpha+\pi/3}^{\alpha+2\pi/3} \sin(\omega t)\, d(\omega t)$$

$$V_{dc} = \frac{3\sqrt{3}V_m}{\pi} -\cos(\omega t) \Big|_{\alpha+\pi/3}^{\alpha+2\pi/3}$$

$$V_{dc} = \frac{-3\sqrt{3}V_m}{\pi} \left[\cos\left(\alpha + 2\pi/3\right) - \cos\left(\alpha + \pi/3\right)\right]$$

$$V_{dc} = \frac{3\sqrt{3}V_m}{\pi} \cos(\alpha) \tag{13}$$

$$V_{dc} = V_{dm} \cos(\alpha) \tag{14}$$

$$V_n = \frac{V_{dc}}{V_{dm}} \cos(\alpha) \tag{15}$$

Where V_{dm} is the average output voltage at$\alpha = 0$and V_n is normanilzed average voltage.The plot in Fig. 6 shows the normalized output DC voltage verses the firing angle α.

It can be seen from Fig. 5 that for $\alpha = \pi/3$ the rectified output voltage reaches zero crossing. If α is increased beyond $\pi/3$ i.e. $\alpha > \pi/3$, the load voltage becomses discontinous for resistive load where as for inductive load the negative voltage appears across load. Fig. 6 shows that by varying α between $0\ to\ \pi/2$ output varies between 1 & 0 i.e. rectification region and by varying α between $\pi/2\ to\ \pi$ output varies between $0 \& -1$ i.e. inversion region. Rectification region is represented by 1^{st}Quardant and inversion region by 4^{th}Quardant resulting in 2 Quardant operation.

There is also an issue in using six pulse converter i.e. the effect of converter on input power factor. The power factor for highly inductive load (motor) can be calculated as:

$$P.F = \frac{P_{av}}{3\, V_{irms}\, I_{irms}}$$

$$P.F = \frac{6\, V_m\, I_o}{3\, I_o \pi \cdot V_m \sqrt{2}} \cos(\alpha)$$

$$P.F = 0.9\ \cos(\alpha) \tag{16}$$

From $Eq.(17)$ it can be seen that by varying α between $0\ to \pi$, the power factor also vary between $0.9 \& 0$for rectification region and $0 \& -0.9$ for inversion region.

4. RESULTS AND DISCUSSION

The circuit consist of sixpulse line-commutated converter (LCC), DC motor and the control system; consisting of PI controller is simulated using Simulink. The simulated system is shown in the Fig. 7. The Synchronized 6-Pulse Generator

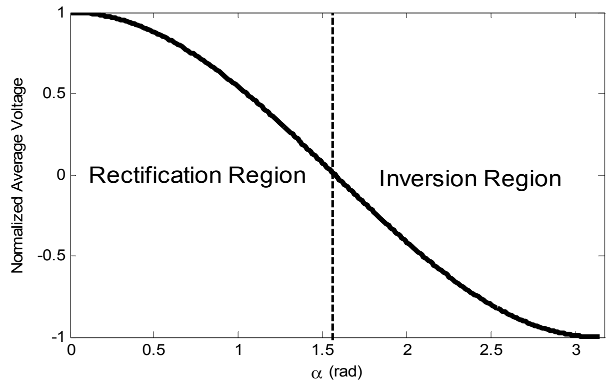

Fig. 6. Normalized average voltage as function of $\boldsymbol{\alpha}$.

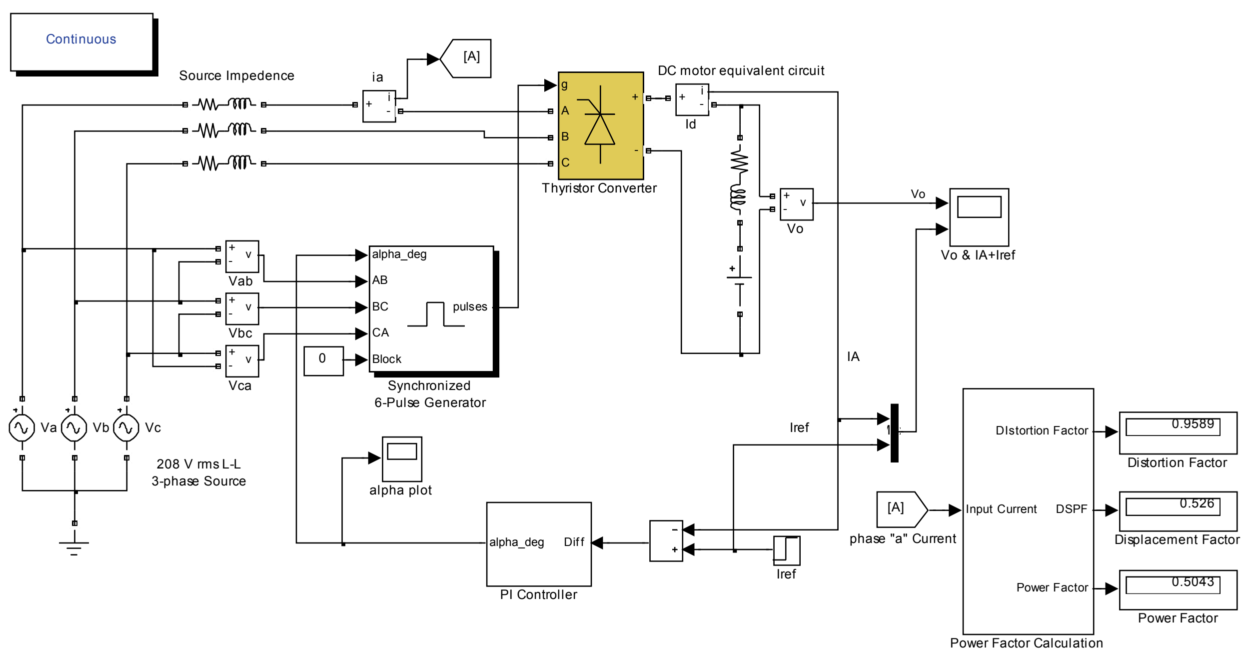

Fig. 7. Model for speed control of DC motor.

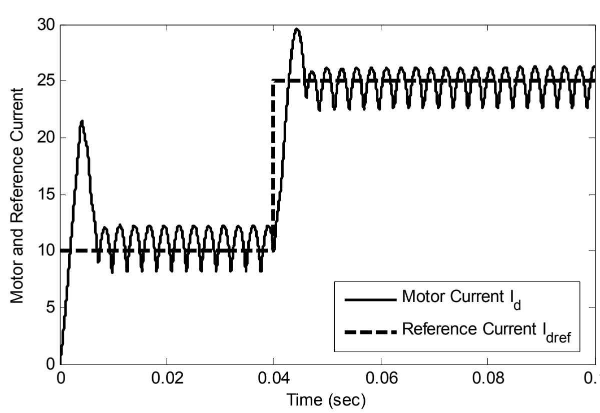

Fig. 8. Variation of Motor Current Corresponding to Reference Current.

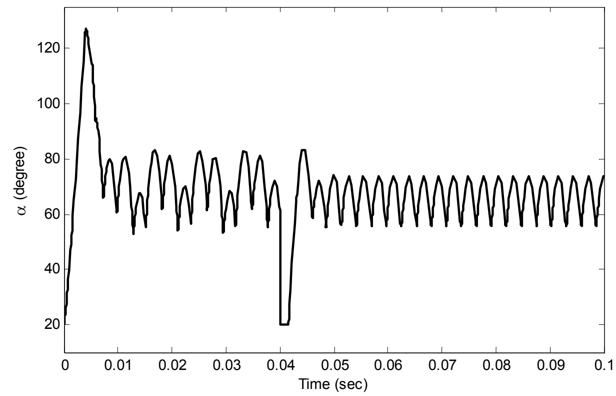

Fig. 9. Variation in $\boldsymbol{\alpha}$ to achieve desired Reference Current.

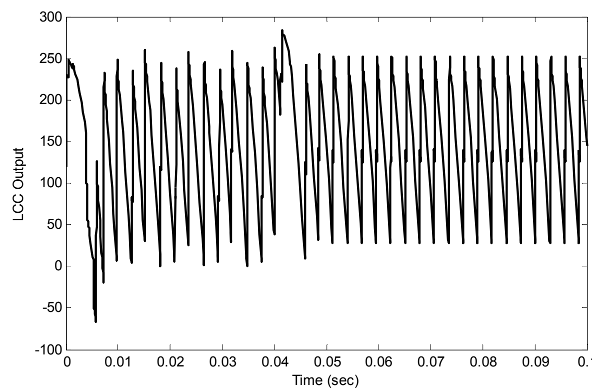

Fig. 10. Variation inconverter output to achieve desired Reference Current**.**

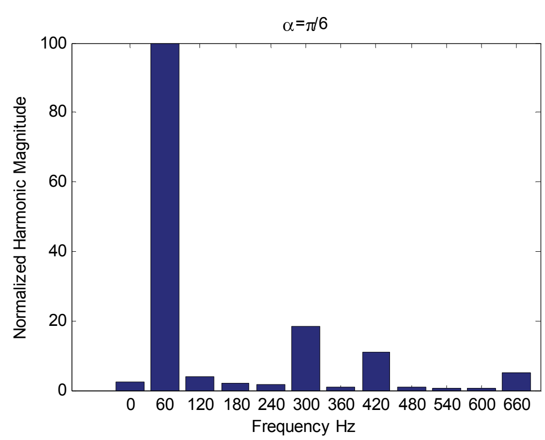

Fig. 11. Frequency Specturm for $\boldsymbol{\alpha} = {}^{\boldsymbol{\pi}}/_{\boldsymbol{6}}$.

block is used here to fire the six thyristors (Thyristor Bridge) of a six-pulse converter. The output of the block is a vector of six pulses individually synchronized on the six thyristor voltages. The DC motor is modelled as series connected RL and a DC source, where the DC source representing the back emf.

In this paper the speed is controlled by conrolling the current through the motor. For a desired value of speed, the reference current is provided and using PI controlled the reference current is achieved in a little time. Thetime domain plot for variation of motor armature current I_A for corresponding reference current I_{ref} is shown in Fig. 8. The pattern of firing angle α and LCC output voltage for desired I_{ref} is shown in Fig. 9 and Fig. 10, respectively. Fig. 8 shows that intially, the current through the motor was zero but when the value of reference current is set as "10", the motor current started increasing from zero level and reached the same level as reference current within microseconds. As the reference current is achieved, current through the motor remained constant for the rest of time. Again, when after sometime the reference current is varied from $10\ to\ 25$, the motor achieved and maintained the same current, which implies that the current is regulated. The current regulation directly implies that the speed is also regulated.

One of the important issue needed to be analyzed, is the effect of converter on input power factor because according to $Eq. (17)$ the power factor is the function of firing angle α. The power factor block in Fig. 7 is used to compute the power factor . Power factor is product of displacement factor(due to phase difference between voltage and fundamental component of input current) and distortion factor(due to distortion in input current). For different values of α, the value of distortion and displacement factor is listed in Table.1. For $\alpha = \pi/6$ specturm of input current is shown in Fig. 11.

Table 1. Six pulse converter power factor, distortion factor and displacement factor for different α's.

α	Displacement Factor	Distortion Factor	Power Factor
$\pi/6$	0.758	0.975	0.739
$\pi/4$	0.639	0.967	0.618
$\pi/3$	0.487	0.955	0.465

5. CONCLUSIONS

The line-commutated converter with conventional PI control was used for speed regulation of DC motor. The system was tested for the step change in reference current and it provided satisfactory results. When the load torque increases due to extra load i.e.$\tau_{load} > \tau_{ind}$, the motor speed ultimately decreases, this will increase the error "e". To minimize the error the PI controller changes the firing angle of SCR to increase the voltage V_A applied to the armature of DC motor, which increases the armature current I_A, thereby increasing the speed of DC motor. The problem arises at low speed values (i.e. large values ofα) as displacement factor reduces by keeping α large.

6. REFRENCES

1. Kushwah, R. & S. Wadhwani. Speed control of separately excited DC motor using fuzzy logic controller. *International Journal of Engineering Trends and Technology* 4(6): 2518-2523 (2013).
2. Afrasiabi, N. & M.H. Yazdi. DC motor control using chopper. *Global Journal of Science, Engineering and Technology* 8: 67-73 (2013).
3. Shastri, S. & P. Pandey. A comparative analysis of firing angle based speed control scheme of DC motor. *International Journal of Engineering Research and Applications* 3(4): 232-235 (2013).
4. Jaiswal, M. & M. Phadnis. Speed control of DC motor using genetic algorithm based PID controller. *International Journal of Advanced Research in Computer Science and Software Engineering* 3(7): 247-253 (2013).
5. Pal, A.K. & R.K. Mudi. Speed control of DC motor using relay feedback tuned PI, fuzzy PI and self-tuned fuzzy pi controller. *Control Theory and Informatics* 2(1): 24-32 (2012).
6. Rashid, M.H. Multilevel inverters. In: *Alice Dworkin, and Dona King. Power Electronics Circuits, Devices and Applications, 3rd ed*. Pearson Education, p. 409-419 (2003).
7. Pyakuryal, S. & M.A. Matin, Feedback controller for a 3-phase 6-pulse rectifier. *The International Journal of Engineering and Science* 2(8): 23-27 (2013).
8. Pyakuryal, S. & M. Matin. Harmonic analysis for a 6-pulse rectifier. *International Organization of Scientific Research Journal of Engineering* 3 (3): 57-60 (2013).
9. Nedeljkovic, M. & Z. Stojiljkovic. Fast current control for thyristor rectifiers. *IEE Proceedings-Electric Power Applications* 15(6): 636- 638 (2003).
10. Gupta, R., R. Lamba & S. Padhee. Thyristor based speed control techniques of DC motor: A Comparative Analysis. *International Journal of Scientific and Research Publications* 2(6): 1-6 (2012).