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Simulation Studies of a Current Source Rectifier - DC Motor Using High Pass Filter With PID Controller

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***Abstract*— This paper describe the three phase sinusoidal pulse width modulation (SPWM) current source rectifier (CSR) fed variable-torque DC motor drive (separately exited) using second order high pass filter in AC supply sides with PID speed controller. The advantages of the developed system are low harmonic distortion in AC supply currents, power factor correction with variable load and constant speed using high pass filter in AC supply sides. The PID speed controller is used to improve the dynamic response of the system as well as to reduce or eliminate the steady-state error. The three-phase SPWM current source rectifier was simulated under the MATLAB/SIMULINK environment.**

Key-Words: **SPWM Current source rectifier, DC motor Drive, THD Reduction, second order high pass filter.**

I. INTRODUCTION

Phase-controlled rectifiers using thyristors are extensively used in DC drives since they do not require any special means of commutation and have large power handling capacity. However, these drives have inherent shortcomings such as slower transient response, torque-pulsation, poor power-factor and increased harmonic especially in the lower speed region of the DC-motor [1]. The current source (buck-type) pulse width modulation (PWM) rectifier is one of the most common topologies studied in detail over the past ten years Buck-type PWM rectifier offers a good solution for direct conversion of AC to DC at high power densities to meet the strict PF penalty limits imposed by electricity authorities and input line current harmonic distortion limits dictated by various harmonic standards such as IEEE Std. 519, IEC 555, etc. One interesting application of this converter may be the upgrading work that can be conducted on DC motor drives still working in industry to comply with present power quality regulations. This converter also offers superior output characteristics, especially for old DC motor designs when combined with a simple and, hence, cheap high-frequency output filter. The PWM current source rectifier is also requires a three-phase filter (LC) at its input terminals [2].

The rectifier DC output current can be controlled by modulation index (M). Alternatively, it can also be adjusted by delay angle (α) in the same manner as that for phase-controlled SCR rectifiers. The delay angle control produces a lagging power factor, which compensates the leading power factor caused by the input filter capacitor. By controlling both modulation index and delay angle simultaneously, the rectifier can potentially achieve unity power factor operation [3].

This paper studies passive filter (second order high pass filter) for harmonics reduction in SPWM (CSR) rectifier fed DC drive variable torque with constant shaft speed. The paper as well as includes the ideal mathematic equations and models for these filter, and operating characteristics of buck type SPWM rectifier in variable load torque DC motor applications using PID speed controller. The PID controller is used to improve the dynamic response of the system as well as to reduce or eliminate the steady-state error.

II. SYSTEM DESCRIPTION

The power circuit diagram of the SPWM current source rectifier with freewheeling diode which supplies power to the armature circuit of a separately excited DC motor is as shown in Figure 1. The block diagram represent the PID control system, and speed feedback loop is also shown in the same Figure. Each power semiconductor switch consists of an IGBT connected in series with an ultra-fast recovery diode, resulting in reverse voltage blocking capability and unidirectional current flow. A second order high pass (RLC) filters is connected to the AC input side of the rectifier to filter out the switching frequency harmonics components in the line currents and to improve input power factor.

In the output load side (DC motor) the switching frequency harmonics are filtered out with a damped output filter (series inductance (Ld.c) with shunt capacitance (Cl)).

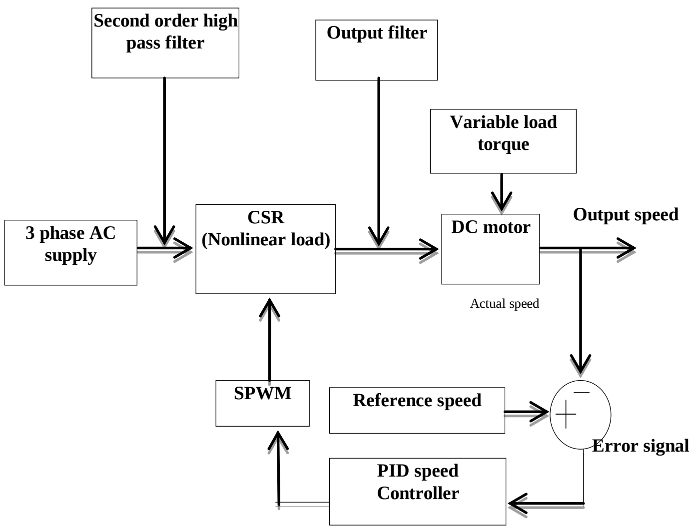

Fig (1). System closed loop block diagram

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A. Inputs Filters Description and Design

Harmonic distortions can have significant adverse effects on power system components and customer devices. Various harmonic-mitigation techniques have been proposed and applied in recent years. Among those techniques, passive harmonic filters are still considered to be the most effective and viable solution to reduce harmonic distortions at the medium- and high-voltage systems (12 kV). Many industrial facilities install the filters to ensure that they comply with the harmonic limits specified by the supply utilities. The passive filters have several topologies that give different frequency response characteristics. The common filters are the single-tuned filter and the high-pass filters. The single-tuned filter is aimed at filtering a single harmonic while high-pass filters are intended to reduce harmonics above certain frequencies.

The high-pass filters have several variations, such as the first order high pass, second order high pass, and third order high pass. The current industry practice is to use the combination of several different topologies of filters to achieve desired harmonic filtering performance [4].

In this work one second orders high pass (RLC) filters is connected to the AC input sides of the rectifier to filter out the switching frequency harmonics components in the line currents and to improves input power factor. The second-order high pass filter is probably the most popular filter utilized in industrial systems. The second-order filter [see figure 2.] consists of a capacitor in series with a parallel inductor and resistor. They are sized such that the filter behaves like the single-tuned filter below the tuning frequency and similar to the first-order high-pass filter at high frequencies. This is because the inductive reactance is small in low frequencies, bypassing the resistive branch, and large in high frequencies, diverting the current to the resistor branch. At the tuning frequency, a notch can be observed. In order to achieve this performance, the capacitor is tuned to the desired frequency with the inductor [4,5]. High pass filter provides low impedance for a wide spectrum of harmonics without the need for subdivision of parallel branches with increased switching and maintenance problems. The sharpness of tuning in the second order high-pass filter is the reciprocal of single tuned filters [6].

$$Q = \frac{R}{\left(\frac{L}{C}\right)} = \frac{R}{XL} = \frac{R}{Xc} ----------(1)$$

Where (Q) gives the quality factor of tuning reactor, (f) is the fundamental frequency (n) the harmonics order. The behavior of damped filter has been described with the help of two parameters.

$$fn = \frac{1}{2\pi CR} ----------(2)$$

$$R = \frac{1}{2\pi fnC}$$

$$fn = f * n ---------(3)$$

$$m = \frac{L}{R^2C} --------(4)$$

$$L = R^2 * C * m$$

Typical values of m are in the range of 0.5 and 2 for a given capacitance these parameters are decided to achieve an approximately high admittance over the required frequency range. Impedance of filter as a function of harmonic frequency is given [6].

$$Z = \frac{R\,n^2XL^2}{R^2 + n^2L^2w^2} + \frac{jR^2wLn}{R^2 + n^2L^2w^2} - \frac{1}{wCn} ------(5)$$

For non-sinusoidal input voltage and current with nonlinear load the Apparent Power (S) can be calculate by using this equation [7,8,9].

$$S^2 = P^2 + Q^2 + D^2 ------(6)$$

(When P is real power, Q reactive power and D is distortion factor power. for filter design the non-active power G can be calculate as shown below the total value of filter capacitance required to compensate the non-active power can be calculated using equation below [7,10].

$$G^2 = (Q^2 + D^2) = S^2 - P^2 ------(7)$$

$$G = \sqrt{S^2 - P^2}$$

$$C = \frac{G}{(2\pi * f(Vrms^2))} --------(8)$$

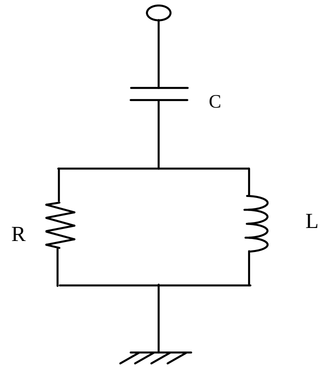

Fig (2). Second order high pass filter circuit

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B. SPWM Method

PWM techniques have been commonly used in voltage and current-source inverters (VSIs and CSIs, respectively) of variable-frequency AC motor drives. The control of unity-PF buck-type rectifiers is also based on these techniques for low distortion in supply currents [2].

In this work, the well-known, sinusoidal PWM technique is chosen to construct the switching signals. SPWM technique is a very popular method of controlling the output voltage; (SPWM) has found a wide range of applications since the early development of PWM-VSI technology. Although the control range of modulation index is relatively narrow. SPWM is a simple technique and has a good transient response [2, 11] .

In this method, a high-frequency triangle carrier wave (fc = 1050 Hz) is compared with a three-phase sinusoidal waveform, as shown in figure 3. The power devices in each phase are switched on at the intersection of sine and triangle waves. The amplitude of the output voltage are varied by varying The ratio of the amplitude of the sine waves to the amplitude of the carrier wave which is called the modulation index (M) and by phase angle (α) which is define as the phase shift between three phase AC supply and three phase sinusoidal waves intersection with triangle wave.

The harmonic components in a PWM wave are easily filtered because they are shifted to a higher-frequency region. It is desirable to have a high ratio of carrier frequency to fundamental frequency to reduce the harmonics of lower-frequency components [11].

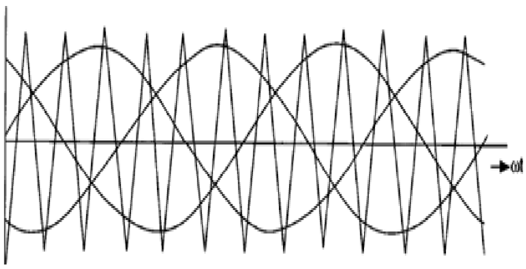

Fig. (3) SPWM method waveforms

C. The PID Controller

The PID controller is used to improve the dynamic response (constant speed) of the system as well as to reduce or eliminate the steady-state error. The derivative controller adds a finite zero to the open-loop plant transfer function and improves the transient response. The integral controller adds a pole at the origin, thus increasing system type by one and reducing the steady-state error due to a step function to zero. The transfer function of PID controller is:

$$Gc = Kp + \frac{Ki}{s} + Kd\, s \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (9)$$

Where Kp, Ki and Kd are the proportional, integral and derivative gains respectively of PID controller. There are many ways to obtain PID controller gains such as trial and error, Ziegler-Necholes method and soft tuning method [12,13].The block diagram of PID controller in MATLAB shown in Figure (4).

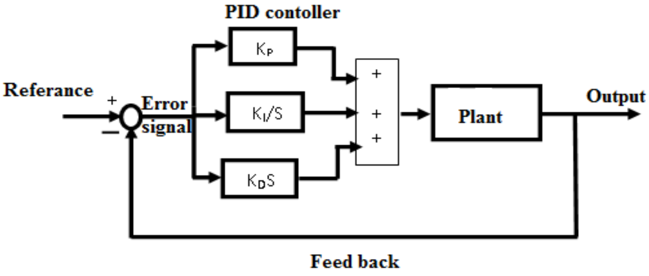

Fig (4). The block diagram of PID controller with plant

III. SIMULATION OF SYSTEM AND SIMULATION RESULTS

The three phase (SPWM) current source rectifier fed variable-torque DC motor separately exited (one Quadrant) using second order high pass filters in AC supply sides with PID speed controller is simulated using MATLAB/ SIMULINK-platform in order to obtain the associated current and voltage waveforms and reduce the distortions in the input AC current waveforms as well as Power Factor Improvement due to presence of nonlinear load (CSR) in the system .The actual system can be modeled with a high degree of accuracy in this package. Figure 5. Shows the system modeled in MATLAB/SIMULINK, and The modeled system parameters values are shown in Table (1).

Simulation results at M=0.9 and α=0 had shown non active power (G) was equal to (227VAR) when the motor load torque at full load (TL=11.5 N.m) and that the dominantly effective harmonics are the (5^{th}, 17^{th}, 19^{th}) harmonics in A.C supply. To filter out these effective harmonics, one second order high pass filter had been designed at 5^{th} harmonic frequency based on equations (2,4,8) mentioned above with small Series Supply inductance (Lss), where the values of the required filter resistance (R), inductance (L) and capacitance (C) had been calculated to composed this second order high pass filter. Table (2) shows the second order high pass filter elements values required to filter out 5^{th} harmonic and all high order harmonics. in order to control the DC motor speed (reference speed) when the load torque changes (from TL=10 N.m to TL=15 N.m) increases or decreases DC output voltage had been varied by varying the modulation index (M) using PID speed controller and kept phase angle constant at (α=20°). A.C current power factor (PF) and total harmonics distortion (THD) and the CSR system efficiency had been calculated based on Matlab-Simulink as well as the settling time (tss), state steady error (ess).

In the present work the gains of PID controller are obtain using two ways ,first way trial and error method and second way Ziegler-Necholes method.

Table (3). Shwon the results of comparision between open loop and close loop with PID speed controller when referance speed (W=73 rad/sec).

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Table (1). System Parameters

Input A.C supply per phase	
Maximum Input voltage (Vm)	120volt
supply Frequency	50Hz
Supply resistance (Rs)	50mΩ
Supply inductance (Ls)	5mH
Series Supply inductance (Lss)	10mH
DC motor (Load side)	
Rated torque	11.5N.m
Rated speed	890 r.p.m
Armature resistance	2.2Ω
Armature inductance	50mH
Armature current	7.2A
Armature voltage	180volt
field resistance	189 Ω
field inductance	21.68H
field voltage	190volt
DC inductance (Ld.c)	50mH
Parallel capacitance (Cl)	10μF

Table (2). Second order high pass filter elements values

Harmonic order	C (μF)	L (mH)	R (Ω)
5^{th}	100	6	6.36

Table (3). The results of comparision between open loop and close loop system using PID speed controller

	THD%	e_{ss} before TL change	e_{ss} after TL change	Efficiency%	PF	$t_{ss(sec)}$
Open loop with load torque change 11.5-15 N.m	3.07	0.7	9.58	80	0.91 leading	0.2
Close loop with load torque change 11.5-15 N.m	3.10	0.1	0.15	82	0.915 leading	0.12
Open loop with load torque change 11.5-10 N.m	3.97	0.7	-2.7	84	0.81 leading	0.2
Close loop with load torque change 11.5-10 N.m	3.04	0.1	-0.2	84.9	0.817 leading	0.12

From the table above, it is show that the performance of the system for the settling time, state steady error, power factor (leading) and efficiency are improved. Efficiency is low due to the resistance of input filter. The THD is keep near value in open and close loop system. PID controller gains are obtained once using trial and error method (Kp=0.15, Ki=0.3 and Kd=0.002) and second way using Ziegler-Necholes method (Kp=0.4, Ki=0.16 and Kd=0.00015). The two methods give same results.

Figure (6) shows the Output open loop speed response with variable load torque (T_L= 11.5- 15N.m) and (T_L= 11.5-10N.m). Figure (7) shows the Output closed loop speed response with variable load torque (T_L= 11.5- 15N.m) and (T_L= 11.5- 10N.m) using PID speed controller to keep speed constant at reference value (W=73 rad/sec). Figure (8) shows the Output open loop torque response with variable load torque (T_L= 11.5-15 and 11.5-10 N.m) and Figure (9) shows the Output closed loop torque response with variable load torque (T_L= 11.5-15 and 11.5-10 N.m). Figure (10) gives Input voltage and current open loop and closed loop responses with variable load torque (T_L= 11.5-10 N.m). Figure (11) gives Input voltage and current open loop and closed loop responses with variable load torque (T_L= 11.5-15 N.m). The input supply current is decreased with controller when the load is changes.

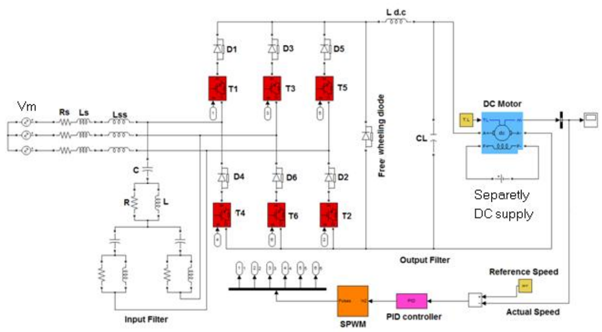

Fig (5). MATLAB SIMULINK closed loop power circuit diagram

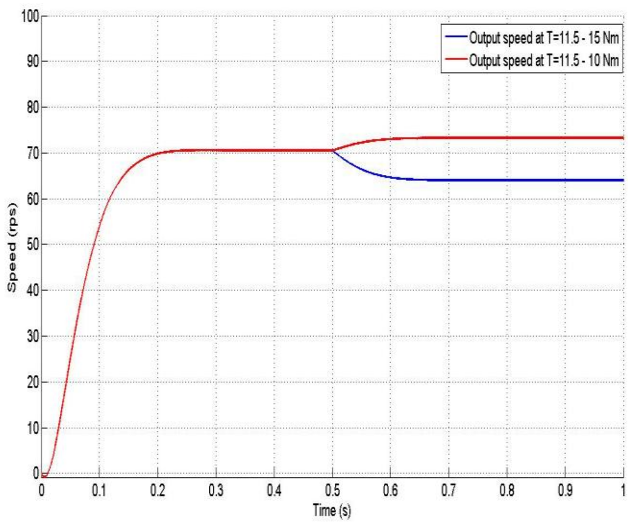

Fig (6). Output open loop speed response with variable load torque (T_L= 11.5- 15 and 11.5-10 N.m).

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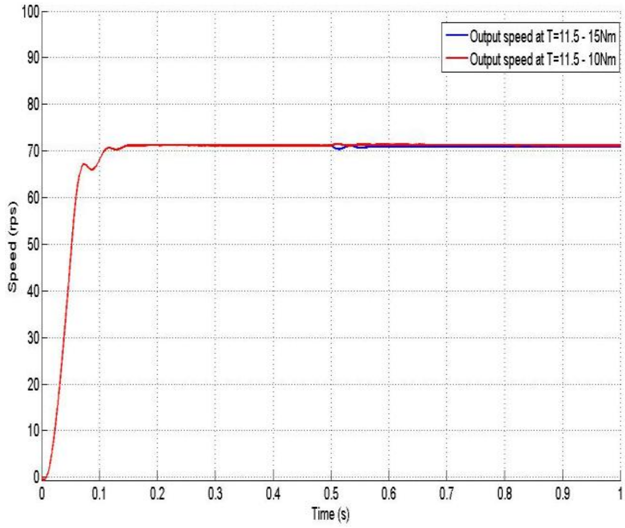


Fig (7). Output close loop speed response with variable load torque (T_L= 11.5- 15 and 11.5-10 N.m)

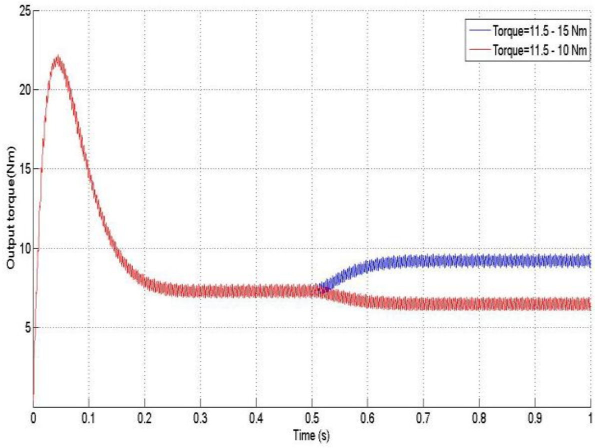


Fig (8). Output open loop torque response with variable load torque (T_L= 11.5- 15 and 11.5-10 N.m)

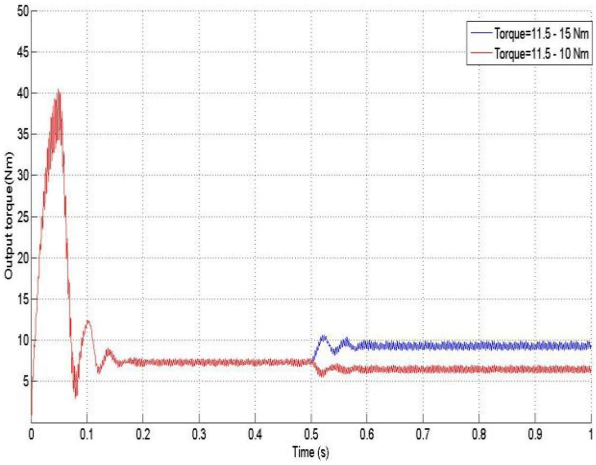
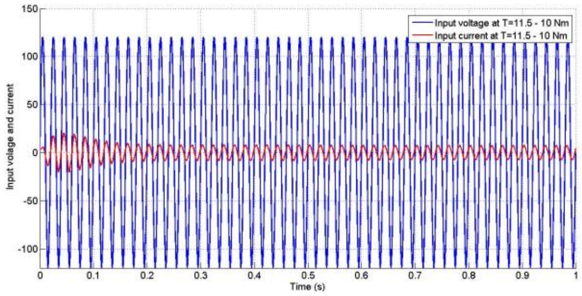
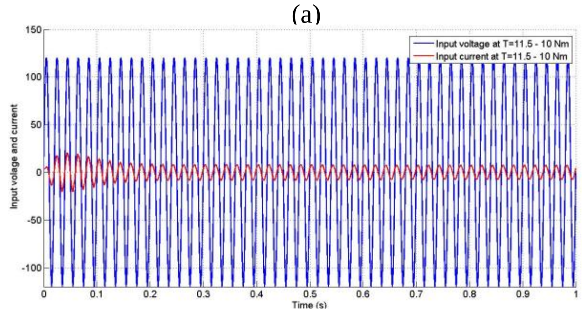


Fig (9). Output close loop torque response with variable load torque (T_L= 11.5- 15 and 11.5-10 N.m)



(a)

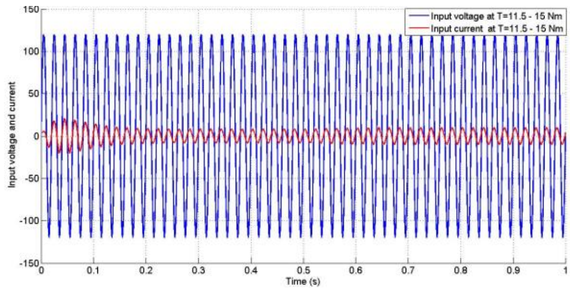


(b)

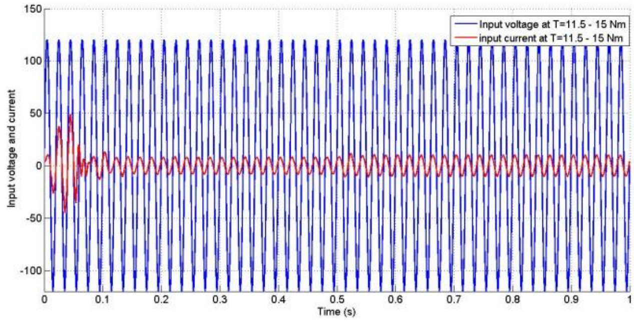
Fig (10):

a) Input voltage and current open response with variable load torque (T_L= 11.5-10 N.m).

b) Input voltage and current closed loop response with variable load torque (T_L= 11.5-10 N.m).



(a)



(b)

Fig (11):

a)Input voltage and current open response with variable load torque (T_L= 11.5-15 N.m).

b) Input voltage and current closed loop response with variable load torque (T_L= 11.5-15 N.m).

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IV. CONCLUSION

In this study, SPWM current source rectifier fed DC motor with variable load torque using passive filter (second order high pass filter) in A.C supply side with PID speed controller has been achieved by using Matlab Simulink. This paper has presented a harmonic mitigation study in the DC motor system. An investigation has been carried out to examine the effectiveness using the High pass filters in eliminating harmonics.

Simulation results at M=0.9 and α=0 had shown non active power (G) was equal to (227VAR) when the motor load torque at full load (TL=11.5 N.m) and that the dominantly effective harmonics are the (5^{th}, 17^{th}, 19^{th}) harmonics in A.C supply. To filter out these effective harmonics, one second order high pass filter had been designed at 5^{th} harmonic to filter out 5^{th} harmonic and all high order harmonics. in order to control the DC motor speed when the load torque changes (from TL=10 N.m to TL=15 N.m) increases or decreases about (1.5) from the rated value DC output voltage had been varied by varying the modulation index (M) using PID speed controller and kept phase angle constant at (α=20°).

The performance of the system for the settling time, state steady error, THD, power factor (leading) and efficiency are improved using PID speed controller. PID controller gains are obtained once using trial and error method and second way using Ziegler-Necholes method.

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