COMPARISON OF SPEED CONTROL FOR DIFFERENT DC MOTORS USING DIFFERENT POWER AC/DC CONVERTERS

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ABSTRACT
The different uses of DC motors (for both domestic and industrial) make changing the speed from one level to another very important to suit the required speed needed for any particular purpose. The control of this machine can be done using AC/DC power converters. However, the edge which these power converters have over themselves when used to control the speed of these machines are not known. This paper hereby compares using MATLAB/SIMULINK the control of separately excited DC motors, series DC motors and shunt DC motors by AC/DC power converters. The types of AC/DC power converters considered are the half wave, single phase converter drive; single phase, semi-converter drive and single phase, full wave, semi-converter drive. Results show that all motors have their maximum speed with a thyristor firing angle of 0 rad and decrease as the firing angle is increased. For the separately excited DC motors, average speeds change of -94 rpm/rad and -160 rpm/rad were realized for the half wave/semi-converter drives and full wave drives respectively. Furthermore, it can be can be deduced that using the full wave converter drive performs speed changing operations at a faster rate than their half wave or semi converter drive counterparts for the various types of DC motors.

Keywords: DC Motor, Speed Control, AC/DC Power Converters

1. INTRODUCTION
DC motors are of high demand in the industry, for example. They are used to drive machines and loads in the industry. However, the speed at which these machines and loads are driven varies depending on the use of the machine. Hence, there is a need to vary the speed of the DC motor to drive the machines according to the required speed. A lot of methods of speed control of these DC motors have been established by different researchers in the past. In all these researches, the speed is either controlled by regulating the supply voltage to the armature, altering the armature resistance or altering the flux per pole of the motor (Krisnan, 2001; Theraja and Theraja, 2005). The method of varying the armature resistance was used to control the speed of a DC shunt motor by simultaneously varying the field and armature effective resistances by connecting rheostats across them (Dwivedi, 2013); a high-speed variation was achieved using this method. However, the method may be expensive as a result of the two rheostats required for the task. By regulating the flux of the armature, (Sharma et al, 2014) used a tapped field control method in controlling the speed of a DC motor. Here, the speed is increased by reducing the flux accomplished by reducing the number of series field windings.
In recent times, digital/electronic devices are used in the speed control of these motors; the analog circuit used in speed control was replaced by a digital system using pulse width modulation technique and was implemented by replacing analog circuit with an Atmel AT89S52 microcontroller circuit (Fatiha, 2005; Raza1et al, 2016 and Adoghe et al, 2017). The approach was characterized by increased precision and greater control efficiency. Also, power electronics components like thyristors have also been used to control the speed of such DC motors. This control is done by regulating the armature voltage by controlling the thyristor firing angle (Krishnan and Ramaswami, 1974; Ringe1et al, 2017 and Saini et al, 2020). This method is very effective and fast in regulating the speed of the DC motors because of the thyristor's high switching rate and they also have a size advantage over the old methods of varying armature voltage. AC/DC and DC/DC Buck converters have also been used in the control of these motors (Lachkar et al, 2006; Zunjani et al, 2015; Rajesh and Krishna, 2016 and Suresh et al, 2023); these power devices have produced excellent speed control with very high efficiencies. However, they are expensive to install and maintain.

Researchers have also tried to compare different ways of speed control of these motors in the past to encourage users on which to use at different times. The speed control of series and shunt DC motors by varying the armature resistance and supply voltage were compared in terms of efficiency and cost of energy involved during the control process (Obi et al, 2018). The speed control of these motors using different thyristors aided circuits were also compared by (Gupta et al, 2012) in terms of efficiency, speed variation and cost.
However, this research compared the speed control of different DC motors, controlled by using different AC/DC power converters. Also, the DC motors considered are those heavy industrial DC motors which will be powered through AC power converters, the block diagram is as shown in Figure 1.

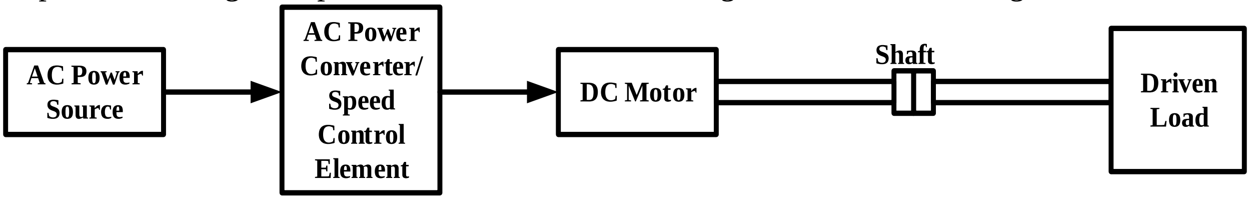


Figure 1: block diagram of DC motor to be controlled

2.0 MATERIALS AND METHODS

The DC motors that were considered include: separately excited, shunt and series DC motors. They shall be controlled by using Single Phase Half Wave Converter Drives, Single-Phase, Simi-Converter Drives and Single-Phase, Full Converter Drives. The nameplate of the motors used for this research is shown in Table 1.

Table 1: Parameters of motors used in the analysis

S/N	Description	Separately excited motor	Series motor	Shunt motor
1	Power rating of DC motor (kW)	5.00	5.00	5.00
2	Voltage rating of DC motor (V)	240.00	240.00	240.00
3	Power rating of comptroller controlling the DC machine (kW)	6.00	6.00	6.00
4	Armature resistance of DC motor (Ω)	0.50	0.50	0.50
5	Field resistance of DC motor (Ω)	25.00	0.75	250.00
6	Firing Angle used (rad)	$0 - \pi$	$0 - \pi$	$0 - \pi$
7	Machine constant (Nm/A^2)	0.025	105.5	K =5.0255 K_f =1.254

The various mathematical models for the various motors were thus developed.

2.1 Separately Excited DC Motors

A separately excited DC motor is a type of DC motor whose field circuit is supplied from a separate constant power supply. The circuit diagram of such motor is as shown in Figure 2.

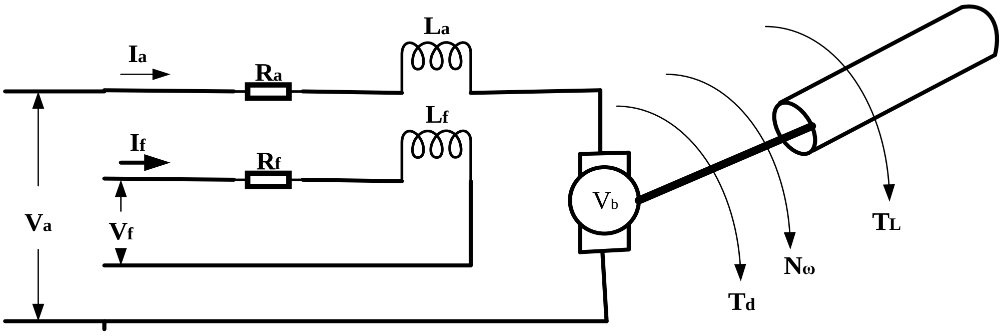


Figure 2: Separately excited DC motor and drive

Using the KVL on the close field circuit, the field voltage V_f is given as:

$$V_f = R_f I_f + L_f \frac{dI_f}{dt} \quad (1)$$

And the armature voltage V_a is given as:

$$V_a = R_a I_a + L_a \frac{dI_a}{dt} + V_b \quad (2)$$

Where R is resistance; L is inductance; V_b is the back e.m.f; I is current, Nω is the speed of rotation and the subscripts ‘a’ and ‘f’ represent armature and field respectively, and

$$V_b = K_a N_\omega \emptyset \quad (3)$$

where K_a is the motor speed constant

Under steady state condition,

$$V_a = R_a i_a + K_a N_\omega \emptyset \quad (4)$$

The speed of the motor is therefore given as:

$$N_\omega = \frac{V_a - i_a R_a}{K_a K_f i_f} \quad (5)$$

2.2 Series DC Motors

A series DC motor is a dc motor whose field windings is in series with the armature windings. The circuit diagram is as shown in Figure 3.

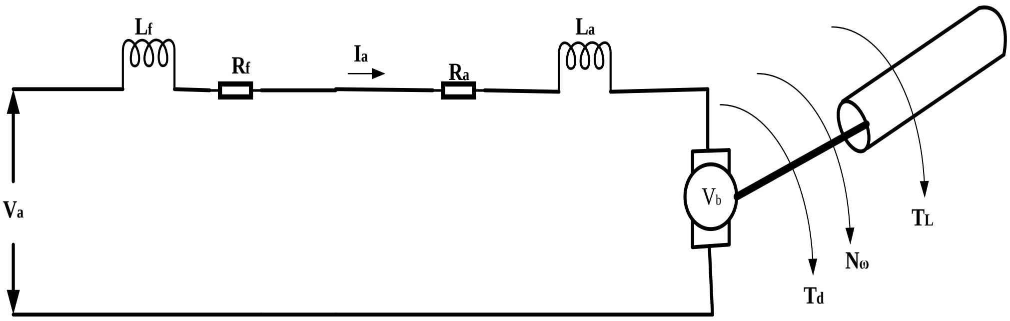


Figure 3: Series DC motor and drive

Using steady state conditions,

$$V_t = (R_a + R_f) i_a + V_b \quad (6)$$

But for series dc motors,

$$V_b = K_a K_f N_\omega i_a \quad (7)$$

hence,

$$N_\omega = \frac{V_t - i_a (R_a + R_f)}{K_a K_f i_f} \quad (8)$$

2.3 Shunt DC Motors

A shunt DC motor is a dc motor whose field windings is in parallel with the armature windings. The circuit diagram is as shown in Figure 4

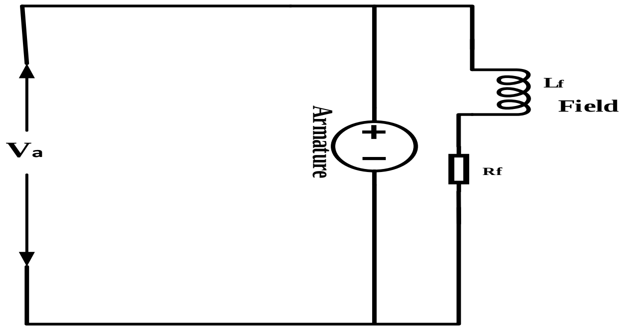


Figure 4: Shut DC motor and drive

Using steady state conditions, the shunt current I_{sh} is given as

$$I_{sh} = \frac{V}{R_{sh}} \tag{9}$$

$$V_t = R_a i_a + V_b \tag{10}$$

But for shunt dc motors, the speed of the motor is given as

$$N = K\frac{E_b}{\emptyset} = K\frac{V_t - i_a R_a}{\emptyset} \tag{11}$$

But the flux is proportional to the field current, hence

$$\emptyset = K_f i_f \tag{12}$$

Therefore, the speed of the shunt DC motor is

$$N_\omega = K\frac{V_t - i_a R_a}{K_f \frac{V_t}{R_{sh}}} \tag{13}$$

From equations 5, 8 and 13, it is seen that the speed of the motor can be controlled by

(i) The armature voltage.
(ii) The field voltage.

We will thus, control the speed of the machines by regulating the terminal voltage supply using single Phase Half Wave Converter Drives, Single Phase, Semi-Converter Drives and Single Phase Full wave Converter Drives.

2.4.1 Control of DC Motors by Using Single Phase Half Wave Converter Drives

This is an active method of drive controller. It uses a thyristor, (TH) and a free-wheeling diode, (DFW) in controlling the armature circuit and a converter circuit in controlling the field windings. The circuit diagram for controlling a separately excited DC motor is as shown in Figure 5.

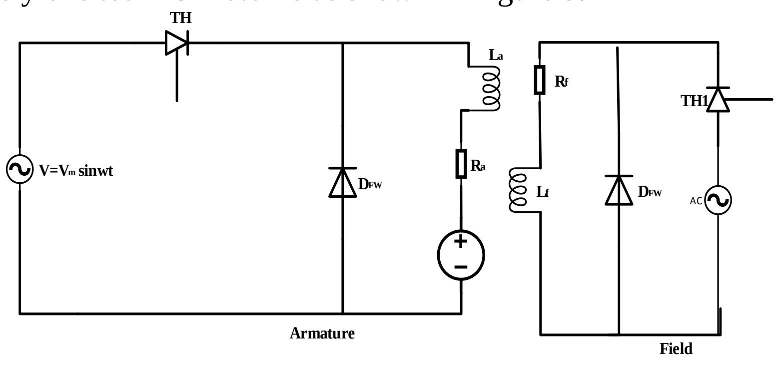


Figure 5: Control of Separately Excited DC Motors by Single Phase Half Wave Converter Drives

If the firing angle of the thyristor is α_a then the average voltage supplied to the dc motor is given by

$$V_{a_{dc}} = \frac{1}{\pi}\int_{\alpha_a}^{\pi} V_m \sin \omega t d(\omega t) = V_{adc} = \frac{V_s}{\pi}[1 + \cos \alpha_a] \tag{14}$$

The speed control of the motors is done by putting (14) into (5), (8) and (13) for the separately excited, series and shunt DC motors respectively.

For separately excited DC motors, the speed is given as

$$N_\omega = \frac{\left[\frac{1}{\pi}\int_{\alpha_a}^{\pi} V_m \sin \omega t d(\omega t)\right] - i_a R_a}{K_{af}\left[\frac{1}{\pi}\int_{\alpha_a}^{\pi} V_m \sin \omega t d(\omega t)\right]\frac{1}{R_f}} \quad (15)$$

For series DC motors, the speed is given as

$$N_\omega = \frac{\frac{V_s}{\pi}[1+\cos\alpha_a] - i_a(R_a+R_f)}{Ki_f} \quad (16)$$

Where $i_a = \frac{V_a}{(R_a+R_f)+K\omega}$ (17)

K = Machine constant, ω = rated angular speed.

For shunt DC motors, the speed is given as

$$N_\omega = K\frac{\left[\frac{V_s}{\pi}[1+\cos\alpha_a]\right] - i_a R_a}{K_f\frac{\left(\frac{V_s}{\pi}[1+\cos\alpha_a]\right)}{R_{sh}}} \quad (18)$$

2.4.2 Control of DC Motors by Using Single Phase, Simi-Converter Drives

This drive makes use of a thyristor and a diode for each conduction cycle as well as a free-wheeling diode. The circuit diagram for controlling a separately excited DC motor is as shown in Figure 6.

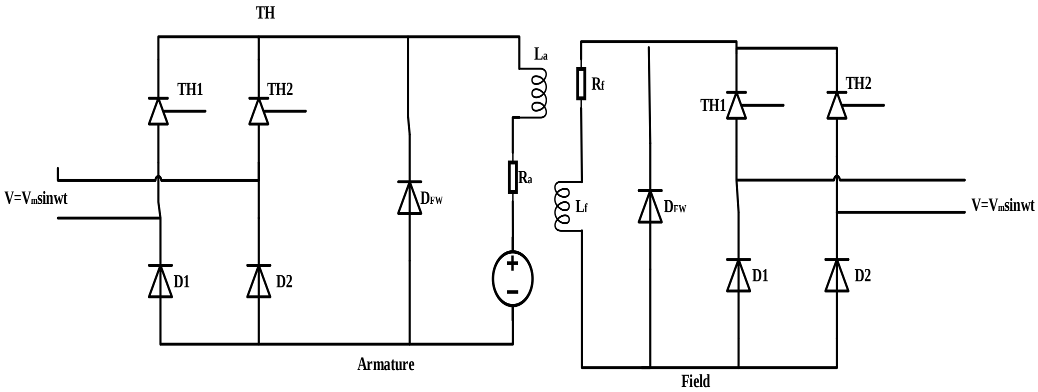


Figure 6: Control of Separately Excited DC Motors by Single Phase Semi – Converter Drives

If the firing angle of the thyristor is α_a then the average voltage supplied to the DC motor is given by:

$$V_{a\,dc} = \frac{1}{\pi}\int_{\alpha_a}^{\pi} V_m \sin \omega t d(\omega t) \quad (19)$$

$$V_{adc} = \frac{V_s}{\pi}[1+\cos\alpha_a] \qquad \text{for } 0 \geq \alpha_a \geq \pi \quad (20)$$

Again, the speed control of the motors is done by putting (20) into (5), (8) and (13) for the separately excited, series and shunt DC motors respectively.

For separately excited DC motors, the speed is given as

$$N_\omega = \frac{\frac{V_s}{\pi}[[1+\cos\alpha_a]] - i_a R_a}{K_{af}\left[\frac{V_s}{\pi}[[1+\cos\alpha_a]]\right]\frac{1}{R_f}} \quad (21)$$

For series DC motors, the speed is given as

$$N_\omega = \frac{\frac{V_s}{\pi}[1+\cos\alpha_a] - i_a(R_a+R_f)}{Ki_f} \quad (22)$$

where i_a is as given in (17)

For shunt DC motors, the speed is given as

$$N_\omega = K\frac{\left[\frac{V_s}{\pi}[1+\cos\alpha_a]\right] - i_a R_a}{K_f\frac{\left(\frac{V_s}{\pi}[1+\cos\alpha_a]\right)}{R_{sh}}} \quad (23)$$

2.4.3 Control of DC Motors by Using Single Phase, Full Wave Converter Drives

This drive makes use of 4 thyristors and does not use any diode. The circuit for driving a shunt motor using this method is shown in Figure 7.

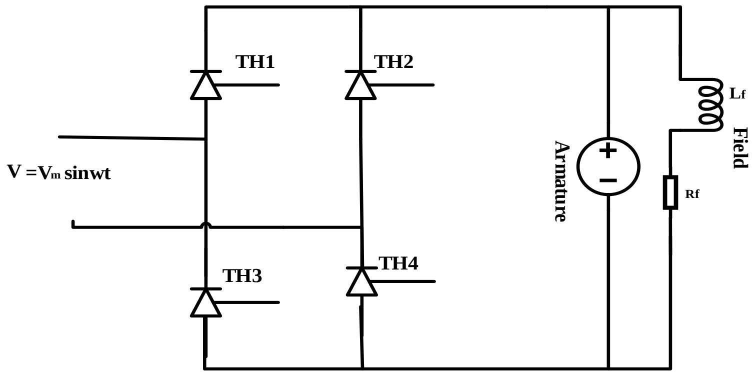


Figure 7: Control of Shunt DC Motors by Single Phase Full Wave Converter Drives

This control method operates in 2 quadrants. It provides both positive and negative Va thereby allowing operations in the first and fourth quadrants, however, the current remains unidirectional as a result of the unidirectional thyristors.

The armature voltage is given as

$$V_{a_{dc}} = \int_{\alpha_a}^{\pi+\propto} V_m \sin \omega t d(\omega t) \quad (24)$$

$$V_{a_{dc}} = \frac{2V_m}{\pi} \cos \propto_a \quad (25)$$

Again, the speed control of the motors is done by putting (25) into (5), (8) and (13) for the separately excited, series and shunt DC motors respectively.

For separately excited DC motors, the speed is given as

$$N_\omega = \frac{\left[\frac{2V_m}{\pi} \cos\propto_a\right] - i_a R_a}{K_{af}\left[\frac{2V_m}{\pi} \cos\propto_a\right]\frac{1}{R_f}} \quad (26)$$

For series DC motors, the speed is given as

$$N_\omega = \frac{\frac{2V_s \cos\propto_a}{\pi} - i_a(R_a + R_f)}{K i_f} \quad (27)$$

Again i_a is as given in (17)

Lastly, for shunt DC motors, the speed is given as

$$N_\omega = K \frac{\left[\frac{2V_m}{\pi} \cos\propto_a\right] - i_a R_a}{K_f \frac{\frac{2V_m}{\pi} \cos\propto_a}{R_{sh}}} \quad (28)$$

3.0 RESULTS AND DISCUSSION

The control of these motors using Single Phase Half Wave Converter Drives, Single Phase Semi – Converter Drives and Single Full Wave Converter Drives were then investigated for different firing angles for the same supply voltage for the motors using MATLAB/SIMULINK.

The control of the motors using Single Phase Half Wave and Semi Converter Drives are similar as noted in Equations 14 and 20. Hence, both cases will be analyzed as one.

3.1 Simulations in MATLAB/SIMULINK

Referring to Equations 15 – 17, 21 – 23 and 26 – 28, the models in MATLAB/SIMULINK were formulated. However, the MATLAB/SIMULINK models for the control of the separately excited and Series DC motors using the single phase half wave/semi and full wave converter drives respectively are shown in Figures 8 and 9.

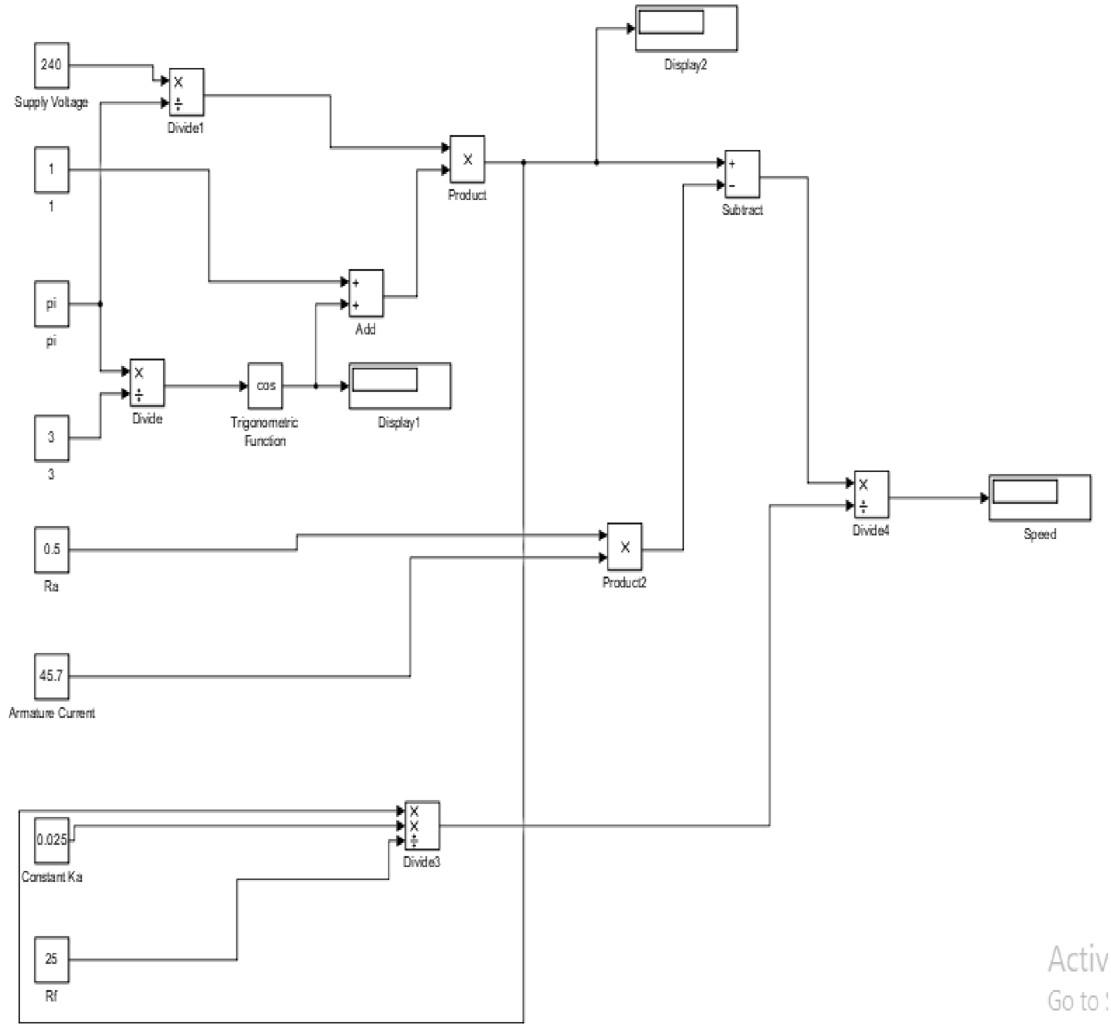


Figure 8: SIMULINK model of Separately Excited Dc Motors Using Single Phase Half Wave/Semi Converter Drives

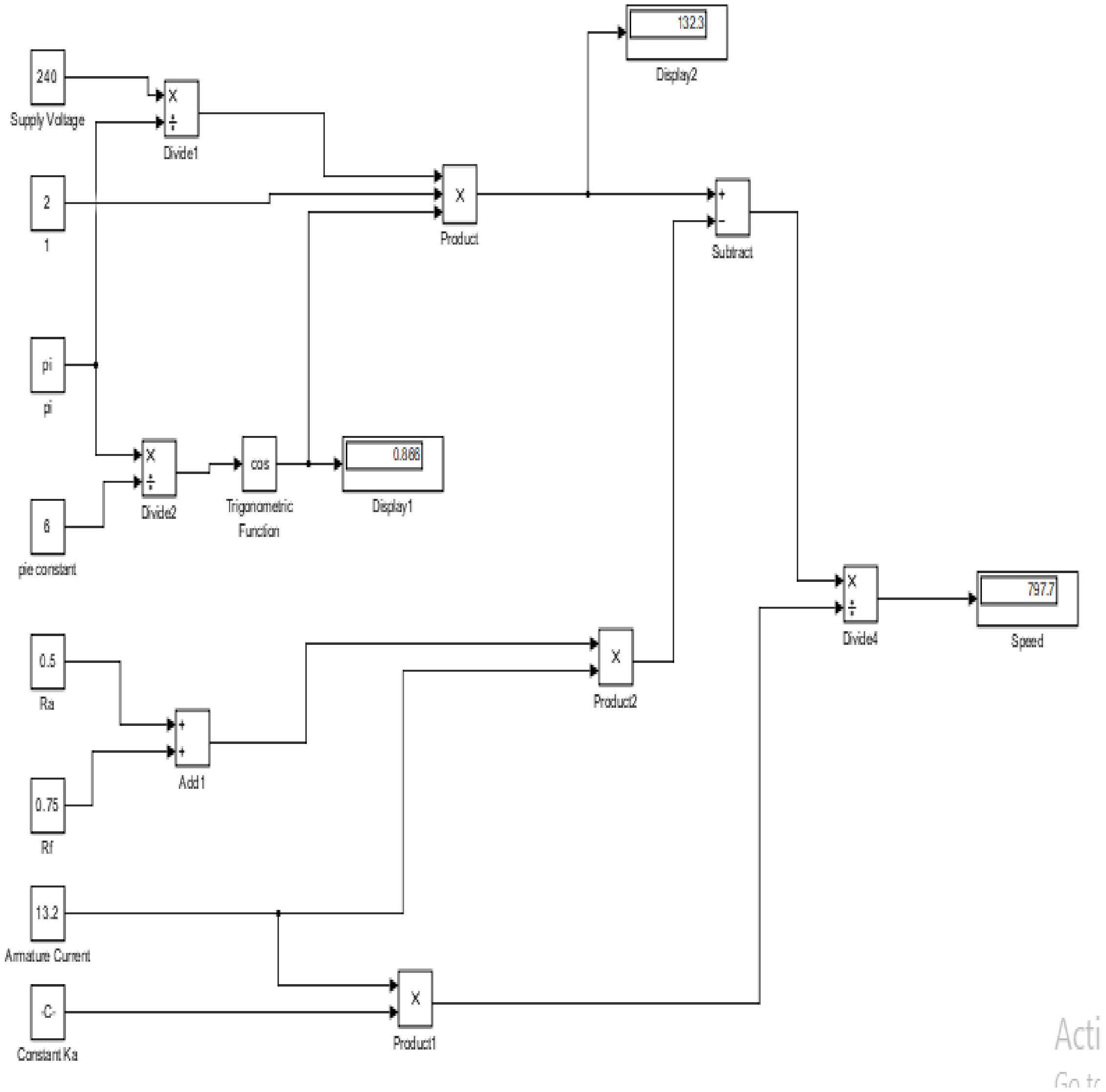


Figure 9: SIMULINK model of Series DC Motors Using Full Wave Converter Drives

Using the Single Phase Half Wave/Semi Converter Drives in the control of the motors, the speed variation for the separately excited, series and shunt DC motors are as recorded in Table 2 for different firing angles.

Table 2: Speed – Firing angle characteristic for control of DC motors using Single Phase Half Wave/Semi Converter Drives.

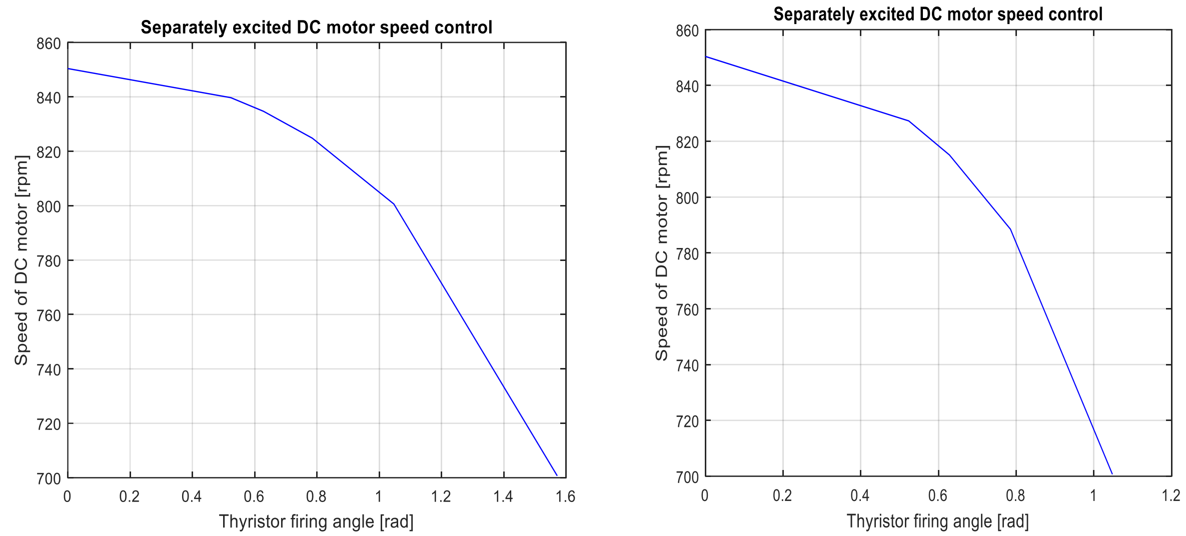
S/N	Thyristor Firing Angle (rad)	Speed of Separately Excited Motor (RPM)	Speed of Series Motor (RPM)	Speed of Shunt Motor (RPM)
1	0	850.4	938.6	785.3
2	$\frac{\pi}{6}$	839.7	868.1	769.2
3	$\frac{\pi}{5}$	834.7	838.1	761.7
4	$\frac{\pi}{4}$	824.8	784.5	746.9
5	$\frac{\pi}{3}$	800.6	675.6	710.7
6	$\frac{\pi}{2}$	700.9	412.5	565.1
7	π	Undetermined	Undetermined	Undeterminable

Also, using the Single Phase, Full wave Converter Drives in the control of the motors, the speed variation for the separately excited, series and shunt DC motors are as recorded in Table 3 for different firing angles.

Table 3: Speed – Firing angle characteristic for control of DC motors using Single Phase, Full Wave Converter Drives.

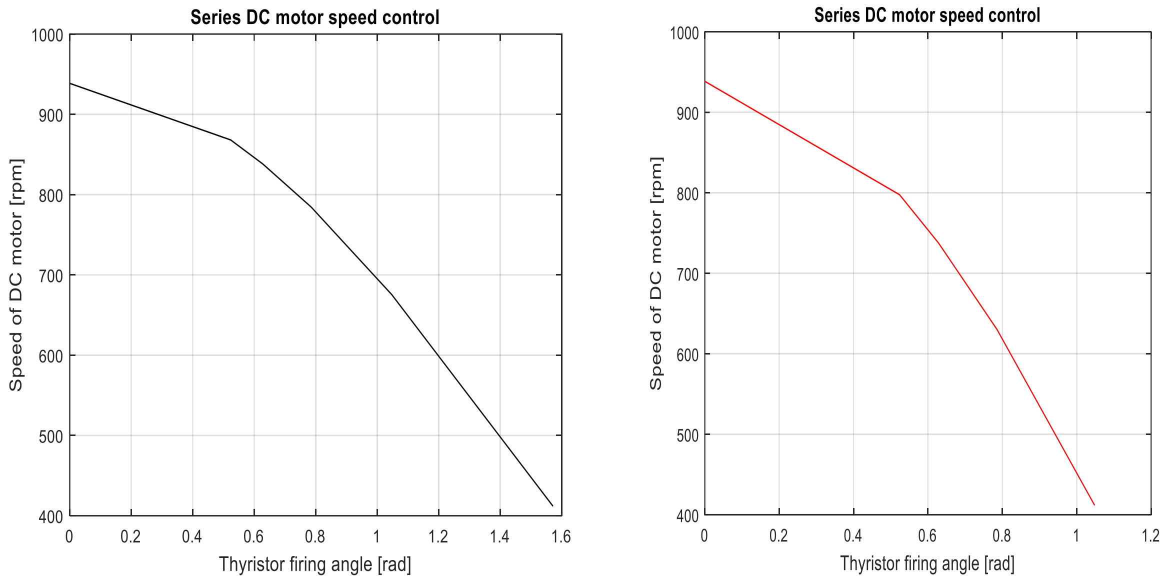
S/N	Thyristor Firing Angle (rad)	Speed of Separately Excited Motor (RPM)	Speed of Series Motor (RPM)	Speed of Shunt Motor (RPM)
1	0	850.4	938.6	938.6
2	$\frac{\pi}{6}$	827.3	797.7	750.7
3	$\frac{\pi}{5}$	815.1	737.7	732.5
4	$\frac{\pi}{4}$	788.5	630.4	692.6
5	$\frac{\pi}{3}$	700.9	412.5	561.5
6	$\frac{\pi}{2}$	Undetermined	Undeterminable	Undeterminable
7	π	Undetermined	Undeterminable	Undeterminable

The plot of the thyristor firing angle against the speed for the motors using the Single Phase, Half Wave/Semi Converter Drives and Full Wave Converter Drives are shown in Figures 10 – 12.



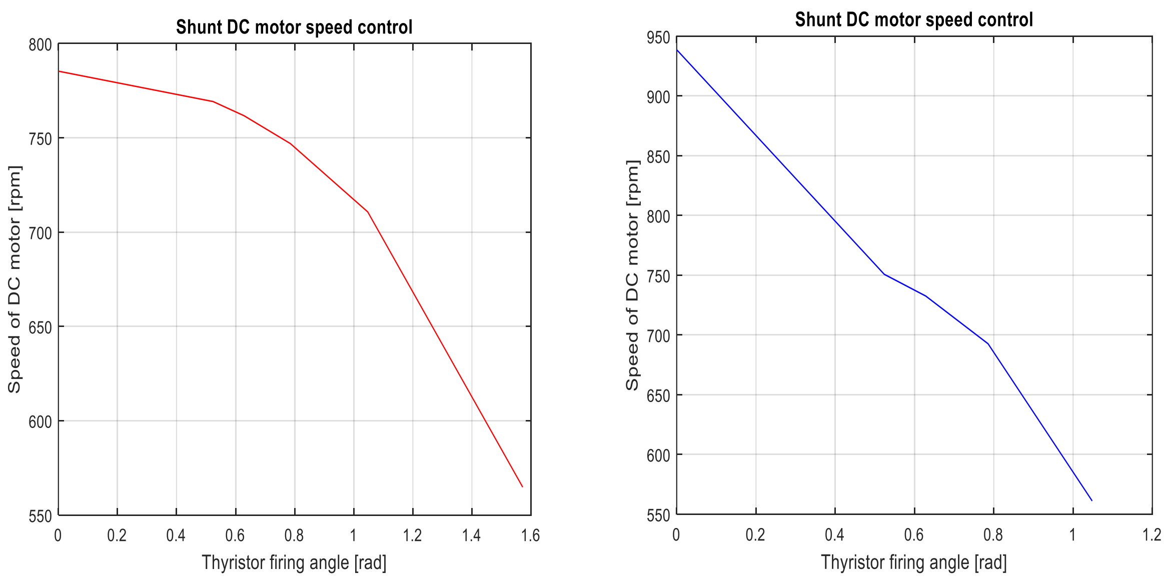
(a): Using 1-Φ, ½ Wave/Semi Converter Drive (b): Using 1-Φ, Full wave Converter Drive

Figure 10: Separately excited DC motor control



(a): Using 1-Φ, ½ Wave/Semi Converter Drive (b): Using 1-Φ, Full wave Converter Drive

Figure 11: Series DC motor control



(a): Using 1-Φ, ½ Wave/Semi Converter Drive (b): Using 1-Φ, Full wave Converter Drive

Figure 12: Shunt DC motor control

3.2 Discussion of Results

In all the control cases, it can be observed that as the firing angle is increased, the speed of the DC motor is reduced from its maximum speed at 0 rad firing angle. However, the rate of speed change differs from control medium for any particular motor. For the separately excited DC motor, the speed change had an initial decreasing rate of $21rpm/rad$, increased to a rate of $71rpm/rad$ and lastly $192rpm/rad$ for the half wave/semi converter drive. This method of speed control for this motor thus has an approximate average of $-94rpm/rad$. On the other hand, by using the full wave converter drive, the separately excited DC motor speed change with firing angle is approximate average of $-160rpm/rad$. Similarly, for the series DC motor, the approximate average speed change per change in firing angle is $-281rpm/rad$ and $-464rpm/rad$ for the single phase, half wave/semi converter drives and the full wave converter drive respectively. Lastly, for the shunt motors, the approximate average speed change per change in firing angle is $-139rpm/rad$ and $-353rpm/rad$ for the single phase, half wave/semi converter drives and the full wave converter drive respectively.

4.0 CONCLUSION

Based on the results obtained, it can be deduced that using the full wave converter drive performs speed changing operations at a faster rate than their half wave or semi converter drive counterparts for the various types of DC motors.

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