Design and Operation of DC Drive Using Class E Chopper

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Abstract: ***This paper presents the design and operation of dc drive using CLASS E chopper for both open loop and closed loop. Dc motor drives are widely used to control the speed for acceleration and deceleration. In this paper the speed of separately excited dc motor can be controlled from 0 to rated speed using chopper. The chopper firing circuit receives signal from controller and the chopper responds by providing variable voltage to the armature of the motor for achieving desired speed. There are two control loops, one for controlling current and another for speed. The controller used is Proportional-Integral type which ceases the delay and provides fast control. In this way, the Modelling of separately excited DC motor is done. After obtaining the complete model of the system, it is simulated using MATLAB (Simulink) in open loop and closed loop. The simulation of DC motor drive is done and analysed and the hardware implementation of the four quadrant dc drive using chopper is done.***

Keywords: Class E chopper, proportional integral

1. Introduction

DC motors are used extensively in adjustable-speed drives and position control applications. Their speeds below the base speed can be controlled by armature-voltage control. Speeds above the base speed are obtained by field-flux control. As speed control method for DC motors are simpler and less expensive than those for the AC motors, DC motors are preferred where wide speed range control is required. DC choppers also provide variable dc output voltage from a fixed dc input voltage. The Chopper circuit used can operate in all the four quadrants of the V-I plane. The output voltage and current can be controlled both in magnitude as well as in direction so the power flow can be in either direction. The four-quadrant chopper is widely used in reversible dc motor drives. By applying chopper it is possible to implement regeneration and dynamic braking for dc motors.

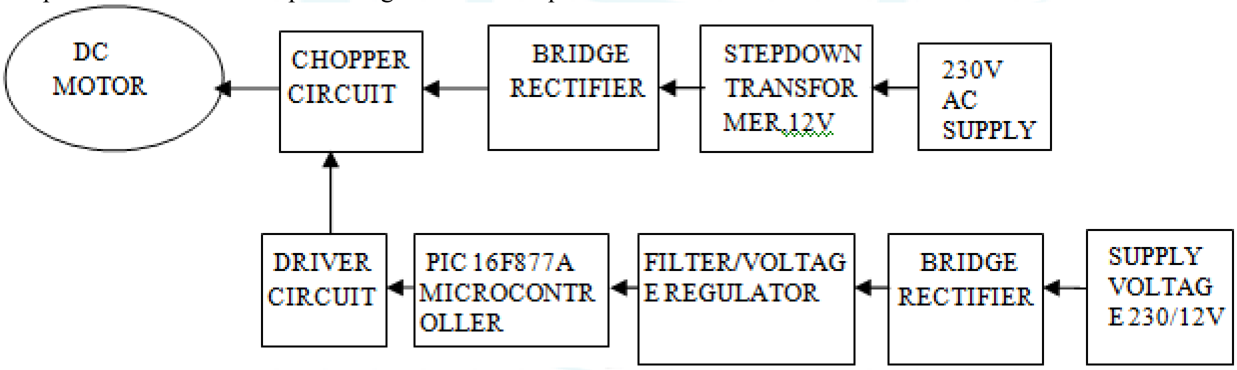


Figure 1: Open loop block diagram

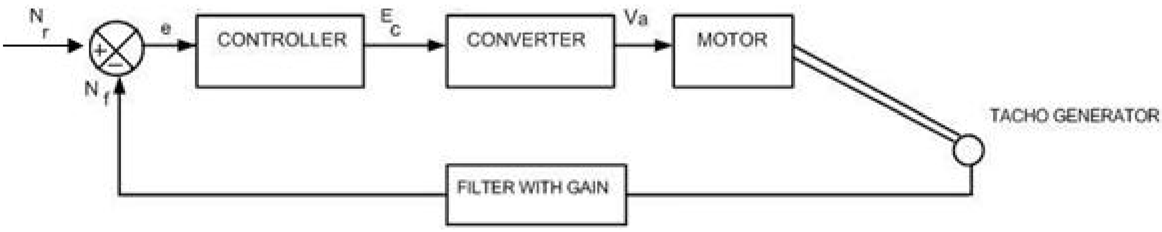


Figure 2: Closed loop block diagram

2. Separately Excited DC Motor

Separately Excited DC motor has field and armature winding with separate supply. The field windings of the dc motor are used to excite the field flux. Current in armature circuit is supplied to the rotor via brush and commutator segment for the mechanical work. The rotor torque is produced by interaction of field flux and armature current.

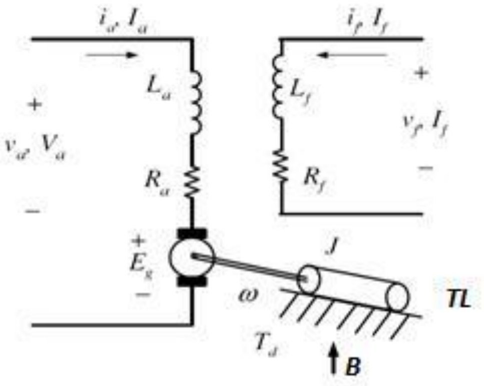


Figure 3: Separately excited dc motor

$$v_f = R_f i_f + L_f \frac{di_f}{dt}$$
$$v_a = R_a i_a + L_a \frac{di_a}{dt} + e_g$$
$$e_g = K_v \omega i_f$$
$$T_d = K_t i_f i_a$$
$$T_d = J\frac{d\omega}{dt} + B\omega + T_L$$

$$Steady - state$$
$$\frac{d}{dt} = 0$$
$$V_f = R_f I_f$$
$$E_g = K_v \omega I_f$$
$$V_a = R_a I_a + E_g$$
$$V_a = R_a I_a + K_v \omega I_f$$
$$T_d = K_t I_f I_a$$
$$T_d = B\omega + T_L$$
$$P_d = T_d \omega$$

2.1 Motor Speed Control

$$V_a = R_a I_a + K_v \omega I_f$$
$$\omega = \frac{V_a - I_a R_a}{K_v I_f} = \frac{V_a - I_a R_a}{K_v\left(\frac{V_f}{R_f}\right)}$$

From the above derivation important facts can be deduced for steady-state operation of DC motor. For a fixed field current, or flux (I_f) the torque demand can be satisfied by varying the armature current (I_a). The motor speed can be controlled by:

- Controlling V_a (voltage control)
- Controlling V_f (field control)

These observation lead to the application of variable DC voltage for controlling the speed and torque of DC motor.

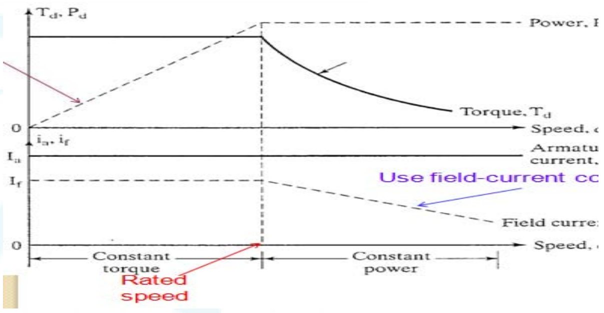


Figure 4: Characteristics of separately excited dc motor

2.2 Modeling of separately excited dc motor

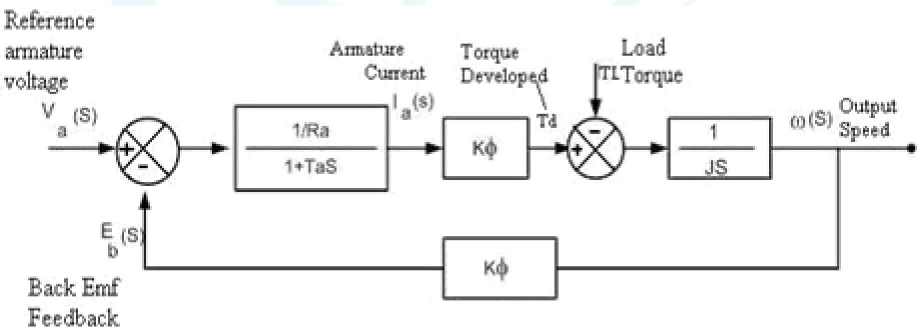


Figure 5: Block model of separately excited dc motor

Ia(s) = (Va – KΦω)/ Ra(1+ LaS/Ra)

ω(s) = (Td - TL)/JS = (KΦIa - TL) /JS

ω (s) / Va(s) = [KΦ /Ra] /JS(1+TaS) /[1 +(K²Φ² /Ra) /JS(1+TaS)]

After simplifying the above transfer equation we get

ω(s) /Va(s) = (1 /kΦ) /{1 +(k²Φ² /Ra) /JS(1+TaS)}

3. Chopper

A chopper is a static power electronic device that converts fixed dc input voltage to a variable dc output voltage.

3.1 Control strategies

The average value of output voltage V_o can be controlled through duty cycle by opening and closing the semiconductor switch periodically. The various control strategies for varying duty cycle are as following:

1. Time ratio Control (TRC)
2. Current-Limit Control.

Time ratio Control (TRC)

In this control scheme, time ratio Ton/T(duty ratio) is varied. This is realized by two different ways called Constant Frequency System and Variable Frequency System as described below:

1. Constant Frequency System

In this scheme, on-time is varied but chopping frequency f is kept constant. Variation of T_{on} means adjustment of pulse width, as such this scheme is also called pulse-width-modulation scheme.

2. Variable Frequency System

In this technique, the chopping frequency f is varied and either (i) on-time T_{on} is kept constant or (ii) off-time T_{off} is kept constant. This method of controlling duty ratio is also called Frequency-modulation scheme.

Current- Limit Control

In this control strategy, the on and off of chopper circuit is decided by the previous set value of load current. The two set values are maximum load current and minimum load current. When the load current reaches the upper limit, chopper is switched off. When the load current falls below lower limit, the chopper is switched on. Switching frequency of chopper can be controlled by setting maximum and minimum level of current. Current limit control involves feedback loop, the trigger circuit for the chopper is therefore more complex.PWM technique is the commonly chosen control strategy for the power control in chopper circuit.

3.2 Chopper types

There are five types of dc choppers, Class A, Class B, Class C, Class D and Class E based on the V-I plane. The five different choppers are classified according to their output (Io, Vo) capabilities as follows:

a) First quadrant - I (Class A chopper) +Vo, +Io.
b) Second quadrant - II (Class B chopper) +Vo, -Io.
c) Two quadrant - I and II (Class C chopper) +Vo, ±Io.
d) Two quadrant - I and IV (Class D chopper) ±Vo, +Io.
e) Four quadrant - I, II, III, and IV (Class E or Type E chopper) ±Vo, ±Io

Class E or four quadrant chopper

The chopper circuit shown in fig can operate in all four quadrants of the Vo-Io plane. That is the output voltage and current can be controlled both in magnitude and direction. Therefore, the power flow can be in any direction.

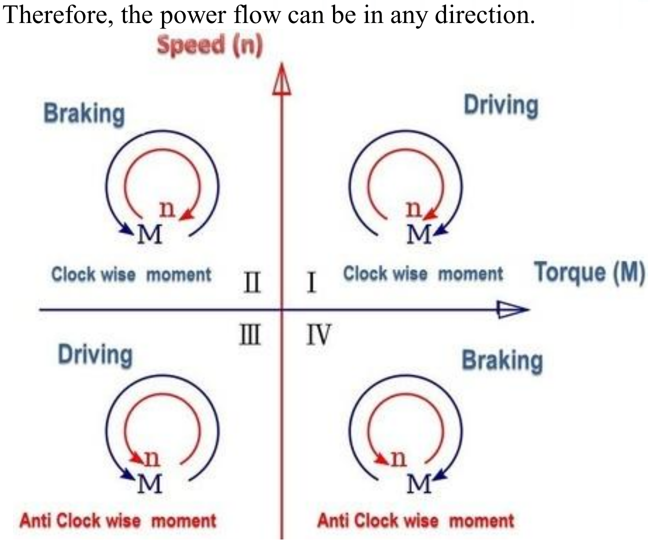


Figure 6: Typical operating regions

Operation of a four quadrant chopper (Class E), is illustrated with a dc motor as load as shown in Fig.8.

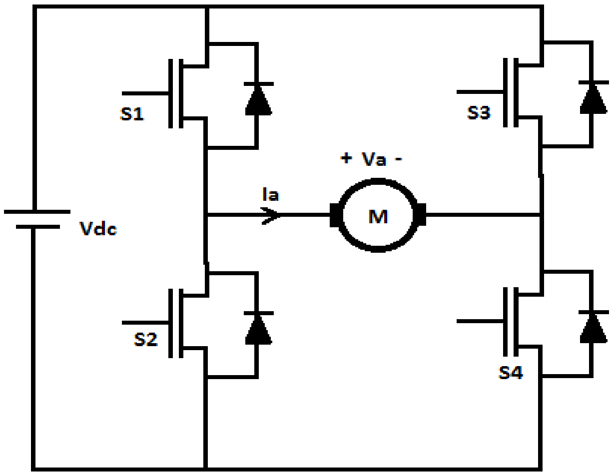


Figure 7: Class E-chopper Circuit Diagram

From Fig.7, for the load to operate in first quadrant (forward motoring), the switches T1 and T4 are operated. Here, the switch T1 is switched whereas switch T4 is kept on. Therefore, both the voltage and current across and through the load are positive rotating the motor in forward direction. Now, the speed of the motor can be varied by varying the duty cycle of the switch T1. As the duty cycle varies, the voltage across the armature of motor varies proportionally thereby varying the motor speed as the N is proportion to armature voltage. Now to apply brake to the motor electrically, the chopper is to be operated in second quadrant. This can be done by operating switch T2. When the switch T2 is on, the inertial energy of the motor is stored in the armature inductance, the voltage across the inductor increases. Once the switch is turned off, the voltage across inductor adds with the back EMF of the motor feeding the inertial energy back to the source through freewheeling diodes D1 and D4. For the energy to be fed back to the source, the combined voltage of inductor and back EMF should be more than source voltage (Vs). If the inertial energy of the motor is feed back to source, it is called regenerative braking and if dissipated in a resistor, it is called electrical braking. In the quadrant, the motor is in forward regenerative mode. To operate the chopper in the third quadrant, switches T3 and T2 are to be operated. Here, switch T3 is switched and switch T2 is kept on. Now the voltage and current across and through the load are negative driving the motor in reverse direction. Also the speed of the motor can be varied by varying the duty cycle (D) of the switch T3. In this quadrant, the motor is in reverse motoring mode. Now to operate the motor in fourth quadrant, only switch T4 is operated. With the switch T4 turned on, the voltage across the armature inductance increases. When the switch T4 is turned off, voltage across the inductor adds to the back EMF. If the combined voltage is more than source voltage, the inertial energy is fed back to the supply.

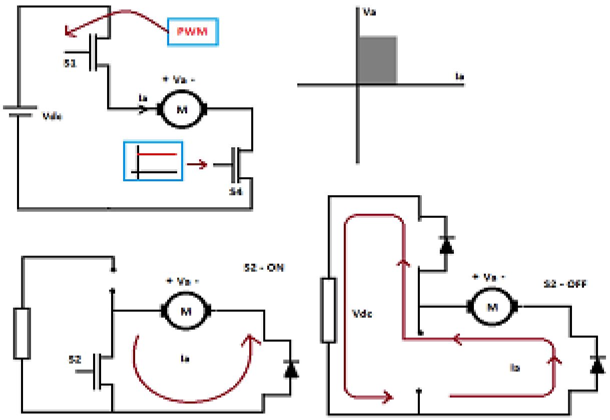


Figure 8: Schematic showing type of triggering in quadrant one (top left), first quadrant representation (top right), Braking mode with S2 closed (bottom left), Braking mode with S2 opened (bottom right).

4. Controller Design

The controller used in a closed loop provides a very easy and common technique of keeping motor speed at any desired set-point speed under changing load conditions. This controller can also be used to keep the speed at the set-point value when, the set-point is ramping up or down at a defined rate. In this closed loop speed controller, a voltage signal obtained from a Tacho-generator attached to the rotor which is proportional to the motor speed is fed back to the input where signal is subtracted from the set-point speed to produce an error signal. This error signal is then fed to work out what the magnitude of controller output will be to make the motor run at the desired set-point speed. We have two mechanisms working simultaneously trying to correct the motor speed which constitutes a PI (proportional-integral) controller. The proportional term does the job of fast-acting correction which will produce a change in the output as quickly as the error arises. The integral action takes a finite time to act but has the capability to make the steady-state speed error zero.

Current Controller Design

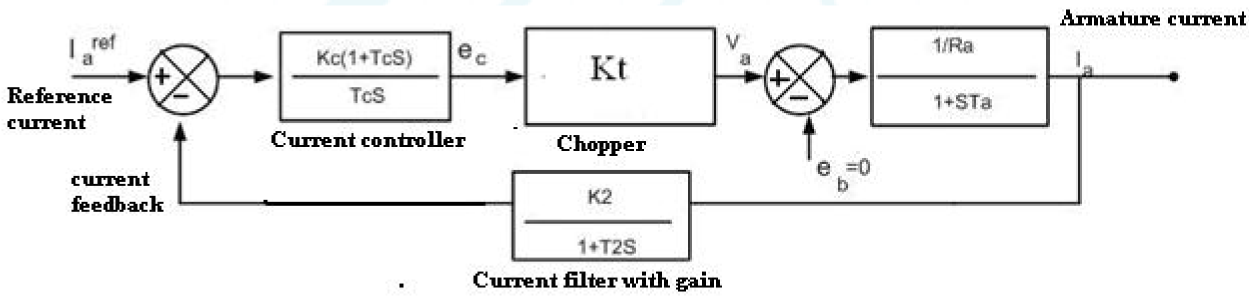


Figure 9: Block model for current controller design

Ia(s)(f)/Ia(s)ref={[Kc(1+TcS)/TcS](Kt)[(1/Ra)/(1+STa)]/{1+[Kc(1+TcS)/TcS]
Kt[(1/Ra)/(1+STa)][K2/(1+T2S)]}

After simplifying the above transfer function we get

$$Ia(S)\,(f) / Ia(S)\,(ref) = (1/K2)/(2S^2T2^2 2ST2+1)$$

Speed Controller Design

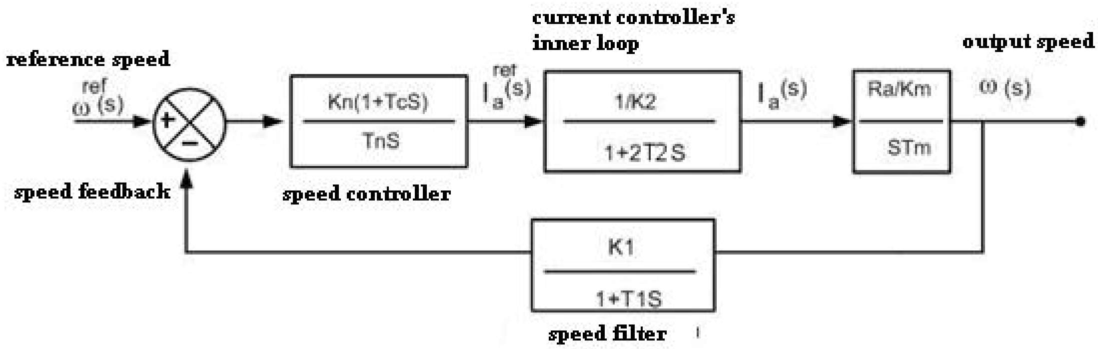


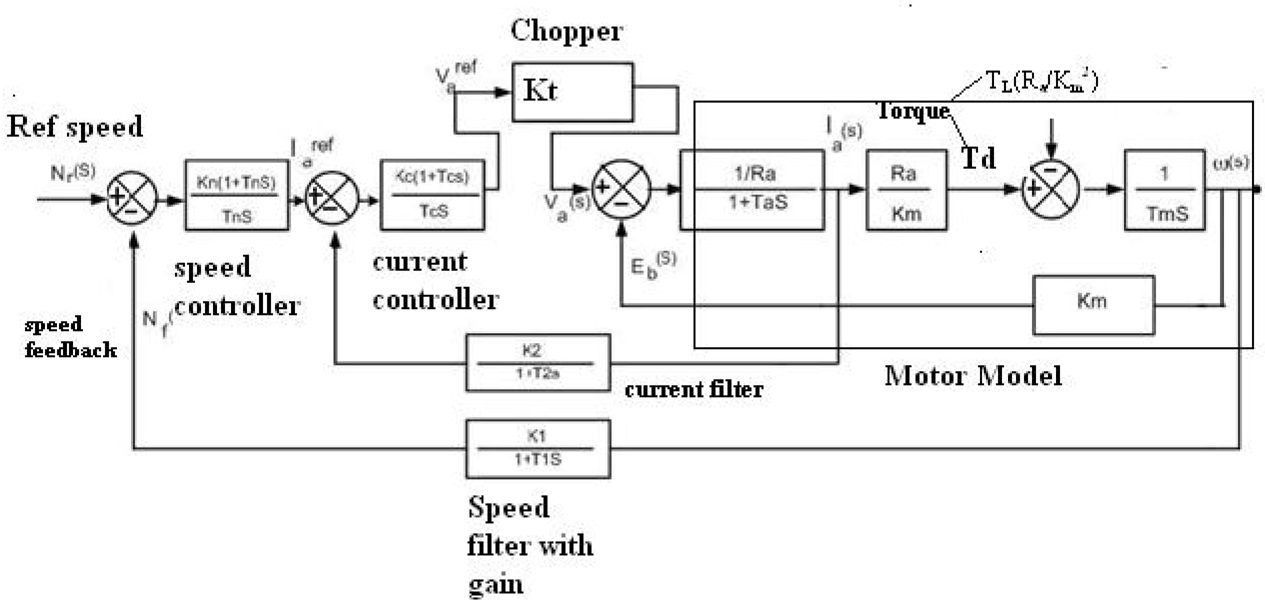
Figure 10: Block model for speed controller design

$\omega(s)/\omega(s)(ref.)=(Kn/K2)(Ra/KmTmTn)(1+TnS/(1+2T2S)S^2)/\{1+(KnRa/K2KmTmTn)(1+TnS/(1+2T2S)S^2)(K1/(1+T1S))\}$

After simplifying above transfer function we get

$\omega(s)/\omega(s)(ref.)=(KnRa/K2KmTmTn)(1+T1S)/\{K2KmTnS2(1+T1S)+KnRaK1\}$

Complete layout for dc motor speed control



5. Simulation Results

Simulation is performed using MATLAB software. Simulink library files include inbuilt models of many electrical and electronics components and devices such as diodes, IGBTs, resisitor, motors, power supplies and so on. The circuit components are connected as per design without error, parameters of all components are configured as per requirement and simulation is performed.

5.1 Class E chopper in open loop

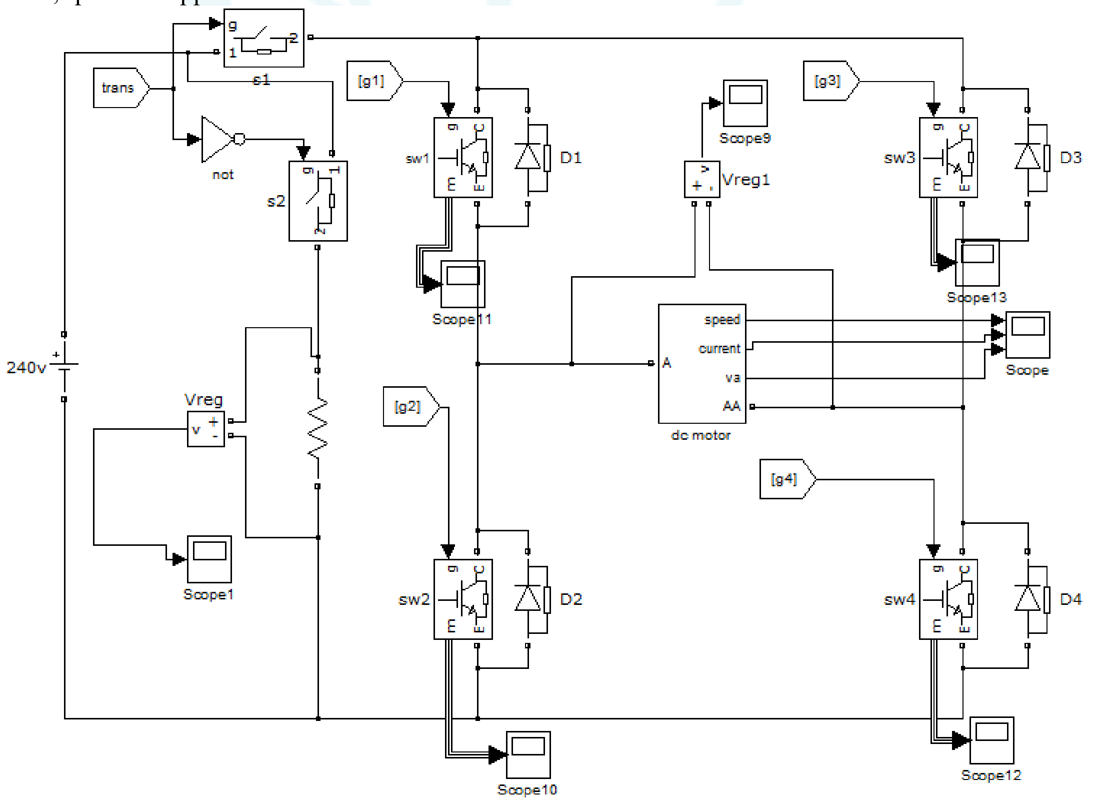


Figure 11: Simulation model for class e chopper

In motoring mode, when the switch 1 is in OFF state, the motor's inductive energy should be allowed through a free wheeling diode. In case of reverse motoring, the same free wheeling diode diverts the motor and creates a dead short circuit across the supply. Hence, the above said logic sequence is utilized to reverse the connections of the free wheeling diode. The reversible diode arrangement and its sub-circuit are shown in the *Fig.12*.

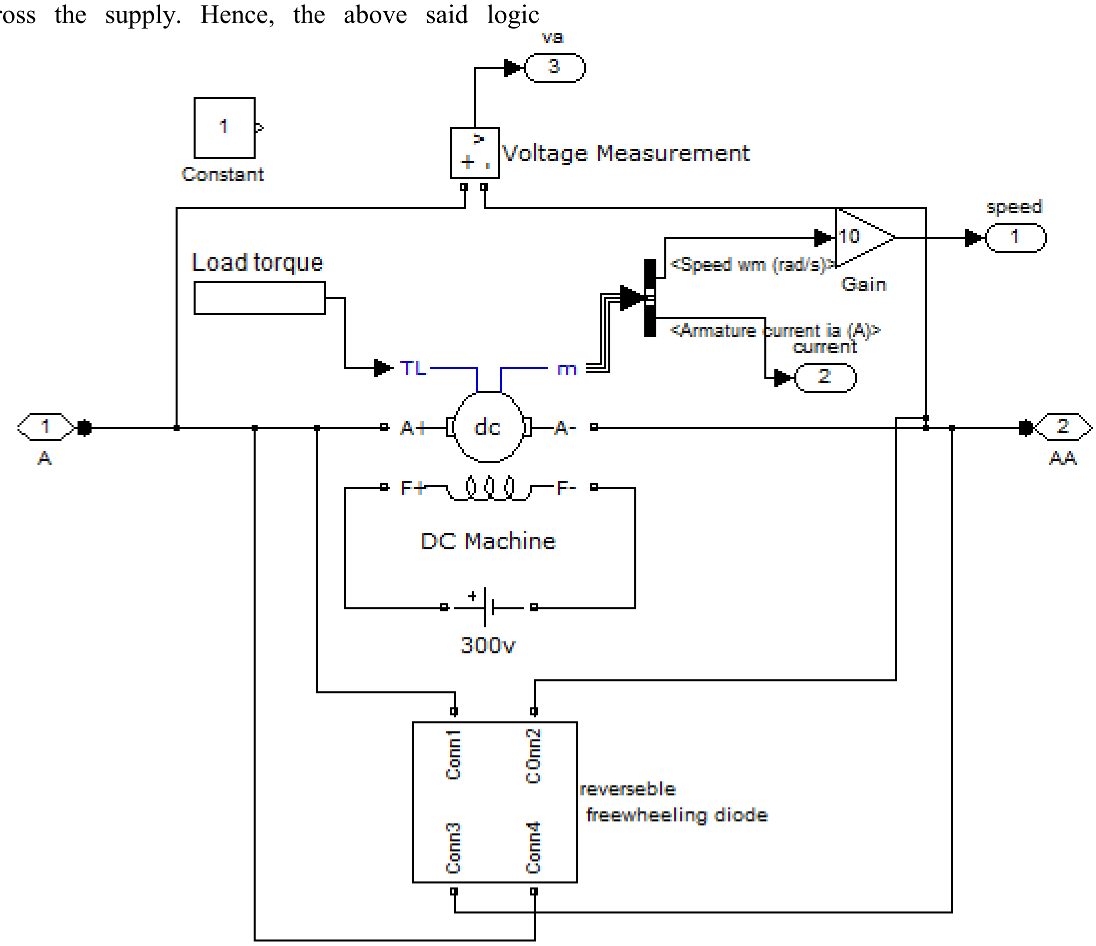


Figure 12: Sub circuit of dc motor

The simulation time line is allotted for 4 seconds in which 2 seconds for forward and 2 seconds for reverse operations. A pulse generator is configured with period 4 seconds and pulse width 50%. This mark time (ON time) of the pulse operates the motor in forward mode and the space time (OFF time) operates the motor in reverse mode.

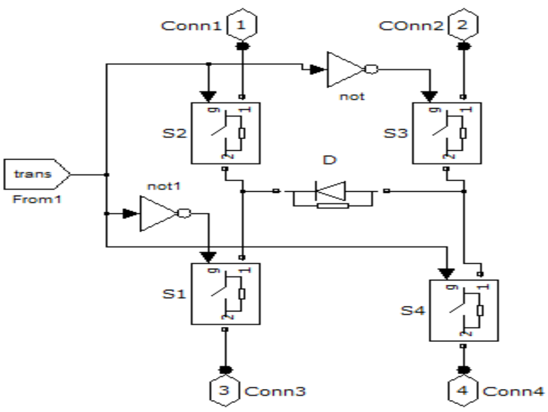


Figure 13: Sub circuit of free wheeling diode

Another pulse generator (transition triggering) is configured with a period of 2 seconds and pulse width 50%. The mark time is for motoring and the space time is for braking. As the period of this pulse (Trans) is half of the time line pulse, this trans pulse creates two motoring and two braking modes of operations. For triggering the IGBTs, the general pulse generators are configured with 1 KHz switching frequency and its duty ration can be adjustable. The logic connections of the pulse generators are shown in the Fig.14.

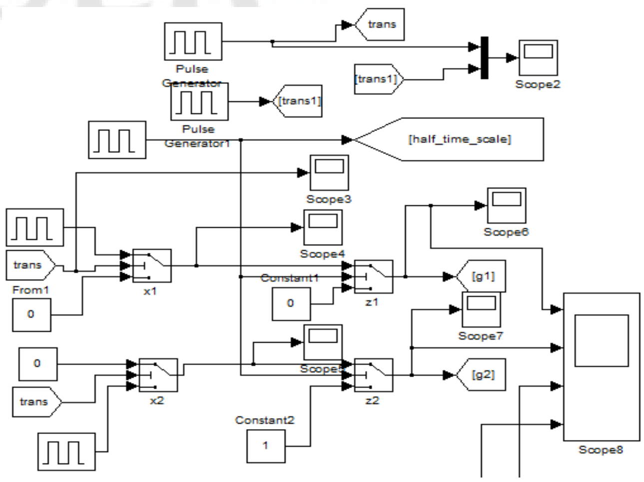


Figure 14: Triggering logic for forward and reverse motoring

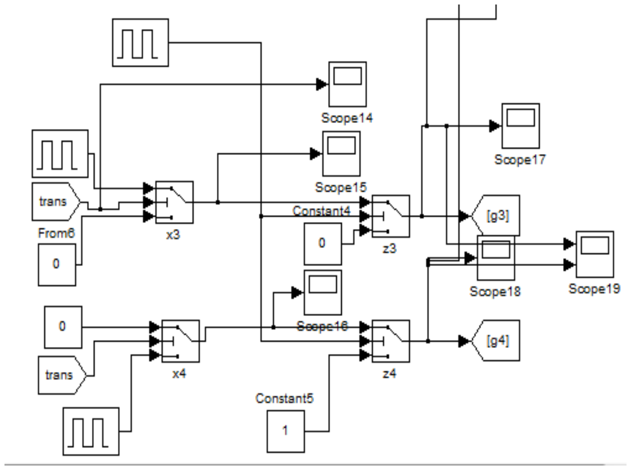


Figure 5: Triggering logic for forward and reverse braking

In forward motoring mode, the switch 4 continuously conducts and the switch 1 will be operated with PWM1. After 1 second, the transition (trans) pulse goes OFF (braking mode) and this makes the changeover switch (x1) to connect to zero (OFF). Simultaneously, the changeover switch (x2) shifts to PWM2. During this braking mode, when switch 2 is ON, the moment of inertia makes the motor to operate as generator and charges the current.

The speed, current and the armature voltage for all the four quadrants are shown in the Fig.16.

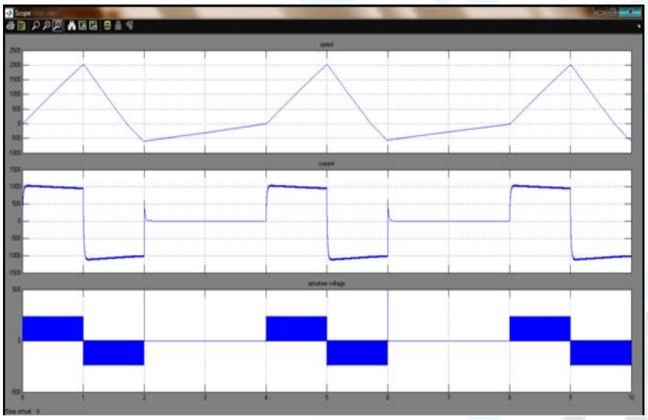


Figure 16: Speed, current and the armature voltage (from top to bottom)

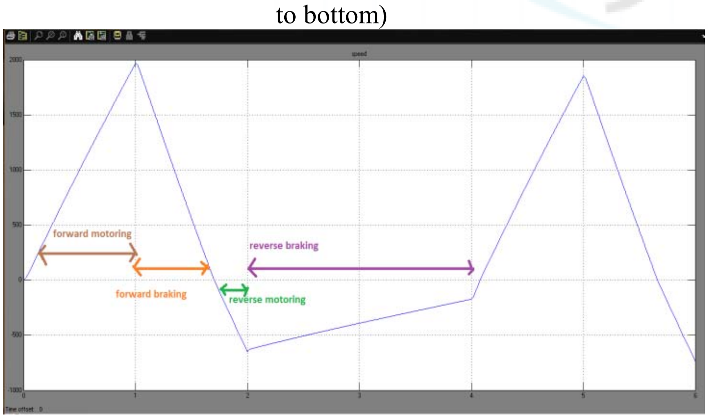


Figure 17: Speed of the motor for all four quadrants

Closed Loop Control

Problem Statement:
A separately excited DC motor with nameplate ratings of 300KW, 420V (DC), 50 rad/sec is used in all simulations. Following parameter values are associated with it.

- Moment of Inertia, J = 75 Kg-m2.
- Back EMF Constant = 7 Volt-sec/rad.
- Rated Current = 700 A.
- Maximum Current Limit = 1000 A.
- Resistance of Armature, Ra = 0.026 ohm.
- Armature Inductance, La = 0.749 mH.
- Speed Feedback Filter Time Constant T1 = 22 ms.
- Current Filter Time Constant T2 = 3ms.

Current Controller Parameter:
Current PI type controller is given by:
Kc {(1+ TcS)/TcS}
Here, Tc = Ta and Kc = RaTa/ (2K2KtT2)
Ta = La/Ra = 0.749*10-3/0.026 = 28.80 ms.
For analog circuit maximum controller output is ± 10 Volts.
Therefore, Kt = 420/10 = 42.
Also, K2 = 10/1000 = 1/100.
Now, putting value of Ra, Ta, K2, Kt and T2 we get: Kc = 0.297.
Speed Controller Parameter:
Speed PI type controller is given by:
Kn{(1+TnS)/TnS}
Here, Tn = 4δ = 4(T1+2T2) = 4(22 + 2*3) = 112 ms.
Also, Kn = TmKmK2/(2K1Raδ).
K1 = 10/50 = 0.192.
Tm = JRa/Km = 75*0.026/7 = 0.278 ms.
Now, Kn = (0.278*7*0.01)/ (2*0.192*0.026*31*100) = 6.28.

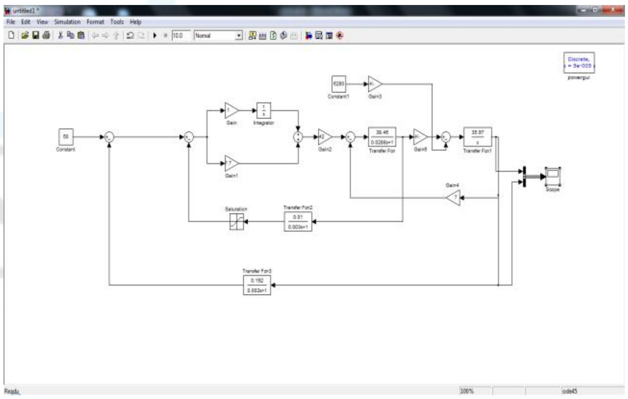


Figure 18: Closed loop speed control without PI controller

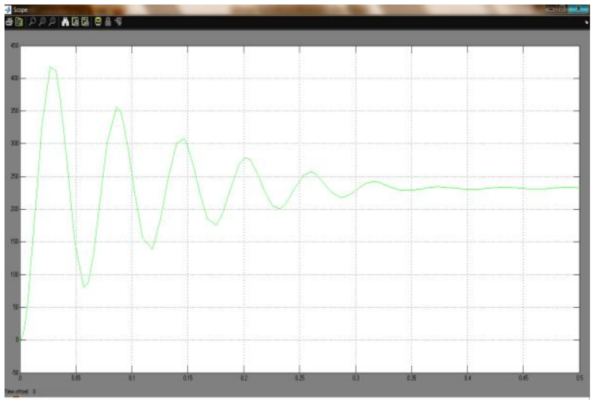


Figure 19: Speed of dc motor without controller

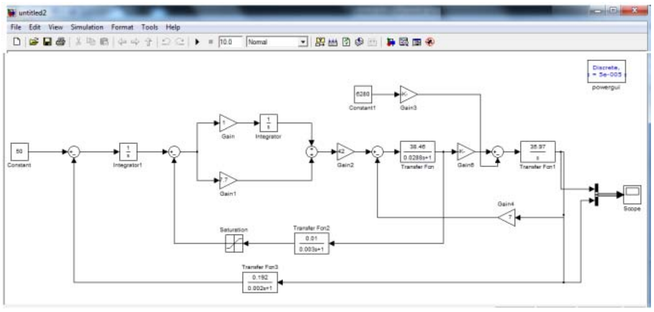


Figure 20: Closed loop speed control with PI controller

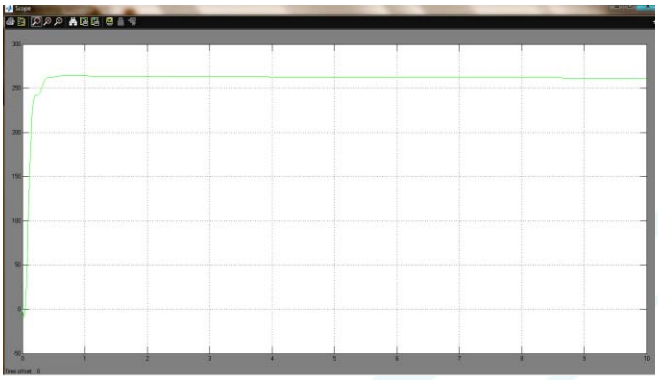


Figure 21: Speed of dc motor with controller

6. Hardware Implementation

Hardware Implementation of dc drive using CLASS E chopper is done by using PIC16F877A Microcontroller and Driver circuit. Controller provides pulses to the MOSFET'S. Driver circuit amplifies the pulses which are coming from PIC Controller. Driver Circuit perform three main operations.

- Impedance matching
- Isolation
- Amplification

It is used to provide 9 to 20 volts to switch the MOSFET Switches of the chopper. Driver amplifies the voltage from microcontroller which is 5volts. Also it has an opto-coupler isolating purpose. So damage to MOSFET is prevented.

Components used
1. IRFP460
2. Diode N4007
3. Capacitors: (1000µF/50V, 1000µF/25V, 1000µF/250V)
4. Optocoupler MCT2E
5. Transistors : (2N2222, CK1OO)
6. Resistors: (1K, 100ohm)
7. PIC MICRO CONTROLLER
8. MOSFET
9. Transformers

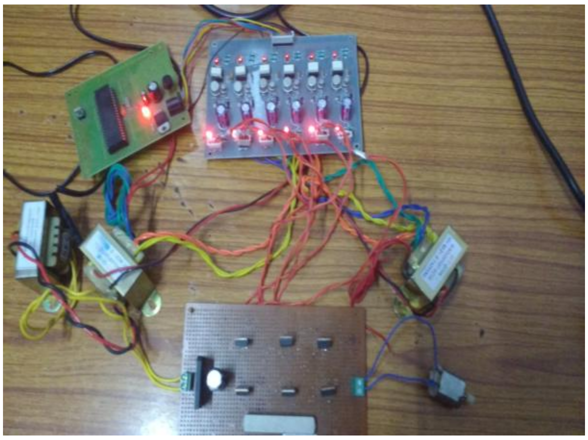


Figure 22: Implemented Hardware

7. Conclusion

In this paper successfully designed and operated the dc drive using class e chopper. CLASS E chopper is successfully operated in closed loop and the open loop and Motoring and regenerative braking periods are observed in the simulation. In hardware implementation with help of pic controller I operated the four quadrants with 10us of delay for motoring and braking. Under motoring period motor will start running and in braking period the regenerative power is dissipated through resistor. By using micro controller the control circuit became simpler.

The speed of the dc motor is operated in closed loop with the help of modulus hugging method. The whole driver can get more simple by using aurdino or a digital signal processor controllers.

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