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FOUR QUADRANT OPERATION OF DUAL CONVERTER BASED DC DRIVES

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ABSTRACT

With recent advances in Power Electronics, electric variable-speed Drives are witnessing a revolution in various applications. Power electronic devices are becoming able to easily tailer the rigid characteristics of the motor (when driven from a fixed DC or AC supply source) to the requirements of load. Because of inherent ease of speed control of the separately excited DC machine, DC drives are used in rolling mills, paper mills, mine winders, hoists, machine tools, traction, printing presses, textile mills, excavators and cranes etc., where speed control is done by varying the applied armature voltage. This variable armature voltage is simply generated by Phase- Controlled Rectification which has now almost entirely replaced the Ward-Leonard systems previously used. Half Converter, Semi Converter, Full Converter and Dual Converter are some of the Thyrister controlled Rectifier circuits. This paper presents matlab simulation model of Dual converter (single phase) circuit. Simulated results show that this converter offer variable DC voltage which is capable of four-quadrant operation of the drive in speed-torque plane. We can thus have bi-directional load current and dc output voltage.

KEYWORDS: Dual Converter, Separately Excited DC Motor, Speed Control, Four Quadrant Operation of DC Drive.

INTRODUCTION

Being invented by Werner Von Siemens in 1856 DC motors have been the backbone of industrial applications, since the Industrial Revolution [1]. This is due to the motor's high starting torque capability and smooth speed control, and its ability to quickly accelerate to speed in the opposite direction. There are three basic types of mechanical loads that are encountered by any AC or DC drive-system - Constant Torque, Constant Horsepower and Variable Torque. In Constant Torque Applications the torque required is 100% and remains constant from zero to base speed . In this type of application horsepower is directly proportional to the speed. The standard belt conveyor is a prime example. In Constant Horsepower Applications, the horsepower required remains constant, while the torque drops off as a ratio of $1/\text{speed}^2$. Example of this application is a center driven winder. Centrifugal fans/pumps are example of Variable torque system.

Speed control by armature voltage variation was first used in the early 1930s using Ward-Leonard system [1]. In this system a constant-speed AC motor coupled with a DC generator is used to produce DC power. This DC generator feeds power to the armature of the DC motor to be controlled. The field magnetism of the DC motor interacts with the magnetism of the armature to produce rotation of the motor shaft. Motor speed is controlled by adjusting the field current of the DC generator. When field winding voltage is smoothly varied in either direction, speed can be steplessly varied from full positive to full negative [2]. Years ago in the rotating machinery industry, this equipment was very traditional equipment. This system also has the ability to control speed accurately and has a wide speed range. It has inherent ability for regenerative braking and allows operation of the drive in all the four quadrants. However, today a system of this type, would carry several limitations. Because of the need for three rotating units, this system has high initial cost, low efficiency, requires more frequent maintenance and produce more noise. Besides, it has huge weight, bulky size & needs large foundation area [2].

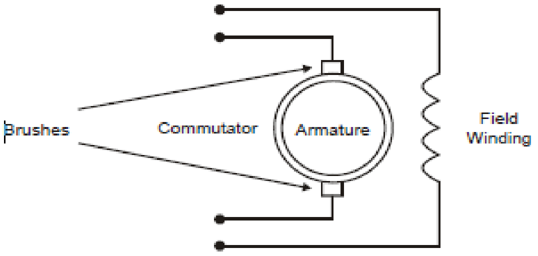
In 1960s Electric Regulator Company brought to market a static, solid state controller that converted the AC line directly to variable DC using silicon based semi-conductor switches [1]. Speed control techniques using the SCR or thyristor have replaced the earlier Ward-Leonard system and are now widely used in modern electronic DC drives.

The DC drive is well known, well proven and widely applied, yet its popularity is in relative decline because of the emergence of the more robust, lower-cost Induction Motor drive [3]. The mechanical commutator and brushes need periodic replacement. Commutator limits the power per unit to 1-2 MW at 1000 rpm and may not be at all accepted in explosion-prone environments. The largest issue with DC-drive systems is the need for maintenance on the DC motor. Another issue is, if the DC drive malfunctions, there is no way to provide motor operation, except through connection of another DC drive. In this day of efficient power usage, the DC drive's varying power factor must be considered when planning any installation. Total operational costs may be a limitation when comparing the DC system with the AC-drive system. Although, since late sixtees, it is being predicted that AC drives will replace DC drives, however there are some definite benefits of DC drive system. This mature technology has been available for more than 60 years. For many years, the brushed DC motor has been the natural choice for applications requiring high dynamic performance. Drives of up to several hundred kilowatts have used this motor.

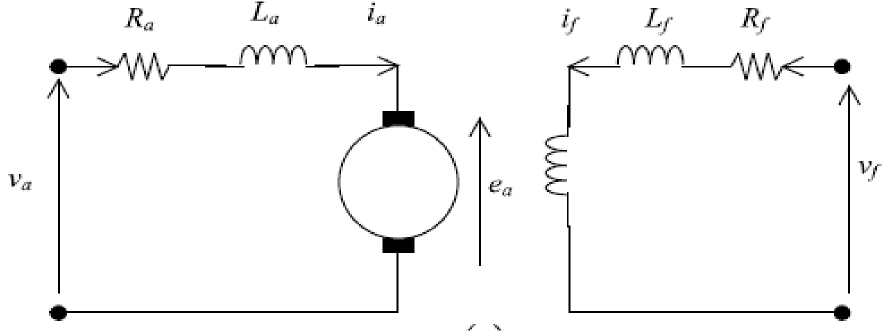
MATHEMATICAL MODELLING OF DC MOTOR

The two major components of a DC motor are the armature and field winding that interact to create rotation. For Separately excited DC motor the field receives voltage from a separate power supply, called as field exciter. When a current is passed through the armature and its field coils excited, torque is developed and the armature rotates. These rotating armature conductors cut the magnetic lines of force and therefore Back e.m.f is induced in the armature conductors. Brushes are the devices that physically connect the voltage supply to the armature circuit.

The dynamic & steady-state responses of a separately excited DC motor are dictated by Eqs. (1)-(5) [1,2,3,4,5], where K is a constant relating motor dimensions and parameters of magnetic circuits. i_a and i_f are the armature and field current respectively; v_a is the terminal voltage applied to the armature and v_f is the field excitation. J, D and T_L are the moment of inertia, damping factor and Load torque of the motor respectively and the subscript 'a' refers to armature circuit and 'f' refers to field circuit. 'ω' denotes Speed of the motor and e_b is the generated back e.m.f. The Basic parts and Equivalent circuit Diagram of the motor is shown in below Fig. 1.A) and 1.B).



1. A) DC Motor Basic Parts



1. B) Equivalent Circuit Diagram

$$\begin{array}{lll} Dynamic & Steady-state & \\ v_a = R_a i_a + L_a \frac{di_a}{dt} + e & V_a = R_a I_a + \mathrm{E} & (1) \\ v_f = R_f i_f + L_f \frac{di_f}{dt} & V_f = R_f I_f & (2) \\ e_b = K i_f \omega & E_b = K I_f \omega & (3) \\ T = J \frac{d\omega}{dt} + D\omega + T_L & T = J\omega + T_L & (4) \end{array}$$

From Eq.(3) it is evident that when load on the motor, armature resistance, strength of the field flux and motor design constant remain constant, Speed of the DC motor is directly proportional to the armature supply voltage. Speed control by sensing armature voltage is therefore feasible. The above formula will work in determining speed, when at or below the base speed of the motor.

Speed is also inversely proportional to the magnitude of the field flux. If armature voltage is at maximum and all the other components remain constant, speed can be increased by reducing the field flux. If the field winding flux is reduced, the motor speeds up and could continue to infinite speed unless safety circuits are not implemented. This method of speed control above base speed is known as the field weakening method.

$$T \approx K i_f i_a \qquad (5)$$

If the field flux is held constant, as well as the design constant of the motor, then the torque is proportional to the armature current. In armature voltage control at full field, the maximum torque that the machine can deliver has a constant value. So Armature voltage control method is termed as constant-torque drive method. In the field control at rated armature voltage, maximum power of the motor is constant; consequently, field flux control is called as constant-power drive method [4].

SPEED CONTROL TECHNIQUES

Speed control techniques of a DC motor can be classified as [2, 5]

(i)Armature Voltage Control

As the armature voltage cannot be allowed to exceed rated value, so this method can provide speed control only below base speed. This method is preferred because of high efficiency, good transient response and good speed regulation. Ward-Leonard schemes, Chopper control and Phase controlled Rectifiers are some methods where by varying armature voltage speed control is done. Thyristor ac-dc converters with phase angle control are popular for large motors, whereas chopper controlled converters are popular for servo motor drives [3].

(ii)Field Flux Control

For speed control above base speed, this method is employed. In a normally designed motor, the maximum speed can be allowed up to twice rated speed and in specially designed machines it can be six times rated speed.

(iii)Armature Resistance Control

In this method, speed is varied by wasting power in external resistors that are connected in series with the armature. It is an inefficient method and was used in intermittent load applications for example in traction.

PHASE CONTROL RECTIFIERS

The phase controlled converters are simple and less expensive and are widely used in industrial applications for industrial dc drives [4]. The phase controlled rectifiers can be classified based on the type of input power supply as

- **Single Phase Controlled Rectifiers .**
- **Three Phase Controlled Rectifiers** .

By employing phase controlled thyristors in the controlled rectifier circuits we can obtain variable dc output voltage and current. Both armature voltage and field excitation variation can be done by varying the firing angle of the thyristors. The thyristors are forward biased during the positive half cycle of input supply and can be turned ON by applying suitable trigger pulses at the gate leads. The thyristor current and the load current begin to flow once the the devices are triggered. These devices turn off due to natural reversal of ac supply voltage, which is called ac AC line (natural) commutation. We can control the thyristor conduction angle from 180^0 to 0^0 by varying the trigger angle from 0^0 to 180^0. The amount of average DC voltage conducted depends on how early or late in the AC sine wave the SCRs are “pulsed” or “gated” on. There are two types of operations possible [4].

- **Discontinuous load current operation,** which occurs for low values of load inductance and for large value of trigger angles. This operation causes deterioration in load performance, more losses in armature circuit and poor speed regulation.
- **Continuous load current operation,** for large values of load inductance and low value of trigger angle the load current flows continuously and does not fall to zero.

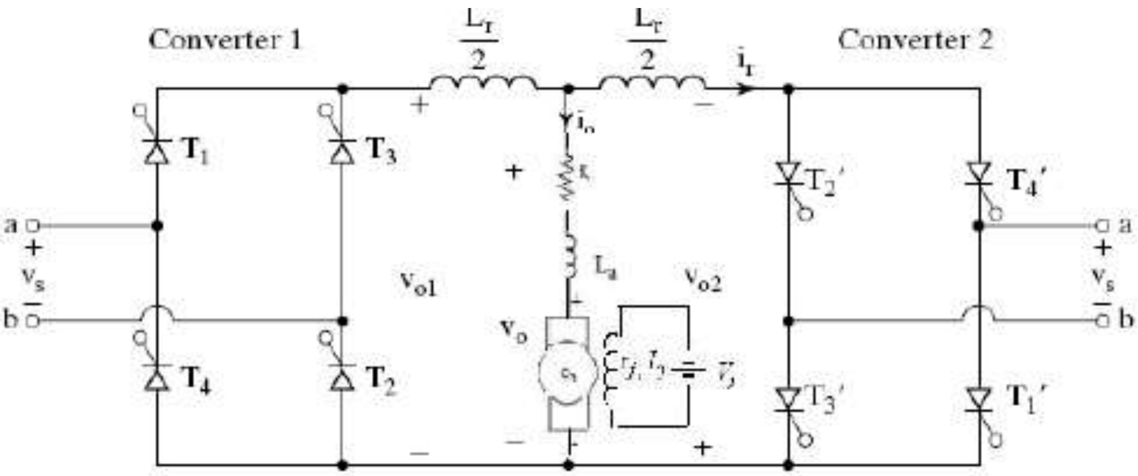
Operation of dc load in continuous current mode is always preferable which is promoted by having freewheeling action and using an external inductor in series with the load. Single Phase Controlled Rectifiers are further subdivided into different types

- **Single phase Half wave converter drives**
- **Single phase Semi-converter drives**
- **Single phase Full converter drives**
- **Single phase Dual converter drives**

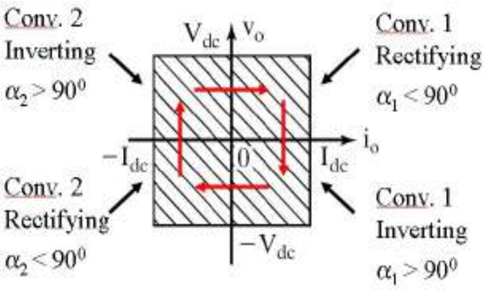
In this paper simulation model of single phase Dual converter drive is presented. The quality of the power output of these converters can be measured and given a rating called Form factor or ripple factor. High ripple causes additional motor heating, reduced load rating, and less overall efficiency. In this type of converters, the gating on and off of SCRs occurs rapidly, in milliseconds. When one SCR is almost shut off, another is starting to conduct. For a brief instant, the bridge circuit actually has a “line-to-line” short. When this happens notching occurs, which is actually fed back into the line, supplying the voltage. To reduce the affect of notching back onto the power line, line reactors are typically specified by the DC drive manufacturer. The line reactor reduces the effects of notching and cleans the power line that is used by other equipment in the building.

Single phase Dual converter drives

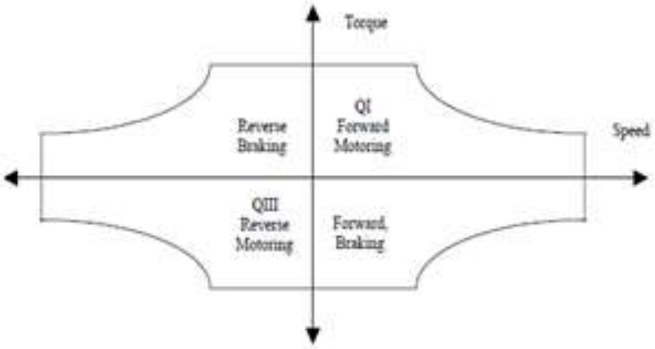
Its application is limited to about 15 kW dc drives.



2. Circuit Diagram of Single Phase Dual Converter Drive



3. a) Quadrant Diagram In V_{dc}-I_{dc} plane



3 .b) Quadrant Diagram In Torque-Speed plane

In the case of a full converter drive, the converter can operate in two different quadrants in the V_{dc}-I_{dc} plane. If two single phase full converters are connected in parallel and in opposite direction across a common load four quadrant operation is possible [4]. Such a converter is called as a dual converter which is shown in the fig.2. Fig. 3.a) & b) it is show that, for working in first and fourth quadrants converter 1 is in operation and for operation in second and third quadrants converter 2 is energized.

Motoring Mode

Converter 1 with trigger angle less than 90^0 operates the motor in forward motoring mode in QI. Whereas converter 2 with trigger angle less than 90^0 is reverse motoring mode in QIII. Operation in motoring implies that torque and speed are in the same direction (QI, QIII) and power flow is positive [2,3,4].

Braking Mode

In regenerative braking power flow is negative and the power could be regenerated back to the supply, or dissipated as heat in the dynamic brake dissipative mechanism [3]. Here the torque is opposite to the speed direction (QII, QIV). In QIV the motor operates in forward regenerative braking where Converter 1 operates with trigger angle more than 90^0 with field excitation reversed; Converter 2 with trigger angle more than 90^0 and with field excitation reversed the motor operates in reverse regenerative braking in QII.

There are two modes of operations possible for a dual converter system.

Non circulating current mode of operation

In this mode of operation only one converter is switched on at a time while the second converter is switched off.

Circulating current mode of operation

Here both the converters are switched on and operated simultaneously. If converter 1 is operated as a controlled rectifier by adjusting the trigger angle α_1 between 0^0 & 90^0; then converter 2 is operated as a line commutated inverter by increasing its trigger angle α_2 above 90^0 and feeds the load energy back to the ac supply. The trigger angles are adjusted such that they produce the same average dc output voltage across the load terminals. But the instantaneous output voltages of the two converters are out of phase, which will result in circulating current between the two converters. In order to limit the circulating current, current limiting reactors L_r are connected in series between the outputs of the two converters. The average dc output voltage of converter 1 and converter 2 are respectively [4]

$$V_{01} = \frac{2V_m}{\Pi}\cos\alpha_1 \qquad (6)$$

$$V_{02} = \frac{2V_m}{\Pi}\cos\alpha_2 \qquad (7)$$

$$\alpha_1 + \alpha_2 = 180^0 \qquad (8)$$

If we want to reverse the load current flow we have to switch the roles of the two converters.

The advantage of the circulating current mode of operation is that we can have faster reversal of load current. This greatly improves the dynamic response of the output giving a faster dynamic response. The output voltage and the load current can be linearly varied by adjusting the trigger angles to obtain a smooth and linear output control. The control circuit becomes relatively simple. The load current is free to flow in either direction at any time.

The disadvantage of the circulating current mode of operation is that we should connect heavier and bulkier current limiting reactors which increase the cost and weight of the dual converter system. The circulating current flowing through the series inductors gives rise to increased power losses decreases the efficiency. Also the power factor of operation is low. The current flowing through the converter thyristors is much greater than the dc load current.

SIMULATION

In this paper MATLAB simulation model of single phase Dual converter (Circulating mode type) based DC drive is presented considering following parameters :

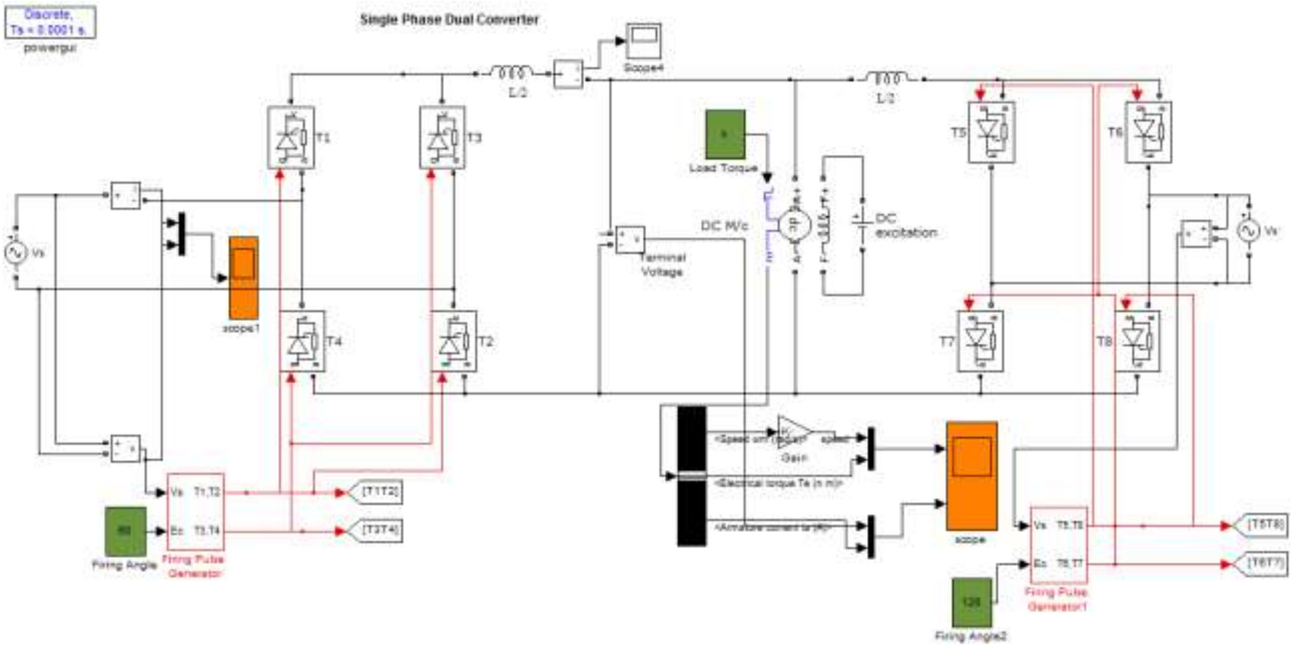


Fig. 4. Matlab simulation model of the proposed system.

Table 1. Simulation Parameters

Simulation parameters	Values
Input Supply Voltage	240 V 50 Hz
Smoothing Inductor	5 mH
DCmachine parameters	
Power	5 HP
Voltage	240 V
Speed	1750 RPM
Field Voltage	150 V

Here firing angles of the converters are varied to show the Four-Quadrant operation i.e. Forward Motoring, Reverse Braking, Reverse Motoring and Forward Braking.

Forward Motoring

In this mode thyristers of Converter 1 are triggered with angle less than 90^0 . Simulation results show that torque and speed are in the same direction (QI) ; output load voltage & current both are positive. Therefore power flow is positive.

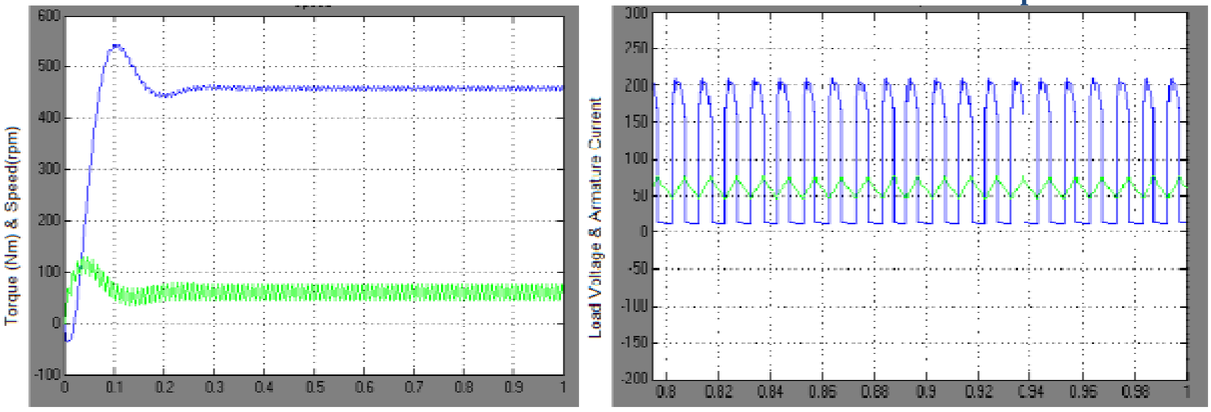


Fig. 5. Simulation results of Forward Motoring mode

Reverse Braking

In regenerative braking power flow is negative and the power could be regenerated back to the supply. Simulation result show that the torque is also opposite to the speed direction. Here Converter 2 is in inverting mode as the thyristers of Converter 2 are triggered with firing angle greater than 90^0 .

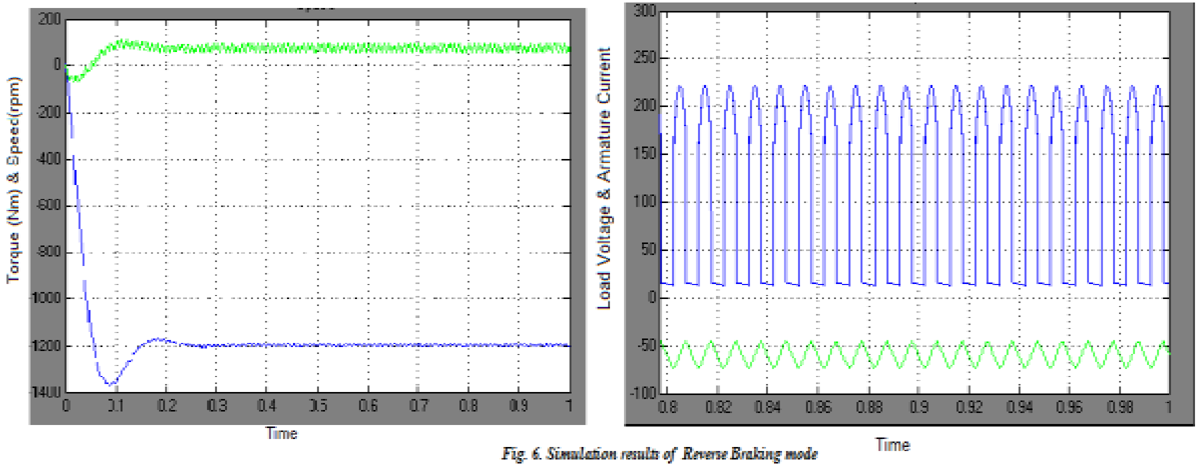


Fig. 6. Simulation results of Reverse Braking mode

Reverse Motoring

This is third quadrant operation. As output load voltage & current both are negative; power flow is positive. Here the thyristers of Converter 2 are triggered with firing angle less than 90^0 .

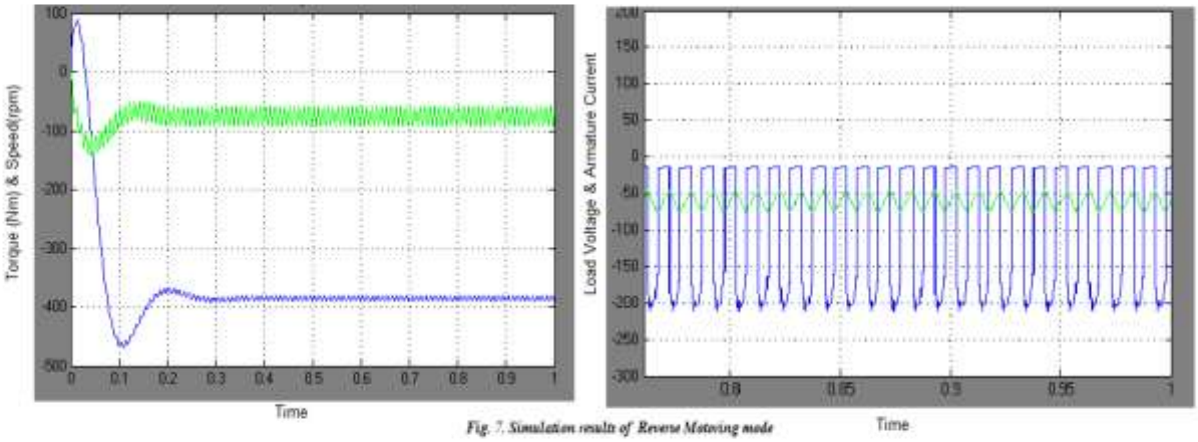


Fig. 7. Simulation results of Reverse Motoring mode

Forward Braking

In this mode thyristers of Converter 1 are triggered with angle greater than 90^0 . So converter 1 is in inverting mode. Simulation results show that torque and speed are in the opposite direction (QIV) .

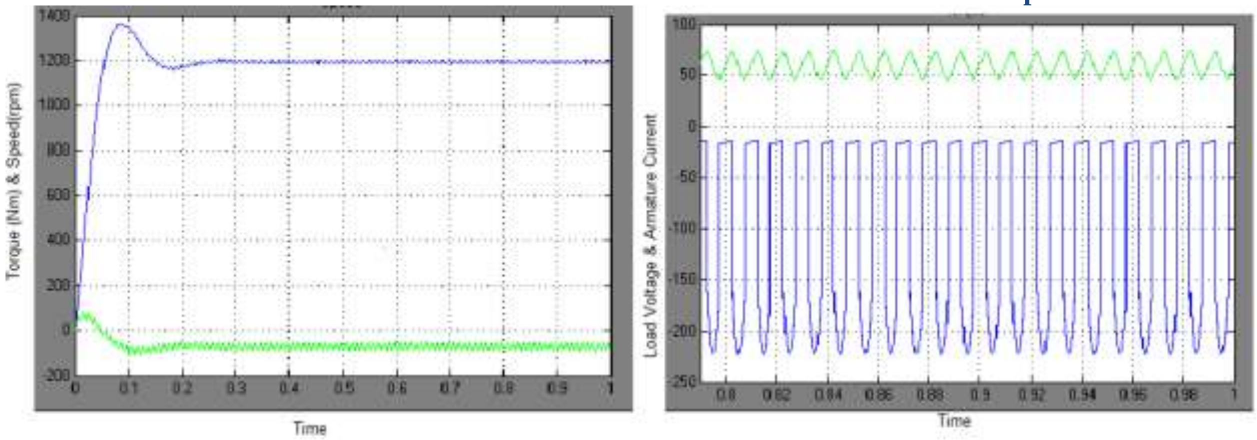


Fig. 8. Simulation result of Forward braking mode

CONCLUSION

There are various methods (both open loop & closed loop) for speed control of DC motor suggested in literature [1]. This paper presents one of the simplest methods of speed control (open loop control). The dual converter system provides four quadrant operation and is normally used in high power industrial variable speed drives. We can have bidirectional load current and dc output voltage. The magnitude of output voltage and current can be controlled by varying the trigger angles of the converters. Moreover, this performance has encouraged us to prepare a closed loop control model for more accuracy in future.

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