A NOVEL REVERSABLE DC SERIES MOTOR DRIVE

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***Abstract*- Series DC motor has a high starting torque and therefore it is used in traction applications. Reversing speed direction of this machine is conventionally achieved via a relay arrangement which results in waste of energy during braking. Regenerative operation reduces the time taken to stop the machine and feeds energy back to the supply, hence improves the overall performance and efficiency. In this paper, a novel reversible DC series motor drive is presented which allows both speed control within the constant torque region and reversing speed direction through regenerative operation while providing the conventional performance of the DC series motor. The field winding is connected to the armature via an uncontrolled bridge rectifier to keep direction of field current unchanged. The armature and rectifier field combination is connected to a DC supply via a class E-chopper. The operation of the proposed reversible drive is explained and the dynamic model is presented. The switching of the chopper is controlled so as to provide positive and negative voltage loops across the series, armature-rectified field windings. The transient response of the open loop control system is theoretically simulated using MATLAB software and experimentally investigated using the PIC16F877 microcontroller.**

***Index Terms*- Regeneration, Reversible Drive, Series motor, H-Bridge, Pulse Width Modulation (PWM), Implementation, Microcontroller, Simulation.**

NOMENCLATURE

E : back emf.
V_f , I_f : field voltage and current.
V_a, I_a : armature voltage and current.
V_s, I_s : supply voltage and current.
V_{FA} : voltage applied to the series field and armature combination motor windings.
ω_r, N_r : angular speed in rad/s and rpm respectively.
T_e, T_L : developed and load torque.
K_m : motor constant.
J, B : coefficients of inertia and friction.
R_a, R_f : armature and field resistance.
L_a, L_f : armature and field inductance.
T_{+ve}, T_{-ve} : Period of positive and negative voltage loops.
D : % duty cycle ratio= $\frac{T_{+ve}}{T_{+ve}+T_{-ve}}$ x 100

I. INTRODUCTION

DC motor plays a significant role in many industrial applications [1]. It is used extensively in variable speed drive as it provides high starting torque and possible speed control over a wide range in a simple and less expensive way than those of AC drives [2]. On the other hand, DC motor requires more maintenance than AC motors besides it is not suitable for high-speed applications due to commutator problems [3]. Shunt DC motor is normally used when an almost constant speed drive is required while series DC motor is used when large starting torque is required especially in traction applications such as subway cars, automobile starter, cranes and blenders [4]. Since the torque developed by the series motor is proportional to the square of the applied voltage, the torque developed can be controlled by controlling the applied voltage [5]. Controlled rectifiers and DC choppers provide, from a fixed AC and DC voltage supply respectively, a variable DC output voltage which can be used in variable speed drives where the motor may operate in motoring, regenerative, braking, plugging or four quadrant modes depending on the structure of the converter used [6-9]. In this paper, the reversable drive of a DC series motor, shown in figure (1) is proposed and implemented using the PIC 16F877 microcontroller. The field winding is connected to the armature via an uncontrolled bridge rectifier to keep direction of field current unchanged. The armature and rectifier field combination is connected to a DC supply via a class E-chopper. This drive makes use of the following:

i) Advantage of high starting torque of the DC series motor.

ii) Possibility of motor speed control up to base speed within the constant torque operating range.

iii) Possibility of reversing armature current direction keeping field current direction constant and thus reversing speed direction through regenerative braking. Conventionally, this advantage was not possible when the contactor/relay arrangement was applied due to the waste of energy during speed reversal.

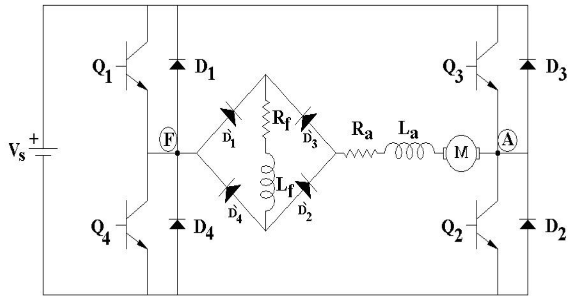


Fig.1 Connections of the proposed four quadrant series motor drive.

II. OPERATION OF THE PROPOSED REVERSIBLE DRIVE

Figure (2) shows the circuit connection analysis of the proposed drive during the different four quadrant operation modes. The two forward modes (i.e. motoring & regeneration) are obtained if the duty cycle D>50% as the average voltage seen by the field-armature combination is positive, hence the armature current is positive. The other two reverse modes are obtained if D<50% since the average voltage is negative and so is the armature current. In all four modes, the field current is always positive due to the action of the 4-diode bridge rectifier. From figure (2a) it can be seen that supply voltage and current are positive and also field and armature currents are positive. Therefore, the electrical power is transferred from the supply to the motor electrical power in the field and mechanical developed output power from the armature. In figure (2b), I_a and I_f are positive, hence the torque is in forward direction, while V_s is positive and I_s is negative, hence the energy is regenerated back to the supply. Same analysis can be seen from figures (2c) and (2d) but since I_a is negative while I_f is positive the torque will be in the reverse direction.

III. DYNAMIC MODEL OF THE PROPOSED DRIVE

The dynamic model of the proposed drive, shown in figure (1), can be derived from the dynamic equations of the DC motor which are given by [10-12]:

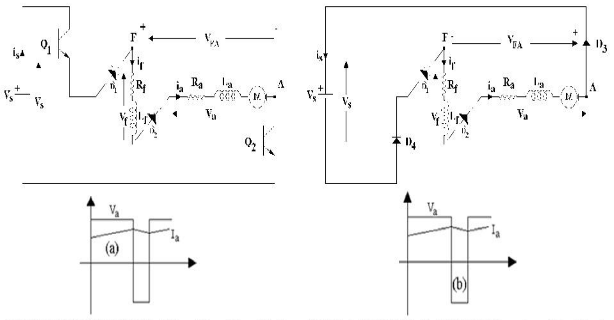
$$e = K_m i_f \omega_r \tag{1}$$

$$L_a \frac{di_a}{dt} + R_a i_a + e = v_a \tag{2}$$

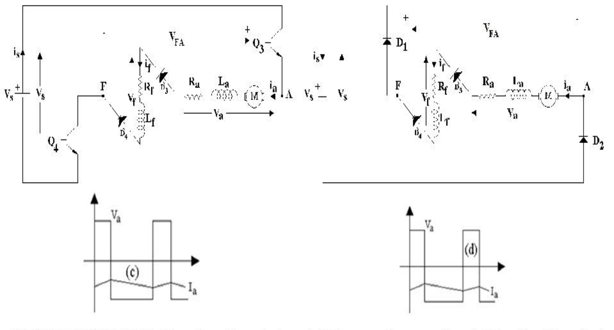
$$L_f \frac{di_f}{dt} + R_f i_f = v_f \tag{3}$$

$$J \frac{d\omega}{dt} + B\omega = T_e - T_L \tag{4}$$

$$T_e = K_m i_f i_a \tag{5}$$



(a) Forward Motoring ($+V_s, +I_s, +I_f, +I_a$) (b) Forward Regeneration ($+V_s, -I_s, +I_f, +I_a$)



(c) Reverse Motoring ($+V_s, +I_s, +I_f, -I_a$) (d) Reverse Regeneration ($+V_s, -I_s, +I_f, -I_a$)

Fig.2 Analysis of the circuit connection during the different four quadrant operation.

Since the direction of field current (I_f) is kept constant because of the bridge rectifier, the torque given in (5) can be rewritten as:

$$T_e = K_m i_a \ \text{abs}(i_a) \tag{6}$$

Also, because of the series connection and the class E chopper, it can be seen that:

$$v_{FA} = v_f + v_a \tag{7}$$

while,

$$v_{FA} = \begin{cases} + v_s \ \text{during positive period} \\ - v_s \ \text{during negative period} \end{cases}$$

The block diagram of the open loop system is simulated using the SIMULINK of the MATLAB software as shown in the figure (3) based on equations (1) to (7). The system has two inputs, the load torque and the chopped voltage applied to the motor from the supply through the power converter. The motor speed can be reversed by reversing the average applied voltage to the motor, dislike the conventional DC series motor as its speed direction is independent of the polarity of the supply voltage. As the speed of the proposed DC motor changes with the load torque and to maintain a constant speed, the average value of the applied voltage should be varied continuously by varying the duty cycle of the four-quadrant DC chopper.

IV. SIMULATION RESULTS

The control signals of the four switches of the class-E chopper are adjusted to enable the four operation modes as described in figure (2).

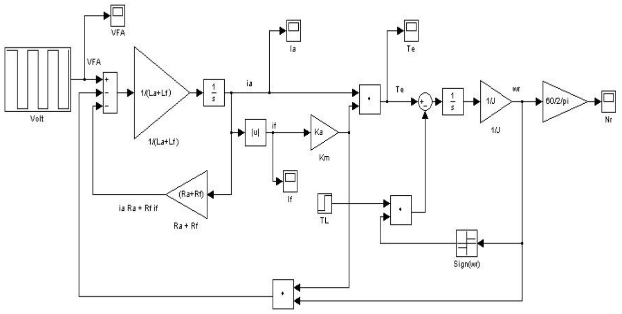


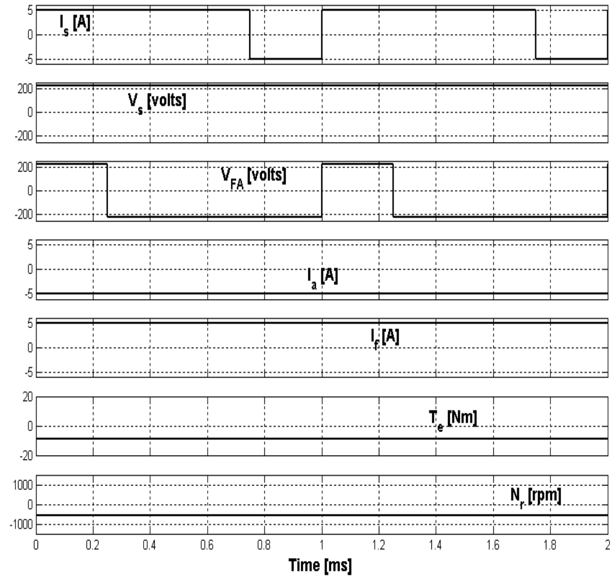
Fig.3 Simulation block diagram of proposed novel DC series motor.

The four switches of the class-E chopper are pulse width modulated where the upper switch of one leg and the lower switch of the other leg are switched on in turn with the other two switches (i.e. $G_1 = \overline{G_2} = \overline{G_3} = G_4$). When switches Q_1 and Q_4 are turned on, the applied voltage to the motor (V_{FA}) is positive and when switches Q_2 and Q_3 are turned on, V_{FA} is negative. With reference to switch Q_1, the duty ratio, D, varies from zero to 100% such that when duty ratio is 50%, V_{FA} is symmetrical rectangular whose average value is zero at which the motor is stalled. When the duty ratio is less than 50%, the average voltage applied to the motor is negative and the machine runs in anticlockwise direction. Conversely, when the duty ratio is more than 50%, the average voltage applied to the motor is positive and the machine runs in clockwise direction. The average voltage to the motor can be expressed as follows:

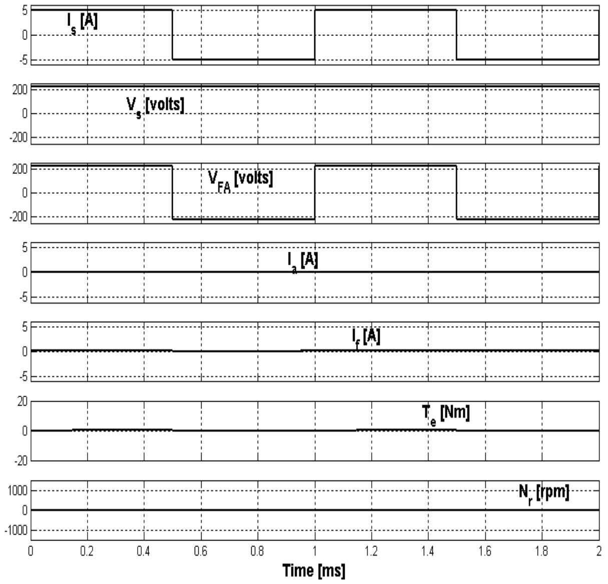
$$V_{FA_{av}} = \frac{V_s}{100}(2D\% - 100) \quad (8)$$

Figure (4) shows the simulated waveforms of V_s, I_s, V_{FA}, I_f, I_a, T_e and N_r for different duty cycle ratios D.

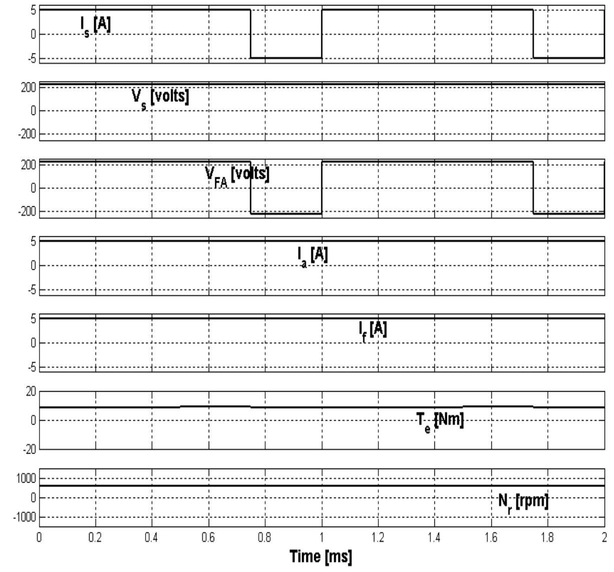
It can be noted from the results of figure (4) that the motor voltage (V_{FA}) is bi-polar whereas the current is uni-polar depending on the average voltage which is determined according to the operating duty cycle. This verifies a two-quadrant (forward motoring and re-generative) operation modes for one speed direction. The same applies to the other speed direction, and therefore a full four-quadrant operation is obtained. Armature and field currents are continuous due to the high inductive value of the armature and field windings. The speed direction is dependent on the average value of the applied voltage, i.e. for duty cycles between 100% to 50%, speed direction is positive and for duty cycles between 50% to zero, speed direction is negative. At D=50% average voltage is zero and the motor is in standstill position. When the average voltage is negative, the armature current is negative whereas the field current is still positive, thus speed is reversed.



(a) D=25%.



(b) D=50%.



(c) D=75%.

Fig. 4 Simulation waveforms for open-loop model of drive system at different duty cycles.

Results form figure (4) show the bi-polarity of the supply current. This shows that for different duty cycle values, energy is exchanged between supply and motor (re-generative). At D= 50%, average supply current is zero showing that equal amounts of energy are given up and recovered by the supply, hence the motor is in stand-still position (N_r = 0). During duty cycles higher or lower than D= 50%, the motor is running in either direction. This explains why the average supply current is positive regardless of duty cycle value. The motor draws more energy from supply than is re-generated which explains its continuous running with no braking. As the duty cycle tends to D = 50%, more energy is being recovered allowing quicker braking performance of motor.

In order to examine the transient response of the motor when a step change in average motor voltage is applied, the motor was loaded with T_L=8.5 Nm from the starting instant and the results are shown in figure (5). As depicted, the value of the motor terminal voltage is suddenly reversed from positive V_{FA} to negative V_{FA} at t_1=4 sec by changing the duty cycle from 100% to 0%. The armature current drops to zero then reverses at t_2=4.01 sec while the field current I_f is always positive due to the bridge rectifier, hence the torque and the speed are both reversed consequently. During the period t_1 to t_2, the motor voltage is negative while its current is positive. For this short time period, the motor is acting as a generator returning its stored energy through the freewheeling diodes path to the supply, hence braking process is quicker yielding higher efficiency in overall performance. Once the armature current has decayed, the motor starts running in the reverse direction. This verifies the proposed re-generative operation. To avoid high transient currents during speed reversing, a current limiter is a must in this application. This limits the current to a safe value ensuring a safe operation.

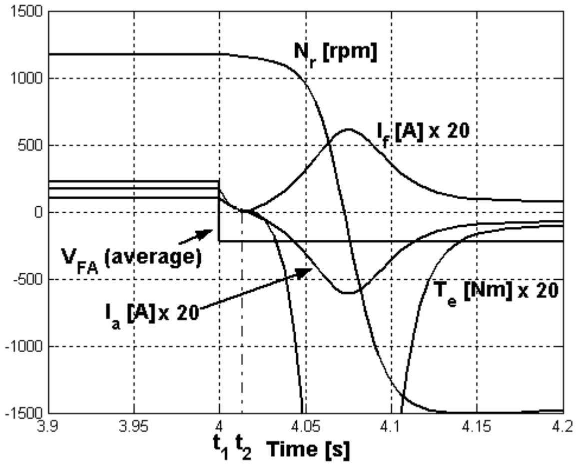
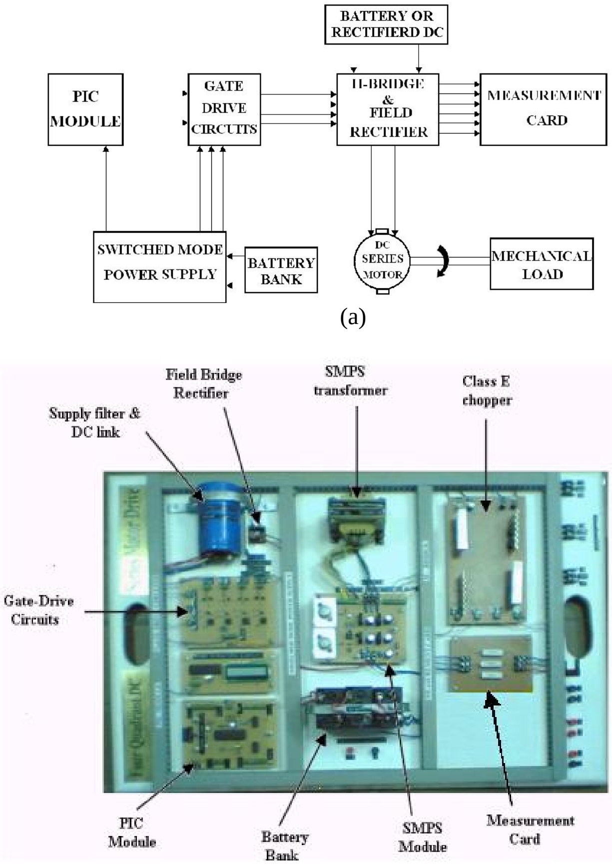


Fig. 5 A step change in average motor voltage to examine the transient response illustrating the regeneration principle at the reversing instant.

V. EXPERIMENTAL SETUP

Figure (6) shows the schematic diagram and a photograph of the experimental rig which represents a traction application. The 2.2kW, 1500 rpm, 220V DC series motor is driving a mechanical load and the field winding is connected to the armature via a bridge rectifier and the armature-field combination circuit is fed from a power battery. Each block of figure (6) has been individually designed, implemented and tested then the overall system has been gathered to drive the motor via a class-E chopper as shown in figure (1).

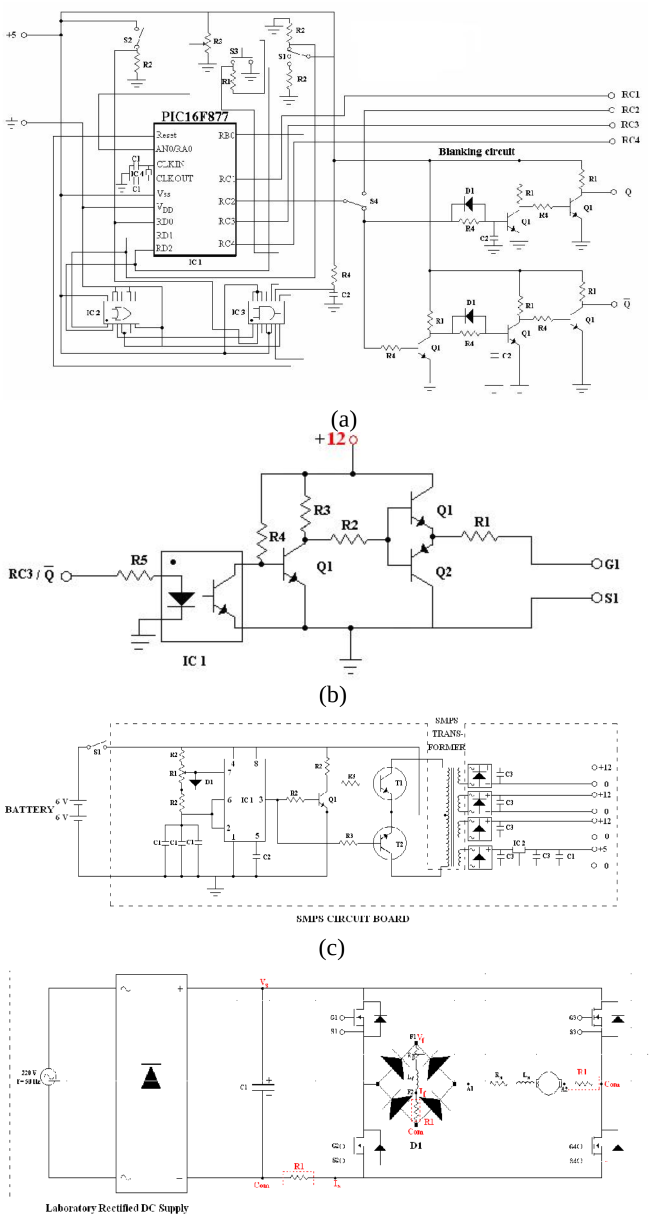
The class E- chopper, shown in figure (7d), of the armature utilizes four N-channel and four IXYS fast recovery free wheeling diodes with designed gate drive circuit and dead band circuit shown in figure (7a) ensuring 12 μsec between two switches in one leg. The bridge rectifier of the field, shown in figure (7d), utilizes Kbpc3506 uncontrolled bridge rectifier. The PIC16F877 microcontroller [13] shown in figure (7a) is used to implement the open loop control circuit. The gate drive circuits, shown in figure (7b), and the PIC module are biased from a designed Switched Mode Power Supply (SMPS), shown in figure (7c) which provides different voltage levels with different isolating ground from a single battery source.



(a)

(b)

Fig.6 The Experimental Setup. (a) Block Diagram. (b) Actual Photograph.



(a)

(b)

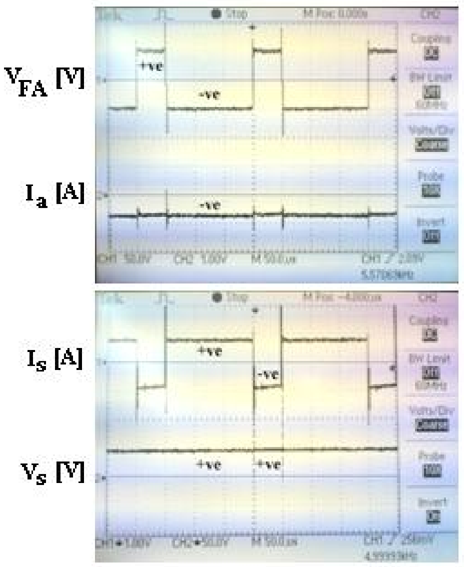
(c)

(d)

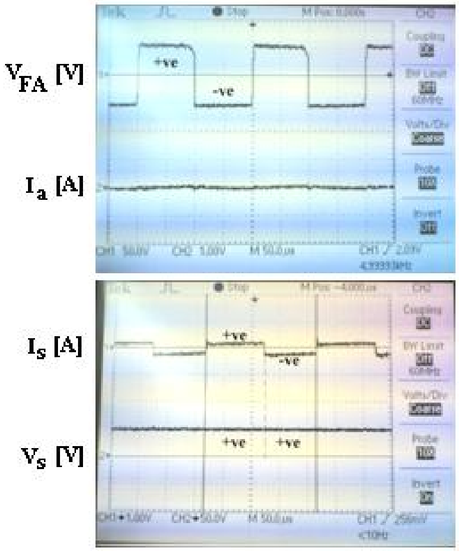
Fig. 7 Schematic diagram of the: (a) PWM signal generation PIC circuit (b) Gate Drive Circuit. (c) Switched Mode Power Supply Circuit. (d) Power circuit of the drive system.

The required command signal is implemented in analogue to the PIC microcontroller and after being digitally converted, the signal (Q) is pulse width modulated and the complement of the signal ($\bar{Q}$) is generated through the NOT and blanking circuit to feed the four switches Q_1 to Q_4. The microcontroller produces TTL signals to the gate drive circuits which provides the MOSFETs with isolated 12V signals (see figure 7b).

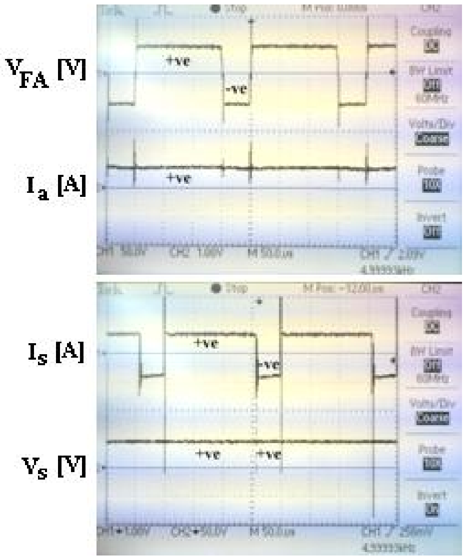
Figure (8) shows the experimental steady state motor voltage and current and supply voltage and current for different duty ratios, while figure (9) shows the experimental transient response of the machine to a step change in the direction of the command reference speed i.e. response to speed reversal.



(a) D= 25% (N_r= -550 rpm, I_a= -0.7A).

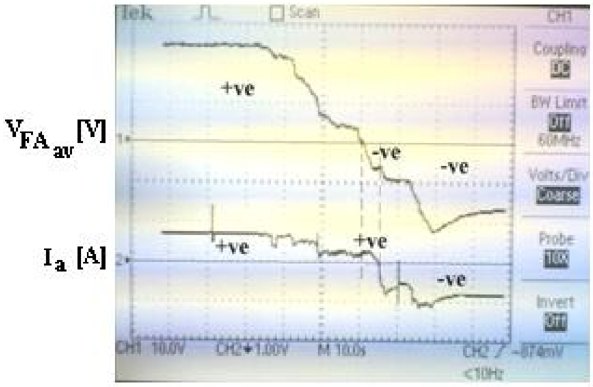


(b) D= 50% (N_r= 0 rpm, I_a=0A).



(c) D= 75% (N_r= 550 rpm, I_a=0.75A).

Fig. 8 Experimental waveforms at different duty cycles.



CH1=Average Armature Voltage (V_a) x10 [V].
CH2=Armature Current (I_a) [A] x10 [V].

Fig. (9) Experimental waveforms showing motor behaviour in response to a step change in command reference speed.

It can be seen that the experimental results shown in figures (8) and (9) are similar to the simulated results obtained in figures (4) and (5) respectively showing the effectiveness of the proposed setup to drive the series motor through a class-E chopper with four-quadrant operation (similar to the four-quadrant drive of the separately excited DC motor) while providing the high starting torque characteristics of the series motor required for traction applications.

CONCLUSION

A drive system to control and reverse the speed direction of DC series motor is proposed. The field winding is connected through a single phase uncontrolled bridge rectifier, in series to the armature winding such that the direction of the field current does not change even if the direction of the armature current does. The armature winding and the field circuit are connected to a DC supply through a class-E chopper. The drive system is simulated using MATLAB software and transient response is shown for positive and negative voltage loops. The experimental setup is tested and the PIC16F877 microcontroller is used to generate the control signal of the switches. As there is no independent control on the field current, the field weakening operation would not be possible. This drive allows high starting torque performance like the conventional DC series motor and reversing speed direction through regenerative braking with control up to base speed within constant torque operating ranges with higher efficiency.

It should be noted that the proposed setup can easily control the speed value and direction with only one reference (single hand drive for traction application instead of the conventional contactor two-hand drive; one for speed direction and the other for speed value).

The paper introduces the open-loop control which is the case of most traction applications as the driver provides the closed loop path, however closed loop operation (cruising) may be provided by simply measuring speed and controlling the PWM according to the error signal which can be implemented through the PIC software programming.

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