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A TRANSISTOR "MOSFET" CHOPPER FOR MICROPROCESSOR CONTROL OF D.C. MOTORS

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ABSTRACT

Power MOSFETs offer many advantages over conventional bipolar transistors . These advantages include very fast switching , absence of second breakdown , wide safe operating area, extremely high gain, and high input impedance with low drive requirements. This paper presents an experemental DC to DC chopper circuit using parallel connected power MOSFETs for speed control of a seperately excited DC motor. The circuit operates from a 48 V battery and provides a maximum motoring current of 20 A . The piloting of the chopper is achieved by microprocessor .

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INTRODUCTION

Efficient speed control of DC motors operating from DC supplies is today accomplished with switching chopper circuits using forced commutated thyristors or bipolar transistors . Battery operated systems rated at hundreds of amperes are in common use in forklift truck,aircraft drives,and electrical vehicle controllers.Larger thyristor choppers rated at thousands of amperes ; at DC voltages up to 1500 V , are in use in high power railway traction applications.

An exciting new power semiconductor switching device is the power MOSFET [1],[2].This offers the advantage of very high gain , very rugged performance , and very fast switching speed. The power MOSFET lends itself readily to paralleling and a power MOSFET chopper operating at currents of several hundred amperes is technically within grasp.

In this paper , a chopper circuit of about 1 KW using power MOSFET is described . This chopper is piloted by microprocessor for speed control of a seperately excited DC motor .

THE POWER MOSFET

The conventional bipolar transistor is essentially a current driven device. A current must be applied between the base and emitter terminals to produce a flow of current in the collector.

The MOSFET is fundamentally different , it is a voltage controlled device. A voltage must be applied between the gate and source terminals to produce a flow of current in the drain . The gate is isolated electrically from the source by a layer of silicon oxide . Theoretically no current flows into the gate when a DC voltage is applied to it , though in practice there will be an extremely small leakage current , in the order of nanoamperes.

When a voltage is applied between the gate and source terminals an electric field is set up within the MOSFET. This field modulates the resistance between the drain and source terminals and permits a current to flow in the drain in response to the applied drain circuit voltage. The amount of current that flows depends upon the amount of voltage applied to the gate (fig.1), assuming that the impedance of the external drain circuit is not limiting. When a sufficient voltage is applied between the gate and source,the MOSFET operates as a closed switch and the drain current is essentially determined by the supply voltage and the impedance of the drain circuit. This mode of operation is comparable to operation of bipolar transistor in saturation regime.

The extremely low drive current requirement of the power MOSFET and the associated extremely high power gain, are a major advantage over the conventional bipolar transistor or Darlington, This feature will often make it possible to drive the power MOSFET directly from CMOS or TTL integrated circuit logic .

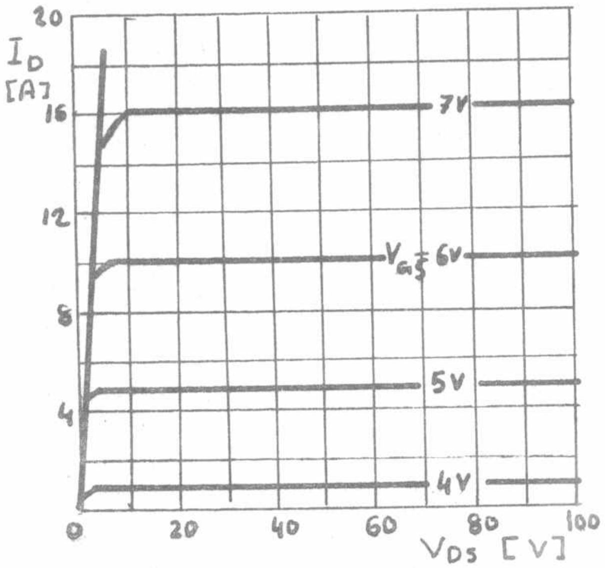


Fig.1. Output characteristics of IRF630

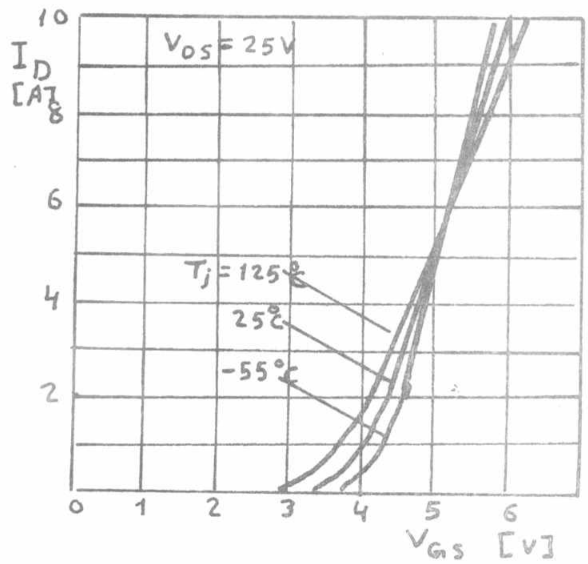


Fig.2. Transfer characteristics of IRF630

Safe Operating Area

One of the outstanding features of the power MOSFET is that it does not display the second breakdown phenomenon of the bipolar transistor and as a result, it has an extremely rugged switching performance . The safe operating area is simply determined by the power dissipation specified for all the values of drain-source voltage till the specified maximum voltage. Also the safe operating area for pulsed mode is greater than that of bipolar transistors.

Threshold Voltage

As the gate to source voltage is increased from zero, initially the drain current does not increase significantly. Only once a certain threshold gate voltage has been reached, does the drain current start to increase appreciably (fig.2).

On Resistance

When the gate is commanded in such a way that the power MOSFET conducts as a closed switch, the drain-source voltage drop is approximately proportional to drain current. In other words, the MOSFET appears essentially as a resistive element in the circuit. So, On-resistance $R_{DS(on)}$ of the power MOSFET is an important characteristic because it determines the power loss for a given drain current.

Paralleling Of Power MOSFET

Power MOSFETs are easy to parallel, because the positive temperature coefficient forces current sharing among the paralleled devices. Current sharing resistors, with their associated power losses, are not necessary. They, therefore, lend themselves well to the construction of a chopper rated at several hundred amperes, and the problems of paralleling will be much less than those associated with bipolar transistors. Some resistance in series with the gates (typically 100 ohms), and close paralleled lead connections may be necessary to assure that the good high frequency response of the MOSFETs does not cause oscillations.

Switching Times

MOSFET power transistors are much faster than bipolar power transistors of comparable size, primarily because they do not have minority carrier delay times. The response times of MOSFETs are determined primarily by the device capacitances and secondarily by such factors as the extremely short channel transit time of the electrons.

The input capacitance, C_{iss} is the primary factor which determines the response time of a MOSFET. Although MOSFETs can be controlled by extremely low currents, the relatively long charge and discharge times of the input capacitance, C_{iss}, results in a trade off of response time against extreme sensitivity. For this reason, the driving circuit must be capable of providing a sufficiently high current in a very short time in order to charge the input capacitance in the shortest possible time.

THE CHOPPER CIRCUIT

Principle Of Operation

The realized chopper circuit[3], given in fig.3 is divided in two main parts: the power part , and the control part . The power part includes the input filter (L_1 , C_1), the output filter (L_2), the main switch (Q), the freewheeling diode (D), the DC supply, and the DC motor (M). The input filter is connected to smooth the supply current and to keep the input voltage constant. The switch (Q) is realized by power MOSFETs and operates at constant frequency. The diode (D) circulates the load current when the switch (Q) is opened. The inductance (L_2) smoothes the chopper output current.

The switch (Q) is periodically closed during the time $t_{on} = \alpha T$, and opened during the time $t_{off} = (1-\alpha)T$, where:

α = duty cycle,

T = chopping period.

Neglecting all losses and assuming that the voltage $V_e = V_c$ = constant, the voltages and currents waveforms will be as shown in fig.4. Assuming a continuous conduction of current in the inductance L_2, we can prove that the output voltage (V_o) depends only on the input voltage (V_e), and the duty cycle α, [4], that is :

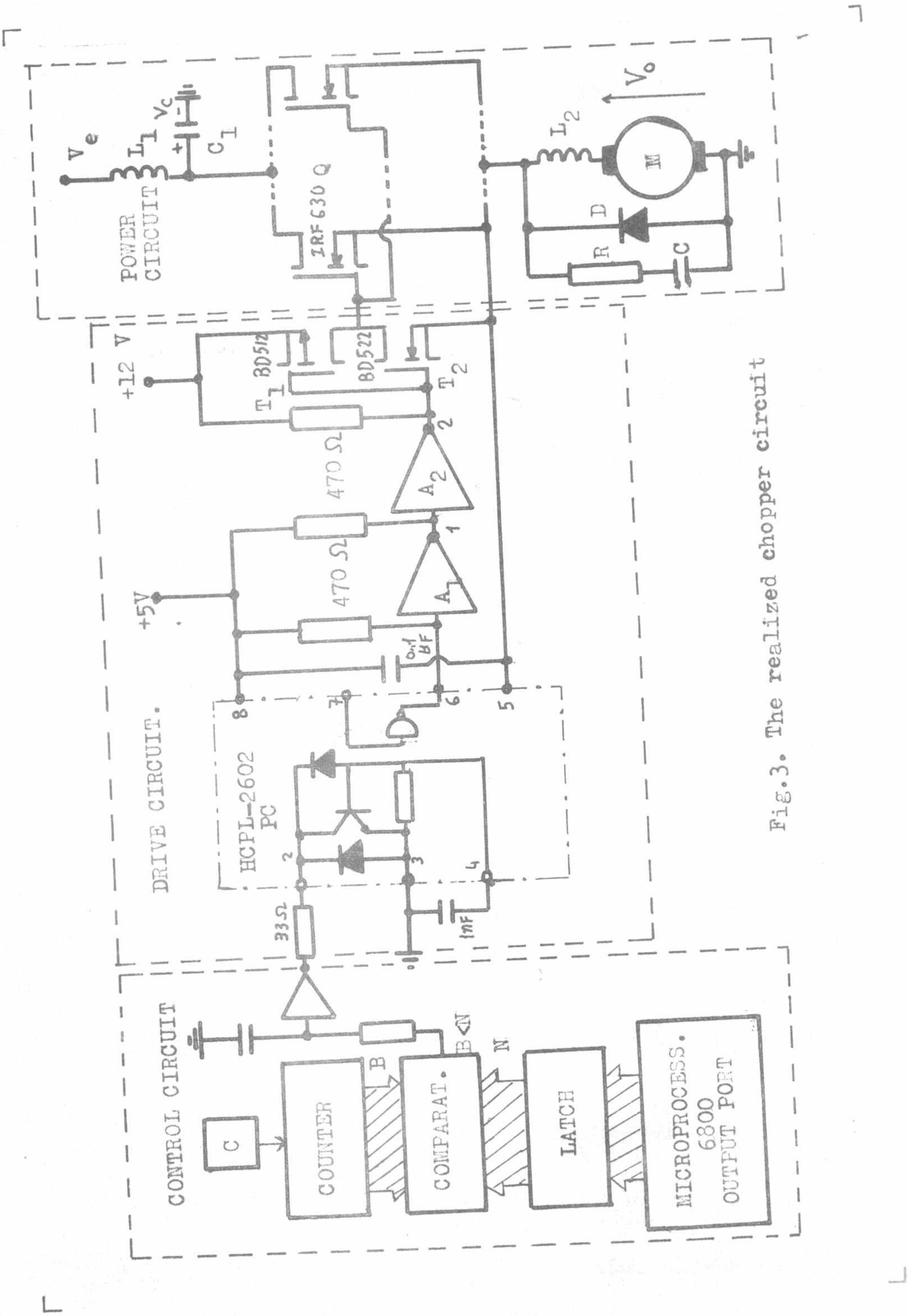


Fig.3. The realized chopper circuit

$$V_o = \alpha V_e \qquad (1)$$

Thus by changing the value of α, the voltage applied to the motor armature is changed. By this way the motor speed can be controlled.

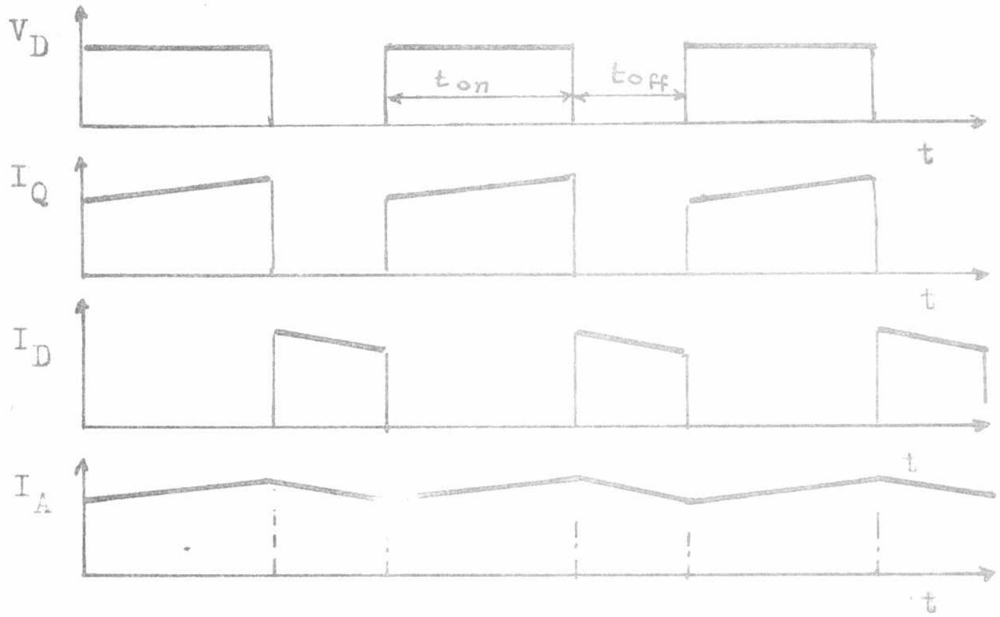


Fig.4. Chopper waveforms

Drive Circuit

The gate drive circuit, (fig.3) ,has a photocoupler PC for galvanic separation between the control part and the power circuit. The inverter A_1 is used for reforming the output pulses from PC. The push-pull connection realized by T_1, T_2 must be able to provide sufficiently high instantaneous currents for fast charging and discharging of MOSFET input capacitances. The gates of T_1, T_2 are attacked by the open collector inverter A_2 to ensure their correct operation,[5].

Control Circuit

This circuit recieves a digital number from the microcalculator and delivers periodically rectangular pulses at a frequency of 80 KHz to the input of the photocoupler PC (fig. 3) [6].The length of the control word depends on the control algorithm and it can be changed from 0 to 255 (decimal). this word is first memorized in a "latch up" circuit in order to keep its value independant on the state of the microcalculator output port during the time of calculation of the next control value.A digital comparator compares the control word with the output of a counter piloted by a clock of 20 MHz . At the output of the comparator we get rectangular pulses at constant frequency and with durations modified according to the control word N recieved from microcalculator (fig.5).

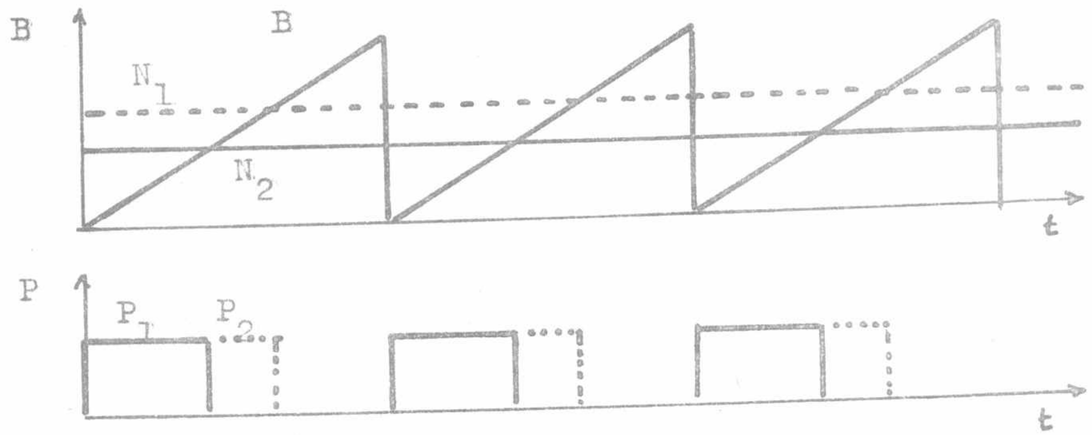


Fig.5. Waveforms of control circuit.

Commutation

The theoretical voltage and current waveforms for different commutation phases are given in fig.6 .At the instant t_o, the MOSFET is blocked and a current I_o flows in the load and the diode D. At the begining of a commutation,the voltage V_{gs} increases till the threshold value V_T (instant t_1). During the period $(t_o - t_1)$,the transistor is still blocked and its drain current is null. At the instant t_1 ,the transistor enter in its active zone. The rate of increase of current I_{DS} is limited by the drain and source inductances and by the reaction of drain and source voltages on the gate voltage. The diode D starts its inverse recovery when I_{DS} reaches I_o . The current I_{DS} continues to increase till it attains its maximum value I_P at the instant t_2,when the diode is able to support an inverse voltage. The value of I_P can be reduced by choosing as fast diode as possible,and if necessary by reducing the rate of increase of I_{DS} through action on the gate voltage. At the instant t_3 ,the transistor conducts and the diode is blocked. The dissipated energy during this phase $(t_1 - t_3)$ is given by :

$$W_{sat} = \frac{V_{pL} \cdot I_p}{2} (t_3 - t_1) \qquad (2)$$

At the instant t_5 a blocking signal is applied on the transistor gate. The voltage V_{gs} decreases to the limit of saturation $(t_5 - t_6)$. From t_6 to t_7 , V_{DS} increases at constant I_{DS} , the diode D is put into conduction at t_7 . The dissipated energy in the transistor during the blocking phase is given by :

$$W_{bl} = \frac{I_m . V_e}{2} (t_8 - t_6) \qquad (3)$$

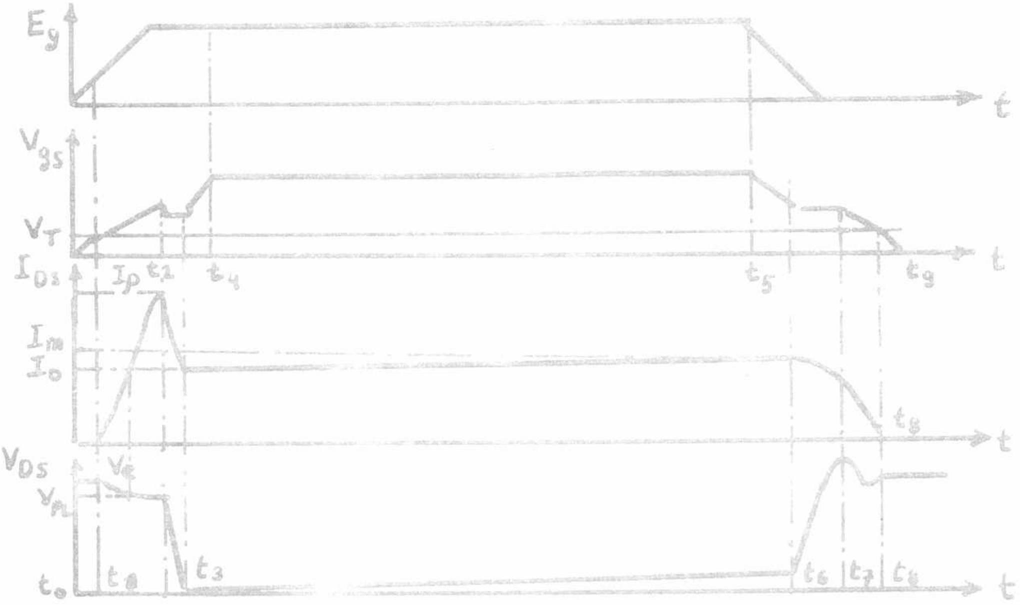


Fig.6. Voltages and currents during commutation.

Chopper Losses

The losses in different components must be minimized in order to have an overall efficiency as neer to one as possible. The losses in the inductances can be minimized by the utilization of ferrite cores and by operation at high chopping frequency. These requirements are easily met when using the MOSFET technology. The losses due to the voltage drop across the freewheeling diode can be reduced when we choose a diode with small forward voltage drop.The losses in the MOSFET are : conduction losses, commutation losses, and that in the drive circuit. The conduction losses depend on the operating current and on the value of resistance $R_{DS(on)}$. These losses can be reduced by choosing transistors with small $R_{DS(on)}$ and by parallel association of transistors which is easily done with MOSFETs. The losses in the drive circuit are very small because MOSFETs are voltage controlled devices.The commutation losses are proportional to chopping frequency and to commutation times. For a given frequency,the commutation times can be minimized,if the drive circuit is capable of supplying sufficiently high current pulses for fast charging and discharging of input capacitances.

SPEED CONTROL OF DC MOTORS

The general scheme of microprocessor speed control of DC motor is given in fig.7. The armature is connected to the DC

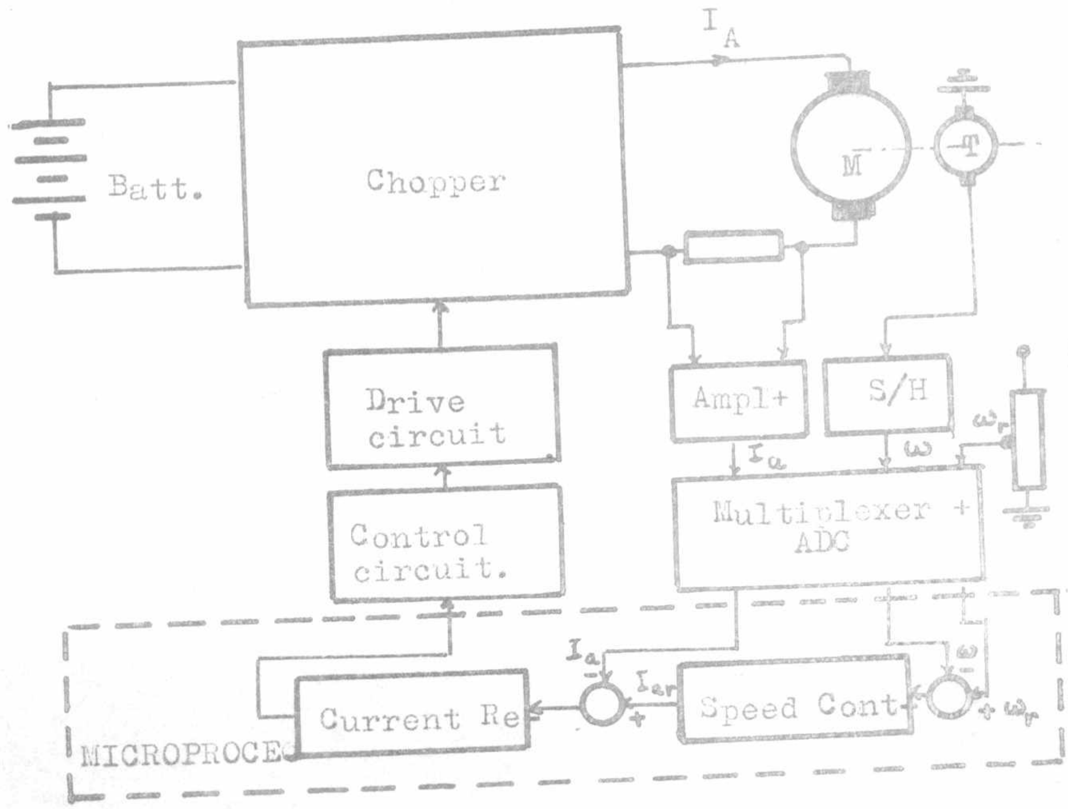


Fig.7. General scheme of speed control.

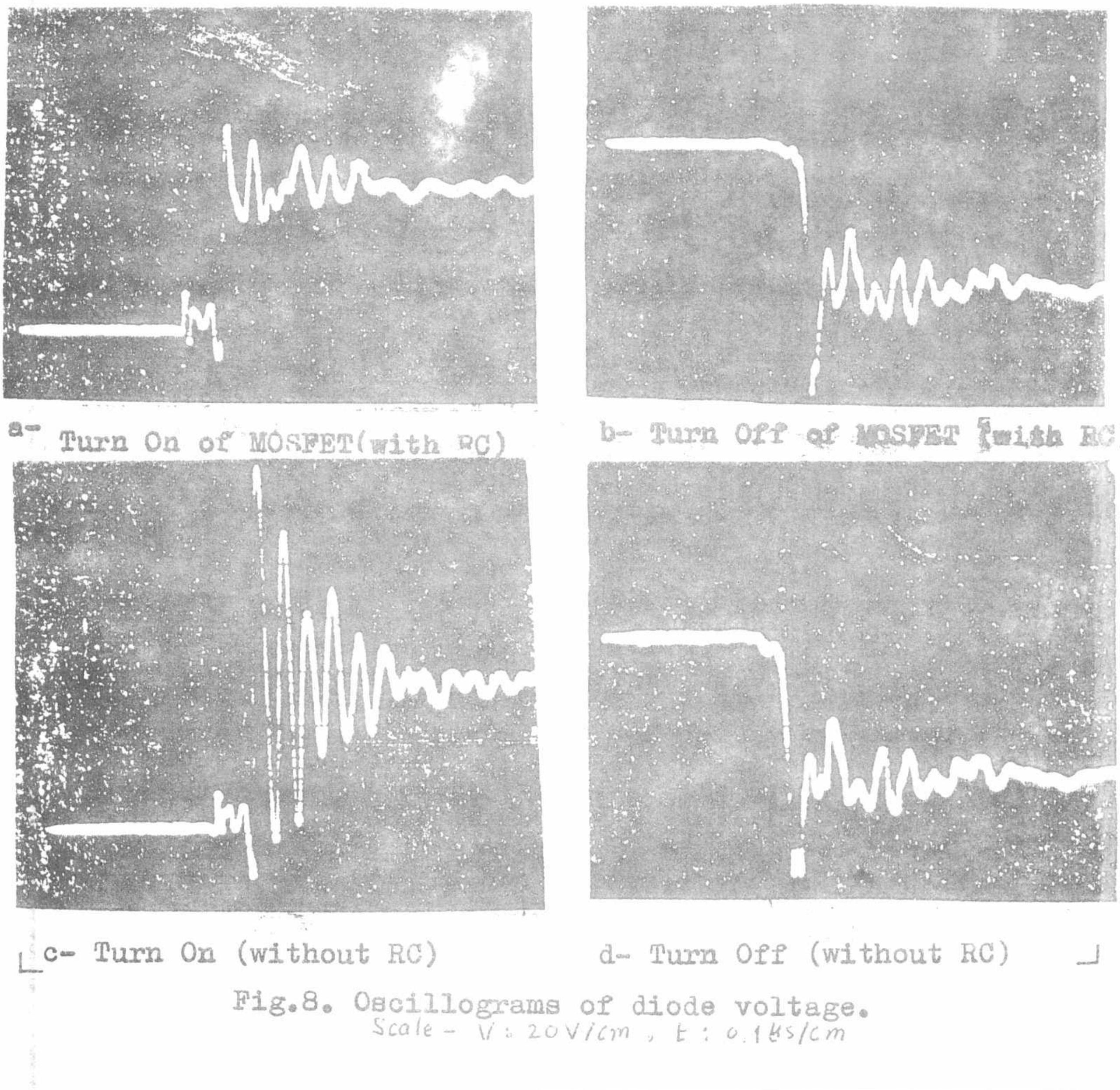
supply through the MOSFET chopper circuit. The control algorithm [6] contains essentially an internal loop for the regulation of armature current and an external loop for the control of the motor speed. The actual speed (ω), is captured by a tachogenerator, the reference speed is represented by an adjustable DC voltage, and the armature current is sensed by an accurate resistance associated with an isolating amplifier. After treatement, the measured signals are then connected to an analog multiplexer, and the analog to digital converter converts these values to digital form successively. In the microcomputer, the measured and reference speeds are compared, and after correction by the speed controller, a value representing the reference current is calculated. The actual and reference currents are compared, corrected by current regulator, and a control signal is ready to drive the MOSFETs.

RESULTS

An experimental chopper circuit is constructed for a power of 1.0 KW. The design data are: V_e = 48 V , I_n = 20 A , and f = 80 KHz. This chopper employs a total of four IRF 630 HEXFETs connected in parallel for the controlled switch and one ultra rapid diode BYW 92 for the freewheeling diode. The utilization of $C_1 = 25\,\mu F$, and $L_1 = 9\,\mu H$ for the input filter gives a peak to peak input ripple,current and voltage less than 5 % . The value of the inductance L_2 necessary for an output ripple current less than 5 % is about 150 μH. This value is smaller than that of the motor armature winding and so , it is not necessary to connect an external inductance for this purpose.

The chopper performance is examined during turn off and turn on of MOSFETs. Fig.8 shows the oscillograms of diode voltage with and without RC circuit connected in parallel with the freewheeling diode. The RC circuit is necessary to attenuate the high frequency oscillations appearing during turn on of MOSFETs.

We have also examined the response of the armature current regulator and that of speed controller to a step increase and a step decrease of the reference values . These results are shown in fig.9.



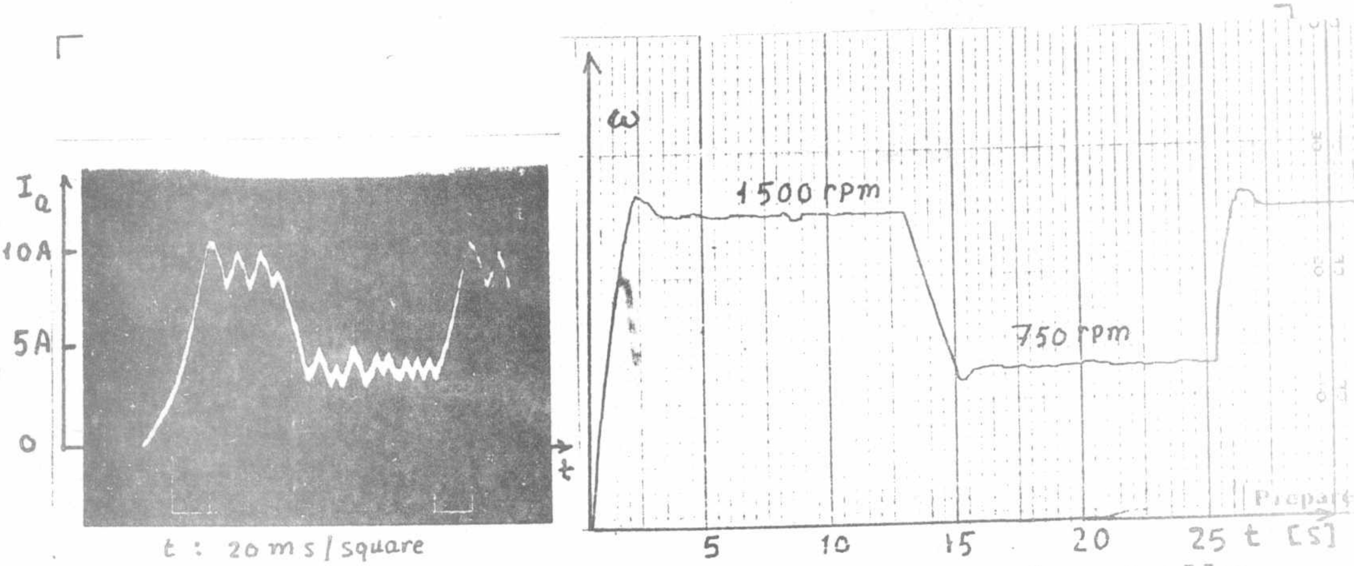
a- Turn On of MOSFET(with RC)

b- Turn Off of MOSFET (with RC)

c- Turn On (without RC)

d- Turn Off (without RC)

Fig.8. Oscillograms of diode voltage.
Scale - V : 20V/cm , t : 0.1μs/cm



a- Response of the armature current regul.

b- Response of speed controller.

Fig.9. Responses of armature current and motor speed.

CONCLUSION

The potential attractions of using MOSFETs in DC to DC chopper are simplicity of drive circuitry, ruggedness, speed of response, ease of paralleling and overall compactness. With the higher chopper frequency made possible by power MOSFETs, small values of inductance and capacitance are sufficient for the construction of input filter. The armature winding inductance is also sufficient to keep the motor ripple current to an acceptable level.

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