A Chopper for Motor Speed Control Using Parallel Connected Power HEXFETs®

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Summary

Today's MOSFETs are rated at currents as high as 28A continuous and 70A peak, at 100V. They are easily parallelable for higher current operation, and are attractive candidates for controlling the speed of electric motors at currents up to several hundred amperes.

This application note demonstrates an experimental DC to DC chopper circuit using parallel connected power MOSFETs, for speed control of a separately excited DC motor. The circuit operates from a 48V battery, and provides "two-quadrant" operation, with maximum motoring and regenerating currents of 200A and 140A, respectively.

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 and electrical vehicle controllers. Larger thyristor choppers rated at thousands of amperes, at DC voltages up to 1500V, are in use in high power railway traction applications.

In this type of application power MOSFETs would offer some advantages, like very high gain, very rugged performance, and very fast switching speed. The power MOSFET lends itself readily to paralleling (providing the proper precautions are observed), and a power MOSFET chopper operating at currents of several hundred amperes is technically within grasp.

In this application note, we demonstrate the technical feasibility of a chopper circuit using parallel connected HEXFETs to provide a 200A, 48V output for motor speed control. A particular feature of the circuit is its facility for providing electrical braking of the motor by feeding electrical energy back to the DC source. This is accomplished through the use of the integral body-drain diode of the HEXFET, which acts as a circuit component in its own right, and provides the "freewheeling" and "flyback" functions for the "motoring" and "regenerating" modes.

The Power HEXFET

The basic structure of a HEXFET is illustrated in Figure 1, and the electrical symbol is shown in Figure 2. Current flows from the drain region vertically through the silicon, then horizontally through the channel, then vertically out through the source.

The HEXFET design is based upon vertical D-MOS technology. The closed hexagonal cellular structure with the buried silicon gate allow for optimum utilization of silicon, and yield a rugged, highly reliable device.

A feature of the HEXFET (actually, of all power MOSFETs) is that it inherently has built into it an integral reverse "body-drain" diode. The full electrical symbol for the power MOSFET includes the reverse parallel rectifier shown dashed in Figure 2.

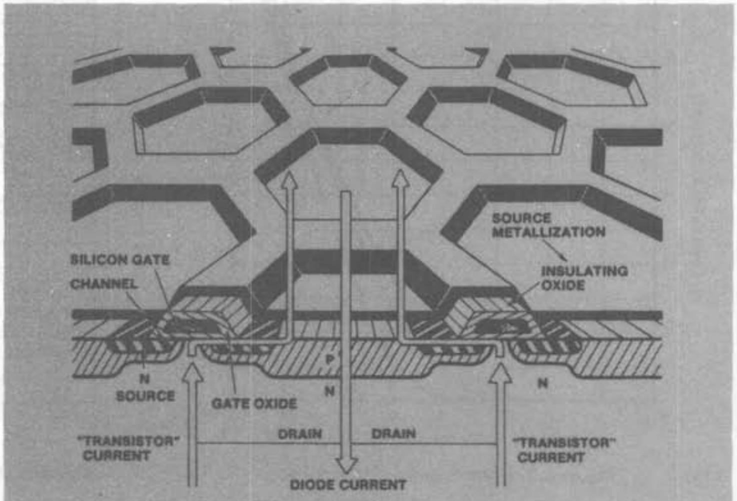


Figure 1. Basic HEXFET Structure

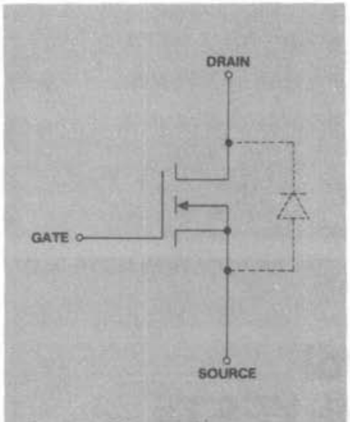


Figure 2. Electrical Symbol for Power HEXFET (MOSFET) including the Body-Drain Diode

The existence of this integral reverse rectifier is explained by reference to Figure 1. Current is free to flow through the middle of each source cell across a forward-biased P-N junction, and out of the drain. The path for this "reverse" current flow is at least comparable in cross-section to that of the "forward" current "transistor" channel. Far from being an inconsequential "parasitic" component, the integral reverse body-drain diode is therefore a real circuit element, with a current handling capability as high as that of the transistor.

The integral reverse body-drain diode may or may not be important in a practical circuit. In some circuits, it is irrelevant, because the circuit operation is such that the voltage across the switching device never changes polarity, and the forward conduction characteristic of the body-drain diode never comes into play. This is the case, for example, in a simple DC to DC chopper circuit for motor control which is not configured for regenerative energy flow, and in which the motor voltage never exceeds the source voltage.

A DC to DC chopper circuit for motor speed control that provides a regenerative braking capability would, however, require rectifiers to be connected across the switching devices, and in this case, the reverse body-drain diode of the HEXFET can be used for this purpose, and, in fact, eliminates the need for additional discrete rectifiers.

Potential Advantages of Power HEXFETs for Motor Drives

The power HEXFET has several unique features which make it a potentially attractive switching component for a chopper drive. These features are briefly discussed below:

High Gain

The HEXFET is a voltage driven device. The gate is isolated electrically from the source by a layer of silicon oxide. The gate draws only minute leakage current, in the order of nanoamperes, and the DC gain — in the conventional sense used for a bipolar transistor is rather meaningless. A more useful parameter is the transconductance. This is the change of drain current brought about by a 1V change of voltage on the gate. The transconductance of the IRF150 HEXFET is typically 10 amps per volt.

Another important advantage is that, unlike the bipolar transistor, the gain of the HEXFET does not decrease with increasing current. This means that the HEXFET is able to handle high peak current, without showing the bipolar transistor's tendency to "pull out of saturation." Typical relationships between gate-to-source voltage and drain current are shown in Figure 3.

Because the gain of the HEXFET is very high, the drive circuitry required is relatively simple. It should be clearly recognized, however, that although the gate consumes virtually no current under "steady" conditions, this is not so under transitional switching conditions. The gate-to-source and gate-to-drain self-capacitances must be charged and discharged appropriately to obtain the desired switching speed, and the drive circuit must have a sufficiently low output impedance to supply the required charging and discharging current. Even once these requirements have been catered for, the fact remains that the drive circuitry required for a HEXFET is considerably simpler than that required for a bipolar transistor.

Ruggedness

One of the outstanding features of the HEXFET 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.

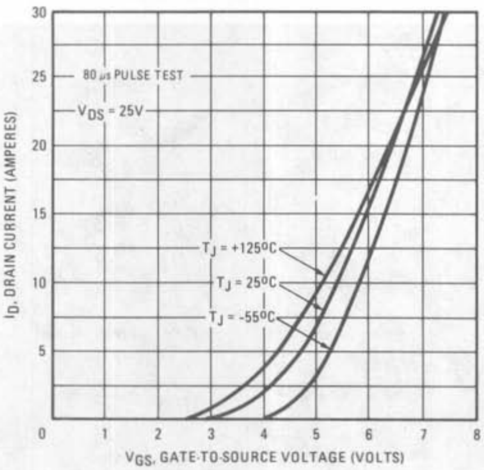


Figure 3. Transfer Characteristics IRF150

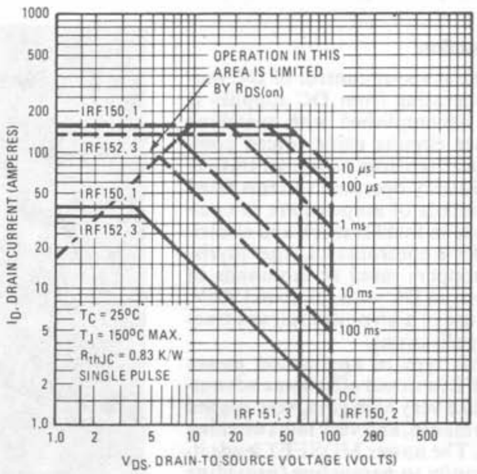


Figure 4. Maximum Safe Operating Area IRF150

A simple physical explanation accounts for this superiority. If localized, potentially destructive heating occurs within a HEXFET, the carrier mobility in that area decreases. As a result, the device has a positive temperature coefficient and acts in a self-protective manner by forcing currents to be uniformly distributed throughout the silicon. The safe operating area of the IRF150 HEXFET is shown as an example in Figure 4. Note that the safe operating area for $10\mu s$ is fully rectangular; this means, in principle, that it is possible to switch 70A at 100V in this device. As a matter of good design practice, of course, one would not operate at this limit.

The absence of second breakdown is, of course, important for this type of application.

Ease of Paralleling

Power HEXFETs are, in principle, easy to parallel, because the positive temperature coefficient forces current sharing among parallel devices. 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.

A Basic HEXFET Two-Quadrant Chopper Circuit

Figure 5 shows the basic circuit of a DC to DC chopper that provides continuous speed control in the "motoring" mode of operation (i.e., with the motor receiving power from the DC source), and also provides the facility for the motor to return regenerative energy to the DC source, over the whole speed range. Idealized waveforms that describe the operation are shown in Figure 6, while Figure 7 defines the two operating quadrants of the circuit developed.

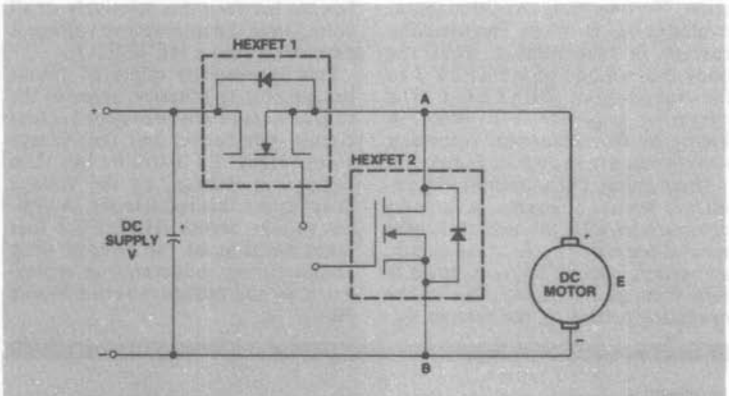


Figure 5. Basic Two Quadrant Chopper Circuit Using HEXFETs

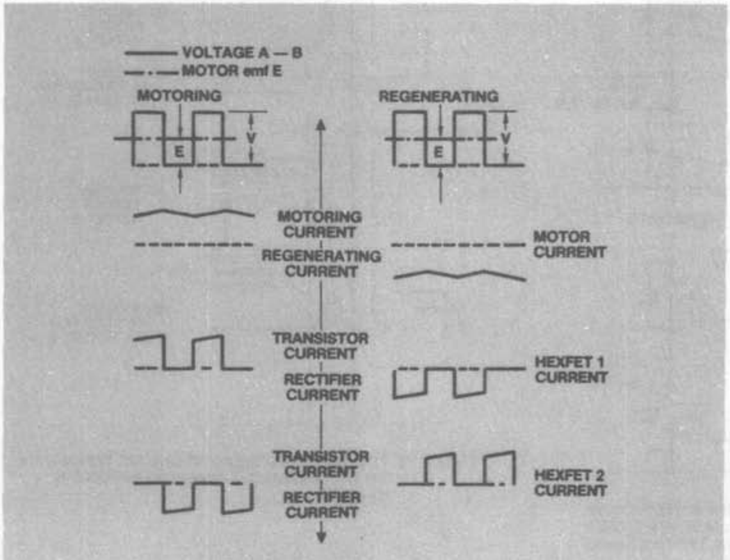


Figure 6. Idealized Operating Waveforms for Figure 5

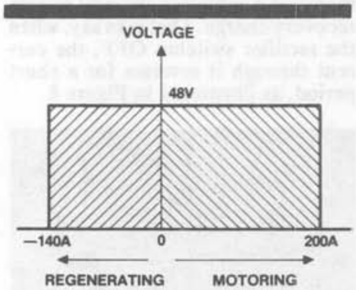


Figure 7. Motoring and Regenerating Operating Quadrants for the Circuit of Figure 5

In the "motoring" mode of operation, HEXFET 1 is switched ON and OFF, at an appropriate repetition rate, and provides control of the average voltage applied to the motor. HEXFET 2 is OFF, but its integral reverse body-drain diode acts as the conventional freewheeling rectifier and carries the freewheeling motor current during the periods when HEXFET 1 is OFF. When the motor is required to act as a generator and return energy to the DC source, HEXFET 2 is chopped ON and OFF, and controls the current fed back from the motor to the supply. In this operating mode, HEXFET 1 is OFF, but its integral reverse rectifier carries the motor current back to the DC source during the intervals when HEXFET 2 is OFF.

In order for the motor to "regenerate," it is necessary for it to have either a shunt or a separately excited field. A series-connected field is not feasible, unless the connections to it are reversed for the regenerative mode of operation, which is not practically convenient.

The major objectives of this application note are to demonstrate the feasibility of operating a group of parallel connected HEXFETs at currents in the order of hundreds of amperes, and of using the reverse body-drain diode of the HEXFET as a circuit element in its own right, in the basic two quadrant chopper circuits shown in Figure 5.

To achieve these objectives, it is

necessary to consider certain detailed aspects of the operation of the HEXFETs. We do this in the following section.

Use of the HEXFET's Body-Drain Diode

An important consideration when using the HEXFET's integral body-drain diode is its reverse recovery characteristic. This rectifier is a conventional P-N junction device, and therefore it exhibits a classical reverse recovery charge. That is to say, when the rectifier switches OFF, the current through it reverses for a short period, as illustrated in Figure 8.

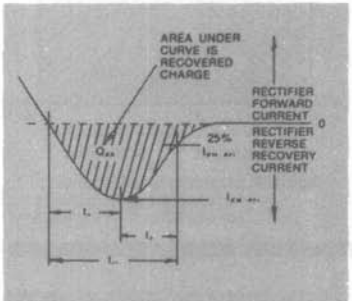


Figure 8. Rectifier Reverse Recovery

The reverse recovery time depends upon the operating conditions. For the IRF150 HEXFET, rated 28A continuous at 100V (the type used here), the reverse recovery time is about 400ns at maximum operating temperature, and about 260ns at 25° C, for an initial peak forward current of 70A, and a di/dt of 100A/μs.

Reverse recovery presents a potential problem when switching any rectifier OFF. The slower the rectifier, the greater the problem. Although the HEXFET's body-drain diode is relatively fast — not as fast as the fastest discrete rectifiers available, but considerably faster than comparably rated general purpose rectifiers — by comparison with the HEXFET itself, it is rather slow. This presents a potential problem in a chopper circuit, as we will now see.

To illustrate the problem, we will consider the motoring mode of operation. The operating condition that is troublesome is when freewheeling current is commutated from the body-drain diode of HEXFET 2 to the transistor of HEXFET 1. The operating sequence is depicted in Figure 9; the theoretical operating waveforms are shown in Figure 10.

Throughout the commutating sequence which, of course, is short by comparison with the overall fundamental operating cycle of the circuit, a constant current, I_M, is assumed to flow through the motor. During the operating period, t_0, the current, I_M, is freewheeling through the rectifier of HEXFET 2. At the start of the operating period, t_1, HEXFET 1 is turned ON, and the load current starts to transfer to the transistor of HEXFET 1. The current, i_1, in HEXFET 1 increases, while the current, i_2, flowing in the rectifier of HEXFET 2 decreases. The sum of i_1 and i_2 is equal to I_M. At the end of period t_1, the current flowing in HEXFET 1 is equal to the motor current, I_M, and the current flowing in the rectifier of HEXFET 2 is instantaneously zero.

Note that during period t_1 (also during the subsequent period t_a), the voltage across HEXFET 1 theoretically is virtually the full source voltage. This is because, as long as the rectifier of HEXFET 2 remains conducting, the voltage across it can be only its conduction voltage; the difference between this relatively small voltage and the total source voltage is developed across HEXFET 1.

This ignores the effect of circuit inductance. In practice, some of the source voltage will be dropped across circuit inductance, and the voltage across HEXFET 1 will be less than the source voltage, by the voltage drop across this inductance. A typical voltage across HEXFET 1 that takes account of the voltage drop across circuit inductance is represented by the dashed wave in Figure 10.

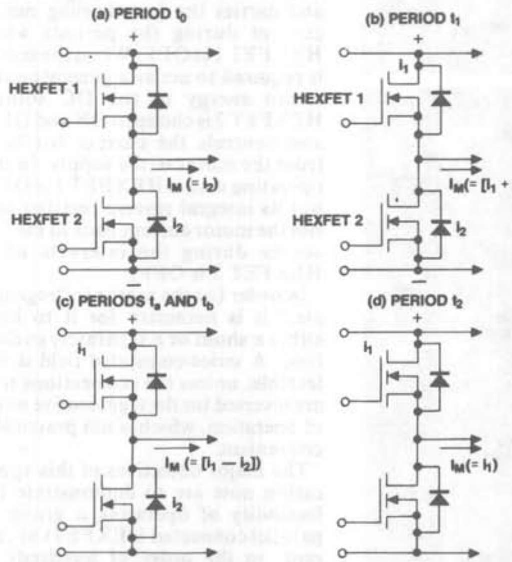


Figure 9. Commutation of Freewheeling Current I_M from the Rectifier of HEXFET 2 to the Transistor of HEXFET 1. HEXFET 1 and HEXFET 2 form a Tandem Series Connected Pair across a DC source.

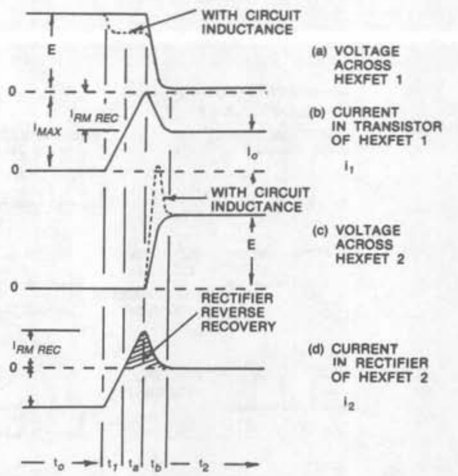


Figure 10. Theoretical Voltage and Current Waveforms for Commutating Sequence Depicted in Figure 9.

If the rectifier was "perfect," with no recovered charge, the commutation process would be complete at the end of period t_1. In practice, the rectifier current reverses during the recovery periods t_a and t_b. During the period t_a, the reverse current i_2 increases until it reaches its peak value, $I_{RM(rec)}$. The current, i_1, through HEXFET 1 is now the sum of the rectifier reverse current, i_2, and the motor current, I_M, and its peak value, I_{MAX}, is the sum of I_M and $I_{RM(rec)}$. The voltage across HEXFET 1 still theoretically remains high, because the voltage across the rectifier of HEXFET 2 is still relatively low.

During the second part of the recovery period t_b, the rectifier of HEXFET 2 begins to support reverse voltage. The rectifier recovery current i_2 decreases, and the voltage across HEXFET 1 falls to its final conduction level. Note the effect that circuit inductance has in producing an overvoltage transient across the rectifier, as illustrated by the dashed wave in Figure 10.

Certain important points are evident. First, t_1, t_a, and to a lesser extent, t_b, are high dissipation periods. Second, the peak current in HEXFET 1 is the sum of the motor current and the rectifier reverse recovery current, and this peak current occurs at an instant when the voltage across the HEXFET is high. It is important that this peak current does not violate the HEXFET's I_{DM} rating. In fact, if the HEXFET is switched at a speed close to its limiting capability, and no other special precautions are taken, it certainly will do. If the peak current was to substantially exceed this rating, diode failure could occur, as explained in Ref. 1.

Fundamentally, the peak reverse recovery current of the rectifier can be reduced only by slowing down the rate of change of current during the commutation process. This is illustrated in Figure 11. The rate of change of current can be controlled either by inserting inductance into the circuit, or by purposefully slowing down the rate-of-rise of the gate pulse that drives HEXFET 1. A linear inductor inserted in the circuit for the purpose of slowing down the rate of change of current when the HEXFET is switched ON is not attractive, because it produces a transient voltage spike when switching OFF, to say nothing of the fact that it is an added "power circuit" component.

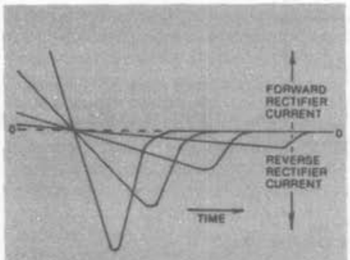


Figure 11. Reducing the Peak Rectifier Reverse Current by Reducing the Rate of Change of Current

The better practical solution is simply to slow down the switching-ON of the HEXFET by slowing down the drive signal. The peak current carried by the HEXFET can be reduced to almost any desired extent, at the expense of prolonging the high dissipation period. This is a necessary compromise in order to keep the peak current within safe limits, and as a practical matter, the switching losses, when averaged over the full operating cycle, are relatively small, for the operating frequencies that will be of interest in this application (normally a few hundred to a few thousand Hz).

Note that it is not necessary (nor desirable) to slow the switching-OFF; hence, the energy dissipation at switch-OFF will be relatively small by comparison with that at switch-ON. As explained in detail in Ref. 1, in this application a substantial dv/dt is likely to be applied across the HEXFET that acts as a diode during its reverse recovery. Since the device is sensitive to dv/dt at that time, a snubber should be added between drain and source, as shown in Figure 21.

Paralleling of HEXFETs

A key question that is fundamental to the successful demonstration of a chopper operating at hundreds of amperes, is the feasibility of multiple paralleling of HEXFETs.

Two questions must be considered: (1) "steady-state" sharing of current, and (2) dynamic sharing of current under the transitional switching conditions.

Steady-State Sharing of Current

During the periods outside of the switching transitions, the current in a parallel group of HEXFETs will distribute itself in the individual devices in inverse proportion to their ON resistance. The device with the lowest ON resistance will carry the highest current. This will, to an extent, be self-compensating, because the power loss in this device will be the highest. It will run hottest, and the increase in ON resistance due to heating will be more than that of the other devices, which will tend to equalize the current.

An analysis of the "worst case" device current in a group of "N" parallel connected devices can be based on the simplifying assumption that (N - 1) devices have the highest limiting value of ON resistance, while just one lone device has the lowest limiting value of ON resistance. The analysis can then be concentrated on the current in this one device.

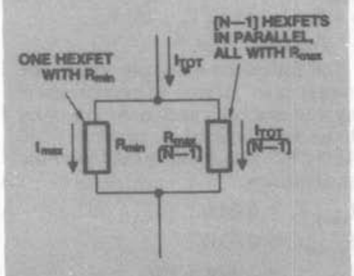


Figure 12. Simplified Equivalent Circuit for Estimating Worst Case Steady-State Current Unbalance

The equivalent electrical circuit shown in Figure 12 simplifies the analysis further by assuming the number of devices is sufficiently large that the current that flows through each of the high resistance devices is approximately $I_{TOT/(N-1)}$. On this assumption, the voltage drop across the lone low resistance device, and hence the current in it, can be calculated.

The ON resistance of each of the "high resistance" devices, at operating temperature, T, is given by:

$$R_{(max)T} = R_{(max)25}\ (1 + [(T_A - 25) + \frac{I^2_{TOT}}{(N-1)^2}\ R_{(max)T}\ R_{JA}]\ K)$$

where $R_{(max)25}$ is the limiting maximum value of ON resistance at 25° C, R_{JA} is the total junction-to-ambient thermal resistance in deg. C/W, and K is the per unit change of ON resistance per °C.

$$\therefore R_{(max)T} = \frac{R_{(max)25}\ (1 + [T_A - 25]\ K)}{1 - R_{(max)25}\ \frac{I^2_{TOT}}{(N-1)^2}\ R_{JA}\ K} \qquad (1)$$

The voltage drop, V, across the parallel group is:

$$V = \frac{I_{TOT}}{(N-1)} \cdot R_{(max)T} \qquad (2)$$

The resistance of the one low resistance device at its operating temperature is:

$$R_{(min)T} = R_{(min)25}\,(1 + [T_A - 25 + V I_{(max)} R_{JA}]\,K)$$

where $R_{(min)25}$ is the limiting minimum value of ON resistance at 25° C, and $I_{(max)}$ is the current in this device.

$$\text{But, } R_{(min)T} = \frac{V}{I_{(max)}}$$

$$\therefore\ I_{(max)} = \frac{-b + \sqrt{(b^2 + 4aV)}}{2a} \qquad (3)$$

where:

$b = R_{(min)25}\,(1 + [T_A - 25]\,K)$

$a = R_{(min)25}\,V\,R_{JA}\,K$

The following example shows the "worst case" degree of current sharing that can be expected, by applying the above relationships to the IRF150 HEXFET, and making the following assumptions:

$R_{(max)25}$ = 0.045Ω

$R_{(min)25}$ = 0.03Ω

R_{JA} = 3 deg. C/W

$\frac{I_{TOT}}{(N - 1)}$ = 20A

K = 0.006 per degree C

T_A = 35°C

Using the relationships (1), (2), and (3) above, it can be calculated that the "worst case" maximum value of device current is 27A for the hypothetical situation where all devices but one have high limiting ON resistance, of 0.045Ω, and carry 20A each, whereas the remaining one has low limiting ON resistance of 0.03Ω.

Dynamic Sharing of Current Under Switching Conditions

Turn-On

It is necessary to take positive steps to ensure that the current is distributed properly between a group of parallel connected devices during the switching transition. Since the HEXFETs will not all have identical threshold and gain characteristics, some will tend to switch sooner than others, and attempt to take more than their share of the current. Adding to the problem is the fact that circuit inductance associated with each device may be different, and this will also contribute to unbalancing the current under switching conditions. A detailed analysis of these waveforms can be found in Ref. 2. Here we will limit ourselves to a brief qualitative description of the different events that occur during a switching transition.

The problem will be introduced by considering the switching waveforms for the basic chopper circuit, shown in Figure 5, which contains a single HEXFET in each of the "motoring" and "regenerating" positions. We will consider the motoring mode of operation, under which HEXFET 1 is switched ON and OFF, while the motor current (assumed to be smooth, due to the motor inductance) alternates between this HEXFET and the body-drain diode of HEXFET 2, which acts as a freewheeling rectifier.

Figure 13 shows waveforms of drain current, drain-to-source voltage, and gate voltage during the turn-ON interval. We have already seen that in order to limit the peak recovery current of the body diode of HEXFET 2, the gate drive voltage for HEXFET 1 must be applied at a controlled rate. This is the reason that the applied drive pulse is shown increasing at a relatively slow rate.

At time, t_0, the drive pulse starts its rise. At t_1, it reaches the threshold voltage of the HEXFET, and the drain current starts to increase. At this point, two things happen which make the gate-source voltage wave-

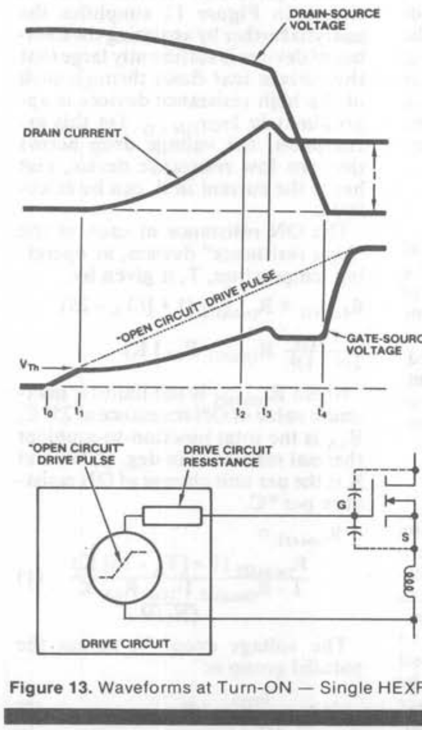


Figure 13. Waveforms at Turn-ON — Single HEXFET

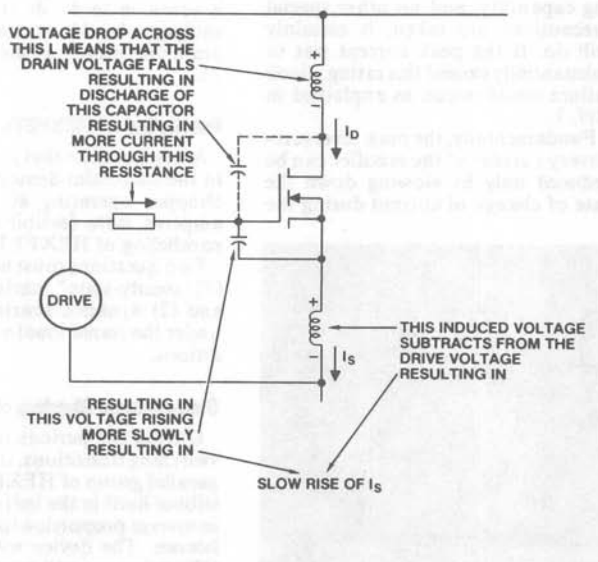


Figure 14. Diagrammatic Representation of Effects When Switching-ON

form deviate from its original "path." First, inductance in series with the source which is common to the gate circuit develops an induced voltage, as a result of the increasing source current. This voltage counteracts the applied gate drive voltage and slows down the rate-of-rise of voltage appearing directly across the gate and source terminals; this, in turn, slows down the rate-of-rise of the source current. This is a negative feedback effect; increasing current in the source produces a counteractive voltage at the gate, which tends to resist the change of current.

The second factor that influences the gate-source voltage is the so-called "Miller" effect. During the period t_1 to t_2, some voltage is dropped across circuit inductance in series with the drain, and the drain-source voltage starts to fall. The decreasing drain-source voltage is reflected across the drain-gate capacitance, pulling a discharge current through it, and increasing the effective capacitance load on the drive circuit. This, in turn, increases the voltage drop across the impedance of the drive circuit and decreases the rate-of-rise of voltage appearing between the gate and source terminals. This also is a negative feedback effect; increasing current in the drain results in a fall of drain-to-source voltage, which, in turn, slows down the rise of gate-source voltage and tends to resist the increase of drain current. These effects are illustrated diagrammatically in Figure 14.

This state of affairs continues throughout the period t_1 to t_2, while the current in the HEXFET rises to the level of the current, I_M, already flowing in the freewheeling rectifier, and it continues into the next period, t_2 to t_3, while the current increases further, due to the reverse recovery of the freewheeling rectifier.

At time t_3, the freewheeling rectifier starts to support voltage, while the drain current and the drain voltage start to fall. The rate-of-fall of drain voltage is now governed by the Miller effect, and an equilibrium condition is reached, under which the drain voltage falls at just the rate necessary for the voltage between gate and source terminals to satisfy the level of drain current established by the load. This is why the gate-to-source voltage falls as the recovery current of the freewheeling rectifier falls, then stays constant at a level corresponding to the motor current, while the drain voltage is falling.

Finally, at time t_4, the HEXFET is switched fully ON, and the gate-to-source voltage rises rapidly towards

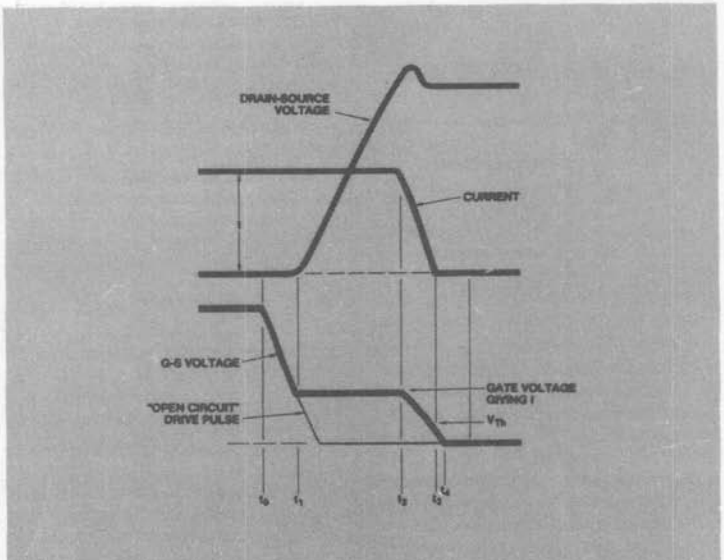


Figure 15. Waveforms at TURN-OFF — Single HEXFET

the applied "open circuit" value.

The gate-to-source voltage waveform for the circuit shown in Figure 5, with just a single device in each position, provides the clue to the difficulties that can be expected with parallel connected devices. The first potential difficulty is that if we apply a common drive signal to all gates in a parallel group, then the first device to turn ON — the one with the lowest threshold voltage — will tend to slow the rise of voltage on the gates of the others, and further delay the turn-ON of these devices. This will be due to the Miller effect. The inductive feedback effect, on the other hand, only influences the gate voltage of its own device (assuming that each source has its own separate inductance).

The second potential difficulty is that if the individual source inductances are unequal, then this will result in dynamic unbalance of current, even if the devices themselves are perfectly matched. Obviously, the solution to this is to ensure that inductances associated with the individual devices are as nearly equal as possible. This can be done by proper attention to the circuit layout.

As examined in detail in Ref. 3, there are several other circuit and device parameters that will contribute to dynamic unbalance. The conclusions presented in the above mentioned paper indicate, however, that the problem is not severe, as long as attention is paid to the following points, in order to ensure satisfactory sharing of current between parallel HEXFETs at turn-ON:

- Threshold voltages should be within determined limits.
- Stray inductances throughout the circuit should be equalized by careful layout.
- Gates should be decoupled with individual resistors, but not more than strictly required, as it will be explained later.

Turn-Off

Similar considerations apply to the dynamic sharing of current during the turn-OFF interval. Figure 15 shows theoretical waveforms for HEXFET 1 in the circuit of Figure 3 during the turn-OFF interval. At t_0, the gate drive starts to fall. At t_1, the gate voltage reaches a level that just sustains the drain current, I. The drain-to-source voltage now starts to rise. The Miller effect governs the rate-of-rise of drain voltage and holds the gate-to-source voltage at a level corresponding to the constant drain current. At t_3, the rise of drain voltage is complete, and the gate voltage starts to fall at a rate determined by the gate-source circuit impedance, while the drain current falls to zero.

Figure 16 shows theoretical waveforms for two parallel connected HEXFETs with their gates connected directly together. For purposes of discussion, the source inductance is assumed to be zero. At t_1, the gate voltage reaches the point at which HEXFET B can no longer sustain its drain current. The load current now

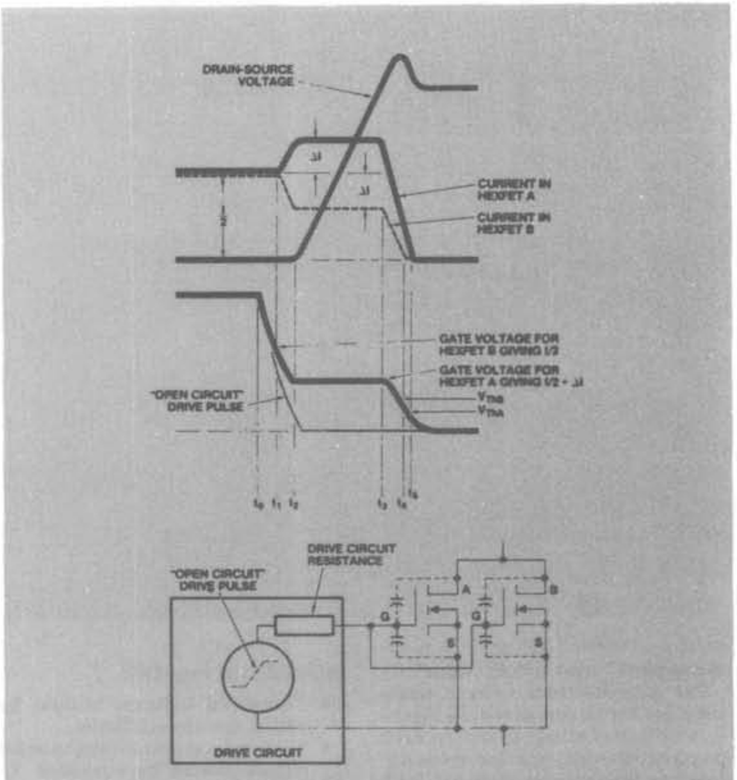


Figure 16. Waveforms at Turn-OFF — Two HEXFETs with Common Gates and Common Sources

redistributes; current in HEXFET B decreases, while that in HEXFET A increases. At t_2, HEXFET B can no longer sustain its current; both HEXFETs now operate in their "linear" region, and the drain voltage starts to rise. The gate-to-source voltage is kept practically constant by the Miller effect, while the currents in the two HEXFETs remain at their separate levels. Clearly, the unbalance of current in this example is significant.

While a turn-off unbalance is potentially a more serious problem, the analysis in Ref. 3 shows that this is not so in practice as long as the devices are turned off with a "hard" (very low impedance) gate drive. This by itself will almost guarantee limited dynamic unbalance at turn-off.

In summary, to achieve good sharing at turn-off the same precautions should be used as for turn-on, with the addition of a "hard" drive.

Figure 17 shows that when using paralleled devices, a low impedance path is generated that may be prone to parasitic self oscillations. For this reason some degree of gate decoupling is needed as necessary to prevent oscillations.

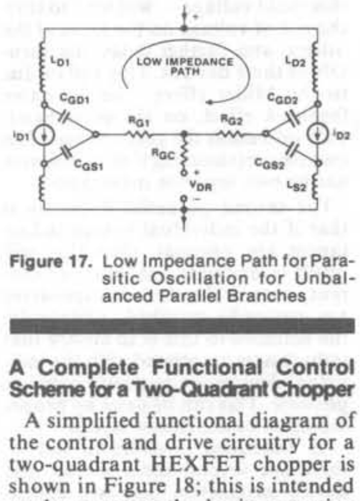


Figure 17. Low Impedance Path for Parasitic Oscillation for Unbalanced Parallel Branches

A Complete Functional Control Scheme for a Two-Quadrant Chopper

A simplified functional diagram of the control and drive circuitry for a two-quadrant HEXFET chopper is shown in Figure 18; this is intended to demonstrate the basic operating principle of the overall chopper system, and differs in some minor details from the actual practical circuitry presented later (Figure 22).

The control system has an outer voltage feedback loop, which compares the motor voltage with a reference voltage and processes the resulting "error" signal to keep the motor voltage essentially equal to the reference value. In a practical system, the voltage control loop could be complemented with a signal proportional to the armature voltage drop, to give a closer regulation of actual motor speed. Alternatively, the voltage feedback signal could be substituted with a signal from a tachogenerator, to give a more precise speed regulation.

An inner control loop regulates the current to the level required to satisfy the load on the motor. The current control loop also determines the chopper switching frequency by regulating the peak-to-peak ripple current between preset upper and lower limits. This it does by switching the HEXFET ON whenever the current falls a given amount below the reference value, and switching the HEXFET OFF whenever the current rises a given amount above it.

The current control loop also provides instantaneous limiting of the peak HEXFET and motor current. This is accomplished simply by setting a maximum limit on the current reference signal and clamping it to this level. Whenever the instantaneous motor current attempts to exceed the maximum current reference by more than the preset peak ripple current, the HEXFET is immediately switched OFF. Thus, the system is completely self-protecting against overcurrent.

Referring to the functional diagram in Figure 18, the voltage reference is compared with the voltage across the motor, and the error signal is amplified through the voltage error amplifier. The output of the voltage error amplifier is the current reference signal. The voltage error signal is also fed into the *motor-regenerate* logic comparator. When the voltage error is positive, the current reference is also positive, and the control circuit is demanding "motoring" current. The output of the *motor-regenerate* logic comparator is high, the *motor* signal has a logic "1" value, while the *regen* signal has a logic "0" value. Switches A and D are closed, while switches B and C are open.

When the current reference is negative, the control circuit is demanding "regenerating" current. The output of the *motor-regenerate* logic comparator is negative, the *regen* signal has a logic "1" value, while the *motor* signal has a logic "0" value. Switches B and C are closed, while A and D are open.

The *motor-regenerate* logic comparator has a built-in hysteresis to

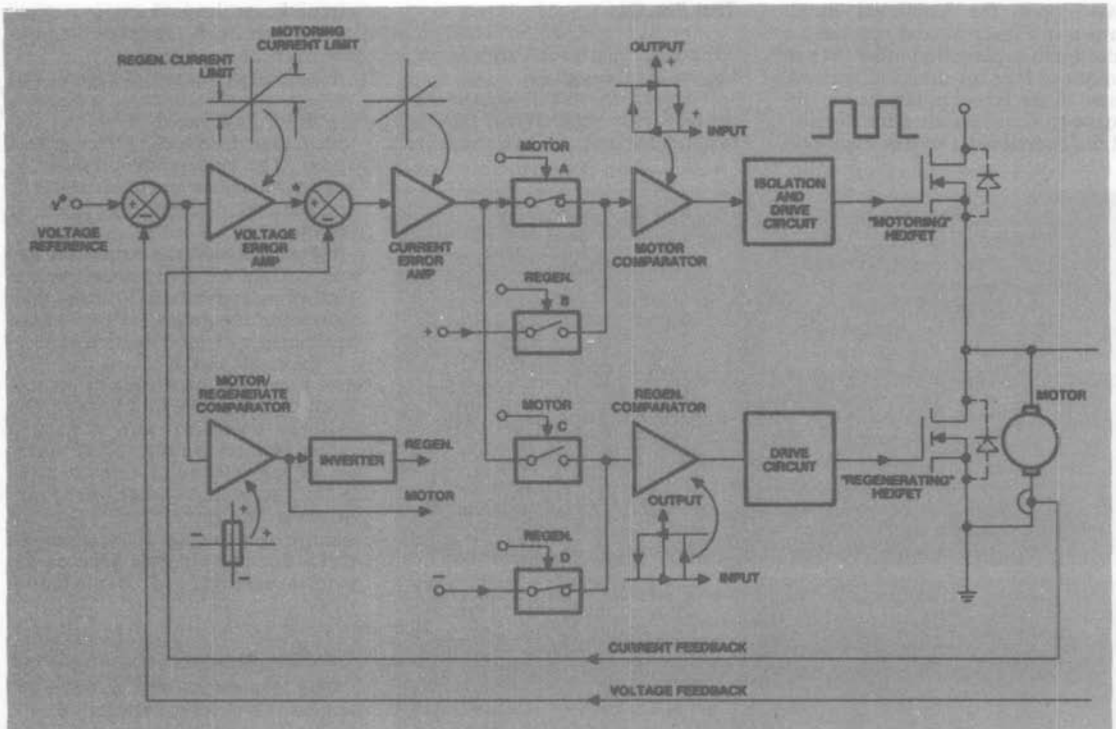


Figure 18. Simplified Control System

prevent unwanted "bouncing" back and forth between the "regeneration" and "motoring" modes of operation, at low current levels.

Consider the "motoring" mode of operation. The positive current reference signal is compared with a signal representing the actual motor current; the difference is amplified through the current error amplifier. The output of this amplifier is fed through switch A, which is closed, to the *motor* comparator. This comparator produces a "0" output signal in response to a positive input signal above a preset threshold level, and a "1" output signal in response to a negative input signal below a certain preset level.

The output signal of the *motor comparator* is isolated and shaped to become the gate drive signal for the "motoring" HEXFET. The "motoring" HEXFET is thereby switched ON when the motor current falls a predetermined amount below the reference and OFF whenever the motor current rises a predetermined amount above the reference value, while the switching frequency automatically adjusts itself to keep the peak-to-peak ripple current constant. The peak-to-peak ripple current and operating frequency can be adjusted by adjusting the hysteresis of the *motor* comparator.

Note that in the motoring mode, switch D is closed, applying a steady negative input to the *regen* comparator, and shutting OFF the gate drive signal to the "regenerating" HEXFET. Theoretical waveforms which illustrate the operation of this scheme in the motoring mode are illustrated in Figure 19.

In the regenerating mode of operation, switches B and C are closed. A continuous positive signal is applied to the input of the *motor* comparator, shutting OFF the drive to the "motoring" HEXFET. The current reference is negative, and the current error signal is fed to the input of the *regen* comparator. This comparator produces a "1" output signal in response to a positive input signal above a certain preset level, and a "0" output signal in response to a negative input signal below a given preset level. The "regenerating" HEXFET is now switched ON whenever the regenerative current from the motor falls a preset amount below the reference value, and OFF whenever the motor current rises a preset amount above the reference value. Theoretical waveforms which illustrate the operation in the regenerating mode are shown in Figure 20.

A 48V, 200A Experimental Chopper

Power Circuit

A schematic diagram of the power circuit of an experimental laboratory chopper is shown in Figure 21. This employs a total of ten IRF150 HEXFETs connected in parallel for the "motoring" switch, and five IRF150 HEXFETs connected in parallel for the "regenerating" switch.

All HEXFETs are mounted on a 22-inch length of aluminum heatsink extrusion, with outer dimensions of 5 inches by 3 inches, with the regenerating HEXFETs being isolated electrically from the heatsink.

The assembly is capable of delivering 200A forward "motoring" current and 140A of "regenerating" current. The "motoring" HEXFETs by themselves actually are capable of carrying about 300A of output current; the 200A limit is set by the current carrying capacity of the five freewheeling body-drain diodes of the "regenerating" HEXFETs.

Control and Drive Circuitry

Figure 22 shows a diagram of the control and drive circuitry. This is based upon the functional circuit shown in Figure 18 and requires no additional explanation other than to point out that for practical reasons, some of the signal polarities are opposite to those assumed for the simplified functional circuit of Figure 18.

Test Results

Practical test results are shown in Figures 23 through 27.

Figure 23 shows the current when the motor accelerates from standstill to about half speed. The current limit circuit keeps the peak motor current to just over 200A. The chopping frequency is about 2 kHz.

Figure 24 shows motor current and voltage waveforms when accelerating from half speed to almost full speed, then decelerating back to half speed. The current limit holds the peak motoring current to about 205A, and the peak regenerating current to about 140A.

Figure 25 shows the output voltage and current of the chopper with a passive inductive load. Note the classical linear rise and fall of the current associated with an inductive load.

Figures 26 and 27 show turn-ON and turn-OFF oscillograms respectively for one HEXFET, with the chopper operating with a passive inductive load of 120A. These waveforms generally agree with the foregoing theoretical discussion. Note, however, in Figure 27, that the gate voltage reverses at a switch-OFF; this is due to resonance between the gate capacitance and circuit inductance.

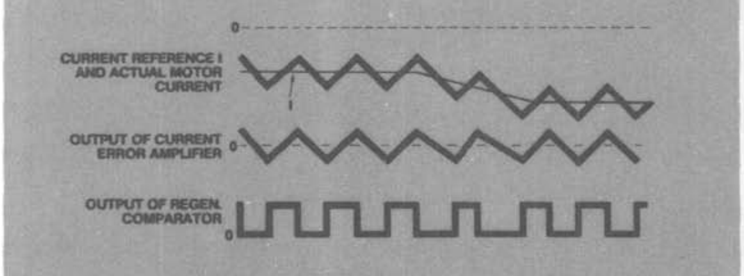


Figure 19. Theoretical Waveforms for the Motoring Mode of Operation

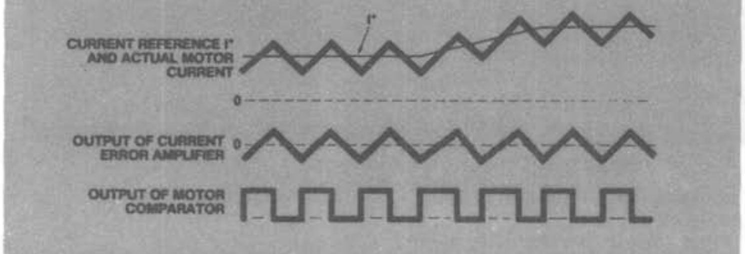


Figure 20. Theoretical Waveforms for the Regenerating Mode of Operation

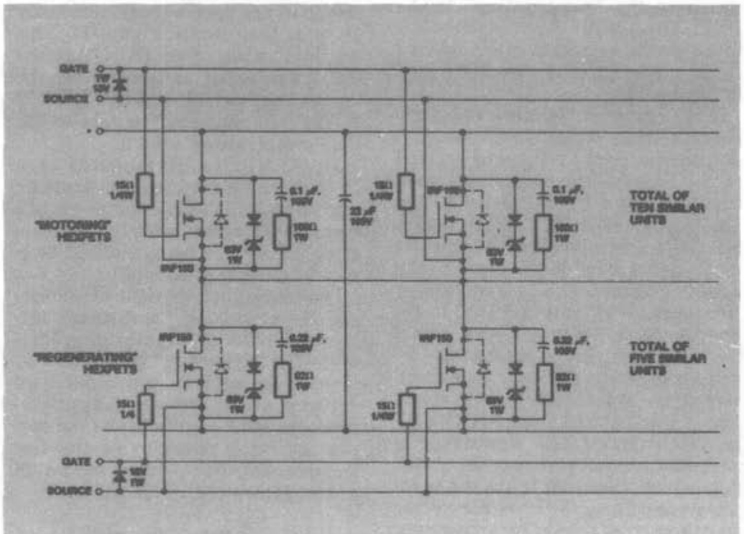


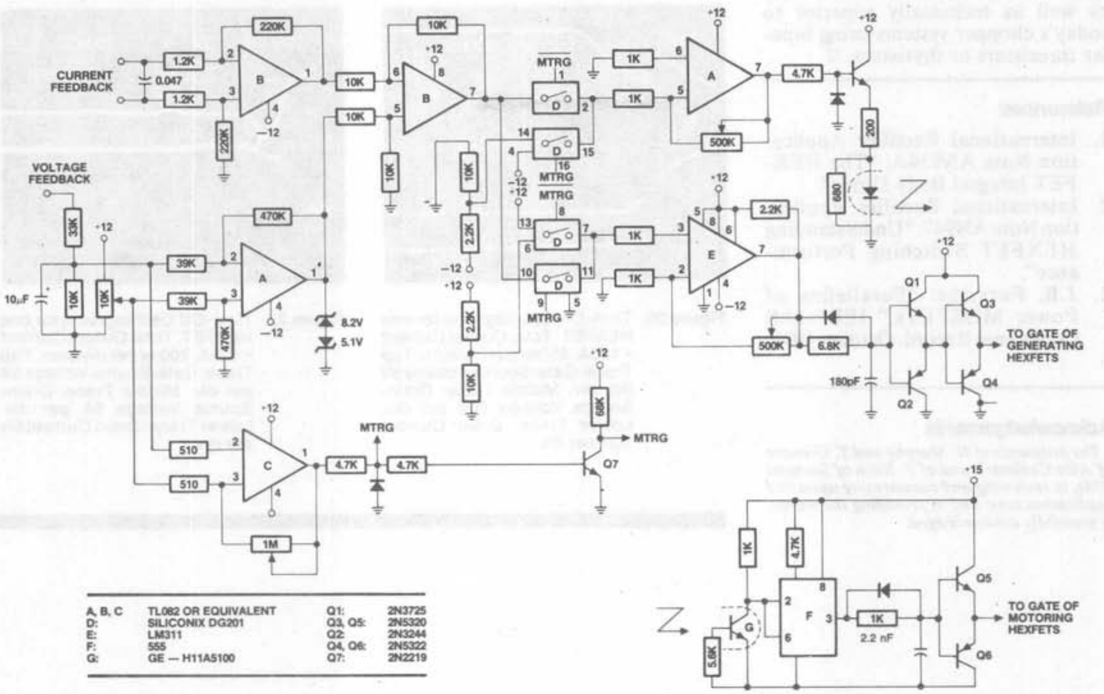
Figure 21. Power Circuit Schematic

Conclusions

This application note has demonstrated the technical feasibility of a DC-to-DC chopper using parallel connected HEXFETs for motor speed control, operating at the 200A level, and the use of HEXFET's body-drain diode to provide the freewheeling and flyback functions needed for two quadrant operation. The potential attractions of using HEXFETs are simplicity of drive circuitry, ruggedness, speed of response, ease of paralleling and overall compactness.

Power HEXFETs also offer an interesting system advantage in this type of application. Due to the ease of operating at high frequency, a separately excited field winding, with the added motor controlability and superior system performance that this provides, becomes a practical reality. Present-day choppers using bipolar transistors or thyristors generally operate at relatively low frequency (in order to keep them simple), and require a series-connected field winding to keep the motor ripple current to an acceptable level. With the higher chopper frequency made possible by power HEXFETs, on the other hand, the inductance of the motor armature is by itself sufficient to smooth the current, thus allowing the field winding to be disassociated from the armature circuit, and to be independently controlled, offering better system performance and superior control flexibility.

As improvements in circuit design, MOSFET technology, packaging,



A, B, C	TL082 OR EQUIVALENT	Q1:	2N3725
D:	SILICONIX DG201	Q3, Q5:	2N5320
E:	LM311	Q2:	2N3244
F:	555	Q4, Q6:	2N5322
G:	GE — H11A5100	Q7:	2N2219

Figure 22. Control and Drive Circuit Schematic

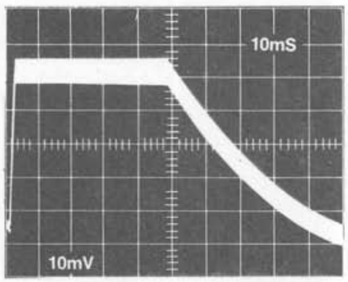


Figure 23. Motor Current under Acceleration. Peak Motor Current = 220A. 40A per division. 10ns per division.

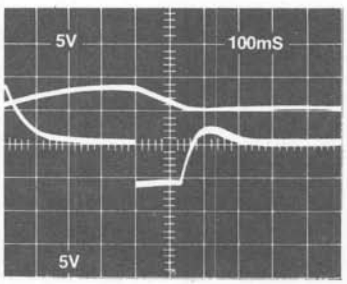


Figure 24. Motor Voltage & Current when Accelerating & Decelerating. Peak Motoring Current = 205A. Peak Regenerating Current = 140A. Top Trace: Voltage 25V per division. Bottom Trace: Current 115A per division.

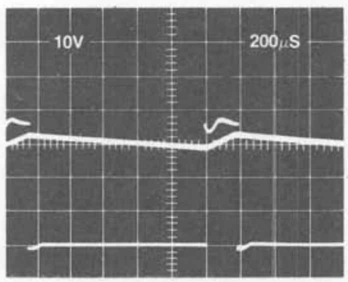


Figure 25. Output Voltage & Current of Chopper into Passive Inductive Load — 220 μs per division. Lower Trace: Voltage 10V per division.

and device costs all take place, the type of system described in this application note will become economically as well as technically superior to today's chopper systems using bipolar transistors or thyristors. □

References:

1. International Rectifier Application Note AN934A: "The HEXFET Integral Body Diode".
2. International Rectifier Application Note AN947: "Understanding HEXFET Switching Performance".
3. J.B. Forsythe: "Paralleling of Power MOSFETs," IEEE-IAS Conference Record, October 1981.

Acknowledgements

The assistance of H. Murphy and T. Gilmore of Allis Chalmers, and of F. Stich of Siemens Allis, in reviewing and commenting upon this application note, and in providing the motor, is gratefully acknowledged.

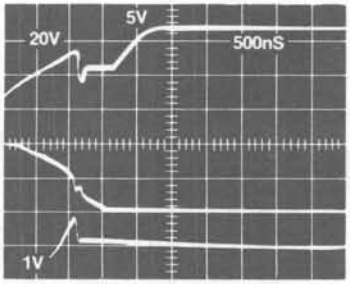


Figure 26. Turn-On Oscillograms for one HEXFET. Total Output Current = 120A. 500ns per division. Top Trace: Gate-Source Voltage 5V per div. Middle Trace: Drain-Source Voltage 20V per div. Lower Trace: Drain Current 10A per div.

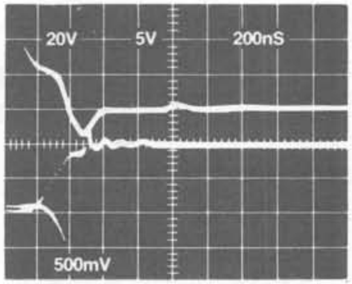


Figure 27. Turn-Off Oscillograms for one HEXFET. Total Output Current = 120A. 200ns per division. Top Trace: Gate-Source Voltage 5V per div. Middle Trace: Drain-Source Voltage 5A per div. Lower Trace: Drain Current 5A per div.