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Paralleling Power MOSFETs in Their Active Region: Extended Range of Passively Forced Current Sharing

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SUMMARY

This paper exhibits a simple passive circuit that improves current balance in paralleled power MOSFETs that are not precisely matched and that are operated in their active region from a common gate drive. A nonlinear circuit consisting of diodes and resistors generates the differential gate potential required to correct for unbalance while maintaining low losses over a range of current. Also application of a thin tape wound magnetic core to effect dynamic current balance is reviewed, and a simple theory is presented showing that for operation in the active region the branch currents tend to revert to their normal unbalanced values, even if the core is not driven into saturation. Results of several comparative experiments are given.

INTRODUCTION

High power linear applications of MOSFETs often require that current be shared among two or more of such paralleled devices in order to stay within their power dissipation ratings. In a linear mode the operating point will typically swing from a high drain-to-source voltage (V_{DS}) at low drain current (I_D) to a point of low V_{DS} at high I_D. The thermal load may be substantial even at low I_D. Hence, to take full advantage of the MOSFET's inherent immunity to second breakdown there is often a need to assure good current sharing from the maximum current down to some small fraction of it. This, however, is well known to be a difficult task because of temperature driven instability (ref. 1). At low I_D, where the gate-to-source voltage (V_{GS}) is below about 6 V, an increase in the junction temperature increases I_D. This is a consequence of a decrease in the threshold $V_{GS(th)}$ overcoming the effect of an increase in the on-state drain-to-source dc resistance $r_{DS(on)}$.

Good remedies are hard to find. Small values of the often used source lead resistors (R_S) work well at high I_D, but hence become ineffective at low I_D. Conversely, a large value of R_S is intolerable at high I_D. Moreover, a circuit that shares current evenly at low speeds can exhibit substantial unbalances when transients amount to several amperes over a microsecond or less. The failure to share current under dynamic conditions is often due to differential inductance in wiring and sometimes to variations in the internal capacitances among the MOSFETs (ref. 2). For these reasons even careful matching of device $V_{GS(th)}$ and transconductance may still not remove all unbalances.

This work reports a simple circuit that reduces unbalance at lower currents and still maintains good balance at higher currents by means of nonlinear

elements. The circuit developed is most effective against mismatches of static parameters. This work will also report on the reduction of dynamic unbalance for pulses of limited duty cycle by coupling source currents through the windings on thin tape wound magnetic cores. While this technique is well known in switching applications (ref. 3), discussions in the literature of its use in the active region of power MOSFETs are very limited. Hence, an example will be reviewed here using a Supermalloy tape wound core.

DIODE NONLINEARITY USED TO EXTEND RANGE OF CURRENT BALANCE

As noted above, any fixed set of resistors R_S can not effectively control current sharing over a wide range of current. Either the losses become too great at large R_S, or the differential voltage drop too low at low R_S. However, if one could in effect shift the current from higher to lower resistance paths as its magnitude increases, this problem would be minimized and he range of control thereby extended. The approach taken here is to use diodes to approximately effect a smooth shifting of the current paths.

The circuit presented in figure 1 extends control over the current balance down to lower currents. At high currents, of the order of amperes, most of each I_D flows through the fractional ohm resistors R_S which then effect current balance in the usual way. The potential drops across the silicon diodes D remain below a volt, and hence their losses stay low; and the splitting resistor R is typically a few ohms. As the current decreases the relatively constant diode drops become significant compared to the voltage drops in each side of R. Thus, as the diode currents drop to where the resistors R_S become ineffective, the resistor R starts providing the differential drop needed to maintain current balance.

The maximum differential V_{GS} that can be provided by this circuit is approximately the diode drop; that can be seen by assuming the tap on R is set to an extreme position. Additional series diodes will of course increase this, but other parameters would then be degraded. Therefore, large mismatches in the MOSFET characteristic curves are perhaps best eliminated by initial coarse screening. Due to the nonlinearities, the results are probably not worth the efforts required to derive analytic formulas for the differential V_{GS} produced as a function of the current deviation. Anyway, this circuit is quite easy to adjust by experiment

REVIEW OF CURRENT BALANCE FORCED BY A MAGNETIC CORE

As already mentioned, certain tape wound magnetic cores are very effective in enforcing current balance for limited durations in circuits operating under pulsed conditions. Desirable properties are magnetic softness, low losses, rapid response and a rounded B-H characteristic. Such a core is then connected as shown in figure 2.

The differential voltage ΔV introduced by the two N-turn windings amounts to

$$\Delta V = 2N \frac{d\phi}{dt} \tag{1}$$

in terms of the rate of change of the flux ϕ. Since the available swing ΔB of the magnetic field is limited, the duration Δt that a ΔV can be maintained is likewise limited to

$$\Delta t = 2NA_c \frac{\Delta B}{\Delta V} , \tag{2}$$

where A_c is the effective cross-section of the core. For a small core with few turns, this Δt may be only a 100 μsec or so. Nevertheless, if the material is magnetically very permeable, then the current balance will also be very good until the core is driven into hard saturation. Both Δt and quality of balance benefit from an increased N as long as the effects of leakage inductance remain negligible.

A more detailed analysis of the action of the core in the appendix shows that a finite permeability always leads to a divergence of the currents away from balance with some finite slope. This theory indicates that for an ideal core of constant permeability and a constant V_G, the current difference is exponentially asymptotic to the normal unbalanced value. However, this final value will often be reached much sooner in real cores because of magnetic saturation.

Flux reset, which takes place during the inactive time between pulses, produces a voltage spike in a sense opposite to ΔV. In many cases its magnitude will not reach anywhere near the levels (~20 V) dangerous to MOSFET junctions because usually the flux swings of concern are rather low and circuit capacitances are sufficient to absorb magnetizing current spikes. Otherwise, one may need special provisions, such as controlled resonant flux reset (ref. 4).

Rather than the destruction of a MOSFET by the flux reset ΔV, one is more likely to observe a current tail. The opposite sense of this reset ΔV tends to cause an unbalance near the end of the fall time of a pulse, because the core tends to prolong the conduction of the MOSFET which was more apt to conduct in the first place. This current tail is most apparent when the quiescent gate voltage is set at just below threshold.

EXPERIMENTAL OBSERVATIONS

The circuit shown in figure 1 was implemented using type MTM15N40 power MOSFETs (N-channel, enhancement mode, 15 A, 400 V, 250 W), type 1N1201 silicon diodes, $R_S = 0.5\ \Omega$ and $R = 2\ \Omega$. The MOSFET drain terminals were connected to a 300-V power supply through 60 Ω noninductive resistors, not shown.

To demonstrate the performance, the total current was controlled to be a triangular wave, rising from and returning to some small value, and having a slope of about 0.03 A/μsec. At this rate, no time-dependent effects could be seen, making it an essentially static test. Figure 3 plots x-y oscilloscope

trace data from this experiment, showing the relative deviation $(I_1 - I_2)/(I_1 + I_2)$, in percent, versus the total current $(I_1 + I_2)$. This plot shows that the relative deviation remains less than 4 percent from 0.8 A to over 7 A of total current. Only at low currents, below about 0.5 A, does the current balance fail rapidly. For the particular transistors on hand, the difference in $V_{GS(th)}$ was 0.25 V, and the tap on R was adjusted to about 0.8 Ω from one end in a subjective judgment of what seemed optimum. Variation of this tap was observed to affect the local minimum in the deviation (here at $I \approx 1$ A) and to displace the I_1 versus I_2 trace. For comparison to the usual method, which uses the resistors R_S alone, experimental data are also shown for this circuit with the R removed and the diodes short circuited.

As the current slew rate is increased, dynamic effects become more prominent and hysteresis, indicating current unbalance, appears in a trace of I_1 versus I_2. For current pulses having rise and fall times of about 1 μsec, this hysteresis was quite evident at a 1 A total current in the circuit of figure 1. For this rise time and current, oscilloscope traces of current pulses in each branch and the corresponding trace of I_1 versus I_2 are shown in figures 4(a) and (b), respectively.

When a magnetic core replaces the nonlinear network of figure 1, the character of current balance is greatly changed. A 1-mil Supermalloy tape wound core having an effective cross-section of 0.15 cm^2 and a mean length of magnetic path of 5.0 cm was bifilar wound to give two 7-turn windings and connected as shown in figure 2. It is apparent from the traces shown in figures 5(a) and (b) that extremely even and hysteresis-free current sharing could then be achieved, at least over the 8 μsec duration pulsewidth shown. No flux reset current tailing is discernible. Unfortunately as the pulse duration is increased, the limit implied by equation (2) begins to assert itself. After about 100 μsec, as the core gets driven progressively harder into saturation, the branch currents revert to their normal unbalanced values and a prominent current tail appears in one of the branches at turn-off. Figure 6(a) shows this evolution of the branch currents using long (~350 μsec) repetitive pulses. Indeed, quantitative agreement with equation (2) is fairly good because the B-field change from remanence to saturation is about 0.20 T in Supermalloy, giving $\Delta t \approx 210$ μsec.

The finite slope of the initial divergence away from balance is also clearly visible at the left edge of figure 6(a). This difference in the current grows initially at a rate of about 500 A/sec, a value which is also in good agreement with a first-order analysis of the action of the core presented in the appendix. For the magnetic parameters used, rapid saturation of the core prevented observation of the predicted exponential-like approach to steady state.

Retaining the branch with the tail, the lower trace of figure 6(b) shows the simultaneous voltage induced in one 7-turn coil; differential gate voltage ΔV amounts to twice this. The control period ΔV of 0.2 V is followed by a saturated dead zone and finally by a flux reset ΔV which peaks sharply but safely at about -2 V.

DISCUSSION AND CONCLUSIONS

The circuit in figure 1 was demonstrated to be a practicable means of extending the range of externally forced current balance in two branches controlled by power MOSFETs that are operated in their active regions from a single gate drive. The main advantages of this strictly passive circuit are simplicity, relatively low power dissipation, and duty cycle up to 100 percent. While the current balance improvement at high currents for the circuit in figure 1 is not much greater than for the standard technique of using only source lead resistors, the improvement is much greater at lower currents. Therefore, one can expect significantly improved current balance only over a broad range, although it may be difficult to attain the precision of balance possible with active feedback circuits. Nevertheless, when only a few tenths of a volt gate differential need be compensated under conditions that would not be termed high precision or high speed pulse, the merits of the circuit in figure 1 outweigh its shortcomings. Moreover, improvements in range and quality may well be possible based on the same idea of current steering by nonlinear devices.

Also the known use, at least in principle, of a highly permeable magnetic core to force current balance was briefly reexamined for application to current control by power MOSFETs in their active region. In the active region, branch currents are forced toward equality by a small induced voltage applied differentially to the gate-source junctions. For short pulse durations, of the order of a few tens of microseconds and a $V_{GS(th)}$ mismatch of about 0.2 V, even a small (A_c = 0.15 cm^2, $\bar{l}$ = 5 cm) Supermalloy tape wound core having a pair of 7-turn windings was shown to be very effective in enforcing current balance. A duty cycle above 50 percent was quite feasible, as any interference with the small flux reset voltage spike was negligible. Eventually core saturation effects dominate, effectively removing the core from the circuit, and the branch currents revert to their usual unbalanced values. In this case, current balance deteriorated from the very start of a pulse at a rate of about 500 A/sec and finally rapidly and predictably after about 200 μsec as the core saturated. The reverse polarity voltage spike caused by flux reset even from a well saturated state was only 1 V per winding--not yet a hazard, but sufficient to produce current tailing in one branch at the end of a pulse.

A simple first-order theory describing the action of the core was developed. The linearized version of this theory shows that the branch currents revert exponentially with time to their usual unbalanced values even if the core remains unsaturated. This theory predicts an initial divergence rate of 320 A/sec for the circuit tested, as compared to the roughly 500 A/sec observed. Depending on parameter values, it appears that in circuits using uncut Supermalloy cores, the core will likely saturate before the exponential of the model using a linearized recoil permeability can run its course. Such was the case here.

Finally, it is suggested that an instrument could be built based on the magnetic core current balancing technique to quickly match the gate voltages of power MOSFETs by observing the induced voltage. This voltage is easy to measure in a tertiary winding. The total current can be kept a constant by means of a feedback signal to a gate drive, and the tertiary winding then gives the gate voltage differential.

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3. Grafham, D.R.; and Golden, F.B., eds.: External Forced Current Sharing. SCR Manual, 6th ed., General Electric Co., Section 6.2.4.

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APPENDIX - ANALYSIS OF CURRENT BALANCE FORCED BY A MAGNETIC CORE

A first-order analysis of the behavior of the magnetic core and MOSFETs in figure 2 is carried out here using the elementary linear model of a MOSFET. The higher order inductive effects of wiring and effects of device capacitances such as C_{iss} are ignored because they typically correspond to submicrosecond modulations of the basic action of the core in this circuit.

Written for each MOSFET, the linearized model transconduction equations are

$$I_1 = (V_G - V_{S1} - V_{th1})g_1 \tag{A1}$$

and

$$I_2 = (V_G - V_{S2} - V_{th2})g_2 \ . \tag{A2}$$

where g stands for the MOSFET common source large signal forward transconductance g_{FS}, and V_{th} stands for the gate-source threshold voltage $V_{GS(th)}$. There is only one V_G because both gates are driven from the same source. The V_S for each transistor is written as the sum of the induced voltage $N(d\phi/dt)$ in each N-turn winding and a small voltage drop IR_O due to wiring and MOSFET channel resistance:

$$V_{S1} = I_1 R_{O1} + N \frac{d\phi}{dt} \ , \tag{A3}$$

$$V_{S2} = I_2 R_{O2} - N \frac{d\phi}{dt} \ . \tag{A4}$$

Assuming the magnetic characteristic of the core to be hysteresis free, although not yet linearized, the flux ϕ will be some monotonically increasing function f of the total mmf $N(I_1 - I_2)$:

$$\phi = f[N(I_1 - I_2)] \ . \tag{A5}$$

These five equations determine the time evolution of the currents I_1, I_2 when $V_G(t)$ is specified as a function of time. However, from the point of view of quality of current balance the interest here is in the current difference

$$\delta = I_1 - I_2 \tag{A6}$$

and the total current

$$I = I_1 + I_2 \ .$$

To this end the system (A1) to (A5) can be rewritten and collapsed to

$$\frac{1}{2}(r_1 + r_2)\delta + \frac{1}{2}(r_1 - r_2)I = V_{th2} - V_{th1} - 2N^2 f'(N\delta)\frac{d\delta}{dt} , \tag{A7}$$

$$\frac{1}{2}(r_1 - r_2)\delta + \frac{1}{2}(r_1 + r_2)I = 2V_G - V_{th1} - V_{th2} , \tag{A8}$$

$$\phi = f(N\delta) , \tag{A9}$$

where a small resistance

$$r = \frac{1}{g} + R_0 \tag{A10}$$

is defined for each branch.

Equations (A7) and (A8) then determine the evolution equation

$$N^2 f'(N\delta)\frac{d\delta}{dt} + r_p\delta(t) = h(t) , \tag{A11}$$

where

$$r_p = \frac{r_1 r_2}{r_1 + r_2} \tag{A12}$$

and

$$h(t) = \frac{r_1 V_{th2} - r_2 V_{th1} - (r_1 - r_2)V_G(t)}{r_1 + r_2} . \tag{A13}$$

It is clear from equation (A11) that for constant V_G and in steady state

$$\delta = \frac{h}{r_p} , \tag{A14}$$

which is the maximum possible unbalance.

A simple formal solution of equation (A11) is not possible for any general magnetization characteristic f. However, the case of a linearly permeable core is trivial to solve and is easily extended to a piecewise linearization should such accuracy be desired. This is so because equation (A11) is of the first order and δ is continuous even when h is not. Hence, discontinuities of the permeability μ can only introduce jumps in the slope $d\delta/dt$, but no oscillatory behavior. A linearly permeable core has

$$f(N\delta) = PN\delta , \tag{A15}$$

where the constant

$$P = \frac{\mu A_c}{\bar{l}} \tag{A16}$$

is the permeance for a core of cross-section A_c and mean length of magnetic path $\bar{l}$. This gives

$$f' = P \ , \tag{A17}$$

and corresponding solutions of equation (A11) are

$$\delta(t) = \delta(t_0)e^{(t_0-t)/\tau} + \frac{1}{\tau r_p} e^{-t/\tau} \int_{t_0}^{t} h(\varepsilon)e^{\varepsilon/\tau}\, d\varepsilon \ , \tag{18}$$

where

$$\tau = \frac{N^2 P}{r_p} \tag{A19}$$

is the time constant.

Both the case of a step in $V_G(t)$ which starts conduction at $t = 0$ and the case of a more general $V_G(t)$ but with $r_1 = r_2$ are included in constant h. Over intervals of constant μ these solutions will have the form

$$\delta(t) = \delta(t_0)e^{(t_0-t)/\tau} + \frac{h}{r_p}\left[1 - e^{(t_0-t)/\tau}\right], \tag{A20}$$

with $\delta(0) = 0$ and $\delta(\infty) = h/r_p$. The initial slope is always

$$\delta'(0) = \frac{h(0)}{r_p\tau} = \frac{h(0)}{N^2 P} \ . \tag{A21}$$

The MOSFETs used in the experiment had $r_1 \approx r_2$ and $V_{th2} - V_{th1} \approx 0.2$ V, which gives $h = (V_{th2} - V_{th1})/2 \approx 0.1$ V. For the static Supermalloy B-H curve rising above remanence, one could assign an average recoil permeability of about 0.021 h/m. Hence, for the given core dimensions and $N = 7$ the $\delta'(0) \approx 320$ A/sec. This value probably underestimates the rate because dynamic permeabilities are usually lower than static ones.

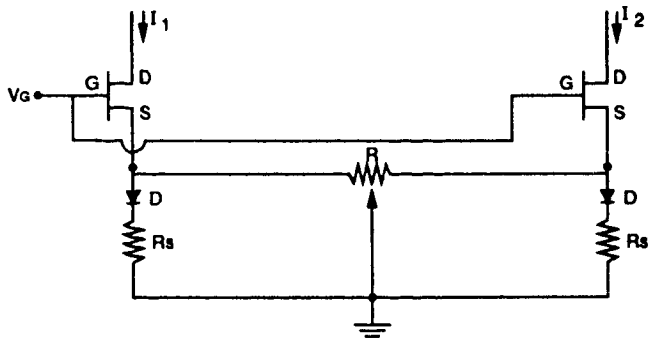

Figure 1. - Circuit for improving current balance at low currents. The tap on R is adjustable to vary performance over specified current ranges.

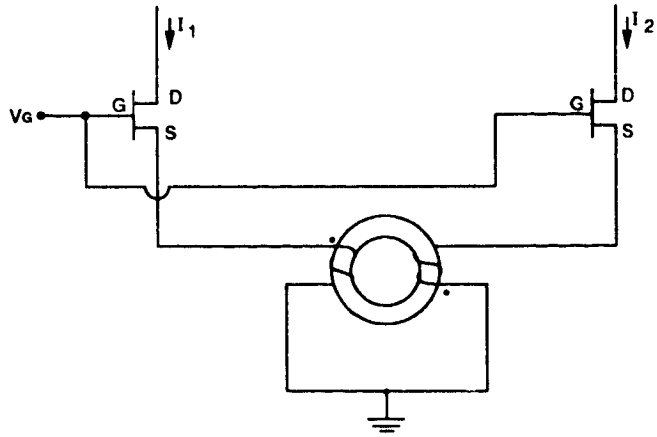

Figure 2. - Dynamic current balance forced by a magnetic core. This type of circuit is well known in power switching applications.

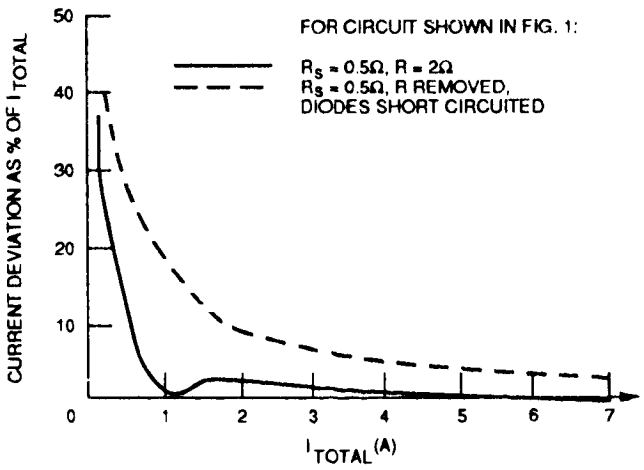

Figure 3. - Static current deviation as a function of the total current observed for the circuit in Fig. 1, with componet values as given in the text.

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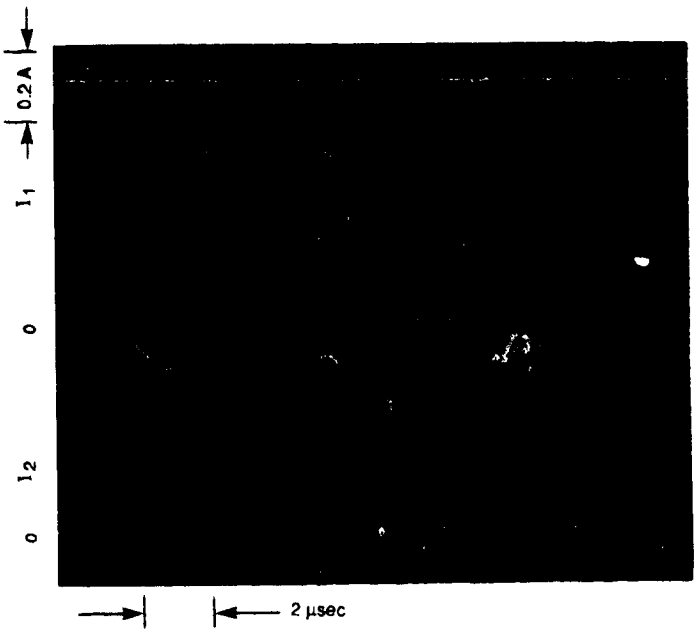
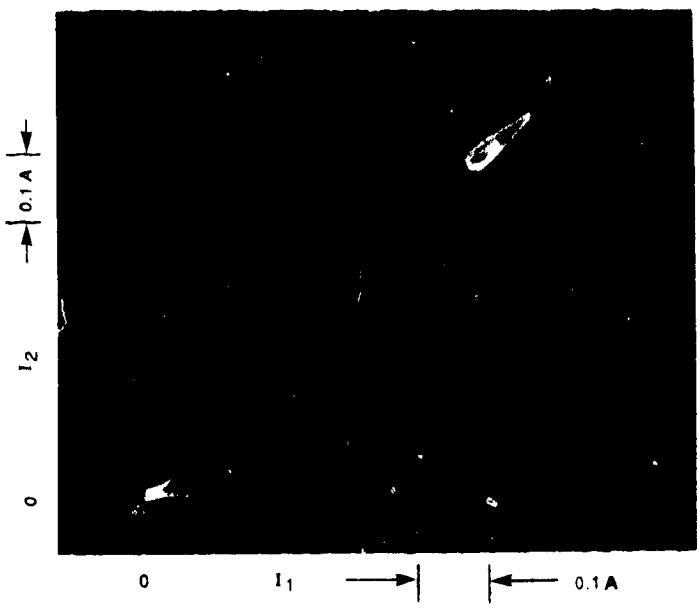
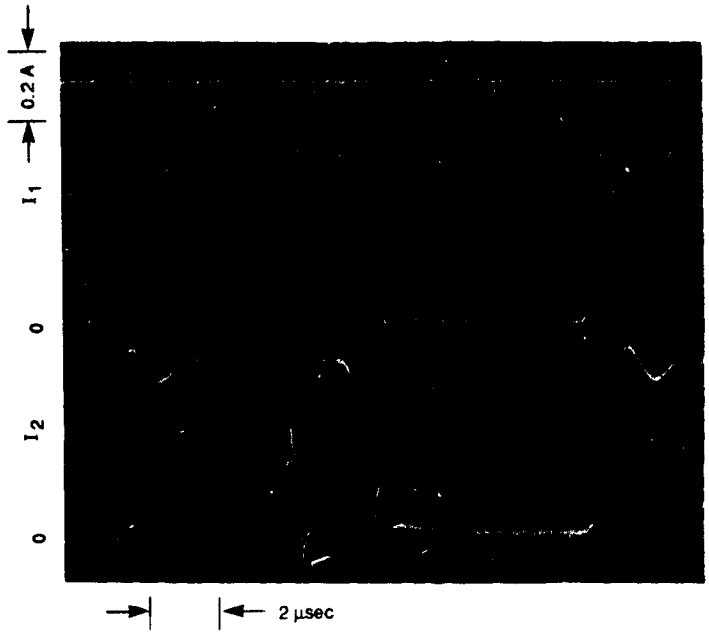


(a) Pulsed I_1 and I_2 vs time.



(b) I_1 vs I_2 for these pulses, showing hysteresis.

Figure 4. - Dynamic hysteresis in the circuit of Fig. 1. Pulse height was adjusted to accentuate the relative nonlinearity.



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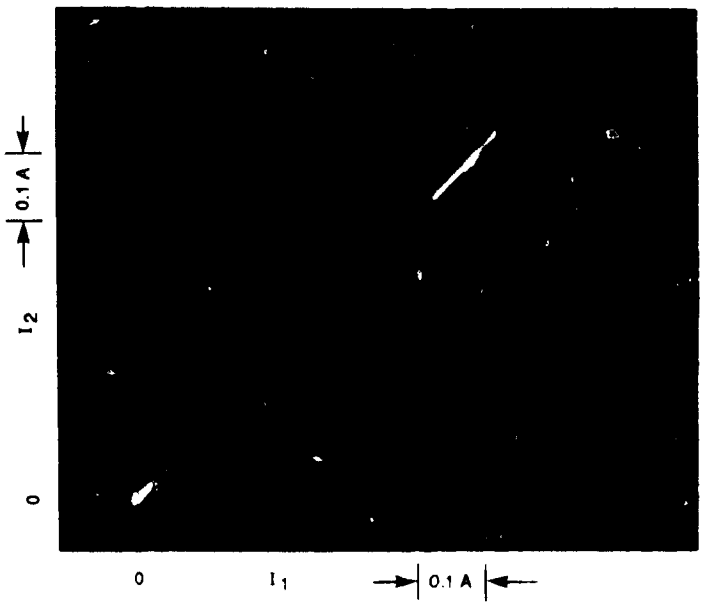
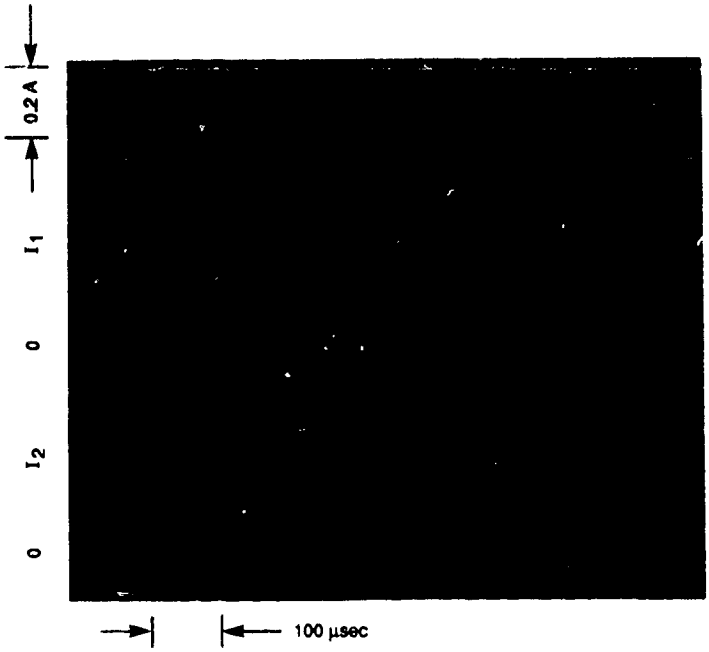
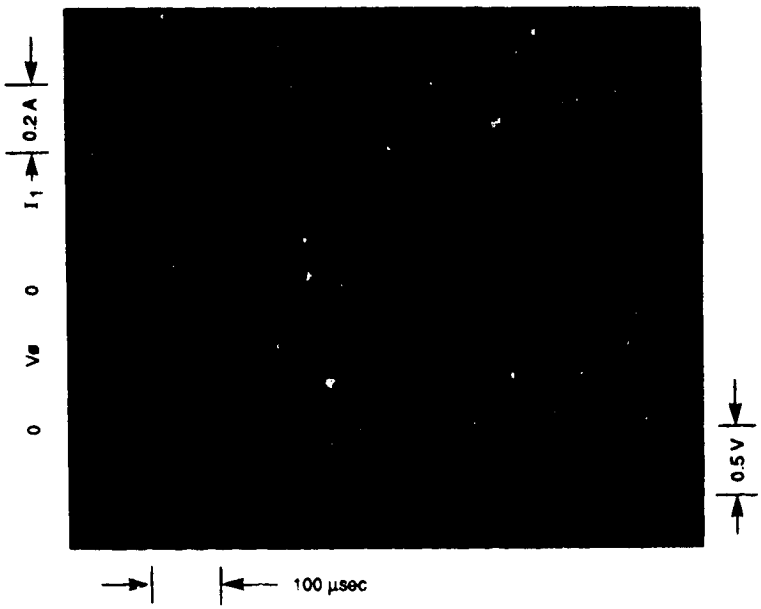


(b) I_1 vs I_2 for these pulses, showing good linearity.

Figure 5. - Short term dynamic current balance achieved by the circuit of Fig. 2, using a small supermalloy tape wound core.



(a) Magnetic saturation causes reversion of I_1 and I_2 to their normal unbalanced values.



(b) Lower trace shows corresponding induced voltage in one winding.

Figure 6. - Approach to failure of long term current balance observed in the circuit of Fig. 2.

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