TECHNICAL NOTE NO. 6

Project No. A-588

INVESTIGATION OF ELECTRONIC SWITCHES FOR ANALOG AND HYBRID COMPUTATION

By John W. Robertson

Prepared for
George C. Marshall Space Flight Center
Huntsville, Alabama

Contract No. NAS8-2473

(Development of New Methods and
Applications of Analog Computation)

31 March 1965

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Engineering Experiment Station
GEORGIA INSTITUTE OF TECHNOLOGY
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ABSTRACT

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On the basis of a preliminary literature survey, selected analog switches were investigated to determine the relative performance characteristics of types considered most promising in analog or hybrid computer applications. Measured performance parameters are tabulated and evaluations given for examples of the modified Guennou chopper, the nonsaturating two- and four-transistor switches, the complementary transistor bridge, the series-shunt unifet switch, and the six-diode bridge gate, all constructed from available standard semiconductor components. From these results, it is recommended that further work be done with the six-diode bridge gate and with the series-shunt field-effect-transistor switch to optimize their performance for specific analog and hybrid computer functions.

Author

FOREWORD

Contract NAS8-2473 was initiated in September 1961 and has covered a variety of assignments relating to work at the Flight Simulation Branch of Marshall Space Flight Center's Computation Laboratory. The MSFC Project Technical Officer has been Dr. W. K. Polstorff (R-COMP-RS). A large portion of the effort on this program is now being provided by personnel of the Georgia Tech School of Electrical Engineering in the general areas of (a) nonstationary noise studies, and (b) error analysis for hybrid computation. However, the laboratory investigations described herein were performed by Mr. John W. Robertson, with technical guidance from Mr. Frank R. Williamson, Jr., in the Special Problems Branch of the Engineering Experiment Station's Physical Sciences Division, under which the project has thus far been administered. It is planned that these investigations will be continued on a more limited basis during the remainder of the current contract period, terminating in December 1965.

F. Dixon
Project Director A-588

CONTENTS

I - INTRODUCTION

The general aim of the work on which this report is based is to obtain a design for an analog switch of improved performance.

Analog switching devices, both electromechanical and electronic, are used in many fields of electronics. In communications, they are variously referred to as commutators, multiplexers, modulators or demodulators, and gates. In analog computation, switching devices may be called choppers, modulators, samplers, sampling switches, input selectors, or simply switches. Other fields also have a variety of technical names for analog switches, each with its own specialized meaning. However, the basic function of all of the devices is really the same, and the different terminologies tend to indicate not so much the nature of a device as its mode of operation or application. Thus, some applications may allow use of devices that are restricted to a particular frequency of operation, while others may require that the device be capable of more or less random operation. But in either case the fundamental objective is to provide, alternately, either lossless transmission or complete attenuation of an input signal, when and as desired.

Typical examples of analog and hybrid computer applications of switches are (1) sampling switches for sample-and-hold circuits, (2) reset switches in mode control logic, and (3) reset pulse generator switches for incremental analog-to-digital conversion devices.* Such applications require switches capable of switching at intervals ranging from infinity (continuous operation) to possibly microseconds, with nonsymmetrical on and off times. In addition, successive on and off times need to be independent.

For a switch to meet the above requirements, it must be capable of continuous operation. This in itself rules out many of the possibilities in the literature, including the majority of switches with ac-coupled drives. Analog switches for computer application must also have dc-coupled signal channels. Several types of switches, such as the diode ring-bridge modulator and the diode capacitance modulator are inherently incapable of continuous operation. Other types, such as the transistorized switch of Williams, have ac-coupled signal channels.

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* As in the "AID Converter" developed by F. R. Williamson, Jr. under Contract DA-01-009 ORD-853 and subsequently incorporated in a generalized analog integrator ("EGI") under the present NASA contract.

Several switches having ac-coupled drive signals, such as the Bright circuit, may be modified to provide continuous operation through the use of a silicon controlled switch (SCS) and a bias source, and would be expected to give the same performance as the unmodified versions.

Other desirable qualities in an analog switch are economy, reliability, high switching speed, and high frequency capabilities. Besides yielding already known performance, the modified units mentioned above are more complex and limited in switching speed. Photoconductive gates also fall into the slow switching speed category with presently available drives (laser diodes excluded).

The switching circuits chosen for further investigation on the bases indicated above are identified and described in the next chapter.

II - DESCRIPTION OF SWITCH TYPES STUDIED

2-1. Modified Guennou Chopper (see References A13,A18)

The Guennou chopper is a simple two-transistor switching circuit, designed by S. Guennou in France and subsequently described by H. Kemhadjian in the April 1960 issue of Mullard Technical Communications (Reference A13). The modified version shown below was arrived at by removing the coupling capacitor of the standard chopper and direct-coupling the load.

Current drive is supplied to the base of each transistor at the value resulting in lowest inverse-mode saturation voltage $V_{CE}(sat.)_i$, achieved by adjusting the base resistors R_{b1} and R_{b2}. The load resistance R_L should be large enough so as not to load the balance potentiometer R, which in turn is chosen so as to make the effects of R_{in} in series with the pot negligible. The transistors are operated in the inverse mode in order to provide a low offset voltage, and they should be matched against one another for inverse-mode current gain β_i, collector-to-emitter leakage current I_{CEOi}, and saturation voltage $V_{CE}(sat.)_i$.

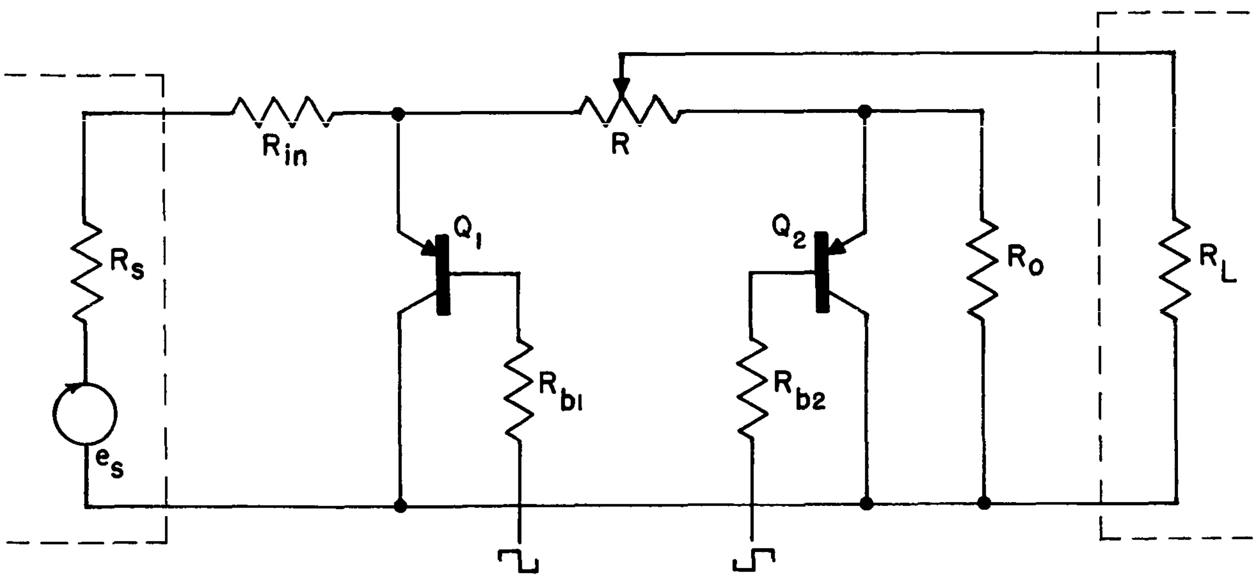


Figure 1. Modified Guennou Chopper.

2-2. Nonsaturating Transistor Switches (see Reference A5)

The nonsaturating transistor switch is a type of switched complementary emitter-follower circuit. Shown below is the "four-transistor" design suggested by Brubaker in Reference A5. His "two-transistor" version is similar but omits the first emitter-follower stage (Q3,Q4).

Voltage drive is supplied to points a and b, thus alternately shorting to ground and releasing the bases of the first complementary emitter-follower (c,d). Transistors for each emitter-follower should be a complementary pair, matched for normal-mode current gain (β_n) and having a high current gain at the temperatures of operation.

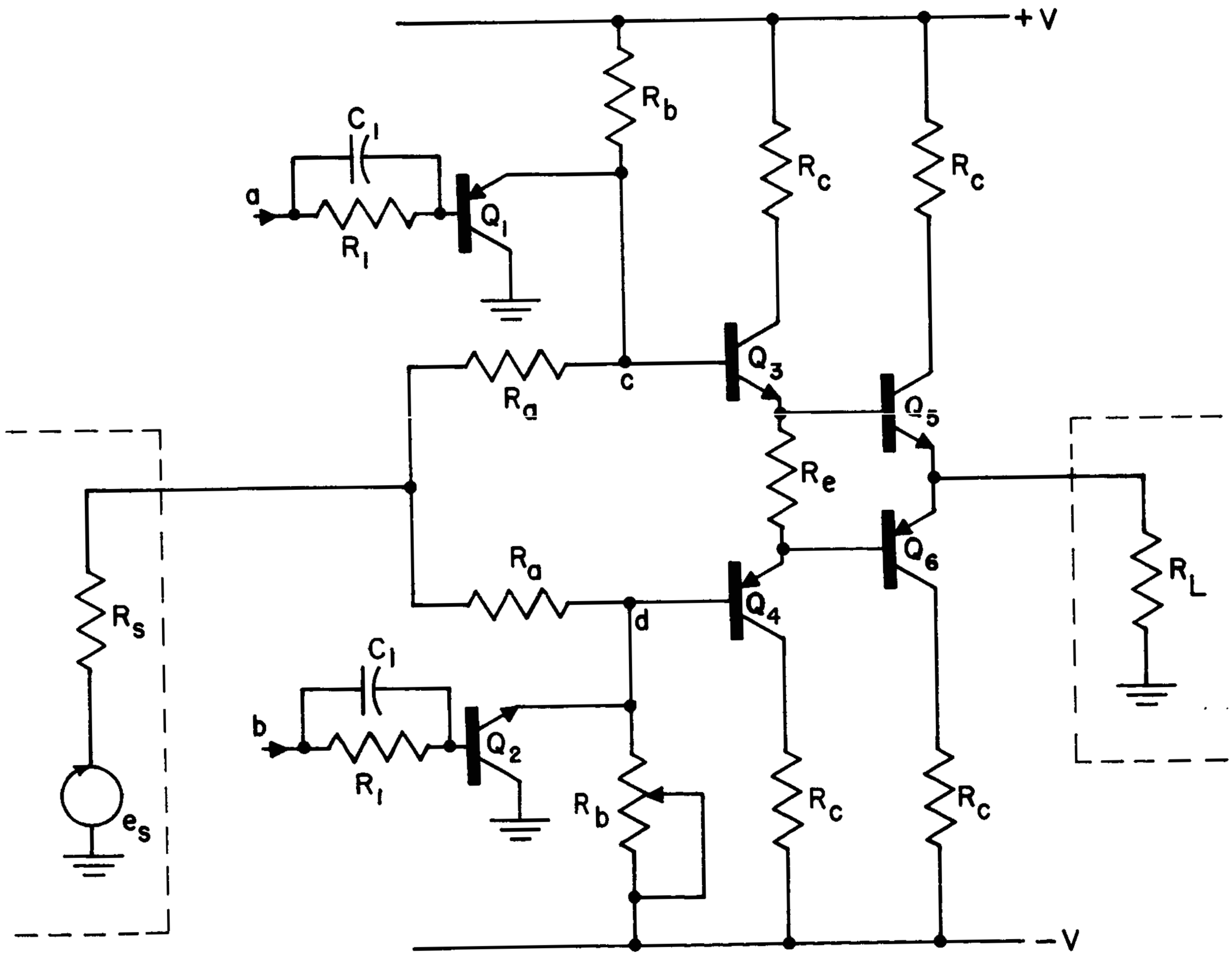


Figure 2. Four-Transistor Nonsaturating Switch.

2-3. Complementary Transistor Bridge (see Reference A12)

Depicted below is the transistor bridge circuit described by Kalfaian in Reference A12 for low-level switching applications. This has been previously referred to on this project as the "complementary microvolt transistor bridge."

Complementary drive signals are applied at points a and b to turn all transistors off or on at the same time. This circuit requires a matched set of four transistors, two npn and two pnp types, matched for normal-mode current gain β_n, collector-to-emitter leakage current I_{CEO}, and saturation resistance R_{CE}(sat.) over the temperature range of interest.

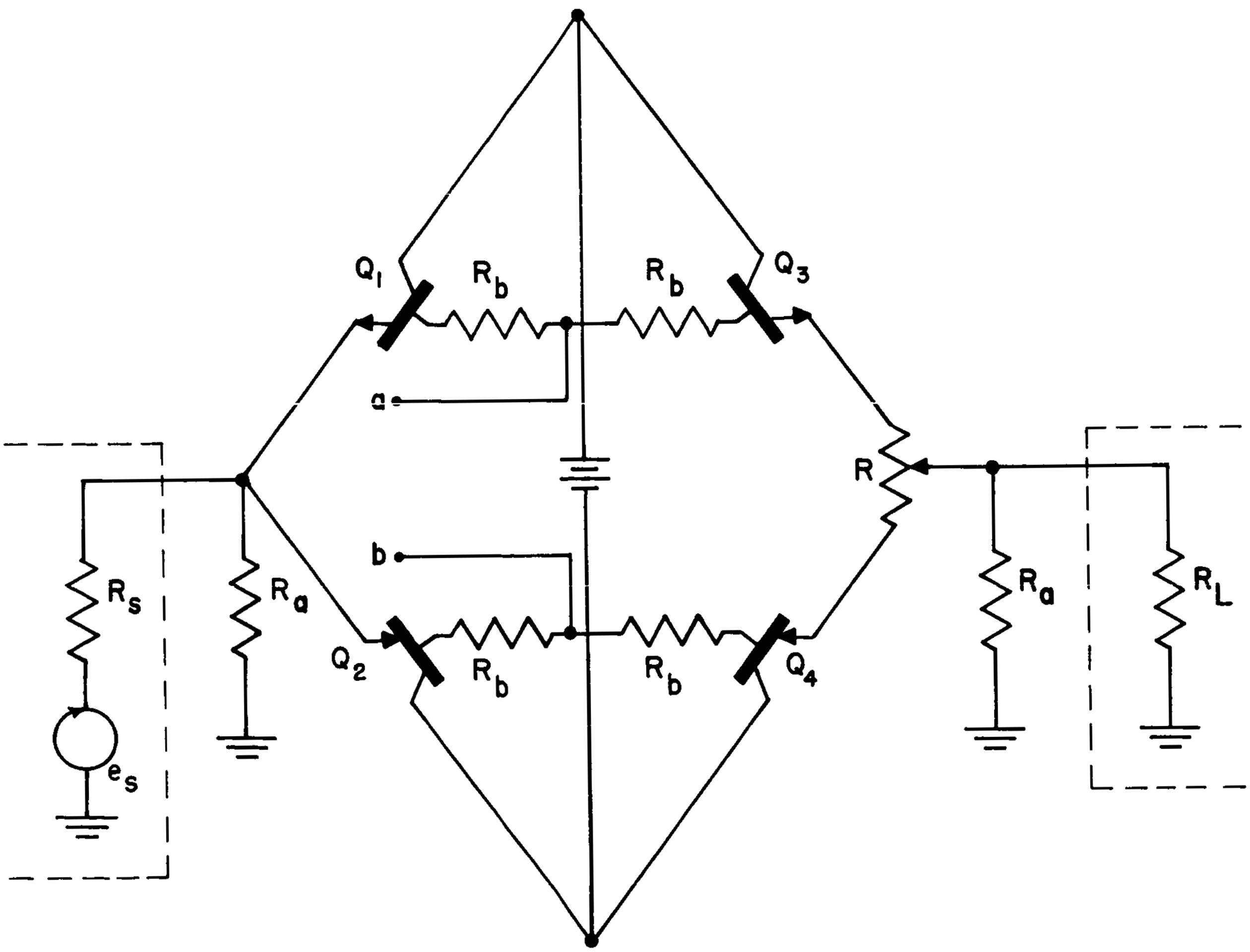


Figure 3. Complementary Transistor Bridge.

2-4. Series-Shunt Unifet Switch (see Reference C3)

The simple switching circuit shown below utilizes a pair of unipolar field-effect transistors (FET's). Push-pull drive signals applied at points a and b serve to turn on one FET and simultaneously turn off the other. There are no matching requirements for this circuit.

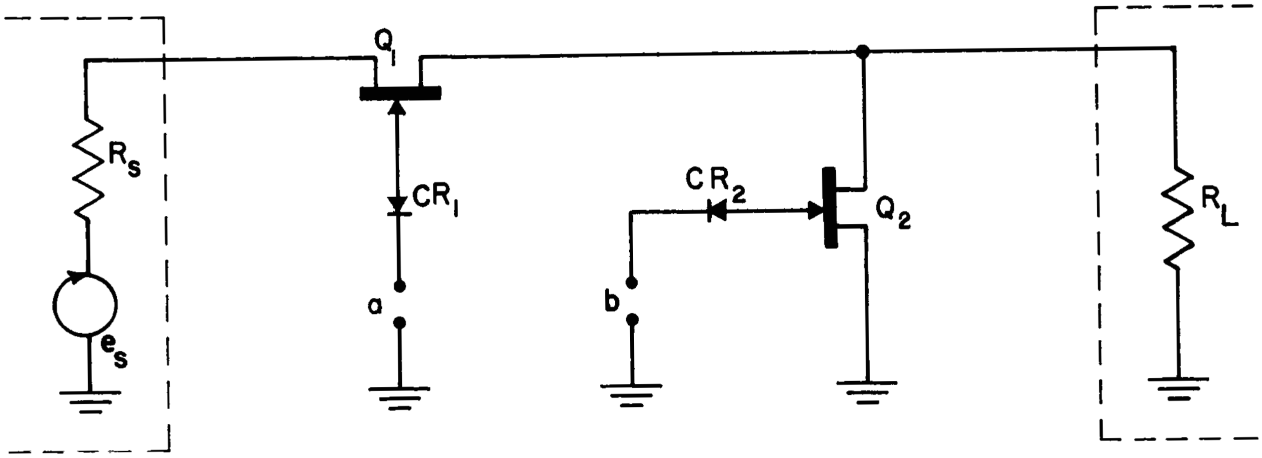


Figure 4. Series-Shunt Unifet Switch.

2-5. Six-Diode Bridge Gate (see Reference B7)

In an excellent 1955 paper (Reference B7), Millman and Puckett analyzed the performance of low-level gating circuits incorporating two, four, or six diode units in a bridge-type configuration. Their results indicated that the six-diode version would be most suitable for further investigation under the present project.

In the circuit as shown below, push-pull control voltages are applied at points a and b and cause the four bridge diodes simultaneously to either conduct or block. For optimal performance, the fixed supply voltages (± V) need to be quite accurately balanced, the four bridge diodes should have a high ratio of forward conductance to reverse leakage, and the two output diodes should be closely matched as regards their leakage currents.

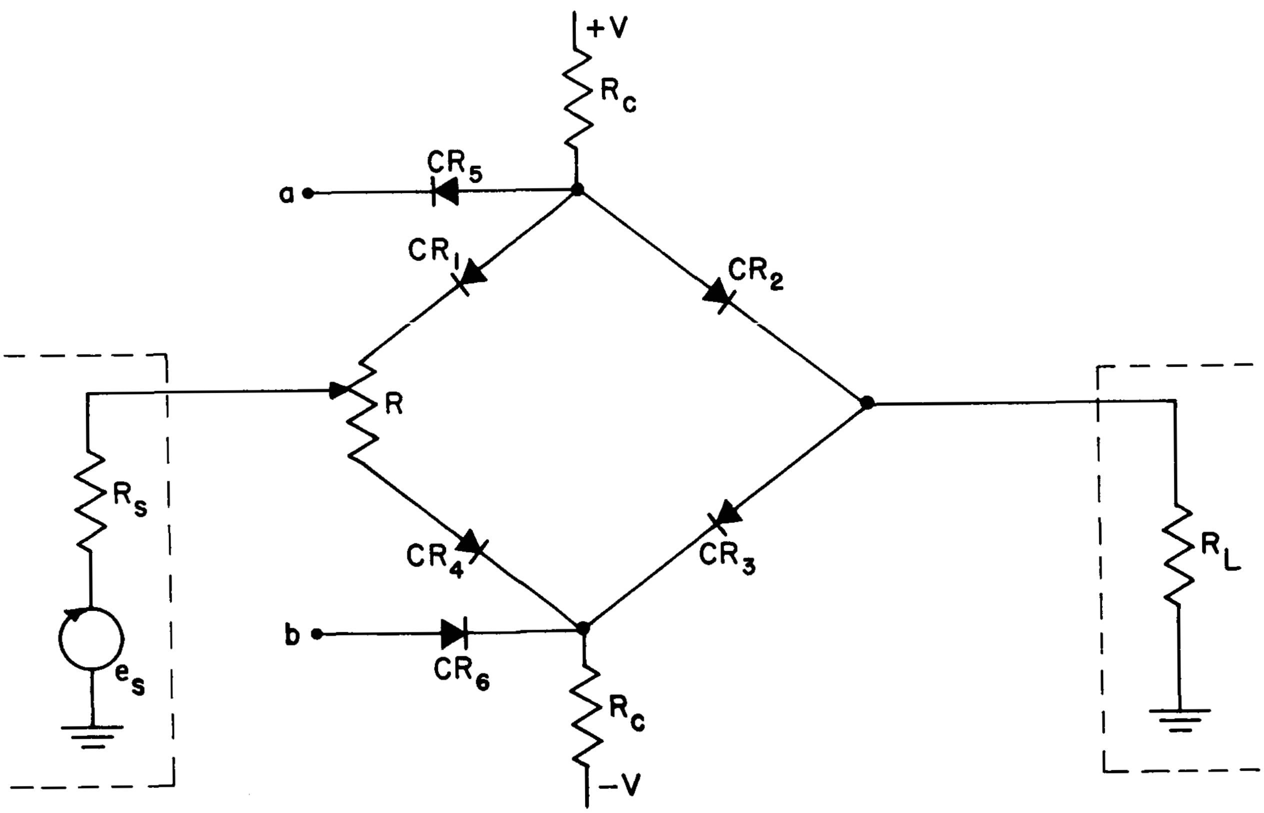


Figure 5. Six-Diode Bridge Gate.

III - SWITCH MODEL DEFINITIONS AND PERFORMANCE CRITERIA

3-1. Ideal and Nonideal Switch Models

Ideally, a switching device should exhibit zero on-resistance, infinite off-resistance, total absence of either offset voltage or drive leakage, and infinite operating speed (zero actuation time). Of course, no real switch can provide perfectly ideal performance. Electronic and electromechanical switches alike are limited in operating speed, have some offset voltage, have less than infinite off-resistance, and more than zero on-resistance. In addition, they are not completely isolated from ground, and electrically actuated types will possess some drive leakage. These nonideal properties, except for the drive leakage, have been represented in the switch equivalent-circuit diagrams below. Alternative models are of course possible (e.g., see Reference A17).

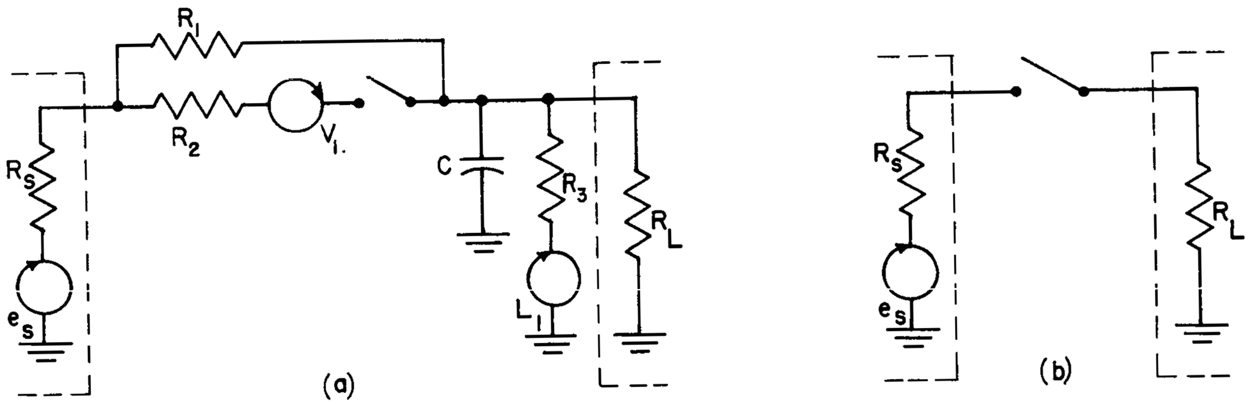


Figure 6. SPST Switch Models: (a) actual, (b) ideal.

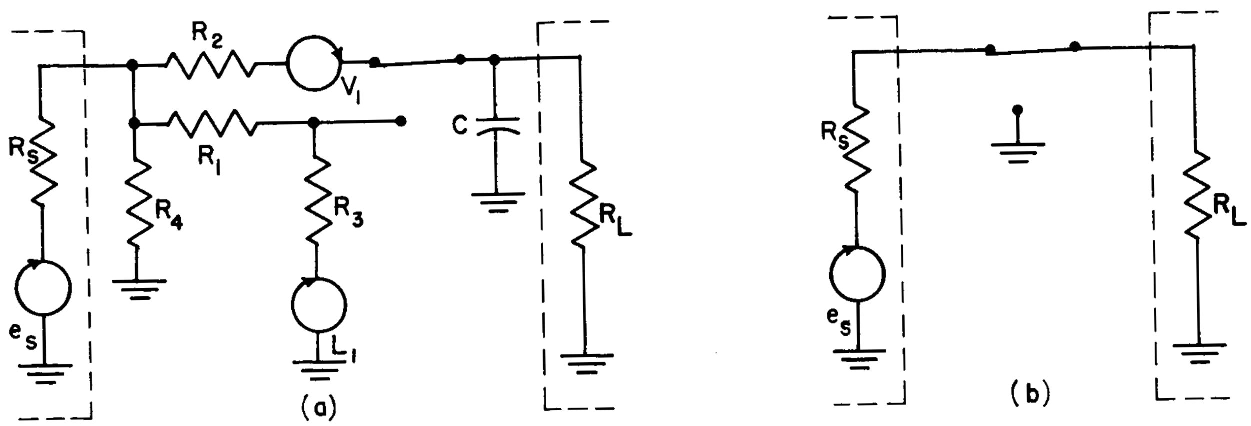
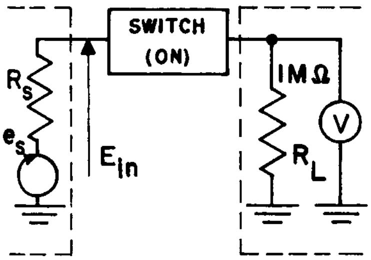


Figure 7. SPDT Switch Models: (a) actual, (b) ideal.

3-2. Switch Performance Parameters

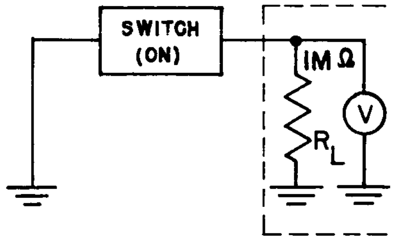
After some consideration, it was decided that the electronic switches to be studied should be treated as amplifiers, with gain and offset measurements made on them under both "on" and "off" conditions. Switching frequency limits were also to be determined, and additional data would be taken if deemed necessary or desirable. Definitions of the primary performance parameters measured are shown in equation and diagrammatic form below.

$$A_v(\text{on}) = \left.\frac{\Delta E_{out}}{\Delta E_{in}}\right|_{\substack{\text{switch on}\\ R_L = 1M\Omega}}$$



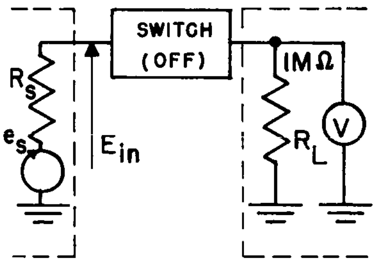
originally a Tektronix 545, later a Keithley 610A, then a John Fluke 823A

$$V_o = \left.E_{out}\right|_{\substack{\text{Switch on}\\ E_{in} = 0_v}}$$



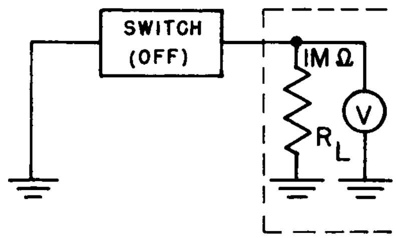
same as above

$$A_v(\text{off}) = \left.\frac{\Delta E_{out}}{\Delta E_{in}}\right|_{\substack{\text{Switch off}\\ R_L = 1M\Omega}}$$



same as above

$$L_D = \left.E_{out}\right|_{\substack{\text{Switch off}\\ E_{in} = 0_v}} - \left.E_{out}\right|_{\substack{\text{Switch on}\\ E_{in} = 0_v}}$$



same as above

Figure 8. Switch Parameter Measurement Circuits.

3-3. Model Performance Parameters

As a matter of general interest, the actual switch performance parameters defined above may be expressed in terms of the theoretical switch models presented under Section 3-1. The following approximate relationships are obtained after eliminating terms of negligible magnitude in accordance with the assumptions noted.

	SPST Model	SPDT Model
$A_V(\text{on})$:	$\dfrac{R_L}{R_L + R_2}$	$\dfrac{R_L R_1}{(R_L + R_2 + R_S)R_S}$
V_o:	$V_1\left\{\dfrac{R_L R_1}{R_L R_1 + R_2(R_1 + R_L)}\right\}$	$V_1\left\{\dfrac{R_L}{R_L + R_f}\right\}$
$A_V(\text{off})$:	$\dfrac{R_L R_3}{R_L(R_3 + R_1) + R_1 R_3}$	$\dfrac{R_3}{R_S + R_1}$
L_D:	$L_1\left\{\dfrac{R_L R_1}{R_3(R_L + R_1) + R_L R_1}\right\}$	$L_1\left\{\dfrac{R_2 R_1}{R_3(R_2 + R_1) + R_2 R_1}\right\}$
Conditions:	$R_2 \ll R_L \ll R_1, R_3$	$R_S \ll R_1, R_4$
	$R_S \ll R_1, R_3$	$R_3 \ll R_1$
	$e_{in} \gg L_1$	$e_{in} \gg L_1(R_1/R_3)$

3-4. Performance Calculations for Specific Switches

Although the foregoing mathematical expressions and the models from which they are derived can provide useful insights into switch behavior, they are not of much help in attempting to predict the performance of an actual switch. One may, however, obtain quantitative estimates of desired performance parameters in any given case by fairly straightforward analysis of the switch circuitry. Presented hereunder are results derived for the two most important switch types considered.

Series-Shunt Unifet Switch

Given I_{GSS} = gate-to-source leakage current of FET,

r_{ds} = drain-to-source resistance with zero gate-to-drain voltage,

R_{off} = (drain-to-source voltage)/(pinch-off drain current),

then for the circuit shown in Section 2-4, provided R_L is small compared to $r_{ds}(Q_2)$ and $R_{off}(Q_2)$, the switch performance parameters may be calculated as follows:

$$A_v(\text{on}) = \frac{R_L}{R_L + r_{ds}(Q_1)} \qquad A_v(\text{off}) = \frac{r_{ds}(Q_2)}{r_{ds}(Q_2) + R_{off}(Q_1)}$$

$$V_o = I_{GSS}(Q_2) \cdot r_{ds}(Q_1) \qquad I_D = I_{GSS}(Q_1) \cdot r_{ds}(Q_2)$$

Six-Diode Bridge Gate

Analysis of the switch given in Section 2-5 is facilitated by use of the diode equivalent cirucit shown below (containing an assumed ideal diode).

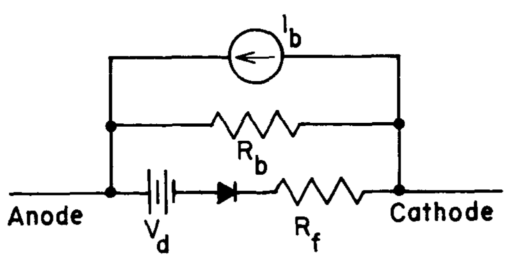


Figure 9. Equivalent Circuit for Diode.

Any offset voltage V_o in the six-diode gate can normally be balanced out by adjusting potentiometer R. This adjustment will typically provide compensation for values of R_f in the bridge output diodes in the ratio of 3:1 (with $R = 50\Omega$, $R_f \approx 25\Omega$).

The drive leakage L_D of the six-diode gate can be assumed to be produced solely by the difference in leakage currents of the two output diodes. This assumption will be valid under the conditions that the bridge output diodes have back resistance (R_b) large compared to the load resistance (R_L), that the two drive diodes have small forward resistance (R_f), and that the impedance of the drive source is small.

Values for on voltage gain and off voltage gain of the six-diode gate may be calculated quite readily with formulas derived from an ac model of the circuit--or, with considerably more calculations, from a dc analysis (see Reference B7). The approximate expressions for predicting switch performance are thus as follows.

$$A_v(\text{on}) = \frac{R_c/2}{R_c/2 + R_f/2 + R/4} \cdot \frac{R_L}{R_f/2 + R_L}, \qquad V_o = 0 \text{ (adjusted)};$$

$$A_v(\text{off}) = \frac{R_c/2}{R_c/2 + R_b/2 + R/4} \cdot \frac{R_L}{R_b/2 + R_L}, \qquad L_D = (I_{b3} - I_{b2})\, R_L.$$

IV - EXPERIMENTAL RESULTS AND DISCUSSION

4-1. Performance Data Summary

Performance data are tabulated hereunder for the various electronic switches that have been constructed and tested on this project. The switches are identified in the table as follows:

- MGC- modified Guennou chopper
- 4TNS- four-transistor nonsaturating switch
- 2TNS- two-transistor nonsaturating switch
- CTB- complementary transistor bridge
- SSUS- series-shunt unifet switch
- 6DG/F- six-diode bridge gate using Fairchild 1N3595's
- 6DG/G- six-diode bridge gate using G.E. 1N4443's

The table includes values for the main performance parameters defined in Section 3-2, namely: on voltage gain, $A_v(on)$; offset voltage, V_o; off voltage gain, $A_v(off)$; and drive leakage, L_D. In the case of the series-shunt unifet switch and the two six-diode gates, these parameters were determined not only at the normal room temperature of 25°C but also at an oven-controlled temperature of 50°C. The two sets of data then yielded values for the nominal temperature sensitivities $\Delta V_o/\Delta T$ and $\Delta L_D/\Delta T$, as shown in the table.

The column designated f_{max} gives the maximum frequency of operation determined by taking the reciprocal of the summed rise and fall times (i.e., times required for the output voltage to reach its final value, rising and falling) of the switching waveform as observed on an oscilloscope. Obviously, this method suffers somewhat in accuracy due to the necessity of determining a point at which the waveform may be said to have reached its final value. A different, more accurate, procedure might be desirable for some applications.

The entries marked E_{in} represent maximum signal input levels permitted for the particular circuit components used. These are not listed as ultimate limits but do indicate what might be considered appropriate levels of operation for each type of switch tested.

As a final point of interest, it should be mentioned that the first four switch models listed were built on standard phenolic assemply boards, with no special precautions for shielding. The last three switch models, on the other hand, were enclosed in small aluminum boxes and were connected to the drive circuitry by shielded cables. The method of construction for these models may be seen from the photographs below, one of which also shows a typical arrangement of the instrumentation involved in a switch performance test.

Table 1. EXPERIMENTAL VALUES OF SWITCH PERFORMANCE PARAMETERS.

Switch	A_v(on)	V_o[mv]	A_v(off)	L_D[mv]	$\Delta V_o/\Delta T$ [$\mu v/^oC$]	$\Delta L_D/\Delta T$ [$\mu v/^oC$]	f_{max} [kc]	$\hat{E}_{in}$ [v]
MGC	0.69	0.2	$.6x10^{-1}$	0.1			60	± 1
4TNS	0.81	0.2	$.8x10^{-3}$	0.2			50	± 5
2TNS	0.72	0.1	$1x10^{-3}$	17			50	± 5
CTB	0.9	3.0	$.5x10^{-3}$	0.1			500	±30
SSUS-25°	0.95	0.040	$.5x10^{-4}$	0.040	0	0	350	± 2
-50°		0.040		0.040				
6DG/F-25°	0.989	0*	$1x10^{-7}$	0.120	24	27.2	2.5	±20
-50°	0.990	0*	$2.5x10^{-7}$	0.800				
6DG/G-25°	0.989	0*	$1x10^{-7}$	0.001	18	0.75	2.5	±20
-50°	0.988	0*	$1x10^{-7}$	0.020				

* V_o given as zero, indicating that circuit permits adjusting to zero for any particular temperature and pair of supply voltages (balanced within 1%)

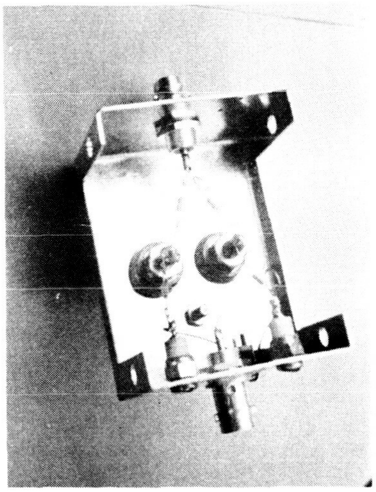


Figure 10. Shielded Construction of Six-Diode Gate.

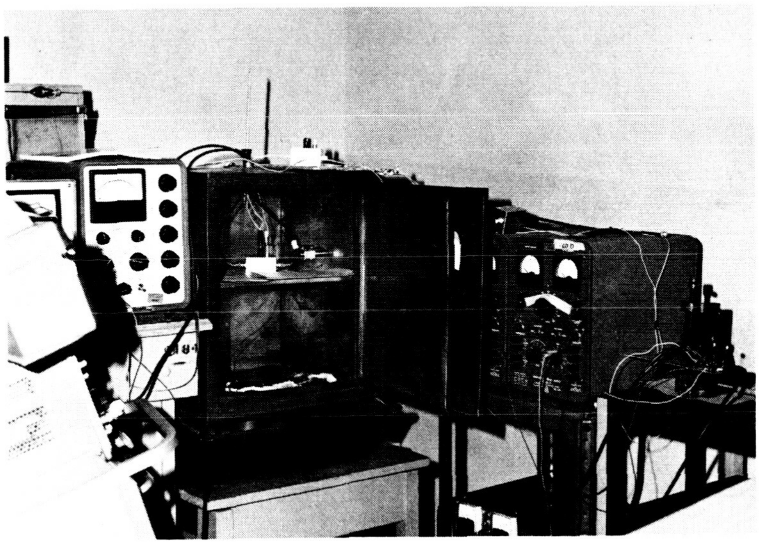


Figure 11. Arrangement of Instrumentation for Switch Performance Tests.

4-2. The Modified Guennou Chopper

The Guennou chopper, in its modified form, offers little benefit over a simple single-transistor shunt chopper. The small improvement afforded lies in making the offset voltage and drive leakage more nearly equal, and thus easing the compensation problem slightly.

A number of different transistor types were tried in the Guennou circuit, but none provided any really outstanding advantage. The types tested included 2N220, 2N404A, 2N697, 2N706, 2N1132, 2N1179, 2N1605A, 2N2102, and 2N2613. Reference A18 points up the need for transistors with inverse current gains (β_i) on the order of 10. Special switching transistors, both silicon and germanium, are available with high inverse current gains. However, from the basic capabilities of the Guennou circuit, it is doubtful whether the construction of further switches of this type could be justified. Even if the transistors were replaced by ideal switches, the ratio of the on voltage gain to the off voltage gain (a suggested figure of merit) would not be greatly enhanced.

4-3. The Nonsaturating Transistor Switches

The two- and four-transistor nonsaturating switches suggested by Brubaker (Reference A5) gave much better results than the Guennou chopper. Construction of this switch employed pairs of complementary transistors (2N697, 2N1132) matched to within 10% for β_n, R_{CE}(sat.), and I_{CEO} on a Tektronix 575 transistor curve tracer. This was the best match possible with the limited number of transistors available. Performance of the switch could undoubtedly be improved by the use of matched pairs of transistors (or matched quadruples) purchased from the manufacturer. Dual transistors, consisting of one npn and one pnp each drawn from a matched pair and mounted in the same can, should provide even better performance by reducing temperature differences between transistors in the same stage of the switch.

It is doubtful, however, whether the off voltage gain can be reduced greatly with the bases of the switch transistors being switched to ground as at present. An arrangement whereby the bases of all of these transistors could be switched to some bias voltage, so as to provide reverse bias to the switch transistors, would probably reduce the off voltage gain by at least one order of magnitude.

The magnitude of the input voltage is limited by the available supply voltage and the limited heat dissipation of the transistors. The supply voltage may be increased up to the limit of the transistor ratings, provided steps are taken to insure that the transistor dissipation remains within limits.

This switch suffers generally from the requirements for matched, high-gain, low-leakage transistors, and balanced power-supply voltages. Unbalance of the supply voltages will be reflected as an offset in the output voltage, as will any mismatch of the switching transistors. Adjustment of the output voltage to remove the offset is accomplished by adjusting the bias current of the switching transistors. This offset adjustment is usable only for long-term variations in supply voltage and hence the short-term stability requirements can become rather acute.

4-4. Complementary Transistor Bridge

Construction of the complementary transistor bridge utilized a matched quadruple of transistors, two npn (2N697) and two pnp (2N1132). Matching of the units was for β_n, R_{CE}(sat.) and I_{CEO}, and was accomplished to within 10% by means of a Tektronix 575 transistor curve tracer. This was the best match possible with the available transistors. Better matching and low leakage transistors would probably result in lower offset voltage, lower off voltage gain, and lower drive leakage. Temperature effects could be minimized by using a matched quadruple of transistors mounted in a single TO-5 enclosure.

The maximum input voltage to this switch (in our case, ± 30 volts) was set by transistor breakdown and can be increased by using higher-voltage transistors.*
Another factor limiting the input signal maximum is the insulation of the bias supply for the bridge and the supplies for the drive circuitry.

The lack of any requirement for balanced voltages by the bridge itself causes the unbalance sensitivity to be zero. Variations in the bias supply have relatively little effect. However, a major disadvantage of this switch is the number of power supplies required.

* Note that it is easier to match transistors of the same type, and that higher voltage ratings are available with silicon transistors of the npn variety than with the pnp type. Thus, a bridge might be constructed using all npn transistors, but at the cost of a higher degree of complexity in the drive circuitry (Reference A12).

4-5. Series-Shunt Unifet Switch

The series-shunt unipolar field-effect transistor switch reported on was constructed from a Siliconix telemetry designer's kit. The FET units involved (types 2N3380 and 2N3386), although giving good results, can be improved upon. Desirable properties include low drain cutoff current I_D(off), low gate-to-source leakage current I_{GSS}, low drain-to-source resistance r_{ds} (at zero gate-to-drain voltage), and low gate-to-channel capacitance C_{GSS}.

Note that some means must be provided to discharge the gate capacitance of the FETs during the on time for each. This may be accomplished by utilizing the leakages of the control diodes CR_1 and CR_2, the gate-channel diode leakages of the FETs Q_1 and Q_2 themselves, or other means.

No matching of components is necessary in this switch, and no supply voltage is required. The field effect transistor presents a pure resistance to the signal with no intrinsic offset voltage. Input voltage is limited by the drive signal levels and gate-to-channel breakdown.

In experimenting with this switch, shielding was found necessary for the first time--at least partly because of the long lines required to allow operation inside the oven for high temperature measurements. Frequency measurements were thus taken with approximately six feet of RG-62/U between the output of the gate and the load. A Tektronix 545A with 47 pf shunt capacitance was used to observe the output.

The absence of a power supply requirement in the FET switch is a major advantage. This feature materially reduces the amount of auxiliary equipment needed for the switch, and at the same time the output contains no components due to power-supply variations or unbalance. Temperature variations have little effect on the gate offset voltage and drive leakage. The inherent simplicity of the circuit should provide greatly increased reliability and lower cost.

Linearity of the series-shunt unifet switch was roughly checked in the course of the laboratory tests by applying a sine-wave input to the switch and observing its output while driven at a high switching rate. No distortion was visible in the chopped output sine wave. A more accurate measurement of linearity would of course be desirable in any subsequent evaluation of improved FET switches.

4-6. Six-Diode Bridge Gate

The six-diode gate gave the lowest value of off voltage gain of any circuit tested. Switch units were constructed using Fairchild type 1N3595 diodes and General Electric 1N4443 diodes. The initial unit using 1N3595 diodes gave very poor results. When the diodes were removed from the bridge and tested, all were found to be out of tolerance in leakage current. As a result of this discovery, the remaining available diodes were tested to ascertain their adherence to the published parameter limits. Only four 1N3595 diodes were found to be within tolerance. All of the 1N4443's were within tolerance for leakage current and only two slightly out of tolerance on forward drop at one value of current. It was decided to utilize the four good 1N3595's as the bridge diodes in one circuit, and 1N4443's as the drive diodes for both circuits.

It was also decided to use the leakage current values measured at the voltages specified in the data in an attempt to provide matched diode pairs for the input and output legs of the bridge. This, in effect, neglected the various phenomena such as surface leakage which cause the leakage currents of diodes to depart from the values predicted by the diode equation: $I = I_s[e^{-eV/KT\lambda} - 1]$. Subsequent measurements indicated that, in this case, the other effects predominate.

Matching of the reverse leakage, of the output diodes particularly, at the actual voltage to be used is necessary for best results. Low-leakage diodes with high forward conductance are desirable in the bridge. The drive diodes' leakage contributes far less to the over-all gate offset voltage. In the particular circuit used, the drive diodes were calculated to produce about 1 microvolt of offset voltage for each 40 nanoamperes difference in leakage current between the two.

Contributions to the gate offset voltage by unbalance of the supply voltages in the on state require extremely stringent regulation of the supply voltages to ensure that the unbalance remains small enough to introduce no significant error. In order to limit this output effect to a 1 microvolt contribution, the necessary regulation of the supplies was calculated to be .00015%. With the actual gates constructed, sensitivity of the output voltage to supply unbalance was observed to be approximately 5 millivolts for each volt of unbalance.

Formulas presented in Section 3-4 enable L_D, $A_v(\text{on})$, and $A_v(\text{off})$ for the six-diode gate to be predicted from measured characteristics of the individual diodes. In general, such theoretical calculations agreed well with experimental results for the actual gates constructed, which were designed to operate at a 20-volt signal level. The formulas were also used to calculate the performance for a gate designed to operate at a 1-volt signal level. The predicted performance was found to be considerably poorer in this case. Indications are that the largest ratios of maximum input signal to drive leakage, and likewise the smallest values of off voltage gain, will be obtained by using the highest practicable supply and drive voltages.

Switching speed could be considerably improved by connecting a second six-diode gate so as to switch to ground the output of the first gate during the time that it is nonconducting.

Although no attempt was made to balance out gate drive leakage during the investigations described herein, it is probable that such compensation could be provided for in the case of the six-diode bridge circuit.

V - CONCLUSIONS AND RECOMMENDATIONS

5-1. Summary Evaluation

The Guennou chopper, in its modified form, offers little improvement over a simple single-transistor shunt chopper. The advantages afforded lie in the drive leakage, which is lower than for the shunt chopper, and the lack of a supply voltage, variations of which could affect the output. The possibility of improving the performance greatly appears quite small.

Advantages of the four-transistor nonsaturating switch are few, except that it will give better performance than the Guennou chopper or a simple shunt transistor chopper. A further reduction in A_v(off) by a factor of β is probable with provision for back-biasing the transistor bases which are now switched to ground. Dual transistors in one enclosure, matched over a temperature range of operation, also should improve performance.

The complementary transistor bridge offers improved performance over the four-transistor switch. Major advantages of this circuit are the increase in maximum signal voltage which can be applied without damaging the components, and the relative immunity to power supply variations. Improvements should be possible utilizing ultra-low-leakage transistors, matched over a temperature range. Dual- and quad-transistors mounted in a single can might also offer some improvement.

The circuit offering the most advantages of any tried thus far is the series-shunt FET switch. No matched components are necessary, no supply voltage variations can affect the output, no adjustments are necessary to the output voltage. Finally, this circuit gave lower A_v(off) than any other except the six-diode bridge. Improvements to this circuit may be possible through the use of FET's with lower r_{ds} and MOS FET's with much lower gate leakage.

The six-diode bridge had the highest ratio of A_v(on) to A_v(off) of any circuit tested, due to the extremely low A_v(off). Few other advantages are offered by this circuit, however. The probability of significant improvements in this circuit's performance is very small at the present time. Diodes having the highest ratio of forward to reverse current known to us were used, and several years will probably be required for production diodes with significantly better ratios of forward to reverse current to reach the market.

5-2. Future Work

It is recommended that further investigative effort be applied to the FET switches. It is also recommended that a bridge circuit incorporating silicon controlled switches (SCS's) in the approximate configuration of the complementary transistor bridge be constructed and tested. The construction of the FET switches would demonstrate the improvement possible with the best available unipolar and MOS type FET's. The SCS bridge would permit use of very narrow drive pulses for on and off periods approaching infinity, thus allowing ac coupling of the drive signal without limiting the lower frequency of operation of the switch.

Appendix - BIBLIOGRAPHY

Initial efforts on this program were applied to a study of the pertinent literature on electronic switching techniques and applications. The literature survey has included a review of The Engineering Index since 1961 and continuing coverage of the DDC Technical Abstract Bulletin from the January 1963 issue on. In addition, several of the major electronic engineering journals are regularly received and scanned, as are new-product announcements and data sheets from a number of manufacturers in the semiconductor components field.

The bibliography presented herein contains 72 entries divided into the following subject categories--(the number of documents cited in each category is shown in parentheses):

A. Transistor Gate References (25)

B. Diode Gate References (9)

C. FET Gate References (11)

D. Miscellaneous Gate References (18)

- Bidirectional Transistor Gates (1)
- Hall Generator Gates (1)
- Photo Gates (6)
- Varicap Gates (1)
- Integrated Tube Gates (2)
- Vacuum Tube Gates (2)
- Nickle Oxide Gate (1)
- Thyristor Gates (3)

E. Supplementary References (9)

The relative importance of various references to the investigations reported herein is indicated by asterisks in the margin. A double asterisk denotes a primary reference--one which provided essential or valuable information for a particular switch under study. A single asterisk denotes a secondary reference--one which served to supplement a primary reference or which provided information permitting the elimination of certain switches from further study.

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