# OFFICIAL PROCEEDINGS OF THE FIFTEENTH INTERNATIONAL

# PCI '88

# CONFERENCE

JUNE 6-9, 1988
MUNICH, WEST GERMANY

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# HIGH-RELIABILITY LOAD CONVERTER FOR POWER-DISTRIBUTION SYSTEMS UTILIZING A HIGH-FREQUENCY A.C. LINK

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ABSTRACT

Using a linear variable inductor (LVI) as a power-flow controlling element in a load converter fed by an unstabilized high-frequency bus, results in an exceptionally reliable topology. The properties of this new converter demonstrate the merits of the LVI approach to power conversion; even certain non-ideal characteristics of this rugged inductive component contribute to the enhancement of the over-all performance/number-of-components ratio of the presented topology.

## 1. INTRODUCTION

In many complex electronic installations, especially in physically large ones numerous subassemblies must be supplied by geographically dispersed power sources connected to different potentials. In the rudimentary cases requiring two to five low-power outputs with unidirectional power flow and located close to each other, this problem is solved using so-called multiple-output power supplies; there are several approaches to their design, depending on the particular application specifications, Refs. 1 to 3.

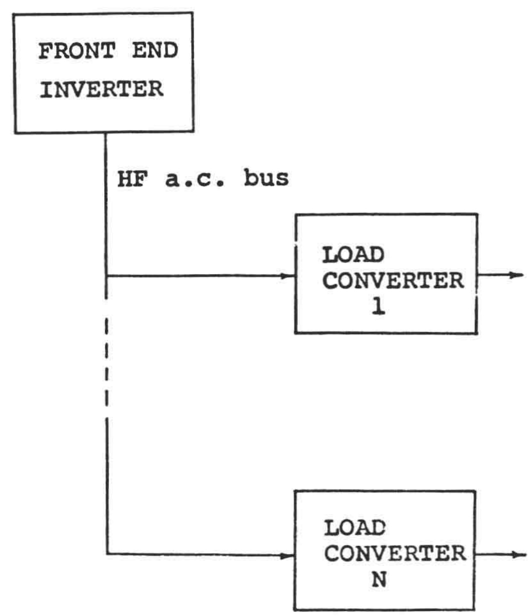



Fig. 1

*Synoptic diagram of a power distribution system utilizing a high-frequency a.c. link.*

If the power level is relatively high, if the loads are physically distant from each other, if the cross-regulation has to be exceptionally good, if a short circuit at one or more outputs should not influence the remaining ones, if some of the loads require a bidirectional power flow and if, in addition to all this, the system should be easily expandable, the classical approaches based on trade-offs among various conflicting requirements are not satisfactory and new ones must be sought.

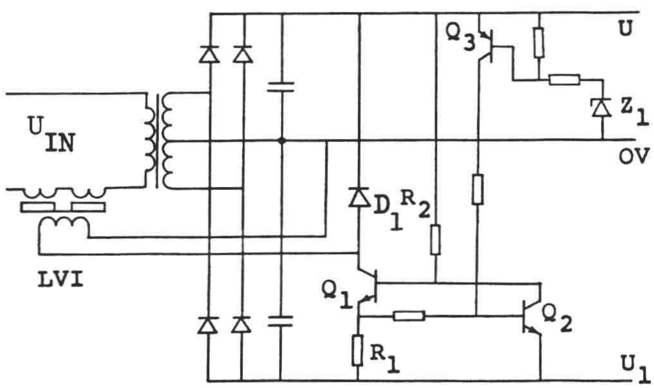



**Fig. 2**

*Load converter utilizing a linear variable inductor (LVI) as a power-controlling element.*

A power-distribution system based on the so-called (high-frequency) a.c. link approach seems to be a very good solution to this problem. As shown schematically in Fig. 1, it consists of a power inverter feeding a high-frequency bus to which as many as necessary load converters are connected. Since the output impedance of the inverter is low, the cross-regulation effects among the individual converters are practically negligible; typically, each load converter would have an individual feedback regulation and one or two outputs. The front-end inverters can feed the a.c. bus with a regulated or unregulated (quasi)-squarewave (Refs. 4 and 5) or sinusoidal (Refs. 6 and 7) voltage.

The simplest topology from among these seems to be a free-oscillating, (quasi)-squarewave inverter (Ref. 8) with or without thyristor duals as switches, (Refs. 9 and 10). The design of both these topologies is straightforward and they are not the object of this paper; their common feature is that the delivered constant-frequency bus voltage is not amplitude-stabilized, a fact which requires load converters with an adequately large regulation range.

In the practical application the use of a linear variable inductor (LVI, Ref. 11), in the role of a power-controlling element results in extremely simple load converter topologies with an outstanding inherent reliability and some unexpected, useful features, consequences of certain general properties of LVIs. This paper presents the simplest of these load converter topologies.

## 2. PRINCIPLE OF OPERATION

The operation of the simplest topology, shown in Fig. 2, can be summarized as follows. The value of the current circulating in the series connexion of the LVI and the primary of the transformer depends, among other parameters, on the inductance of the LVI. This current consists of a magnetizing component and of an active component transmitting energy to the secondary, thus, the energy delivered to the load depends on the value of the inductance of the LVI, a quantity which can be electronically regulated, (Ref. 11). The LVI control current is determined by a switching-type regulator (of a buck-boost topology) comprising the control winding itself and switching elements $Q_1$ and $D_1$. The on and the off intervals of the switch are determined by the amplified voltage error so that in the end effect the output voltage remains in the vicinity of the desired value.

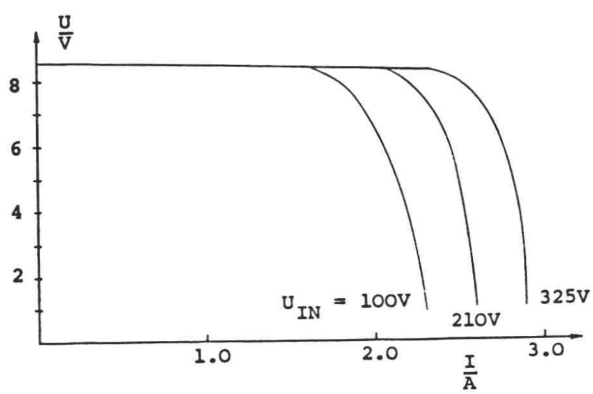



**Fig. 3**

*Output characteristics of the load converter in Fig. 2 with a separate LVI bias source.*

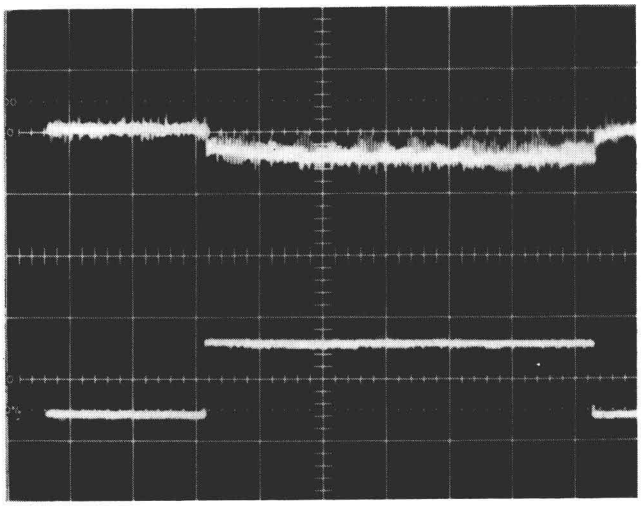
Note that the principle of operation of the particular magnetic component, the LVI, used as a power-controlling device in this converter is fundamentally different from all other known magnetic components using the saturation characteristics of the core material employed. Ideally, an LVI is a linear device, i.e. a sinusoidal input voltage produces a sinusoidal input current and vice versa. The trajectories of the operating point in the h-b plane of all other devices must be strongly influenced by the signal if the desired effects are to be produced; and this substantial displacement of the operating point must occur in each period of the signal frequency. This is in sharp contrast to the operation of the LVI where the position of its operating point need not be influenced at all by the signal. This fact makes possible a design of circuits with entirely new properties, such as, for example, the electronically variable attenuator of Ref. 11 and which definitely cannot be realized with any other known 'saturable' components or their combinations.

## 3. PARTICULAR FEATURES

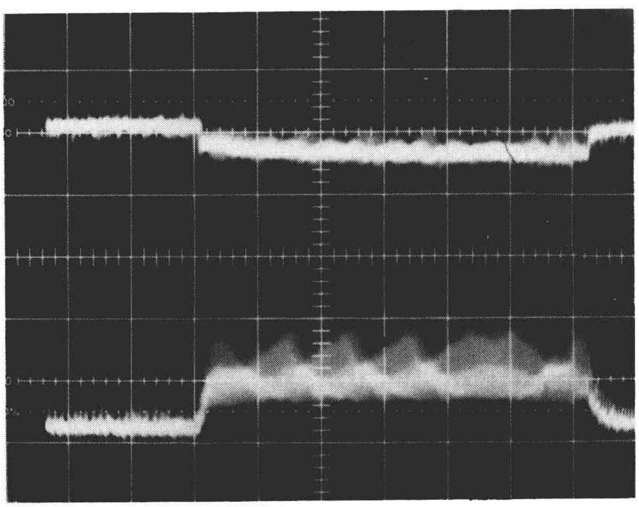
The following features should be highlighted.

The regulated output is the output U. The output $U_1$ is tightly coupled to the regulated output and can be used as a second load output; in fact, if the application specifications allow it, other isolated outputs can be added if a corresponding number of windings and associated elements are implemented.

It is obvious that the converter is short-circuit proof; indeed, at a zero output voltage no current can be delivered to the control winding of the LVI and its inductance assumes a high value and only a negligibly small current circulates in the



a) *Upper trace: Output voltage $U_1$, 100 mV/div. Lower trace: Output current 1 A/div.*



b) *Upper trace: Output voltage $U_1$, 100 mV/div. Lower trace: LVI bias current, 100 mA/div.*

Fig. 4

*Large-perturbation transient behaviour of the load converter of Fig. 2; 500 μs/div.*

primary winding of the transformer.

It is less obvious that, even if the LVI bias power is provided by a separate source, the output current of the converter is limited; this feature requires a more detailed explanation. During the operation intervals when the flux increments are small, the control winding of the LVI is virtually de-coupled from the inductor windings; with larger flux increments, non-linearities begin to play a noticeable role and an a.c. current component proportional to the LVI inductor current circulates in its control winding; in these non-ideally-compensated intervals the LVI operates as a current transformer the secondary of which is closed via the transistor $Q_1$ and the resistor $R_1$, (or via the diode $D_1$); as long as this current can circulate, the LVI impedance remains relatively low. However, as soon as the secondary current of the 'current transformer' meets an obstacle for its free circulation, the inductance of the LVI rises sharply and the primary current of the power transformer is limited. The resistor $R_1$ and the transistor $Q_2$ are implemented to this effect; as soon as the reflected primary current is large enough to cause $Q_2$ to conduct, it reduces the LVI control current and the primary current is thus limited. In Fig. 3 a typical output characteristic of such a converter is shown. Note that this limitation is of a pulse-by-pulse nature.

The converter of Fig. 2 is regulated employing the bang-bang principle which is entirely satisfactory for numerous applications; its great practical merit is that its implementation is extremely simple. An analytical approach to the design of this circuit is rather complex, (Chap. 9 of Ref. 13 and the bibliography given in it), and is further complicated by the inherent nonlinearity of the LVI inductance versus control current characteristic and by the synchronising action of the voltage across $R_1$. An exact analysis has not yet been carried out.

The rudimentary (but fast and highly reliable) error amplifier consisting of $Q_2$, $Q_3$ and $Z_1$ can, if an improved voltage regulation is required, be replaced by an IC error amplifier with associated compensating networks. This amplifier should then be followed by an additional pulse-forming circuit driving the switching transistor $Q_1$. The designer's preference should, whenever the load specifications allow it, be given to the fast and rugged solution represented in Fig. 2.

At turn-on the LVI control winding is not energized and only a relatively low voltage is available at the secondary of the transformer; during the design, care must be taken to ensure starting at all load conditions. The nature of the load should be carefully examined and if it transpires that some external help is necessary, a voltage multiplier feeding the resistor $R_2$ is recommended; in most cases a voltage doubler will prove sufficient. (Caution: In the event of any auxiliary circuit shorting out during the turn-on phase the transistor $Q_1$, the current-limiting properties of the converter would be impaired!). With extremely difficult loads it may be necessary to disconnect them during the turn-on sequence.

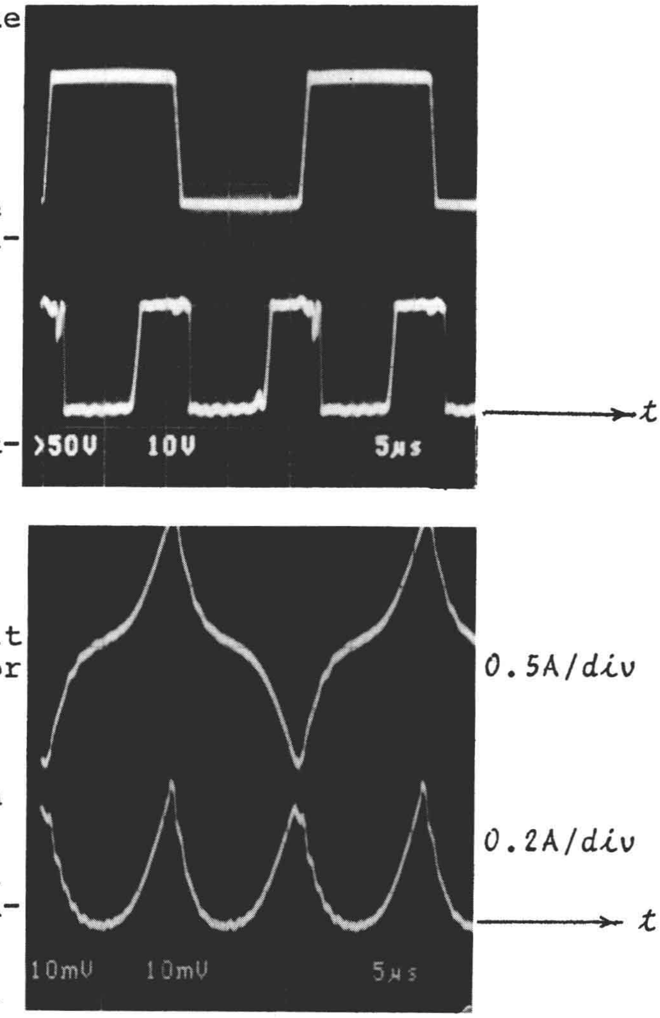



Fig. 5

*Essential waveforms of a load converter synchronized with the bus.*

In some systems, if the front end inverter comprises a commutating inductor (Ref. 5), a portion of its reactive power can be employed to provide the initial energy needed to ensure starting of the critical load converters. The starting problem is entirely eliminated if the LVI is located on the secondary of the isolation transformer.

In some applications the bang-bang operation of the simplest topology of Fig. 2 cannot be accepted and the boost-type regulator of the LVI control current must be synchronized with the bus voltage. This

| | N | $\frac{\lambda_G}{10^6 h}$ | $\pi_Q$ |
|---|---|---|---|
| Transformer | 1 | 0.020 | 3 |
| LVI | 1 | 0.020 | 3 |
| Diodes | | | |
| Full power | 2 | 0.0027 | 1.4 |
| Reduced power | 3 | 0.00066 | 1.4 |
| Zener | 1 | 0.0027 | 1.4 |
| Resistors | 5 | 0.00120 | 1 |
| Shunt (power) | 1 | 0.012 | 1 |
| Transistors | | | |
| NPN | 1 | 0.0025 | 2.5 |
| PNP | 1 | 0.0038 | 2.5 |
| Power | 1 | 0.048 | 2.5 |
| Capacitors (electrolytic) | 2 | 0.073 | 3 |

**Table 1**

*Reliability parameters of the components of the converter in Fig. 2.*

can be achieved by preventing the saturation of all three transistors in Fig. 2 - six additional Baker-clamp diodes is all that is needed, so that the reliability of the synchronized topology is not seriously impaired as compared to the simplest one.

The introduction of the synchronization signal into the bias current regulator occurs via the resistor $R_1$ across which a ripple voltage with twice the bus frequency, due to the imperfections of the LVI, is developed. The waveforms illustrating this situation are shown in Fig. 5. The uppermost waveform (not to scale) is the bus voltage and the second one is the voltage across $Q_1$; note that the boost-type regulator operates at twice the bus frequency; the third waveform is that of the LVI current and the last one is the current circulating in the resistor $R_1$.

## 4. GENERAL DESIGN CONSIDERATIONS

As already stated in the Introduction, this type of load converter can be used with either a (quasi)-squarewave or with a sinusoidal bus voltage . In the case of a square-wave bus, the expression (1) of Ref. 12 can be used to determine the necessary LVI inductance range as a function of other parameters, some of them arbitrarily chosen. An equation corresponding to the sinusoidal bus has not yet been derived. For both bus voltage waveshapes, it should be checked that the flux increment in the LVI cores is compatible with the chosen operating frequency, the core material specifications and with the applied voltage.

Most of the time, the maximum thermal loading of the LVI occurs during short-circuit conditions when the LVI is exposed to the full bus voltage. If some form of thermal fuse is allowed, or if the bus voltage is stabilized, a substantial reduction of the LVI size can be achieved.

## 5. A REALIZATION EXAMPLE

A wide input range (100 to 325 V) load converter according to Fig. 2 has been built. Its transformer has been implemented with an EC35 core and the LVI employed 37-mm 3E1 cores with the power windings with 100 turns and the control winding with 235 turns; at an output voltage of 8 volts and at a switching frequency of 50KHz the static error was less than 150 mV (zero to full load, full input voltage range). The speed of the regulator response is illustrated in Fig. 4. If the value chosen for $R_1$ is adequate, the converter is, as the measurements shown in Fig. 3 demonstrate, protected against overloads and short circuits. If, as has already been explained, two desaturation diodes are added to each transistor, the boost-type cell controlling the LVI bias current is, as can be seen from Fig. 5, operating at twice the bus frequency.

The efficiency of this load converter, measured at an output power of 12 W and including a front-end inverter, was 78.8 percent.

## 6. RELIABILITY

The failure rates of the various components employed in the converter shown in Fig. 2 have been determined in accordance with Ref. 14 and are shown together with the corresponding quality factors, in Table 1. The converter environmental operating conditions have been assumed to belong to the category $G_B$, (Ground, Benign).

The reliability parameters of the LVI and of the transformer have been assumed to equal those of the power transformers of Non-Mil type. The diodes are assumed to be of a Non-Mil hermetic type; the power rectifier diodes are chosen to be of an avalanche type and those handling only the LVI control power are considered to be general purpose silicon diodes. The resistor $R_1$ is considered to be a power resistor. Two of the transistors are assumed to be hermetic Non-Mil types and $Q_1$ is a hermetic Non-Mil power transistor. The parameters of the Zener diode are considered equivalent to those of the avalanche diodes. Both capacitors are assumed to be commercial quality and of a wet electrolytic type.

The data presented in Table 1 results in an MTBF of 1,378,000 hours. Contestable as the individual failure rates and the associated quality factors may be, this result speaks for itself. Note also that the converter shown in Fig. 2 is in reality a twin-output unit and that this fact further enhances the significance of the MTBF obtained.

Considering also that the front-end inverters with extremely simple topology and low number of components are feasible, (Ref. 8), one arrives at a conclusion that highly reliable power distribution systems can be realized if the approach proposed here is applied to the load converter design.

## 7. SUMMARY AND CONCLUSIONS

Novel load converter topologies for high-frequency link power distribution systems, utilizing a minimum of components, have been described. It has been shown that the outstanding reliability of these converters is achieved by virtue of a linear variable inductor (LVI) as the controlling element. The unique properties of these converters have been presented and considerations related to their design have been formulated.

It has been shown that the LVI opens new avenues for the design of high-reliability power processors.

## ACKNOWLEDGEMENT

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# UNINTERRUPTED OPERATION OF A CONVERTER IN CASE OF FAILURE OF A POWER SEMICONDUCTOR DEVICE

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Abstract.

The power switching capability of one power transistor is limited, consequently designers connect several devices in parallel to increase power switching capability. In such configurations, the failure of one device often causes destruction of other devices in parallel, and in every case causes the failure of the equipment. To avoid these serious consequences the authors propose to disconnect the damaged device as soon as possible, without interruption of the equipment.

The physical phenomena of device destruction and the behavior of destroyed device in its environnement are presented. Consequently a disconnection mechanism with its drive is implemented. It is shown that a fast blowing fuse can be used as the disconnection device. The failure detection problem is solved in an original way. A fail safe base drive circuit is designed to sustain the failure stress during the fault condition.

The design and practical results of a 400V, 500A DC chopper prototype utilizing the uninterrupted operation principle successfully are presented.
This work has been supported by the French Direction des recherches, études et techniques (DRET).

In some equipments, like uninterruptible power sources for instance, safety is the most important parameter. The operation must be never interrupted.
The usual way to obtain high safety is redundancy, putting. several equipments in parallel.
But it is also possible to obtain redundancy inside of equipment on each switch: we have developped this idea in the practical design of a bipolar transistors chopper.

## I- POSITION OF THE PROBLEM - STATE OF THE ART.

To day, the designer of high performance power equipment often uses transistors in parallel, to increase current capability, improve thermal dissipation, etc ...

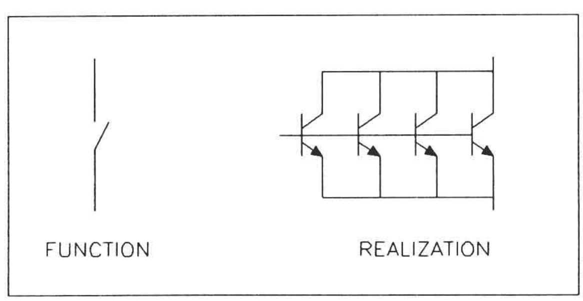


Fig.1. Paralleled transistors switch.

But in such configurations, the failure of one device always causes the failure of the equipment. To reach redundandy from paralleled operation, the damaged device is due to be disconnected.

Thyristors equipments designers are used to disconnect destroyed thyristors by fuses. This is named "internal protection". Those methods can be adapted to transistor converters, in regard of several differences :

- disconnection times must be shorter
- overcurrent capability of transistors is ten times smaller than thyristors.
- on the drive side, the bases of bipolar transistors are connected together, where as gates of thyristors are isolated from inch others by pulse transformers.

## II- FAILURES AND ELECTRICAL RESULTS.

A safety system must be able to act on every kind of failures. Therefore, we have first investigated the different failure mechanisms and analysed their influence on the environnement.

There are three types of failure :

a) Overvoltage

An overvoltage causes the breakdown of the Collector-Base junction. The breakdown current creates a melting spot.
Collector and Base are short-circuited.

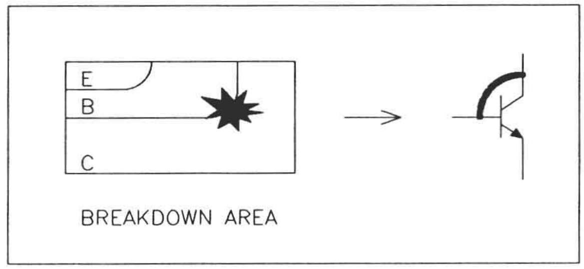


Fig.2. Overvoltage failure.

Sometimes, the failure extends the short-circuit to the Emitter.

b) Second - breakdown

Second-breakdown is a local thermal run-away, which generally occurs during switching times. Switching losses are dissipated in a very small area. If the increase of temperature becomes too important, the thermal generation of minority carriers starts the run-away. The Silicon melts from Collector to the Emitter, over the total thickness.

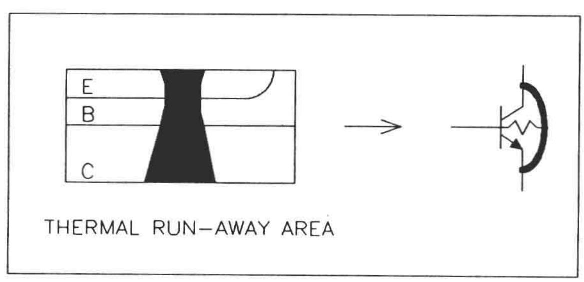


Fig.3. Second breakdown failure.

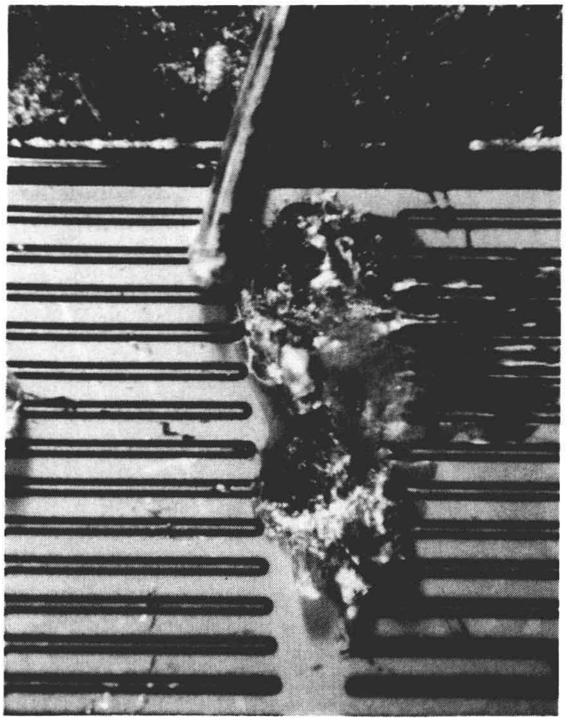

Fig.4. Vue of second-breakdown failure.

This results in a short-circuit between Collector and Emitter, with a small resistance to the base (maximum a few Ohms).

c) Thermo mechanical failure

Thermal fatigue, mounting stresses, or over current can create cracks, breaks or fusion areas in silicon or bounding aluminium wires. This leads to an open-circuit and the defect transistor is isolated from the rest of the equipment.

Electrical influence

On the power side, problems occur because the broken device remains ON, ignoring the drive status.
On the drive side, the base of the broken transistor maintains the other ON, disturbing the drive circuit.

To ensure the safety of other transistors and drive circuit, the first action must be the disconnection of the failed transistor base.

## III- FAILURE CONSEQUENCES ON THE SYSTEM.

### III.1. Failure occuring time

A switch can only be in four states: ON state, OFF state, turning ON or turning OFF. Considering that the failure is always a short-circuit of the switch, the ON state and the turning-ON do not lead to an immediate consequence.
So, it is very difficult to detect the failure during these periods.
On the contrary, if the switch fails during OFF state or turning OFF, the consequence is immediate and leads to serious problems.

### III.2. Topological structure of the converter

The most important structure encountered in industrial equipment is the bridge. In such a configuration (fig.5) two switches are connected in series accross the voltage source. Two remarks can be made about a failure in this configuration :

- If a switch fails and the other is turned-on the source is short-circuited generally leading to the complete breakdown of the equipment.

- If the failure of one switch is detected before the other is turned-on (this is possible because of the dead-time between switchings) the control of all the switches can be desabled and then the failed switch can be disconnected from the load and the source. This makes the isolation of the failed part possible independantly of the load or the source. After that, the converter can restart normally.

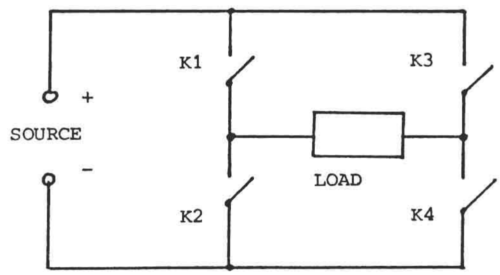


Fig.5. Bridge.

Another type of converter topology is the single-ended chopper (fig.6.). In this structure, a failure of the switch leads to an over current through the load and the source, which can be very dangerous. This configuration seems to be the worst case referring to the switch failure.

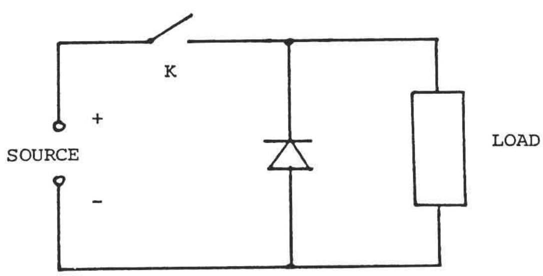


Fig.6. Single ended chopper.

## IV- DETECTION AND DISCONNECTION PRINCIPLE.

The principle is based on the four following steps :

- failure detection
- turn-off of the other switches of the structure (bridge legs)
- disconnection of destroyed device
- failure signalisation and restart.

### IV.1. Disconnection

When a transistor fails in a N parallel-connected structure, the main problem is how to disconnect it from the others. A solution is to insert fast blowing fuses in each base and emitter connection (fig.7.). This configuration allows a complete disconnection of any of the paralleled devices.
Of course, it is necessary to put an extra transistor in parallel with just the right number of devices to switch the nominal current.

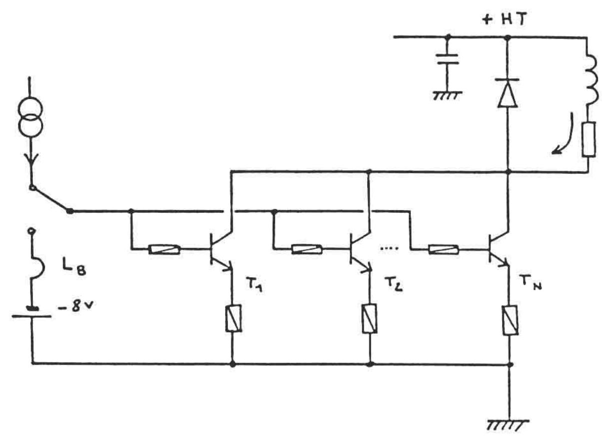


Fig.7. Disconnection system.

### IV.2. Failure detection

It has been previously stated that the failure has immediate consequences only when occuring during the normally off-state of the switch, that is to say when the bases are connected to the negative source.
In this case, due to the collector-base short-circuit, a high reverse base current (equal to the total collector one) flows through the negative source.
Consequently the negative base drive circuit must be designed to accept this overload.
The failure detection principle is based on the monitoring of the reverse base current.