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TRANSISTORIZED POWER-CONVERTERS COME INTO BLOOM

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I. FOREWORD

In the past, power transistors were used in the output stages of amplifiers, DC regulated power supplies (series regulator, switching regulator), etc. to obtain outputs of several hundred watts or less. More than 10 years ago we forecast the appearance of transistorized power-converters and began our research and development. First, we pursued the conditions demanded of power transistors as switching devices for power-converters from the stand-points of characteristics, functions, and cost, and the results were reflected in the elements made by Fuji Electric to realize power transistors having excellent dynamic characteristics and a wide safe operation area. After that we continued our pursuit of cost/performance of power transistor for power-converter , in the spring of 1980, we shattered existing concepts by successfully practicalizing $V_{CEO(SUS)}$=450V $I_C$max=100A high capacity (BBT) power transistor, which is the first modular construction transistor in the world. Moreover, the interrelation between the various characteristics of the power transistor were clarified from the changes in the characteristics by the various parameters, basic application research on characteristics which make use easier as a switching device for static power-converters was begun, and the results were applied to the product. Static power converters using these Fuji Electric power transistors utilize the features of the power transistors to the fullest and provide features not found in ordinary thyristor converters. Its theory has spread widely, first generator exciting equipment, next to VVVF inverters for AC motor drive, then CVCF inverters for uninterruptible power supplies, inverters for rolling stock auxiliary power supplies, etc.

The advances made in power transistors and their basic application research, and the popularity of power transistor-applied products has been amazing. Of these, the application of power transistors to low capacity static power converters has become common. Fuji Electric has made many achievements during this period. This is the reason we planned this "Transistorized Power-Converter Special Issue" Fuji Electric Review.

II. PROGRESS OF POWER TRANSISTOR FOR POWER-CONVERTERS

The characteristics demanded of power transistors for power-converters are:

(1) Low saturation voltage.
(2) Short switching time.
(3) Wide safe operation area.
(4) Easy mounting and dismounting at the power transistor heat sink and a simple stack construciton consisting of power transistor, heat sink, etc.
(5) High reliability.
(6) Reasonable price.

Efforts are being made to reach this goal.

There are two types of power transistors for power-converters: measa type and planar type. Fuji Electric uses the planar type bacause of its high reliability and high degree of junction design freedom. Recently, the construction of the element package has also changed considerably. Specifically, until the appearance of the Fuji Electric 450V, 100A BBT, power transistors of 100A and higher were mesa type and the flat or stud package. This type is difficult to process in the base region facing the emitter. This and the package itself contribute to their high cost. In the single-end type typified by the module transistor, connections to the emitter electrode are made by wire bonding. However, the problem of the increase in the complexity of the wire bonding process as the capacity increases is solved by using the chip design freedom. Nowadays a triple diffused junction construction and the module type package construction is becoming predominant.

Since power transistors are mostly used for inverters and have essentially low reverse breakdown voltage, recently many units with high-speed diodes having excellent reverse recovery characteristics connected in auti-parallel with base-emitter terminals and housed in a single package have become standard. Various module transistor configurations such as the example shown in *Fig. 1* representing the pursuit of cost-performance are available. Besides those shown in the figure, consideration has also been given to modules with independent collector and emitter terminals for each

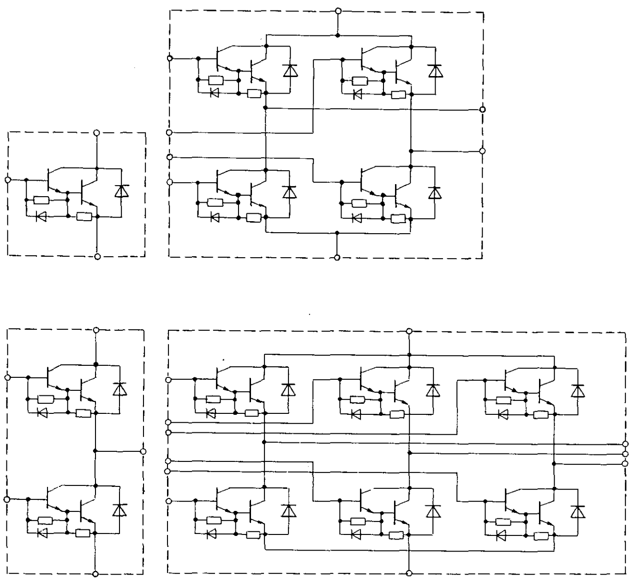

Fig. 1 Transistor modules

transistor even when the module contains two transistors, modules, which has the output stage base terminal as well as the base terminal of the pre-stage of a Darlington transistor, etc.

High blocking voltage of 1000V and large current flow up to 200A are in the practical range. 300 and 400 ampere class units have also been developed. The superior cost-performance power transistor is steadily replacing the thyristor, just like the thyristor replaced the mercury-arc rectifier because of its superior cost-performance when it appeared about 25 years ago. Besides that, the power transistor has performances that the thyristor does not have and is already opening up new fields.

The author made a current evaluation and a forecast for five years from now on the "Territory of Power Transistors and Thyristors With Thinking About Cost/Performance" while comparing them to those by J.D. Harnden of GE Company (*Fig. 2*) in June of 1978. And B.R. Pelly of IR Company showed the current state of power transistors as shown in *Fig. 4*.

Today, because power transistor parallel connection technology in noticeable advanced, current flows of 1000A to 1200A obtained by connecting five or six power transistors in parallel are common. Therefore, comparison by current of a single device is virtually meaningless. *Fig. 5* shows the power transistor voltage and current ratings up which its cost/performance is superior to that of static converters consisting of thyristors and GTO, etc., with this also taken into consideration. The power transistor completely satisfies the demanded cost/performance up to 300A for 250V class and up to 200A for 500V and 1000V class, and many are now in use. On the equipment level, 1000 to 1500A class units are steadily entering the power transistor territory through parallel connection of elements and multiplexing of equipment.

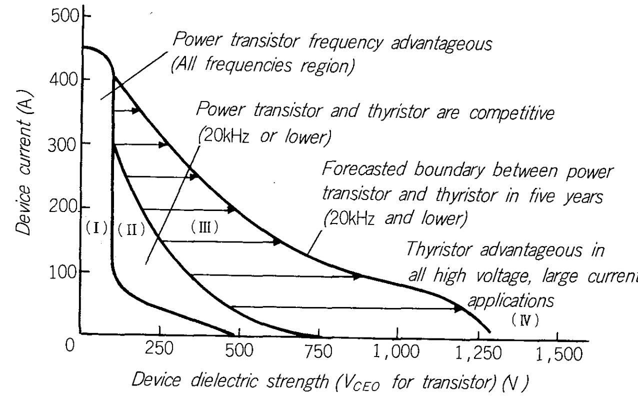

Fig. 2 Territory of power transistor and thyristors with thinking about cost/performance (By J.D. Harnden, 1977)

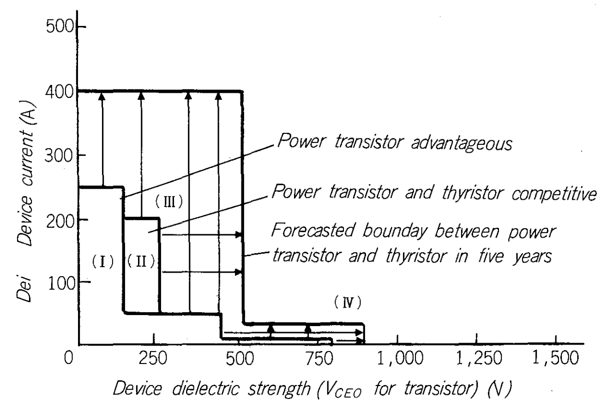

Fig. 3 Territory of power transistors and thyristors with thinking about cost/performance (By the authors of this paper, 1978)

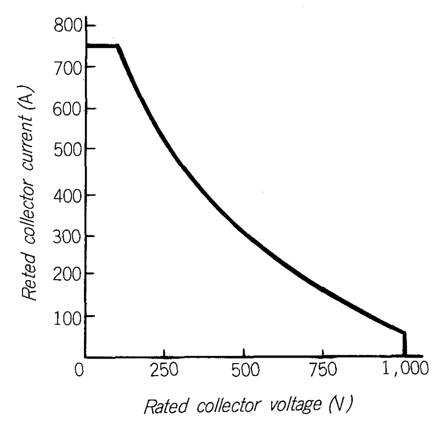

Fig. 4 Present-Day's power-transistor rating capabilities (by B.R. Pelly)

If compared with regions (I) and (II) of *Fig. 2* and *Fig. 3* as corresponding to region (I), the progress exceeds the forcast.

This progress is continuing and within the next three

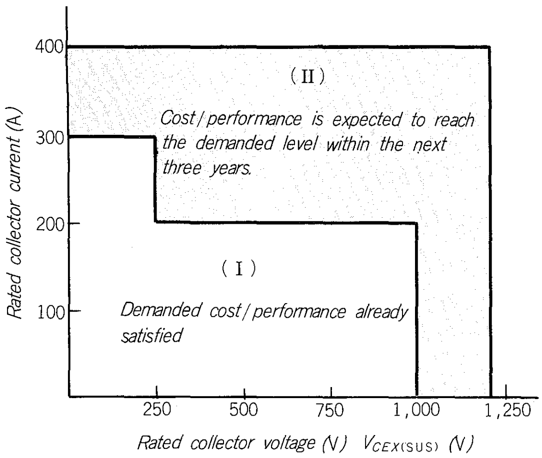

Fig. 5 Power-transistor's rating and its cost/performance

this relationship, we harmoniously designed the base drive circuit and snubber to obtain the desired turn-off time while still maintaining a sufficient RBSOA margin.

Similarly, it has recently become possible to clarify the safe operation area for overcurrents. When an overcurrent flows in a power transistor turned on by base forward bias, the overcurrent is quickly detected, the base forward bias is removed, and the transistor itself is quickly tripped. However, clarifying the safe operation area guaranteed at this time has made protection harmonization including the detection delay possible.

Automatically maintaining a constant power transistor saturation has also made it possible to substantially shorten the turn-off time.

Besides, although in a different sense, remarkable progress has also been made in multiple parallel connection without using a balancer for current balancing made possible by managing the necessary parameters by clarifying the current distribution mechanism when power transistors are connected in parallel, etc.

years, the blocking voltage will almost 20% increase and the demanded cost/performance will be satisfied up to currents of about 400A.

Here, the cost/performance in the case of static power-converter with power transistor means smaller size, lighter weight, lower price, higher efficiency, lower noise, higher reliability, and other advantages compared with equipment which use other power devices.

III. PROGRESS OF POWER TRANSISTOR BASIC APPLICATION TECHNOLOGY

In a very early stage we clarified that the various characteristics of the power transistor are effected by the various parameters and showed that obtaining the characteristics desired in a static power-converter is very important. Most of the power transistor characteristics which were unclear in the beginning have now been clarified and more severe design has become possible.

For example, looking at the safe operation area, which represents the capacity of the power transistor, generally, even if it is known that the safe operation area at base reverse bias (RBSOA) is narrower than that of the safe operation area at base forward bias (FBSOA), instances in which the actual RBSOA data was clarified were rare. Therefore, we designed a sunbber with the FBSOA data as the criteria without knowning the RBSOA and finally confirmed its validity by experiments.

Recently, cases where the RBSOA is not given are unusual. The RBSOA becomes narrower as the base reverse bias current is larger. On the other hand, the storage time t_{stg} and fall time t_f, which determine the power transistor switching time, decrease as the base reverse bias current increases. That is, the turn-off time (t_{stg} + t_f) and RBSOA have a trade-off relationship. From our acute awareness of

IV. SPREAD AND POPULARITY OF POWER TRANSISTOR-APPLIED PRODUCTS

The advances made in the power transistor and its basic application technology described above have, naturally, widened its fields of application. *Table 1* shows the power transistor static power-converter products manufactured by Fuji Electric. As can be seen from this table, the Fuji Electric power transistor static power-converter equipment is widely diverse, including VVVF inverters, and is available with capacities of several kVA to several hundred kVA. In other words, all of medium and low capacity self-commutated coverters and converters in which faster response control is necessary and when smaller size is demended in fields in which natural commutated converters were used in the past have been transistorized. Of the equipment listed in the table, typical types are introduced in this special issue. These units amply display the features of the power transistor and have such merits as small size, light weight, low price, low noise, high efficiency, high reliability, fast response, etc.

The pwoer transistor has many special features which offer many advantages in power transistor static power-converter equipment, such as:

(1) Since it has a self-quenching capability, self-commutated equipment and switches without auxiliary devices for commutation and quenching can be obtained.
(2) Fast switching and operation at a frequency one digit higher than that of thyristors and GTO are possible.
(3) Because the affect of dv/dt can be eliminated by base drive circuit refinements, a voltage clipper type can be used as a snubber. The snubber loss can be made much smaller than that of thyristor and GTO snubbers, especially in high frequency operation.
(4) Because the current gain can be adjusted by changing the connection of power transistors, the power requir-

Table 1 Transistorized power-converters in Fuji Electric

Objective	Equipment name		Scale
General industry	Generator exciter (HI-REX80)		For 2700kVA or less brushless generator
	CVCF inverter		3ϕ, 50 or 60Hz, 100/110 or 200/220V, 1~40kVA 3ϕ, 60 or 400Hz, 200/220V, 20~300kVA
	VVVF inverter	For general constant torque loads (FVR-G)	3ϕ, 50 or 60Hz, 200V, 12.5~3kVA microcomputer DDC PWM
		For general fan pum (FVR-P)	3ϕ, 50 or 60Hz, 2.5~10kVA PWM
		For industrial constant torque load (FRENIC 5000G)	3ϕ, 50 or 60Hz, 200V, 8~ 60kVA 400V, 10~120kVA PWM
		For industrial fan pump (FRENIC 500P)	3ϕ, 50 or 60Hz, 200V, 8~ 70kVA 200V, 10~140kVA PWM
		For high precision four quadrant operation (FRENIC 5000V)	For 3ϕ, 50 or 60Hz, 200, 3.7/5.5~30.37kW vector control microcomputer DDC PWM
		For high frequency output (FRENIC 5000H)	3ϕ, 240~3,000Hz, 200V, 2~8kVA PAM
	For 30-280kW motors		For 30-280kW motors
Railroad rolling stock	Axle generator exciter		DC 30V, 144A
	Inverters for control, lights, cooling		1ϕ or 3ϕ, 2~40kVA
Electric automobile chopper			DC 120V, 140/360A
Solar electric generating system inverter			1ϕ, 50 or 60Hz, 1~3kVA 3ϕ, 50 or 60Hz, 50kVA

ed at base forward biasing is comparatively small. Moreover, since the reverse bias needed to improve the turn-off characteristic is also several amperes or less, the base drive circuit is less complex than that of a GTO.

(5) Since the collector current is held at the current value determined by the base forward current and the current gain, even when a short-circuit or other overcurrent flows, the fault current is quickly detected and the base current is tripped so that the elements are protected against destruction.

In this way, our venture in applying the power transistor to static power-converters which began as a bud more than ten years ago has burst into full bloom to become a ¥10,000,000,000 market.

V. COMPARISON WITH MOS-FET OR GTO

Recently, the MOS-FET, which are typical unipolar-transistors, and GTO have been discussed frequently compared with bipolar transistors. Furthermore, examples of application of these devices to static power-converters have also been reported. We of course, evaluated these new devices. therefore, we should give our opinion of them in this article. MOS-FET have such fascinating characteristics as switching devices as:

(1) Drive with very little power is possible.
(2) Operation at an very high frequency is possible.
(3) Positive operating resistance-temperature coefficient. Parallel operation is easy.

However, their high on resistance (1.5 to 3.5Ω for 400 to 1000V class) is a fatal defect. The on resistance of bipolar transistors is two to three digits lower and is not even comparable to that of MOS-FET. However, if the switching frequency is increased so high, the loss by the switching frequency increases in the total loss of the bipolar transistor and soon the MOS-FET becomes advantageous. Recently, base drive technology which automatically limits the on-state operating point to the second saturation by adjusting the base current according to the collector current has also been developed for bipolar transistors. Technology which suppresses the switching loss by combining this technology with the base reverse bias at turn-off is also being improved and it has become possible to obtain ample advantages even in use at a switching frequency of several tens of kHz and high currents of 100A or greater. In this way, the technological revolution has taken a sharp turn, and the frequency limit of MOS-FET and bipolar transistors has reached several tens to several 100kHz for switching regulators of several tens to several hundred watts and about 20 to 30kHz for inverters, choppers, etc. having a somewhat higher capacity of several kVA. In the case of the latter, the problem is not with the device itself, but with the other main circuit components.

On the other hand, the big advantage of the GTO is that a higher blocking voltage than that of the power transistor can be obtained. However, it also has such disadvantages as:

(1) High latching current.
(2) Low turn-off gain.
(3) Large di_g/dt required when turned-off.
(4) When the anode current is more than the product of the gate reverse bias current and the turn-off gain, it has no current self-quenching possibility. Moreover, it is not fail-safe when the turn-off gate current is lost.
(5) There is a tail time after the turn-off time and the upper limit of the switching frequency is suppressed by their sum.
(6) The device is costly.

Even when viewed from the equipment level, the gate drive circuit and snubber are large, a current control reactor is necessary, etc. and it does not reach the power transistor in cost/performance.

The power transistor has an upper limit of about 1000V from the standpoints of safe operation area, current gain, collector saturation voltage, etc. Therefore, especially in fields where a self-quenching type device having a blocking voltage of 2500V calss or higher is required, such as medium and large capacity converters for railroad rolling stock, for example, the GTO is the practical device. In the actual market place, there are many cases where the power transistor is applied at AC input 400V or DC input 700V or less and the GTO is applied in regions exceeding this and delimiting of their territory has been clarified.

Of course, in today's severe competition, research is on the pursuit of cost/performance, and there are also examples in which advantages have been obtained by applying the power transistor by refining the circuit construction depending on the capacity even for DC750V and DC1500V input as also introduced in this special issue.

VI. CONCLUSION

The power transistor static power converter which has come into bloom has been described while following its recent progress. The power transistor is not only superior to other devices, but is a device which has become superior to other devices through improvement of its characteristics by basis application research, and has advanced from the age of use of a certain device to the age of pursuit of high cost/performance through the use of the device.

Other new devices were also mentioned. Our intent is to give an unbiased opinion from the standpoints of development and design of static power converters using the device. To be able to use and to be the most suitable are different. We consider the selection of the device best for the objective from among many devices to be very important.

The advances made in semiconductor devices and their application research have been amazing and we do not know where they will end. Customer needs also change day by day. Therefore, today's evaluation scale is not necessarily the same as tomorrow's scale. In this sense, we are continuing our studies from entry into new fields and are considering the necessary action. We are depending on the judgement and unchanging guidance of our readers.

References:

(1) J. D. Harnden : Powersemiconductors Looking Ahead, IEEE Spectrum, pp. 40～45 (Aug. 1977)

(2) 森春元・沢邦彦：進歩するパワートランジスタとその静止電力変換装置への応用，富士時報，**51,** 6, pp. 279～281 (1978)

(3) B. R. Pelly : Power Semiconductor Devices-A Status Review IEEE/IAS ISPCC, pp. 1～19 (May 1982)

(4) 沢邦彦・春木弘：パワートランジスタ読本，オーム社 (1978)

(5) 沢邦彦ほか：パワートランジスタのスイッチング回路への適用基礎技術，富士時報，**51,** 6, pp. 287～294 (1978)

(6) 沢邦彦：新形電力用半導体スイッチングデバイスとその応用，第43回パワーエレクトロニクス研究会 (1981)