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PROSPECT OF TRANSISTOR INVERTER

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1 FOREWORD

The development of transistor inverters in recent years is soemthing to be wondered at. They have become possible to be applied to variable speed drive system of almost every sort in small and medium capacity type in view of control performance and capacity range.

We should never forget that behind this development there was a foresight of engineers who have started early 70's trying to apply power transistors, that have been used mainly as elements of control and auxiliary circuits, for elements of main circuits. Fuji Electric did not loose any change in this early phase and organized a close working team among engineers specializing element developing, element application techology, as well as inverter control technology and its application in order to develop elements for new types of inverters and inverters themselves.

History of transistor inverters is repetitions of capacity increasing and getting higher performance and making them lower in cost. At all the time, the balance between performance and cost was the most difficult problem to conquer.

It is not that the inverters of present phase have attained 100% satisfaction of all, but we can say that in the context of their cost and performance, they have reached now to the time for a wide diffusion acquiring sufficient esteem for their qualities. Now that the transistor inverters have reached to certain epoch dividing one phase from another, we will, learning from the foresight of our forerunners, offer a prospect for the future of inverters, in full recognition and reflection of the reality of today.

2 PRESENT SITUATION OF TRANSISTOR INVERTERS

It is a widely known fact that in order to change speed of an AC electric motor efficiently, it is necessary to have a variable voltage and variable frequency power source (that is, inverters). Up to now, for this kind of purpose, a thyristor inverter was used, but its application for a range of small capacity was economically unfavorable. Thanks to the development of high-power transistors and economic inverters that use the former, it was made possible to drive with variable speed even small-capacity electric motors also.

The early-phase inverters were those with square-wave output that carried out control on voltage and frequency by separate parts. Then, PWM inverters with equal pulse width, provided with inverters that functioned also for output voltage control, were developed, for which and further through a simplification of main circuit composition, compactization of the device was made possible. As the sqaure-wave inverters and equal pulse width PWM inverters fundamentally output the components of square-wave voltage, it was set as their goal to solve the problem of minimizing the temperature rise in electric motor due to low-order harmonics and to reduce the torque ripple in low-speed range.

And for resolving these problems, sinusoidal-wave inverters were developed, since then the developing efforts were directed to enlarging of capacities and improving of control functions and their performance.

As for enlargement of capacity range, it did not remain only in the range of 200V series power source but also the development of high withstanding voltage power transistors has positively propelled and inverters that can directly be connected to the 400V series power source were also serialized.

As for the control functions and control performance, their degree of need is different depending on their applications. Technically speaking, whole demands can be satisfied, but that would be considerably expensive and would not be practical. So that in the present, their use are divided into several groups and machine types suitable for each group are prepared for obtaining, thus, economicity in production.

In the following, the actual situation of each application group is explained by taking an example of Fuji Electric's product series shown in *Table 1*.

(1) For fans and pumps (FVR-P3, FRENIC 500P3)

This is a load known not to demand a large starting and accelerating or decelerating torque. In the early stage, the main purpose was to save energy through variable speed operation instead of flow regulation by dampers or valves. At present, there are increasingly more and more cases where they are used for pressure control systems for air conditioners and tankless pumps. and they are equipped with speed change functions by 4-20mA, bias adjustment

Table 1 Fuji Electric VVVF transistor inverter product system

Series name	Control system	Capacity range (Maximum capacity of electric motors applied) (kW) 0.3 1 3 10 30 100 300	Application
FVR-G2	Primary frequency control (Sinusoidal wave PWM)		For universal type constant torque loads
FVR-P3	Ditto		For universal type fan and pumps
FRENIC 5000 G 3	Ditto		For industrial type constant torque loads
FRENIC 5000 P3	Ditto		For industrial type fans and pumps
FRENIC 5000 VI	Vector control (Sinusoidal wave PWM)		For industrial type high precision speed control
FRENIC 5000 M	Primary frequency control (Sinusoidal wave PWM)		For machine tool wide range speed control
FRENIC 5000 V2	Vector control (Sinusoidal wave PWM)		For machine tool high precision speed control
FRENIC 5000 VH2	Ditto		For machine tool high speed and high precision speed control
FRENIC 5000 H	Primary frequency control (PAM)		For driving ultra high speed motors

(Note) Upper lines in the columns of capacity range denote 200V series, lower lines, 400V series and broken lines denote ones under development.

function, and upper and lower limiter functions as standard functions.

(2) For constant-torque loads (FVR-G2, FRENIC 5000G3)

This is an inverter suitable for application where a large torque is required at the time of starting, accelerating and decelerating. There is a tendency to include many functions in this type of inverter as a typical model of universal inverter as torque boost adjustment for adjusting the starting torque, electronic thermal function for protecting electric motors, and swithing over function of wide range voltage/ frequency patterns.

(3) For driving machine tool spindles (1) (Non speed control FRENIC 5000M)

This is an inverter having no speed control loop, but in order to cope with the needs of small machine tools which increase and decrease speed frequenctly, resistance regerative braking and DC braking are equipped as standard function and by curve accelerating and decelerating command accelerating and decelerating capabilities are enhanced. Also, for dialogues with NC machines, it is equipped with interfaces for attaining of the speed and zero speed detection.

(4) For driving machine tool spindles (2) (Speed Control FRENIC 5000 V2/VH2)

This is an example of application to the field up to now DC variable speed system has been used, and the inverter will use vector control system for carrying out speed control with good response. This requires a servo function for fixed position stopping of the spindles and for controling angle indexing. And for dialogue with NC machine tools, the inverter is provided with various interfaces as standard function.

As the new development in this type of machine, a new tendency of abbreviating the mechanical speed change gears by providing them with a wide range speed changing capability is noticeable and a new trend to modify a little the control performance and function for adapting them for general industrial applications.

(5) For driving ultra high-speed machines (FRENIC 5000H)

This is for driving ultra-high speed electric motors by ouputting high frequencies of order of several kHz. Also, the system of the main circuits, unlike those of other inverters, is that of square wave intervers in which the voltage and the frequency are controlled indivisually.

3 ELEMENT TECHNOLOGY OF TRANSISTOR INVERTERS AND ITS TRENDS

The transistor inverter has a relationship with a wide technological field from microelectronics to electric motor technology. *Table 2* shows the element technology and the effect of technical development. In this setion, we will describe the latest trends in the element technology that has developed remarkably in recent years.

As for the details of applied technology and electric motor related technology of transistor inverters, please refer to the separate article of this number.

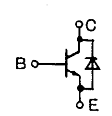
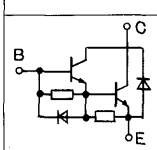
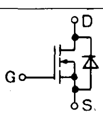
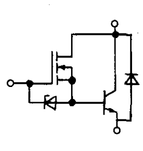
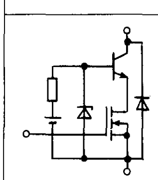
3.1 Progress of transistor as semiconductor element for power source

Table 3 shows types and characteristics of transistors as the semiconductor element for power source, and the bipolar transistor having a designation of "Power Transistor" are the most widely used elements at present. The Power MOS FET is an element that has registered a remarkable progress as high-speed switching element that can effectuate voltage driving, and as ON resistance is large when the

Table 2 Element technology and effect of technical development of transistor inverter

Technological field	Technonlogical item	Effect
Semiconductor elements for electric power	Manufacture technology and applied technology (driving and protection)	High withstanding voltage, high capacity, compactness in size and higher reliablity
Control technology	Digital control, PWM control, vector control, application of modern control theories	Higher precision and higher performance
Microelectronics	Introduction of micro-computer, gate array and hybrid IC	Higher precision and higher integration
Electric motor technology	Insulation and cooling technologies and higher speed	Higher performance and expansion of applicable fields
Sensor technology	Detection of voltage, current, speed, position, temperature, etc. Observation of quantity of state according to the modern control theory (sensor system)	Higher precision, higher perfromance and higher reliability
Electric power conversion technology	Regeneration of power source, multiplexing technology and low reactive power conversion (including low harmonics)	Higher work factor and efficiency, higher capacity
Inverter application technology	System planning, peripheral equipment, power source harmonics reduction of radiowave interference	Shortening of delivery term, higher functionality and higher quality

Table 3 Types and characteristics of power transistor

Type	Composition	Characteristics
Power transistor (bipolar transistor)		• Low ON voltage • Parallel connection comparatively easy • Current amplification rate is small and large driving power is necessary.
		• ON voltage is comparatively low. • Drivingpower can be comparatively small.
Power MOS FET (Unipolar transistor)		• Voltage driving is possible. • Switching speed is high. • Parallel connection is easy. • ON voltage is high.
Composite element		• Voltage driving is possible. • For making speed during OFF time higher, a large current reverse bias is necessary. • Withstanding voltage is limited in MOS FET part, and making the withstanding voltage higher is not adequate.
		• Voltage driving is possible. • Since the withstanding voltage is determined in the bipolar transistor part, it can be matched also to high withstanding voltage. • Provided with overcurrent suppressing function.

voltage rating is more than about 300V, and since the single body current capacity is as small as 10 to 15A (V_{DS} = 500V class), it is suitable for the field that requires a high speed switching with comparatively small capacity. The composite elements are the combination of power MOS FET with bipolar transistor, and can be driven with small power and high speed switching is possible, as this is the outstanding features of power transistor, they are now under study as to their application for transistor inverters.

In VVVF transistor inverters, the switching frequency of semiconductor element is, generally, about several kHz and bipolar transistors are applied. In the beginning, the bipolar transistors used to be of small capacity and discrete type, they made a steady progress and now their mainstream is from high speed diodes of reverse parallel connection to insulated modules compounded with several elements. With these, making equipment smaller in size and lighter in weight was made possible and, at the same time, total enclosing of the equipment was made possible also, consequently the resistance to adverse environment was much enhanced. With advancing of enlarging their capacities and withstanding voltage, it is now possible to obtain module transistor of $V_{CES\ (SUS)}$ = 1,200V, $I_{C\ MAX}$ = 300A. also.

The maximum capacity of transistor elements and that of inverters have a close relationship between them, and as shown in *Fig. 1*, expansion of inverter capacity was developed in a close cooperation with element manufacturing engineers.

Also, the efforts for elucidation of transistor characteristics and the progress of the basic technology applied were remarkable contributing to making equipment larger in capacity and higher in reliability.

3.2 Progress of Micro-electronic Technology and Control Technology

Progress of micro-electronic technology is wondrous and even for transistor inverters, micro-computers are introduced so that a high-degree of control can be effectuated and high functionality and high performance of controls were planned to pursue. Also, the circuits demanding high-speed processing are made higher degree of integration by making circuits those of gate array and hybrid IC. Here, in this section, the explanations are made on transistor inverter control technology through use of micro-computers.

(1) PWM Control

Fig. 1 Progress of transistor inverters towards larger capacities

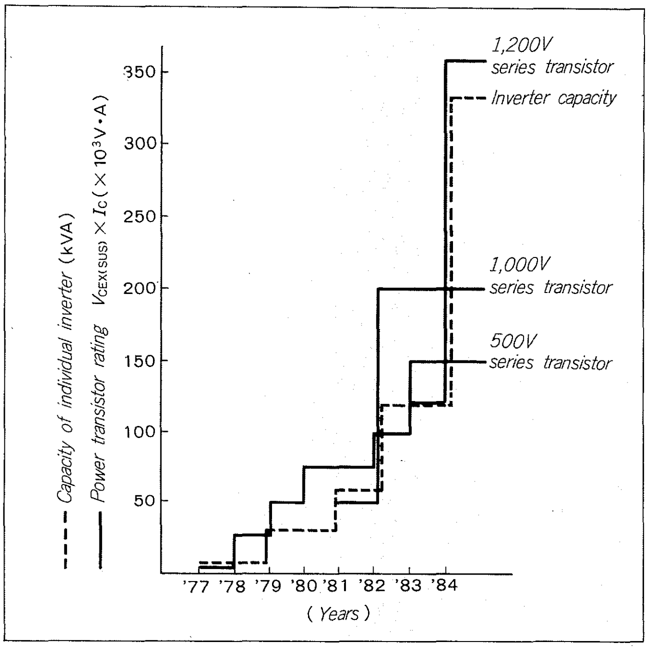


Fig. 2 Operating waveform at the time of sinusoidal wave PWM control

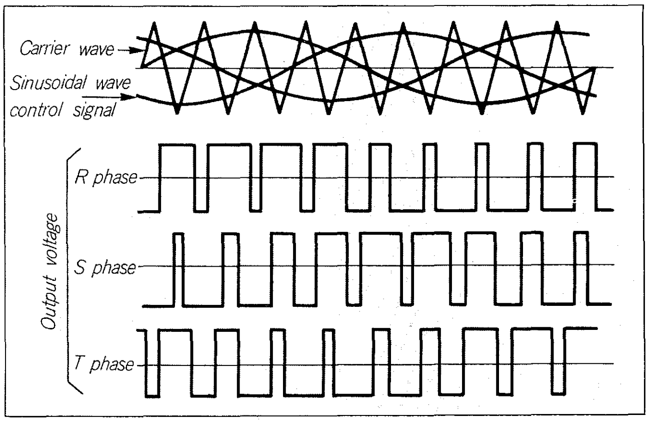
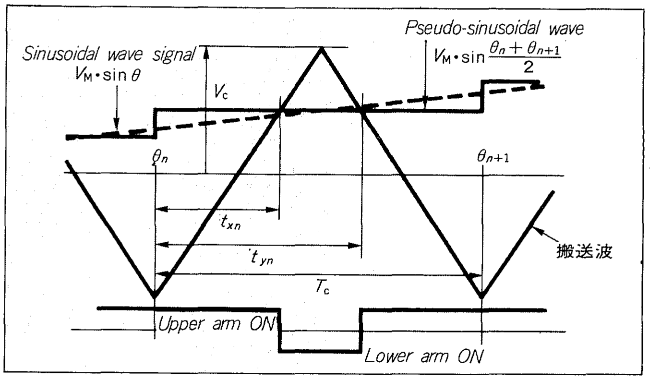


Fig. 2 shows the operating waveform during sinusoidal wave PWM control. It has the same frequency as that of inverter output, and it is for obtaining AC by setting ON and OFF the transistor of each phase according to the size of triangular wave (carrier wave) with constant peak value, and for obtaining sinusoidal wave control signal whose amplitude is in proportion of desired output voltage.

There is a method of digitalizing this control, that is, the above-mentioned ON-OFF pattern is stored previously in memory for whole range of frequency control, and to read it out according to the frequency. By this method, as memory capacity will be enlarged if the resolution of the output voltage were to be raised, it is widely adopted for inverters that require no continuous speed change.

On the other hand, there is another method in which the pulse width is counted at each cycle of carrier wave T_C. In *Fig. 3*, the sinusoidal wave control signal V_M is approximated by pseudo sinusoidal wave of peak value V_M that

Fig. 3 Explanatory diagram of pulse width computation



changes at each carrier wave period in step form. The time from θ_n to two points of intersection, to carrier wave and pseudo-sinusoidal wave, t_{xn} and t_{yn} are given by the following formula.

$$t_{xn} = \frac{I_C}{4} \times \left\{ \lambda \times \sin\left(\frac{\theta_n + \theta_n + 1}{2}\right) + 1 \right\} \ldots\ldots\ldots \quad (1)$$

$$t_{yn} = T_C - t_{xn} \ldots\ldots\ldots \quad (2)$$

whereas, $\lambda = VM/Vc$.

T_C and λ can be obtained directly from set frequency, while $\sin[(\theta_n + \theta_n + 1)/2]$ can easily be obtained by using the sinusoidal-wave table. Therefore, by setting data corresponding to t_{xn} and t_{yn} tq two timers, the pulse width desired from these output conditions can be obtained.

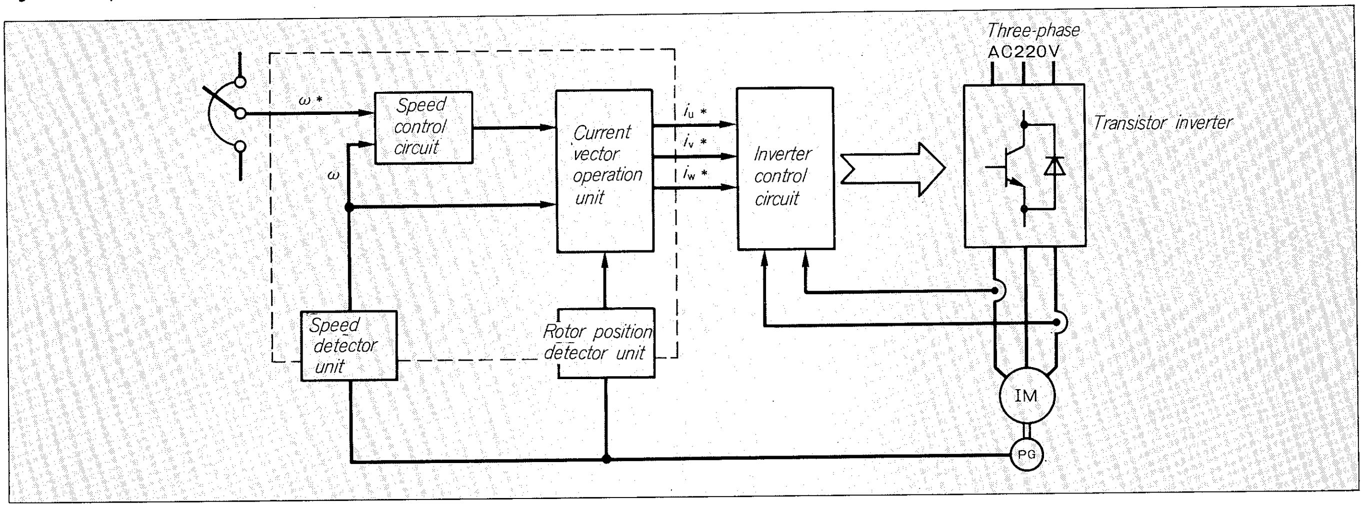
Recently, study on PWM control algorithm suitable for micro-computer such as control method by voltage vector is under way.

(2) Vector Control

Vector control is a method controlling the electric motor torque by separating the primary current of the electric motor into components of the same direction as that of magnetic flux and those orthogonalize them, and by making them not interferring one another then, by controlling them individually, so that a computation of complicated and high-precision order would be required.

It was made possible, recently, to construct stable systems by comparatively simple construction by introducing micro-computers into vector operating unit. *Fig. 4* shows the composition of vector control transistor inverter and the processing range of micro-computer is not limited to the vector operating unit but to the area surrounded by the broken lines. With this, improvement of speed control precision also can be expected. In general, those of current model with comparatively simple system configuration (also called frequency type vector control) are most widely adopted. This aims to obtain the position of magnetic flux by computation from the electric motor current and the rotor position, and when the electric motor constant fluctuates, there will be calculating error as to the position of real magnetic flux, and torque may become oscillatory producing, at times, excess or insufficiency in output power. For this reason, in order to prevent this in convenience, by detecting the motor temperature, the constant to be used

Fig. 4 Composition of vector-control transistor inverter



is compensated.

Recently, studies on the vector control technology through voltage control system that receives less influence from the variation of motor constant are under way.

4 FUTURE PROSPECT

The transistor inverters now take up an important position in the field of variable speed drive systems. That is, together with improvement of function and performance, the improvement of quality is stroven for, and reorganization of machine types is expected to advance.

Actually, there are various models available with which functioning and performance necessary for wide variety of applications are attained in the most economic way. The progress in the control technology that we can predict is the possibility of obtaining one model of an equipment that is provided with various functions and performance simultaneously without the necessity of pushing up the cost. Consequently, in the final stage, the following four models will become prevailing.

(1) Universal type inverter
(2) High-performance inverter
(3) Simple variable speed inverter, and
(4) High-frequency inverter

(1) will be the type, inspite of its small in size, light in weight and low in cost, of high-function inverter and versatility is really remarkable and would include all features of present universal type inverters. As a fundamental practice, the control will be that of primary frequency without having closed loop for frequency, and in order to take up the capacity of electric motor to the maximum, a very high-class control on the basis of present-day control theory such as adaptive control and observer, will be adopted. The control circuit will be made up from several LSI's highly integrated through use of gate array and/or exclusive use micro-computers, and for main circuit, MOS gate modules that require small drive power will be adopated so that it is expected to have smaller and smaller equipment.

(2) will be the type best represented by AC servo, and by combining it with exclusive-use electric motor, it will become that of system with high precision, good response and wide range high-speed change up to several tens of thous-and rpm. The control will be digitalized through the use of micro-computers and gate array system, and by utilizing this versatility, software sensor and auto-tuning will be put into practical use. With this, correction and compensation of electric motor constants in the vector control will be possible and the change in characteristics due to fluctuation of electric motor constants can be avoidad. For the main circuit, high-speed switching device is adopted and the improvement of responsiveness will be realized. Also, information feedback function to upper order computer system will be perfectioned, and this will be expected to give a good effect to operation control, failure diagnosis, etc.

(3) will be provided with special structure suitable for being incorporated into another system, being itself low in cost and having all the necessary functions as an equipment of exclusive use. Control will be carried out with a single piece of LSI being its system, that of pattern read-out system PWM. The main circuit will be modularized through which the size will be even smaller.

(4) belongs to the category of (1) if seen from the point of view of control function, but the independent properties will persist for its main circuit system.

The problems common to all machine types, that is, quantitative improvement of the inverters, are important. The diffusion into various industrial fields is increased and the functioning and performance of the transistor inverters have come to be highly appreciated. Small in size and light in weight, that is the demand of the time, and together with this demand, needs for precision class machine tools are increased and transistor inverters are adopted also for field of fine mechanics answering the clamour for reducing the vibrations of electric motors and irregularities of rotation. Furthermore, since these machines have come to be installed in very vicinities of human habitat, there emerged the problem also of noise and pollution of environment by electromagnetism. For these, analysis will be made coming back to the principle of generation, and the method of reduction will be proposed and, at the same time, an effective countermeasures will be taken with an increase knowledge accumulated in the field know-hows.

We have summarized in the above, the progress of transistor inverter and their recent trends and made a forecast on the direction of their evolution. Further development of the transistor inverters is expected in the future.

We sincerely request the supports and cooperations from users and all concerned with the products.