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TRANSISTORIZED INVERTER FOR AC MOTOR ADJUSTABLE SPEED DRIVE

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I. FOREWORD

The appearance of the thyristor, a typical power electronics device, has led to efforts in making apparatus and equipment static, tremendous improvement in reliability, operating safety and maintenance and to a noticeable growth in the field of adjustable speed drives from the standpoints of performances and functions.

However, since the thyristor is incapable of interrupting current by itself, a commutating circuit to forcefully interrupt the current is required in selfexcited thyristor converters (for instance, inverters), and it is impossible to apply to all applications because of the limits imposed by switching speed.

On the other hand, amazing progress has been made in power semiconductor devices in recent years and attention has been focussed on high voltage, large current power transistors, gate-turn-off thyristors and other similar power switching devices capable of interrupting current by themselves to replace the conventional thyristor, and the development and growth of application technique has been accompanied by the development and commercialization of inverters and other power converters employing these devices.

Fuji Electric has been promoting the development of power transistors and research on their application technique, and has applied them to various applications and equipments, and has built-up a large number of operating achievements over the past few years. Of these, the technique which permits variable speed operation of AC motors by inverter with frequency control has developed rapidly in recent years because of the demands for labor saving, simplified maintenance, rationalization and effective utilization, and it is being adopted a production equipment in small capacity range in combination with its other features such as high speed, explosion-proof construction, and usability in bad environments.

Transistorized variable voltage, variable frequency inverter "FRENIC 5000G" as the AC motor adjustable speed drive which was standardized up to 25 kVA based on deliveries- and operation-results up to the present will be introduced here.

II. PRINCIPLES OF ADJUSTABLE SPEED DRIVE BY FREQUENCY CONTROL

The slip-torque characteristic in constant frequency drive of an AC motor, for example, an induction motor, is generally well known. In this operation, the slip changes according to torque change of the load, however change of the speed is slight. Therefore adjustable drive in wide speed range is impossible. Adjustable speed drive system by frequency control accomplished by such as thyristor inverter, has already been developed to make such adjustable speed drive possible. Basically, this system supplies power of a variable frequency to the motor.

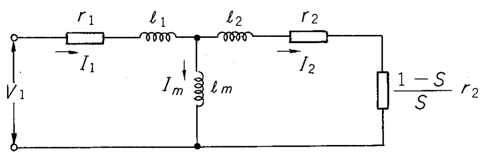
Fig. 1 shows the equivalent circuit of an induction motor. The generative torque in this equivalent circuit is given as follows:

$$T=3P_F\phi^2\frac{\Delta\omega\cdot r_2}{r_2^2+(\Delta\omega l_2)^2}\ (N\cdot m)$$

But, flux of air gap

$$\Phi = l_m I_m = l_m I_1\sqrt{\frac{1+[\Delta\omega l_2/r_2]^2}{1+[\Delta\omega(l_m+l_2)/r_2]^2}}$$

P_F: Pair of poles
$\Delta\omega$: Slip angular frequency (rad/s)
$\Delta\omega=\omega_1-\omega_2=S\omega_1$



r_1, l_1: Primary winding resistance (Ω) and leakage inductance (H)
r_2, l_2: Secondary winding resistance (Ω) and leakage inductance (H)
l_m: Excitation inductance (H)
S: Slip $S=(\omega_1-\omega_2)/\omega_1$
ω_1, ω_2: Primary and secondary angular frequency (rad/s)
$\omega_2=(1-S)\omega_1$

Fig. 1 Equivalent circuit of induction motor

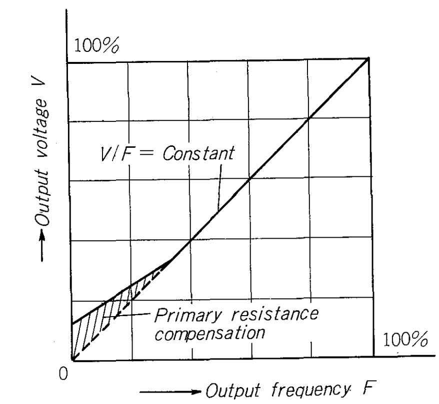


Fig. 2 V/F characteristics of inverter output

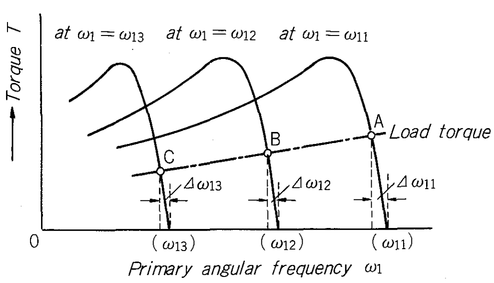


Fig. 3 Torque vs. angular frequency at variable frequency drive for induction motor

To drive motor stable by variable frequency, the air gap flux Φ must be almost constant at any frequency. Since the flux Φ equals $(V1/\omega 1)$ if the primary winding resistance and leakage inductance are ignored, the output voltage of the inverter must be proportional to the output frequency. *Fig. 2* shows this relationship. But since the voltage drop produced by the primary resistance reduces the flux in the low frequency, that is, low speed range, voltage compensation such as that illustrated in the figure is performed. As a result, the generative torque becomes a function of $\Delta\omega = S\omega 1$ only, and the torque characteristic is shifted almost in parallel for changes of ω_1. Therefore, the motor is adjustable speed driven by changing ω_1, that is, the its frequency.

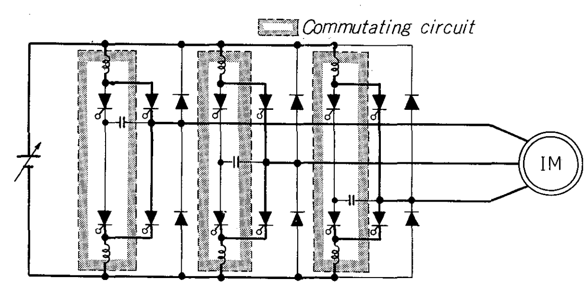
The relationship between ω_1 and torque T when a motor is adjustable speed driven by a inverter with a V/F constant control and a primary resistance compensation in low frequency region such as that previously described is shown in *Fig. 3*.

Since ω_1 is adjusted continuously at inverter operation, the characteristic curves in the figure are actually given infinitely. If the load torque is given as shown in the figure, the motor speed is set established at the intersection of the characteristic curve of each ω_1 and the load torque line (A, B, C) and is continuously changed from point A in the figure to point B and point C according to the adjustable speed demand. Moreover, reverse operation of the motor is also easily accomplished by switching the output phase order of the inverter electronically. Braking is accomplished by connecting a resistor to the DC intermediate circuit and shifting $\Delta\omega$ in the previously given equation to the minus side. Such a transistorized inverter is said to be driver having good control characteristics which provide the desired torque (including braking torque) stably over a wide rotational speed range.

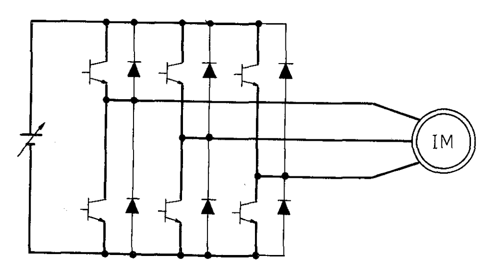
III. TECHNOLOGICAL DIFFERENCES BETWEEN TRANSISTORIZED INVERTER AND THYRISTOR INVERTER

In the preceding section, the basic principles when an induction motor is adjustable speed driven by primary frequency control using inverter were discussed. In the past, thyristors were generally used as main switching devices in inverters. However, in recent years, the application of power transistors to inverters in the small capacity range has grown rapidly. The technological differences between a transistorized inverter and thyristor inverter and reason why the used of power transistors is limited in the small capacity range will be discussed here.

As is well known, since a thyristor has not a current self-interruption capability, when adopted in an inverter, a commutating circuit to forcefully cut-off the thyristor is necessary, and both the main circuit and control circuit are complex. On the other hand, since the collector current of a power transistor can be turned on and off by controlling the base current (that is, it has a self-current-turn off capability), the same as the conventional transistors for small signal use, a commutating circuit is unnecessary, and inver-



(a) Thyristor inverter



(b) Transistorized inverter

Fig. 4 Basic main circuit

ter construction is extremely simple as shown in *Fig. 4*(b). This simple construction simplifies manufacture and maintenance, and contributes substantially to improved reliability and operating safety. This is the most important difference between a power transistor and thyristor.

In addition, since the thyristor inverter requires a commutating circuit, it is subject to the following restrictions and its output performance is, therefore, adversely effected.

(1) High-speed thyristors have appeared in recent years, but they are still expensive and the price of inverters used them in the small capacity range cannot be said to be low. Moreover, when the efficiency of the inverter is considered, an output frequency of only about several hundred hertz is obtained.

(2) Presently, pulse width modulated type inverters, in addition to square voltage waveform type inverters, are being practicalized to improve control performance and lower price, but with the thyristor type, the output frequency limit is lowered still further because of the turn-on and turn-off times and other restrictions.

(3) Since the voltage of the DC intermediate circuit of a square voltage waveform type inverter for motor drive changes proportionally with the output frequency of the inverter, the capacitor voltage of the commutating circuit also changes. Especially, since the drop in this voltage is accompanied by a reduction in the necessary energy for commutation and the commutating capability becomes low, the adjustable speed range is restricted. When a system which is not subject to this restriction is considered, countermeasures such as providing a separate auxiliary charging circuit that charges the commutating capacitor positively without regard to the frequency, that is, the speed control range, are necessaty.

(4) When an arm short has occurred at the DC side of an inverter, current detection is slow and the effect of the commutating capability or thyristor turn-off time, etc., is large and protecting the thyristors is difficult from the standpoint of control and a protection fuse must be provided in series with the thyristors.

On the other hand, a transistorized inverter is not subject to these restrictions and output performances or the introduction of a control system unobtainable with a thyristor inverter is possible.

For example,

(1) Since the switching time of a power transistor is extremely short, AC power having a frequency of up to several tens kHz can be supplied to a motor and adjustable speed drive of a high frequency motor is possible.

(2) Since the inverter loss can be improved substantially by improvement of the base drive circuit, etc., fast response type inverter such as a high frequency pulse width modulated type inverter, instantaneous current value controlled type inverter can be realized.

(3) Power supply for wide frequency range can be easily obtained without modification or addition of the main circuit.

(4) The power transistor can be protected against erromeous operation by noise overloads. Therefore the inverter can be made by fuseless.

(5) Since a commutating circuit is unnecessary, the equipment is small and lightweight, and maintenance and inspection are easy.

However, at the present stage, the transistorized inverter also has the following disadvantages which must be given adequate consideration in its application:

(1) A power transistor has not such a high voltage, large current element as the thyristor and the manufacture of inverters having a comparatively large capacity is difficult. Presently, power transistors are considered to be applicable to inverters having an AC voltage of 220 V and an output capacity of up to several tens kVA.

(2) The overcurrent capacity of power transistors is smaller than that of thyristors, and consideration is necessary so that the power transistor is not departed from the safety operation area in each operating condition. However, we feel that this problem will reach a good level without considering it a disadvantage through clarification of the destruction mechanism of the transistor itself and advancement of application technology.

(3) A power transistor has a low reverse breakdown voltage, and when used in a current source type inverter or other applications in which a reverse voltage is applied to the element, connection of a reverse voltage blocking diode in series and other countermeasures must be taken.

The main technological differences between the transistorized inverter and thyristor inverter in the small capacity range at the present stage were discussed above. Substantial advances in improved control performances and lower prices with advances in high voltage, large current of power transistors and expansion of their capacity range and the adoption of new inverter technologies in the near future.

IV. FRENIC 5000G CIRCUIT COMPOSITION, OPERATION & PROTECTION

The variable voltage, variable frequency transistorized inverter FRENIC 5000G standardized up to 25 kVA is an inverter for the AC motor adjustable speed drive provided with a voltage control function and frequency control function. Its circuit composition and operation will be described below. The circuit composition of the FRENIC 5000G is shown in *Fig. 5*.

1. Main circuit composition

A 180° conduction square voltage waveform type inverter is used in the frequency control loop and a transistor chopper system is employed in the voltage control loop. These have the following features:

1) Square voltage waveform type inverter

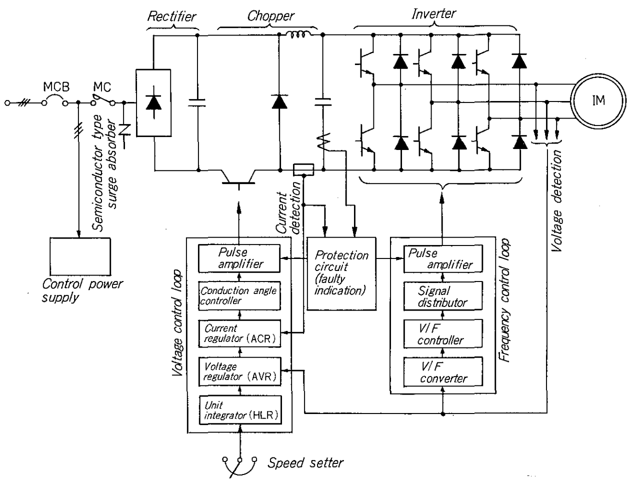


Fig. 5 Circuit composition of FRENIC 5000G

The output voltage of the square voltage waveform type inverter is not effected by the load and features superior control stability. The output voltage has also a higher fundamental wave voltage than that of the pulse width modulated type inverter and is advantageous from the standpoint of temperature rise of motor. Moreover, in addition to single motor operation, multiple operation is possible, and an emergency motor drive or drive when the commercial power fails can be realized by combining it with a battery, etc.

2) Voltage control loop by chopper

The voltage control loop consists of a diode rectifier and a high frequency operation type transistor chopper, and has the following features:

(1) Power factor is good,
(2) Control response is fast and
(3) Voltage smoothing filter is smaller.

2. Control circuit composition

The control circuit is divided into a voltage control loop and a frequency control loop. The former operates to maintain the "voltage/frequency" = constant. In order to adjustable speed driving stable and accurate, a circuit having the following features is employed:

1) *V/F* characteristic

The *V/F* characteristic, the ratio of the inverter output voltage and output frequency, is an important characteristic in adjustable speed drive of an a.c. motor as described in section **II**. The *V/F* characteristic of this inverter employs a system which performs resistance compensation at the low speed range shown in *Fig. 2*. Its value is suitably selected for constant torque control of an induction motor for general use over the 10 :1 speed control range.

2) Voltage control loop

The voltage control loop is given a superior control stability and control response through the employment of a current control minor loop. It is especially effective as a countermeasure against current oscillation.

3) Frequency control loop (Patent Pending)

The frequency control loop employs our unique system which commands the frequency based on the output voltage of the inverter. Since the voltage and frequency are maintained at the specified relationship, in all states, including load change, power supply fluctuation and other transient vibration, introduction of this loop permits stable control over a wide range. Since the frequency is lowered automatically and the *V/F* characteristic is maintained constant according to the drop in the output voltage when the output voltage has dropped because of operation of the current limiting function at acceleration and overload, a drop in the torque is prevented and acceleration up to our set speed automatically is possible after removal of the overload and it is strong against other disturbances.

3. Main circuit voltage and current detection

All detection system is employed the insulated type to prevent electrical interference and increase safety in case of inspecting the control circuit.

4. Protection

1) Overcurrent protection (Patent pending)

Since an inverter using power transistors can be protected against current from the standpoint of control as described in section **III**, we utilize this feature to perform current protection and have achieved effective co-ordinative protection. Current limiting facilities are common knowledge today, but we employs the following three additional protection technique:

(1) For over current of inverter, the instantaneous value of the discharge current of the filter capacitor is detected, and when it exceeds the standard value, the base of transistor in the inverter section is immediately opened.
(2) For over current of chopper, the instantaneous value of the DC circuit current is detected, and when it exceeds the standard value, the base of transistor in the chopper section is immediately opened.
(3) For overloads, when an overload current over a certain fixed value has continued for more than a fixed time, the base of transistor in the chopper section is opened. Moreover, when these protection circuits have been opened, its status is memorized and displayed.

2) Overvoltage protection

Absorption of switching surges generated internally is performed by a semiconductor type surge absorber having good limit characteristics and operation in the safety operation area is secured with an RC snubber.

V. FRENIC 5000G CONSTRUCTION

The FRENIC 5000G construction is a unit type as the basic type, and the construction best suited to the usage conditions can be selected from an open type to which circuit brakers and other peripheral devices have been added

(a) Unit type (5 kVA) (b) Cubicle type (5 kVA)

Fig. 6 Exterior views of FRENIC 5000G

to this type and a cubicle type housing the units, main circuit apparatus, operation control devices, etc.

1. Unit type

The unit type is an inverter unit with the main circuits required to control the motor and their control circuits compactly and functionally housed in a single unit, and is the minimum structural unit of the FRENIC 5000G. At the present time, 1.5~25 kVA units have been standardized. The exterior view of a 5 kVA unit is given in *Fig. 6*(a). Special consideration has been given to heat dissipation of the semiconductors, insulation between semiconductor elements, assembly and fabrication workability, ease of handling at maintenance and inspection in the unit construction. These have been added to the special construction shown in the figure. Especially, all the control circuits are mounted on printed circuit boards and a system which

Table 1 Standard specifications of FRENIC 5000G

Rated capacity (kVA)		1.5, 3, 5, 10, 15, 20, 25
Input	Number of phases	3
	Voltage	200 or 220 V ±10%
	Frequency	50 or 60 Hz $^{+3}_{-2}$ Hz
Output	Number of phases	3
	Rated voltage	Output voltage 200 Vr.m.s at input 200 V / input 220 V
	Rated frequency	60, 120 or 240 Hz (up to 3 kHz possible upon request)
	Overload capacity	30 sec at 150% of rated current
	Frequency accuracy	±1% (25 ± 10°C)
	Frequency control range	10 : 1
	Voltage/frequency ratio	Constant (with resistance compensation in low speed region)
	Voltage waveform	Square wave
Acceleration/deceleration time		2~10 sec (variable)
Protection functions	Overload	30 sec at 150% of rated current
	Instantaneous overcurrent	Instantaneous at 200% of rated current
	Control voltage drop	−15% of rated input voltage (200 V)
Inverter efficiency		90% or more
Cooling method		5 kVA maximum: Self-cooled, 10 kVA minimum: forced air cooled
Ambient temperature		−10~+40°C (however, when housed in a panel, panel interior temperature 50°C maximum)
Altitude		1000 m maximum
Construction		Unit type Open panel type Cubicle type
Input for setting	Constant value control	Variable resistor (1 kΩ, 3 W)
	Variable value control	0~(−) 10 V/0~100% (input resistance 1-kΩ)
Options	Reversible operation	Inverter phase order switching by logic
	Generative braking	Generative braking
	Speedmeter	0~(+) 10 V/0~100% (maximum 5 mA)
	Checker	

can be rotated forward by a rotating mechanism is employed to facilitate maintenance and inspection.

2. Open panel type

The open panel type combines a input circuit breaker, magnetic contactors etc. with the unit type in a single structure assembly. The adjustable drive equipment is completed by adding the control switches and speed setters to this assembly. This type is advantageous when it is housed in a cubicle with other equipment.

3. Cubicle type

The cubicle type has control switches, speed setters, meters, etc. in addition to the open panel type. There are two models, a wall mounted type and a self-stand type. The exterior view of the self-stand cubicle type is shown in *Fig. 6* (b).

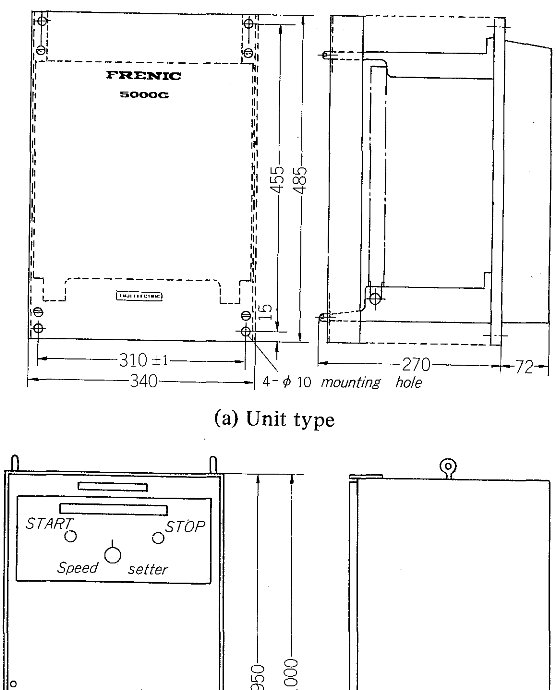
VI. FRENIC 5000G STANDARD SPECIFICATIONS AND DIMENSIONS

1. Standard specifications

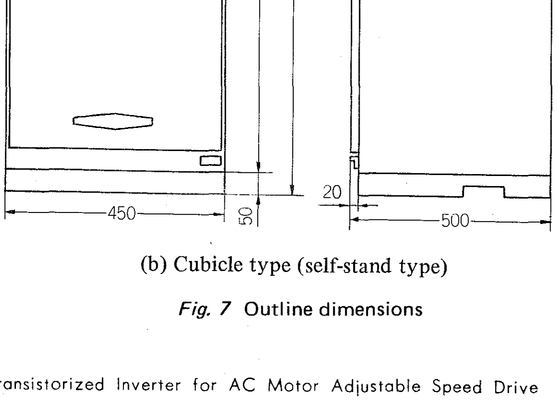
The standard specifications are given in *Table 1*. In the future, the specifications and performances will rapidly grow through advances in large capacity power transistors, parallel connection techniques and new control technique and these standard specifications should be viewed as preconditions at the present stage.

2. Dimensions

Fig. 7 shows the dimensions of the FRENIC 5000G. The 5 kVA unit type and cubicle type (self-stand type) are shown here.



(a) Unit type



(b) Cubicle type (self-stand type)

Fig. 7 Outline dimensions

VII. FRENIC 5000G OPERATING CHARACTERISTICS

The FRENIC 5000G is a 180° conduction square voltage waveform type inverter having the features previously mentioned. The typical operating characteristics by combining with a standard induction motor (2.2 kW, 4 poles) will be described here.

1. Inverter characteristics

The inverter output voltage is related to the effective value of the input power supply voltage. When the power supply voltage is 220 V/200 V under power supply voltage fluctuation ±10% conditions, the output voltage of the inverter is a square wave having an effective value of 200 V. The rated output voltage/frequency of the test inverter is 200V/60 Hz. As a result of tests, the overall efficiency of the inverter is 90% or more at the rated output and rated frequency, and the inverter guarantees 150% overload, 30 seconds maximum capacity.

2. Combined operation characteristics

1) Speed-torque characteristic

The FRENIC 5000G is provided with a *V/F* characteristic with in low speed region. The speed-torque characteristic at the frequency control range 10 : 1 region provides ample torque as shown in *Fig. 8*. Moreover, for load change from no load to rated load, the speed regulation rate in the 5 : 1 frequency control range is 10% or less. Furthermore, the maximum torque at each setting frequency is determined by the current limiting value. However, the test motor had a maximum torque of 200% of the rated torque and its high instantaneous overload withstand as an inverter was proved.

2) Starting torque

Usually, a current of 6~8 times of the rated current

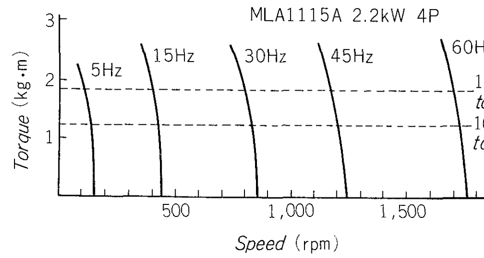


Fig. 8 Example of speed vs. torque

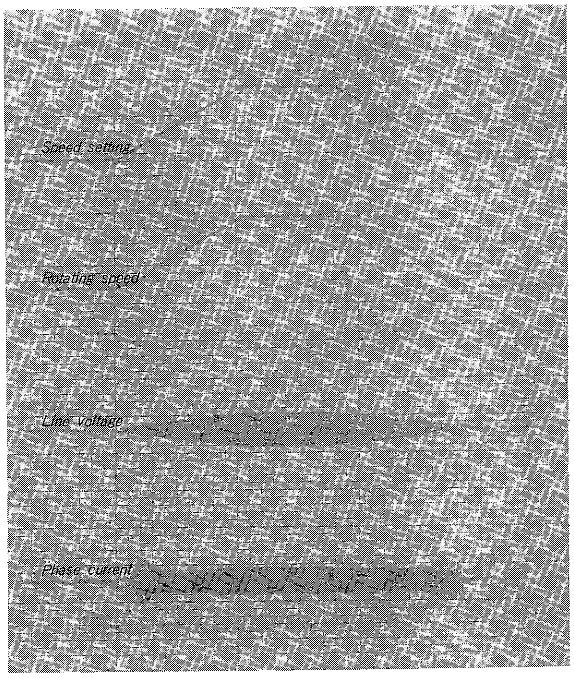


Fig. 9 Oscillogram of start and stop condition

flows in a 3-phase induction motor and a starting torque of 2.5~3 times of the rated torque is obtained when a 3-phase induction motor is started with a commercial power supply. With this inverter, a starting torque of 150% or more of the rated torque is guaranteed. And the surge current to the motor is suppressed by soft starting and a current limiting function. Furthermore, the minimum value of the maximum torque envelop line in the entire speed range from zero to the rated speed is 140% of the motor rated torque and is an adequate acceleration torque.

3) Dynamic characteristic

The estimation of the dynamic characteristic depends on the control response of the control loop. This inverter has an excellent characteristic because of the quick response of voltage control loop and current control loop. As a typical example, the starting and stopping oscillograms are given in *Fig. 9*. The acceleration and deceleration times can be set to an arbitrary value between 2 and 10 seconds by means of a variable resistor on the control printed circuit board. Furthermore, the speed overshoot for sudden power source change and load change is small and stable control is possible. Moreover, automatic resetting for instantaneous power failures of less than the allowable value is also possible by operation of the protection circuit. In addition, good results are also obtained for forward and reverse operation and braking.

VIII. CONCLUSION

The features of the transistorized inverter, an outline of the FRENIC 5000G and the outlook for the future were given above. The transistorized inverter is making a large contribution to adjustable speed drive in many industrial fields through its advantages, and its fields of application are expected to expand substantially in the future with the introduction of new circuit systems and new control technologies.