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APPLICATION TECHNIQUE OF TRANSISTOR VVVF INVERTER

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1 FOREWORD

The transistor inverters that had started by applying for the purpose of energy saving operation of small-capacity fans and pumps, are now expanding their use in almost every sector of industries. Also their capacities are being enlarged more and more and they have attained the capacity as large as 400 kVA.

Fuji Electric's transistor inverters have a large family so that the users can choose the most suitable inverter for their particular application.

Together with the expansion of fields of application and capacity range, there emerged a problem of making errors in picking up unsuitable machine type and capacity as well as in interference with peripheral equipment. In this report, correct use of each machine model, choice of capacities, and compatibility with power source and peripheral equipment are described in order to use correctly the transistor inverters.

2 CHOICE OF INVERTER TYPES AND CAPACITIES

2.1 Choice of Inverter Types

In order to provide transistor inverters most suitable for various types of variable speed drivnig, Fuji Electric serializes a wide range of inverter families. Here in this section, their uses are described.

Demands for the speed changing equipment seen from the load side include wide speed control range, high-frequency accelerating and decelerating capability, and high precision of speed control, and when we pick up the suitable types according to these conditions, we can summarize it in a way shown in *Table 1.*

FRENIC Series 5000V, 5000VH and 5000M are supplied in a form of combination with specially designed electric motors, and their output is nominally indicated in shaft output of the electric motor.

FRENIC Series 5000P, 5000G, FVR-P and FVR-G are used in order to speed control for standard motor as their main duty, and they are supplied in a form of inverters themselves and their output is indicated nominally in current value. When FV motors for exclusive inverter use, the shaft output of the electric motor will be the guaranteed value.

Table 1 Choice of machine types

Speed control range	Load variation	Precision	Choise of machine models
General speed (Commercial frequency class)	Stable	General (Note 1)	FRENIC 5000P, FVR-P
		High-precision	FRENIC 5000V
	High-frequency acceleration and deceleration	General (Note 1)	FRENIC 5000G, FVR-G
		High-precision	FRENIC 5000V
High speed (Commercial frequency x 3 to 4)	Stable	General (Note 1)	FRENIC 5000G, FVR-G
		High-precision	FRENIC 5000V
	High-frequency acceleration and deceleration	General (Note 1)	FRENIC 5000M (FRENIC 5000G, FVR-G) (Note 2)
		High-precision	FRENIC 5000V, FRENIC 5000 VH
Ultra high speed (Commercial frequency x 4 or more)	—	—	FRENIC 5000 H

[Note 1] : Speed varies slipping parts of induction motor as per variation of the load.

[Note 2] : It is necessary to have a motor of special design that withstands high-speed rotations.

FRENIC Series 5000H has the basic duty of providing inverters only, but since they are entrusted with the duty of driving ultra-high speed electric motors of various specifications including those of imported products, their adjustable range of output frequencies and voltage is made to be extremely wide.

2.2 Characteristics of Combination of Standard Type Induction Motor with Inverter

In case of driving electric motors designed exclusively for inverters, studies on the application would be sufficient if we should see the guaranteed shaft output torque, but if we were to drive the standard type induction motors, we should know the combined operation characteristics

Fig. 1 Combination operation characteristics [FVR-G2 +standard type motor (4-poles)]

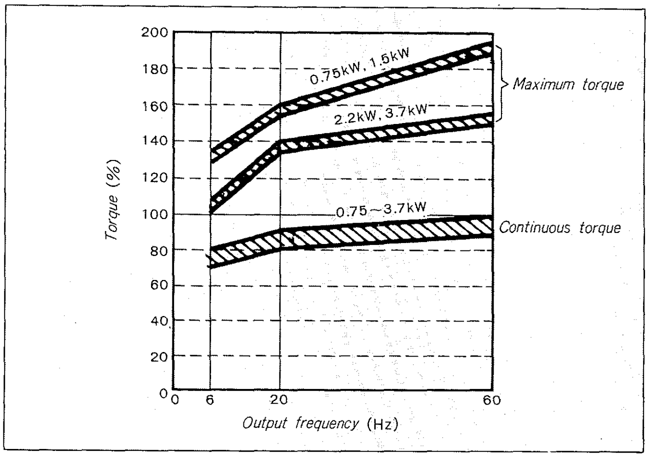
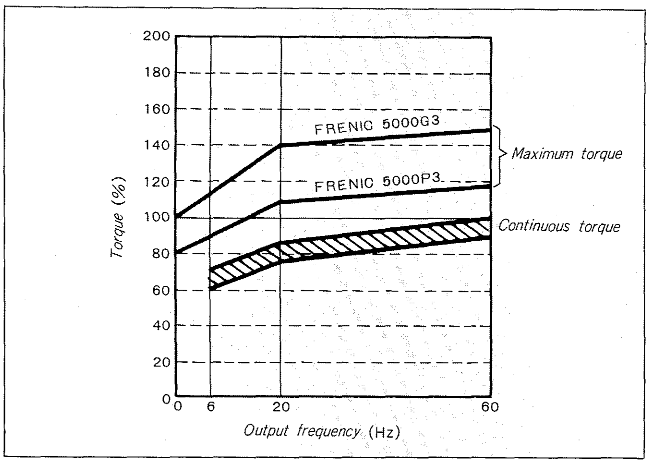


Fig. 2 Combination operation characteristics [5000 G3/P3 + standard type motor (4-poles)]



with the inverter.

Fig. 1 and *Fig. 2* shows examples of operation characteristics of the combination of Fuji standard type induction motor with inverter.

(1) Continuous torque

This refers to a critical torque in order that the electric motor temperature rise should remain within the specified value when the load is driven with a constant speed.

When the electric motor is driven by an inverter, motor loss will increase somewhat due to the harmonic current, so that the operation should be made by lowering the output torque. But in case of electric motor with smaller capacity, since the designed value itself is provided with an ample margin, a 100% torque can be obtained with rated frequency. In case of larger-capacity electric motors, such margin is not provided, so that reduction of 10 to 15% is necessary. In the region of low-speed operation, care should be taken for lowering of torque due to the decrease in cooling effect of electric motor shaft fan and voltage drop in the primary winding.

(2) Maximum torque

It is determined by notch selection of the torque boost and inverter output current capacity. Generally, a larger torque can be obtained by using a larger inverter. The reason why the maximum torque of 0.75 kW, and 1.5 kW shows a large value in *Fig. 1* is that it is due to the fact that inverter capacity application is relatively large. And the difference between FRENIC 5000G3 and 5000P3 in *Fig. 2* is due to the fact that the overcurrent capacity is set to 150% and 120%, respectively.

(3) Starting torque

The strength of starting torque is determined by adjusting the torque boost. As a general rule, when the torque boost is set to a higher value, an increase in starting torque can be expected, but when it is set too high, the electric motor will be overexcited when it is running no-load, and this brings about the problem of excessive increase of no-load current due to magnetic saturation. Since this depends on the number of poles and capacity of the electric motor, the setting must be made individually within a range that should not produce the magnetic saturation.

(4) Braking torque

When inverter output frequency is lowered than the induction motor speed, the motor will produce a braking torque and energy is regenerated to the inverter's DC intermediate circuit. By discharging this, a braking torque equivalent to the accelerating torque can be obtained. As for FVR-G Series with small capacity, discharge resistance is equipped as standard accessories, and it is optional for FRENIC 5000G and 5000P series. Even if we do not use the discharge resistance, by circulating a current between inverter and the electric motor, a loss is produced in the winding of the electric motor and inverter, a braking torque of 15 to 20% is generally obtainable.

2.3 Choice of Inverter and Motor Capacities

In the Inverter Catalogue, capacities of standard electric motors to be applied are described taking 4-pole standard type electric motors, however, these values are only theoretical. Capacities should be chosen meeting with the conditions the load demands on basis of combination operation characteristics of electric motor and inverter as mentioned in Section 2.2 above.

(1) Continuous operation characteristics

The load torque in case of continuous operation must be within the limit of continuous torque shown in Figs. 1 and 2. Generally, in case of the load of square reduction torque characteristics as fans and pumps, the torque near the rated frequency constitutes a problem, and in case of constant torque characteristics load as conveyors, the torque in the range of lower frequencies constitutes the problem. So that is would be necessary to provide countermeasures as equipping limiters to operating frequency range and/or making the electric motor capacity one size larger.

(2) Accelerating and decelerating time

The fundamental of the universal type inverters consists in linear acceleration and deceleration. Their time will be determined by the conditions making the torque minimum within the accelerating and decelerating range. The time necessary for accelerating or decelerating the speed from N1 to N2 is expressed by the following formula:

$$\text{Accelerating time} = \frac{GD^2}{375} \times \frac{(N_2 - N_1) \times 100}{T_0 \times (\%T_M - \%T_L)\min} (s) \quad \ldots (1)$$

$$\text{Decelerating time} = \frac{GD^2}{375} \times \frac{(N_2 - N_1) \times 100}{T_0 \times (\%T_M + \%T_L)\min} (s) \quad \ldots (2)$$

where,

GD^2 : Composite value of $GD^2{}_M$ (kg·m²) of electric motor itself and $GD^2{}_L$ (kg·m²) of load converted to motor shaft value.

T_0 : Rated torque of the electric motor (kg-m)

$\%T_M$: Electric motor output torque in inverter oepration (%).

$\%T_L$: Load torque converted to electric motor shafr (%).

(3) High-frequency accelerating and decelerating operation

When the operation is repeated with high frequency more than the limit of continuous operation, it is necessary to study in detail both electric motor and inverter. The calculating method is explained taking an example of repeated operation shown in *Fig. 3.*

Fig. 3 shows the variation of speed in repeated operation and that of electric motor current in function of time. For this operating pattern, the inverter and electric motor must be chosen by the following formulas, respectively.

$$I_I \geq \frac{I_1 \cdot t_1 + I_2 \cdot t_2 + I_3 \cdot t_3 + I_4 \cdot t_4 + I_5 \cdot t_5}{t_1 + t_2 + t_3 + t_4 + t_5} \times 1.2 \text{ (A)} \quad \ldots (3)$$

where, 1.2: Safety coefficient

$$I_M = \sqrt{\frac{I_1{}^2 \cdot t_1 + I_2{}^2 \cdot t_2 + I_3{}^2 \cdot t_3 + I_4{}^2 \cdot t_4 + I_5{}^2 \cdot t_5}{K_1 \cdot t_1 + K_2 \cdot t_2 + K_3 \cdot t_3 + K_4 \cdot t_4 + K_5 \cdot t_5 + K_6 \cdot t_6}} \text{ (A)} \quad \ldots (4)$$

In the above formula (4), $K_1 \sim K_6$ are the coefficient indicating the cooling of the electric motor whose example is shown in *Fig. 4.*

(4) Grouping operation of electric motors

Generally, in case it is necessary to operate N units of electric motor simultaneously, the rated current I_1 of the inverter must be chosen as:

$$I_1 \geq N \times I_M \text{ (A)} \quad \ldots (5)$$

where, I_M : Rated current per 1 unit of electric motor

Also, when an electric motor with small capacity is consecutively one by one, the requirement of the formula (5) must be met and at the same time, that of the following formula (6) also must be met.

Fig. 3 High-frequency accelerating and decelerating operation

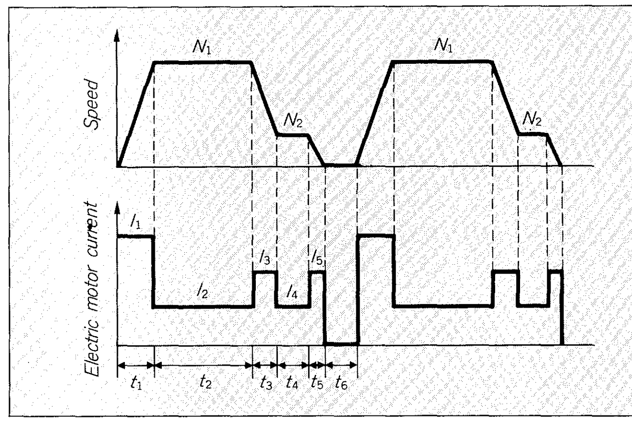
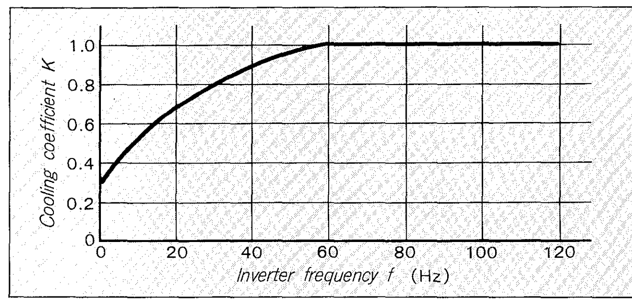


Fig. 4 Example of electric motor cooling coefficient



$$I_1 \geq \frac{(N-1) \times I_M + I_S}{K_{OC}} \text{ (A)} \quad \ldots (6)$$

where,

I_S : Directly coupled starting current per one unit of electric motor (A)

K_{OC}: Inverter overcurrent resisting value (1.5 for FRENIC 5000G3 and 1.2 for FRENIC 5000P3).

N and I_M : The same as the formula (5).

3 COMPATIBILITY WITH POWER SOURCE EQUIPMENT

3.1 Input Higher Harmonic Current and Power Factor

Fig. 5 shows a diagram of transistor inverter main circuit. Since the input circuit is condenser input type rectifying circuit, the input current waveforms differ greatly depending on the impedance of the power source. It is due to the fact that among the source impedance, reactance components in particular change greatly the intensity of harmonic current. *Fig. 6* shows the example of change in fundamental current I_1, harmonic currents $I_5 \sim I_{19}$, and whole RMS value current I_{eff}. The % value of each current indicates each current component when 100% load is applied to electric motor taking the rated current of the electric motor as the reference.

Fig. 5 Main circuit diagram

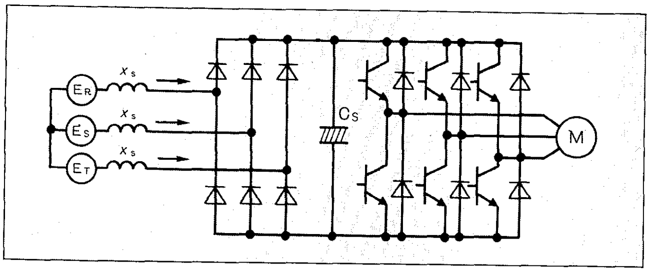
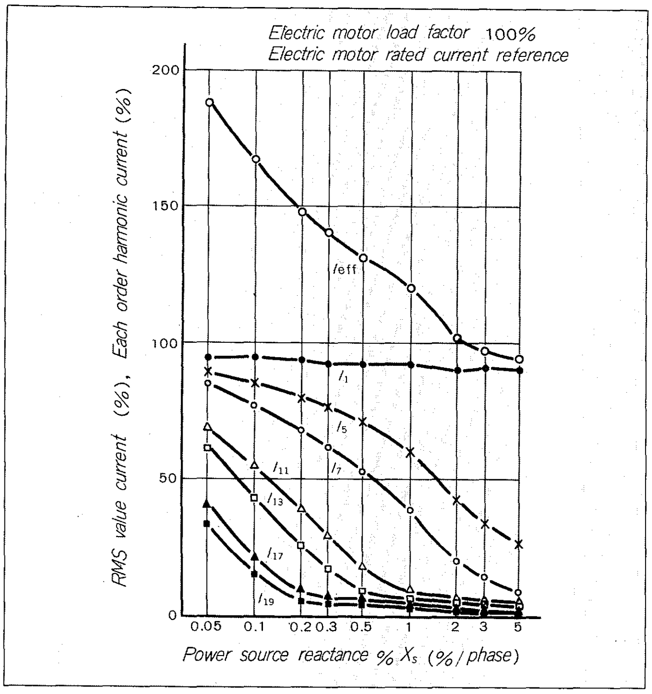


Fig. 6 Example of input current harmonics and RMS value current



As it is obvious from *Fig. 6*, the fundamental current I_1 will become constant without having to do with impedance, but when the impedance becomes smaller, the harmonic current will be increased and, as a result, total RMS value current also increases.

By expressing the phase voltage of the power source as E, and fundamental wave power factor, as $\cos\theta_1$, we obtain:

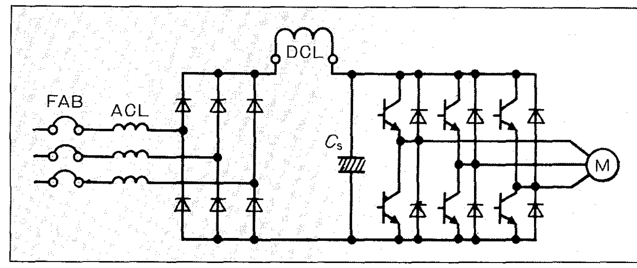
$$\text{Input power factor} = \frac{3 \cdot E \cdot I_1 \cdot \cos\theta_1}{3 \cdot E \cdot I_{eff}} = \frac{I_1}{I_{eff}} \cdot \cos\theta_1 \quad \ldots\ldots (7)$$

As $\cos\theta_1$ will be more or less constant value of 0.97 having nothing to do with impedance, so that the power factor will be determined by the change of I_{eff}, that is the change in harmonic current.

3.2 Improvement of Power Factor

Since the main cause of the lowering of the inverter input power factor is due to an increase of harmonic current, the improvement of power factor must be through reduction of harmonic current. As for the countermeasures, as shown in *Fig. 7*, there are methods of inserting AC reactor or DC reactor. Inserting AC reactor has a shortcoming of generating the voltage drop when a commutation is made and there must be an excessive number of connecting terminals.

Fig. 7 Connection of AC reactor and DC reactor



3.3 Reactor Compatible with Power Source

When a thyristor converter of large capacity or a phase advancing condenser for automatic adjustment of power factor is connected to a bus bar to which the inverter is connected also, the voltage will momentaneously present sinking waveforms and the input diode of the inverter may be broken down. For avoiding this, the fundamental method is to provide sufficiently the commutating reactor of the thyristor converter and serial reactors of phase advancing condenser to minimizing the sinking of the voltage waveform. However, when the existing installation has a capacity as large as several times more than the projected inverter capacity, it would be more economic if the countermeasures should be taken in the periphery of the inverter.

Fuji Electric has prepared for this purpose, power source compatible AC reactors as options.

3.4 Connection of an Ammeter

An ammeter is mounted on the inverter panel besides the frequency meter as a meter to detect the load condition. In this section, a discussion is made as to the correct mounting position and type of ammeters in connection with purpose of the ammeter.

In the conventional distribution board which operates an electric motor with commercial power, an ammeter is connected in order to detect the magnitude of the electric motor load. If it is used for the same purpose for the inverter panel, too, the whole problem would be solved if we connect a moving iron type ammeter to the inverter output side. But when the output frequency is low, the meter indication would be a swing with certain range. Also, it is necessary to pick up previously ones with large VA capacity in order to prevent errors due to saturation if we are to use those with a current transformer (CT).

And in case of connecting an ammeter in order to find out the effect of the energy saving devices, if they are introduced to the equipment, the efficient method of connecting is to connect a rectifier type ammeter to inverter input side. With this method, since the ammeter indicates the fundamental wave current component I_1 shown in *Fig. 6*, the input power can be calculated approximately as:

$$P = \sqrt{3} \times V \times I \times \cos\theta_1 = \sqrt{3} \times 0.97 \times V \times I \text{(W)} \quad \ldots . \quad (8)$$

4 GENERATION OF ELECTRIC NOISE AND ITS COUNTERMEASURES

4.1 Noise Generation

Transistor inverters effectuate harmonic switching in order to minimize their own loss and to make their output waveform into sinusoidal waves. As the result, since the potential difference between output wiring themselves and between output wiring and the earth, generates various sorts of high-frequency noise as high-speed step change is made. So that when an inverter is used, some short of measures against these noise must be considered.

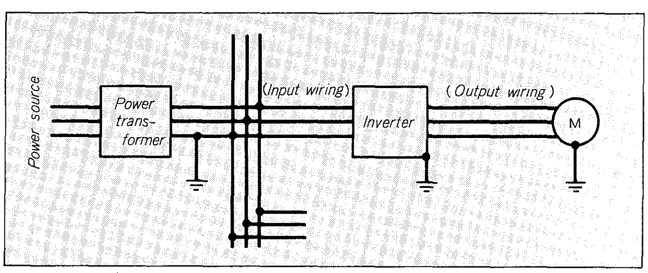
4.2 Noise Transfer Route

Fig. 8 shows a block diagram of the case an inverter is connected. With this block diagram, some important points in noise generation are explained.

(1) Output wiring

This is the part where the noise can be generated most among the system being connected with an inverter. There are influences by static induction and electromagnetic induction, and for radio equipment, they will receive an adverse influence from radiation noise.

Fig. 8 Block diagram of an example of connection of an inverter



(2) Electric motor

For the straying capacity between electric motor winding and frame, high-frequency charging and discharging current will flow. This will be conducted to the earth through the grounding wire, but when this grounding resistance is large or when the grounding wire is extended to a long distance, generation of noise from the motor frame and grounding wire constitues a considerable problem.

(3) Inverter body

The radiation noise from inside is absorbed by the metallic case of the main body and led to the grounding wire. Also, the high-frequency current running to the straying capacity of the internal equipment flows through this grounding wire, so that when the grounding resistance is large or when the grounding wire is extended long, noise generation from the inverter itself and grounding wire may constitute a problem.

(4) Input wiring

The noise level is considerably lower when compared with that of output wiring, but since the high-frequency current running to each part of the electric motor from the inverter main body flows partially through the grounding wire of the power transformer, so that when the parallel wiring is long, care should be taken for the induction.

Also, since these high-frequency currents are almost zero-phase currents, they may misoperate the leak current are almost zero-phase currents, they may misoperate the leak current relay connected to the power source side.

4.3 Countermeasures Against Noises

Fundamentals of countermeasures against noises consist in suppressing the generation of noise itself and interrupting the noise transfer routes. Which of these two should be taken up mainly for eliminating noises depends on the cost needed for the measures and efficiency of suppression. So that this should be determined individually. In this section, countermeasures against noises are discussed as a general rule.

First, as for the measures that should be taken on the generating side, the following should be considered:

(1) Metalic conduit wiring

Pass the inverter output wiring through a metallic conduit and ground this conduit, then the radiation noise will greatly be reduced. Also, this is an efficient method for induction noise.

(2) Grounding wire

It is necessary that the grounding wires of an electric motor, inverter and metal conduit should be of low-impedance for high-frequencies. They should be "thick and short" and this should be the motto for installing the grounding wire. They should be connected to the nearest grounding point.

(3) Reactor for reducing radio noise

When inverter input wire or output wire is wound around a core (ferrite core or such similar material) having a good frequency characteristic binding three phases together, zero-phase impedance will be increased so that high-frequency current will be reduced.

(4) Filter for reducing radio noise

Noise filter intended for reducing radio noise transferred through input power source wire of the inverter is available in commercial market. This is efficient for inline noise also and has a reducing effect of 20 to 30 dB in the radio frequency band.

In the following sections, discussions are made on the countermeasures and precautions that should be taken up on the noise receiving side.

(1) Prevention of leak-current relay misoperation

One method is to raise the setting of the relay detecting level, but this may injure the original function of leak-current detection, so that the most efficient method is to use the leak-current relay already treated for inverter operation. It leaves the detecting sensitivity for the current of commercial frequency level for detecting any leak as it is and making the sensitivity for high-frequency current less sharp, so that its detecting capability for deterioration in insulation is not affected.

Fuji Electric has brought forth these countermeasures on all models of leak-current interruptors and leak-current relays produced since July, 1983.

(2) 4 to 20 mA signal line

Since these lines are often extended up to a long distance, it is important to install them separated as long as possible from the inverter output wiring. The 4 to 20 mA signal lines are, generally, those of shielded wire, but as the high-frequency current may flow through the shielded wire in case of long-distance wiring, the shielding effect will be somewhat lowered. When the noise influence persists, it will be efficient way to eliminate it to insert an L-C filter in the terminal part of the signal line.

(3) Sensor signal line and amplifier input power line

Often various types of sensor signal lines have feeble signals. So that it is important to install the amplifier for sensor as near as possible to the sensor in order to avoid the adverse effects from the noise.

Also, as for the amplifier handling feeble signals, since it is susceptible to adverse effect from power source wire noise, in order to avoid such influence, connect a noise filter commercially available to its input part.

(4) Separation of grounding wire

The grounding wires for measuring instruments and signal line shield must be installed separately from the grounding wires of inverters and electric motors. By the fact that much high-frequency current flows through the grounding wires of the main circuit equipment, high frequency voltage due to their impedance drop is generated.

5 SUMMARY

We have summarized in this report the method of selecting types and capacities of transistor inverters. Also we have described the negative aspects of inverters as harmonic current generated by inverters and electric noise in the radio frequency range in an outlined form as well as measures that should be taken for coping with them.

We intend further to develop the possibilities of variable speed driving system using inverters and to endeavor for furnishing the market with better and better systems. We sincerely request the supports and cooperations form the users.