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Intelligent Control Unit for Ultrasonic Cleaning System

***Abstract**. This paper presents the results of simulation and experimental investigation concerning intelligent automatic control of output voltage frequency ultrasonic generator supply sandwich transducers unit in an ultrasonic cleaner. The mechanical resonance frequency of the oscillating system is a function of many parameters and varies during the process to obtain high efficiency cleaning should be continuously monitored and fine-tune the frequency inverter to the resonant frequency band transmitters.*

***Streszczenie.** W artykule przedstawiono wyniki symulacji modelu cyfrowego i badań eksperymentalnych inteligentnego układu sterowania częstotliwością napięcia wyjściowego generatora zasilającego przetworniki piezoelektryczne w myjni ultradźwiękowej. Częstotliwość rezonansu mechanicznego przetwornika zmienia się w trakcie procesu technologicznego w funkcji wielu parametrów, żeby zatem uzyskać wysoką efektywność mycia należy kontrolować i dostrajać częstotliwość napięcia wyjściowego generatora do częstotliwości rezonansowej przetworników. (**Inteligentny system sterowania czyszczeniem ultradźwiękowym**)*

Keywords: intelligent adaptive system, ultrasonic cleaning system, power electronics, piezoelectric ceramic transducer
Słowa kluczowe: sterowanie rozmyte, ultradźwiękowe mycie technologiczne, układy przekształtnikowe, piezoceramiczne przetworniki mocy

Introduction

The ultrasonic piezoelectric ceramic transducers [9], [10], [11] are now the most popular source of high power ultrasound and is used in many industrial applications.

High power ultrasonic waves are generally used in such industrial processes as welding, acceleration of chemical reactions, scavenging in gas medium, echo sounding and underwater communication (sonar systems), picture transmission, and, above all, ultrasonic cleaning [3]. In practice is now the most widely used the sandwich type power transducers.

Typical units of the ultrasonic generators attuning these transducers operate at frequencies between 20 kHz and 100 kHz with output power to 5 kW. In this case the group of piezoelectric ceramic transducers are the source of power ultrasounds and the vibration is activated by a ultrasonic generator. The output voltage frequency of generator most by equals the mechanical resonance frequency of the transducers and most by tuning with high precise. In the case of untuning, the frequency feed-back control system of the generator change the output voltage frequency and tuning the inverter to the mechanical resonance frequency of transducers. The task of the control system is therefore the output voltage control frequency inverter, piezoelectric ceramic transducers to vibrate with the greatest efficiency. In real circuit the mechanical resonant frequency is function of many parameters of piezoelectric material, among others, the most important are temperature, time, and for industrial cleaning systems also factor of the column, and the surface of the cleaned elements. For automatic control of output frequency voltage power converter we proposed intelligent adaptive system with fuzzy logic algorithm.

Ultrasonic Cleaning System

For example the standard ultrasonic system for cleaning technology (Fig. 1) includes [3]:

1. ultrasonic generator,
2. transducer or set of transducers,
3. cleaning tank.

Piezoelectric ceramic transducers placed in the tub generate ultrasonic waves that pass through the liquid and reach the element immersed in the tank. As a result, created in the liquid, with very high frequency, alternating areas of high and low pressure. In areas, where low pressure is forming millions of bubbles of vacuum. When the pressure in the alveoli increases and is high enough, bubbles implode, releasing enormous energy at the same time. This phenomenon is called cavitation. Emerging implosions work as a whole series of small cleaning brush. The phenomenon is spreading in all directions and causes intense but controlled detachment of particles of pollutants on the entire surface of cleaning detail. Washed away dirt particles collect on the surface of the cleaning solution from where they are blown into a nearby basin, and then be filtered and recycled.

Ultrasonic cleaning is more effective in cleaning hard materials, than the cleaning of soft or porous materials.

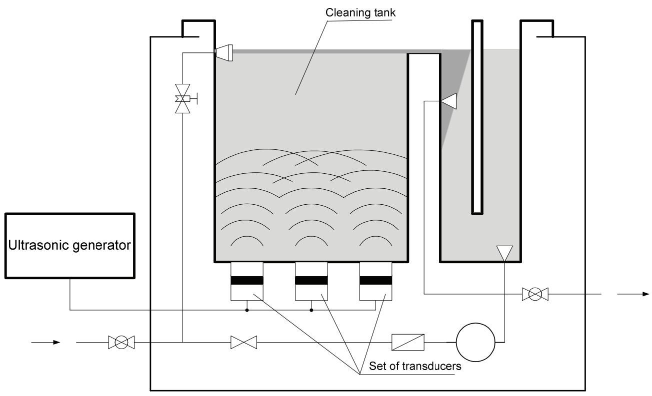

Fig. 1. Ultrasonic cleaning system

Generator

The first part of standard ultrasonic system for cleaning technology are ultrasonic generator [3].

Block diagram and the main circuit of the generator, which are shown in Figure 2, consists of:
- converter AC/DC,
- full-bridge inverter FBI (T1-T4, D1-D4),
- isolating transformer T, where $z_2/z_1=n_1$, $z_1/z_3=n_2$,
- special filter F (L_f, C_f),
- piezoelectric ceramic transducer PT,
- sensor of vibrations S,
- control unit CU.

Stabilization of amplitude ultrasonic oscillation is important in processes such as ultrasonic welding. The generators of ultrasonic cleaning technology are not necessary, because in this case, the vibration should have the greatest possible amplitude. Thus, to ensure maximum effectiveness of the piezoelectric ceramic transducers ultrasonic generator must be supplied at a voltage with a frequency such as the mechanical resonance frequency [8].

Because the mechanical resonance frequency is not constant and changes during system operation, e.g. under the influence of temperature for the control you can use the signals that a function of frequency changing their average values or effective for state and local resonance are extreme points.

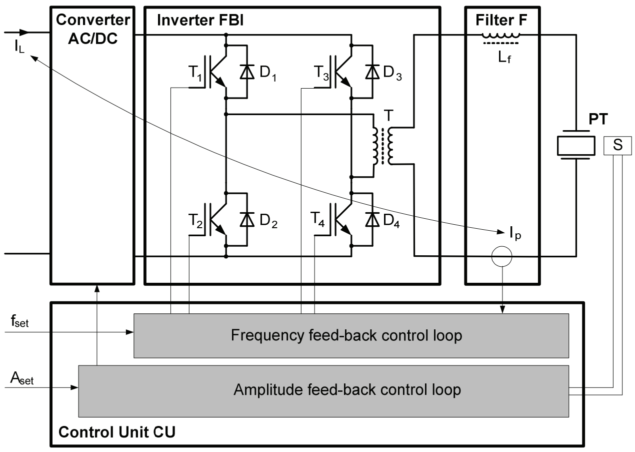

Fig. 2. The block diagram of the ultrasonic generator

The control unit consists of two parts. The first part consider full-bridge inverter FBI is the frequency feed-back control loop and the second part consider AC/DC converter is the amplitude feed-back control loop. This two coupling loop works independently.

In the case of overload inverter system of current limiter disconnect supply of AC/DC converter.

Signal f_{set} make possible to set up manually frequency switching inverter FBI and signal A_{set} establish amplitude ultrasonic oscillation.

Stabilization of amplitude ultrasonic oscillation is important in such processes as ultrasonic welding, but in the generators of ultrasonic cleaning technology is not necessary, because in this case, the vibration should have the greatest possible amplitude.

Thus, to ensure maximum effectiveness of the piezoelectric ceramic transducers, ultrasonic generator must be supplied by a voltage with a frequency such as the mechanical resonance frequency of transducer. Because the frequency is not constant and changes during system operation, (eg under the influence of temperature) for that for control we can use the signals which is a function of frequency changing their average or effective values and in the state of resonance have local extreme points.

Such signals include:

- signal from the mechanical vibrations generated by the transmitter, or another signal appointed by numerical calculation whose instantaneous value is proportional to the amplitude of vibration,
- signal from the measuring circuit of active power transducer,
- signal from voltage measuring circuit on the converter terminals,
- signal from the transducer current measuring system, as well as with certain assumptions
- signal from the current measuring circuit in the intermediate circuit DC inverter or current signal consumption from the mains.

In Figure 3 are shown examples of normalized power frequency characteristics by a single transducer and also a set of three transducers [5], [6], [7].

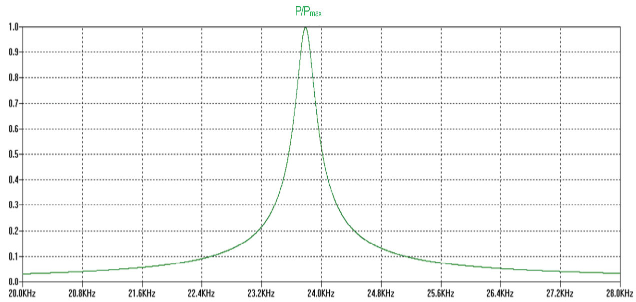

Fig. 3. Normalized active power consumed by a single transducer as a function of frequency of supply voltage

In order to increase energy ultrasound used for example in the washing process technology, piezoelectric ceramic transducers are joined together in parallel. In Figure 4 are shown graph active power consumption by a set of three transducer joined together in parallel. This combination of transducer, often leads to their disproportionate load, caused by the different resonant frequencies. In this case, the resonant frequencies of transmitters differ by 1%.

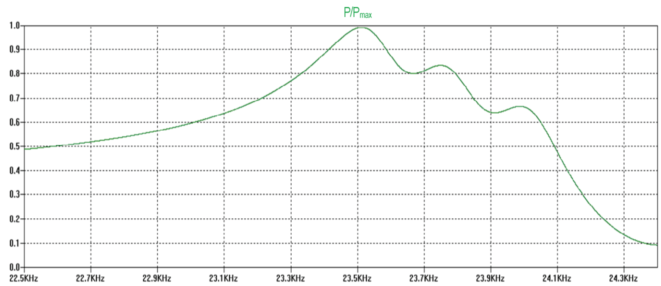

Fig. 4. Normalized active power consumed by a team of three transducers as a function of supply voltage frequency

In Figure 5 are shown graph of change of standardized current effective values consumed through each transducer as a function of supply voltage frequency. You will notice that when one transducer gets the maximum current and operates in mechanical resonance, the other two are not tuned to their resonant frequencies.

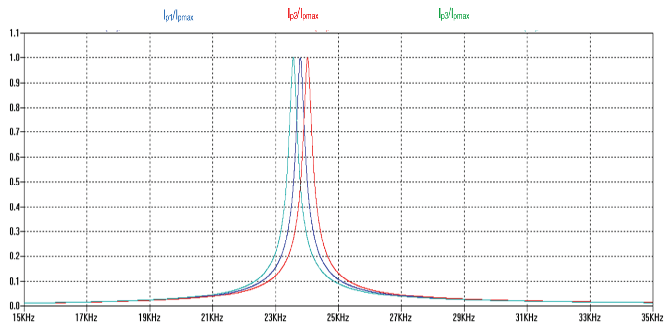

Fig. 5. The normalized effective value of current consumption by each transducer as a function of supply voltage frequency

Frequency Control System

Figure 6 shows a graph of changes normalized effective current value drawn from the mains by an ultrasonic generator.

This function has local maxima, which practically coincide with local maxima function of normalized active power consumed by the converters. It can therefore control system for controlling the inverter frequency band power converters use current measurement signal received by the generator from the AC mains.

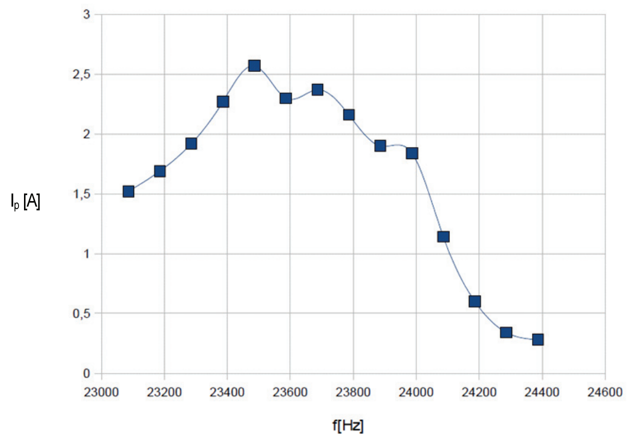

Fig. 6. Normalized effective current value of current supply ultrasonic generator

Digital model

The model of the automatic frequency control developed in Simulink is shown in Figure 7. The control system, based on the measurement of the effective current value I_L (Fig. 2) produces a voltage generator tuning the frequency of the Voltage Controlled Oscillator (VCO).

Oscillator VCO generates a rectangular voltage wave with a fixed maximum value, which maps the output voltage of the inverter. Adjustment system examines the current trend in the effective value of current I_L and generates the appropriate control voltage. One of the main functional blocks of the system is a comparator *(Relational Operator)*, which compares two signals: the current value of the effective current I_L and the measured value of current I_L in the previous time moment. Depending on the outcome of the comparison at the output of the comparator is either a low state (value 0) or high (value 1). After adding the constant component of the value of -0.5 the output of the comparator is sent to the input of the decision-making (*Product*).

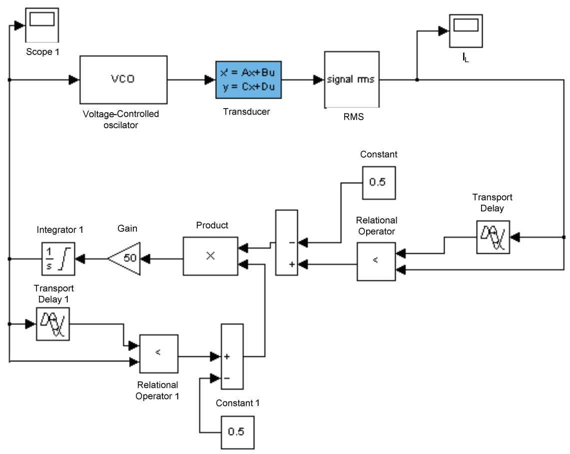

Fig. 7. The model of the automatic frequency control

To control system worked correctly in the decision-making system (Product) is provided additional information concerning the direction of change tuning signal oscillator VCO.

These data are collected based on the examination VCO control signal generator in analogous manner to determine the current trend of I_L. As a result of the decision-making system *(Product)*, after amplification *(Gain)* and integration *(Integrator 1)* generator VCO input signal of a monotonically decreasing or increasing depends on two trends: the frequency and current I_L.

Algorithm used in the system automatically adjust the output voltage frequency inverter combinations should focus on four direction changes the effective value of current I_L and the frequency of the inverter output voltage. This allows you to tune the generator to the resonant frequency of the transducer.These four cases summarized in Table 1 are also shown in Figure 8

Table 1. Rules of logic control system

	derived of current	derived of frequency	rules of logic control
1	$di_L/dt > 0$	$df/dt > 0$	Do not change the sign of frequency of trade growth
2	$di_L/dt < 0$	$df/dt > 0$	Do not change the sign of frequency of trade growth
3	$di_L/dt > 0$	$df/dt < 0$	Change frequency gain sign
4	$di_L/dt < 0$	$df/dt < 0$	Change frequency gain sign

In this situation, to obtain the maximum value of converter efficiency, its important role of fuzzy logic control system to assure the optimal mechanical resonant frequencies of converter.

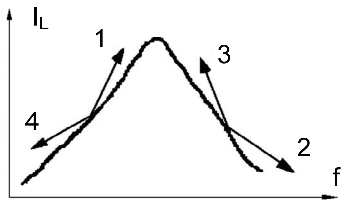

Fig. 8. Four case variations of change effective value of current I_L and frequency of output voltage of inverter

Fuzzification is process, where non-fuzzy values of power and frequency are converted into fuzzy values. It is done by membership function. In our case membership function have a trapezoidal shape. The most important part of fuzzy controller in a block of rules. The rules were derived from system behavior. This block makes connection between input side and output side. The rules were derived for power and frequency values as Table 2.

Table 2. Matrix control for current I_L and frequency f

df/dt dI_L/dt	NB	NS	Z	PS	PB
NB	B	B	B	S	S
NS	B	B	S	Z	S
Z	B	S	Z	S	B
PS	S	Z	S	B	B
PB	S	S	B	B	B

With the referred lookup table a fuzzy controller was synthesized by following the control algorithm:

Step 1: Determine the current error,
Step 2: Determine the current error variation,
Step 3: Quantization of the current error,
Step 4: Quantization of the current error variation,
Step 5: Calculate the controller's output scale,
Step 6: If the quantization error and error variation lever are not the smallest possible go to Step 1
Step 7: Adjust the universe of discourse,
Step 8: Go to Step 3,
Step 9: Extract the controller's output value from Matrix control,
Step 10: Adjust the controller's output value using the output scale value.

Defuzzification means transfer of fuzzy value current and frequency in to non - fuzzy values.

Operation of closed loop control of output voltage of the generator frequency ultrasound could be carrying the digital model to simulate power electronic circuits of the system: a special filter – piezoelectric ceramic transducer.

Diagram of the circuit is shown in Figure 9.

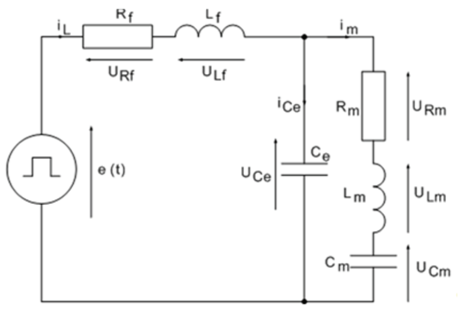

Fig. 9. Alternate wiring diagram circuit special filter-converter piezoelectric ceramic transducer in a state of resonance

This circuit can be described by the following system as a function of state variables:

$$\dot{\mathbf{x}} = \mathbf{Ax} + \mathbf{Bu} \tag{1}$$

$$\mathbf{y} = \mathbf{Cx} + \mathbf{Du} \tag{2}$$

where

$$\mathbf{x} = \begin{bmatrix} u_{Cm} \\ u_{Ce} \\ i_m \\ i_L \end{bmatrix}, \mathbf{u} = [e], \mathbf{A} = \begin{bmatrix} 0 & 0 & \frac{1}{C_m} & 0 \\ 0 & 0 & \frac{-1}{C_e} & \frac{1}{C_e} \\ \frac{-1}{L_m} & \frac{1}{L_m} & \frac{-R_m}{L_m} & 0 \\ 0 & \frac{-1}{L_f} & 0 & \frac{-R_f}{L_f} \end{bmatrix},$$

$$\mathbf{y} = [i_L], \ \mathbf{B} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ \frac{1}{L_f} \end{bmatrix}, \ \mathbf{C} = [0 \ 0 \ 0 \ 1], \mathbf{D} = [0]$$

where: x-vector state, u-force, A-matrix of coefficients, y-vector of output signals, y = I_L output response.

In a laboratory model of the control system blocks *(Product)*, *(Gain)* and *(Integrator 1)* were replaced by the genetic algorithm [1], [2], which keep changing the parameters of electrical equivalent circuit transducer assembly (Fig. 9) calculated the value of the inverter output frequency ultrasonic generators.

Simulation results

Figure 11 shows the voltage change over time changing the VCO frequency generator, and Fig, 12 shows the changes during the effective value of current I_L .

After a time of 0.2 seconds from the beginning of the experiment abruptly changes the resonant frequency of the transducer. In response, the automatic control system changes the VCO control voltage (figure 10).

There has been tuning frequency inverter output voltage to the new resonant frequency of the inverter. After tuning the effective value of current again increased (Figure 11) and has practically the same value as before the change.

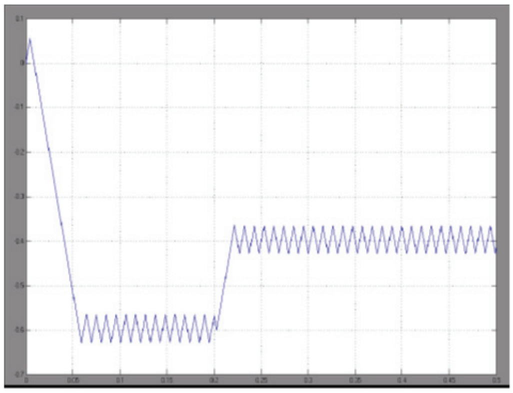

Fig. 10. Time waveform voltage tuning VCO generator

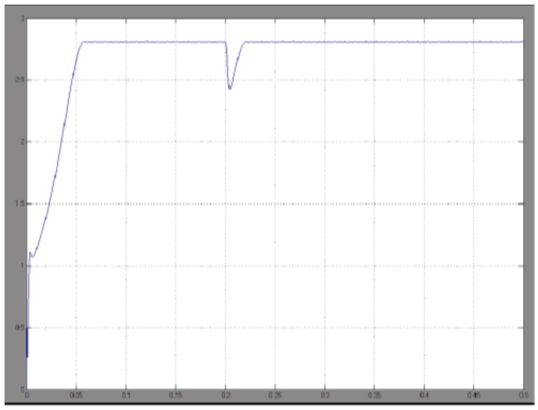

Fig. 11. Changes the effective value of current I_L in the process of adjustment

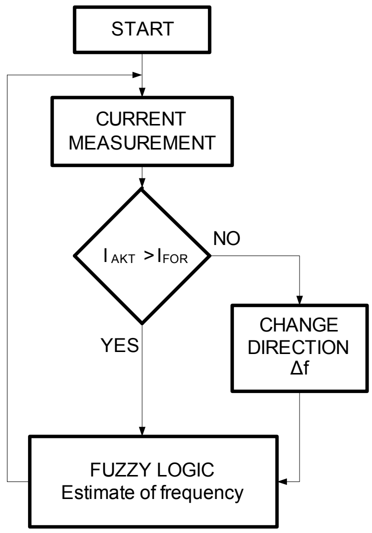

Fig. 12. Control algorithm

Research laboratory model

Our designed system of the ultrasonic generator is shown in Figure 2. Control algorithm (Fig. 12) is realized by the 8-bit microcontroller from Atmel ATmega8, which processes data from the sensor measurements and controls the current I_L by the SPI interface of the generator operation of the oscillator VCO.

To generate the control signals connections FBI inverter (Fig. 2), a system Analog Devices AD833. This system uses to generate the waveform synthesis of the DDS (Direct Digital Synthesis).

AD833 circuit generates a square wave. When an external clock signal clock frequency of 25 MHz, which is produced by the quartz generator, it is possible to obtain the output process frequency range from 0 – 12,5 MHz with a resolution of 0,1 Hz.

Fig. 13. The value of average current drawn by the transmitter in the process of tuning the output frequency of the inverter to the mechanical resonance frequency

Oscillogram (Fig. 13) shows changes in the average value of current drawn by the transducer during the tuning frequency of the inverter output to the mechanical resonance frequency.

Along with decreasing the difference between the frequency voltage converter, and its resonant frequency increases the average current consumption. Jumping changes in current resulting from the mode of action of the control system, which changes the frequency of the inverter output voltage in jumps every 5 s. Effect of changes in load transducer at the average current consumption is shown on Figure 14.

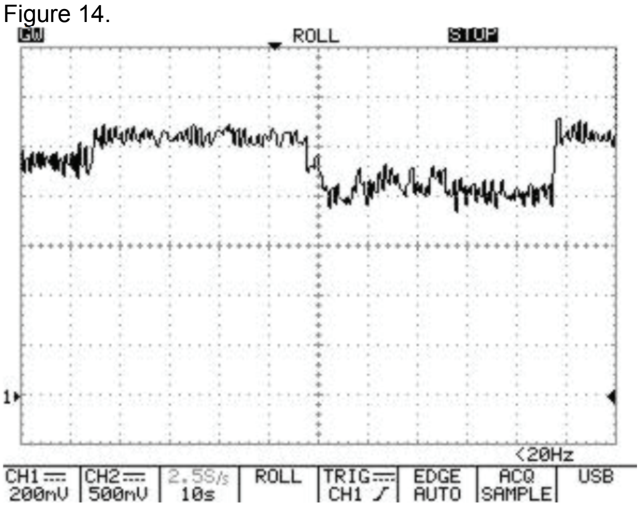

Fig. 14. Change the value of the average current drawn by the transmitter due to changes in load transducer

Conclusion

Described in this paper an automatic frequency control output voltage meets accepted requirements and working conditions regardless of the team adjusts the oscillating frequency of the inverter output voltage to the mechanical resonance frequency transducers. Feedback signal in this case the signal from the measurement system current drawn by the converter from the AC mains. In order to simplify calculations in the model of the digital frequency control system uses an fuzzy logic adaptive controller. Results of investigations of this model confirmed the correct operation of the approved type of feedback signal.

In a laboratory model an adaptive controller was replaced by the genetic algorithm, which is constantly changing the electrical parameters of equivalent circuit transducer assembly (Fig. 9) generates populations of new models and calculated on the basis of the frequency inverter output voltage power converter assembly. Obtained in this case the results are also satisfactory.

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