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A Closed-Loop Control System for the Reduction of Reactive Power Required by Electronic Converters

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***Abstract*—A closed-loop control system to reduce the reactive power required by electronic converters is proposed. The instantaneous reactive power which consists of both displacement of fundamental current and harmonic distortion current is measured and compensated by a reactive power source connected parallel between the power lines and the converter. A combination of a dc choke and a forced-commutated inverter is used for the reactive power source.**

The principle and the construction of the control system are presented as well as some experimental results. Accurate compensation of the reactive power and fast response to the sudden change of the load are attained.

Introduction

A LARGE VARIETY of electronic converter circuits are available for use in a growing number of applications. For high power equipment, semiconductor thyristors and diodes are most often used. However, the use of electronic power converters reduces the power factor of the electric power systems. The reactive power required by electronic converters consists of two components: a leading or lagging displacement of the fundamental current drawn from the supply lines and harmonic distortion current [1].

Parallel capacitors are usually used for compensating lagging displacement of the current. Multi-stage configurations of the converters are also used for this purpose. For the reduction of harmonic distortion current, tuned filters are often used.

Manuscript received August 9, 1975; revised October 3, 1975. This work was supported in part by the Toshiba Electric Company, Ltd., and in part by the Fuji Electric Company, Ltd.
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In these methods, the reduction of reactive power is limited to some special frequency components. The reactive power required by electronic converters may vary in accordance with load conditions. Then, the technique to reduce reactive power with any wave shape is required.

The possibility of compensating instantaneous reactive power has been shown by Erlicki and Eigeles [2] and Fukao *et al.* [3], and the use of semiconductor switching devices to reduce reactive power has been proposed [2], [4]. However, in these papers, only constant load conditions are considered. Furthermore, the accuracy of compensations of reactive power is not sufficient. Precise compensation of reactive power during transient states as well as steady-states is necessary to eliminate the disturbances of converters to power lines.

This paper presents a possible solution to this problem. A closed-loop control circuit is used to reduce the reactive power. The instantaneous reactive power including both harmonic distortion current and the displacement of fundamental current is measured and compensated by a regulated reactive power source which is connected parallel between supply lines and the converter. The system proposed in this paper consists of three parts shown below:

1) Measuring circuit of instantaneous reactive power. This circuit computes the instantaneous reactive power as the difference between the converter input current and the effective power required by the converter. The Fourier expansion method is used for this purpose. The detecting time of a half cycle of the line frequency is obtained.

2) Closed-loop control circuit. The inversed sign wave-

form of the detected reactive power is generated by a closed-loop control circuit and then injected to the input of the converter. This closed-loop control circuit has the bandwidth of 0–800 Hz. Fast response to the load changes and the compensation for fundamental component through higher harmonics are gained.

3) Regulated reactive power source. This reactive power source consists of a forced-commutated inverter and a dc choke. The reactive power of arbitrary waveform can be generated by the gate control of the inverter.

Principle of Operation

Fig. 1 shows the reactive power compensator which is connected parallel to the converter and the ac supply line. The supply voltage E_i and the load current I_L are given by

$$E_i = A \sin \omega t \tag{1}$$

$$I_L = B_1 \sin \omega t + C_1 \cos \omega t + \sum_{n=2}^{\infty} B_n \sin (n\omega t) + \sum_{n=2}^{\infty} C_n \cos (n\omega t). \tag{2}$$

The load current I_L consists of the effective component and the reactive component including both displacement of fundamental current and harmonic distortion current. The first term of eq. (2) is the effective component of load current and the other terms are the reactive components. The instantaneous value of the reactive current is defined as follows:

$$I_{cr} = B_1 \sin \omega t - I_L. \tag{3}$$

If the reactive power compensator generates the current corresponding to I_{cr} and adds this current to the load current, then the supply current I_i is equal to the effective current only, that is to $B_1 \sin \omega t$.

A closed-loop control circuit is used to generate the compensating current. Fig. 2 gives the block diagram representation of this system.

Calculation of Instantaneous Reactive Power

Calculation of instantaneous reactive current I_{cr} is made on the basis of (3). The circuit configuration used in our experiment is shown in Fig. 3. The amplitude of the effective current B_1 is given as the coefficient of ($\sin \omega t$) component as is shown in (2). In order to calculate the value of B_1, a multiplier, an integrator and a sample-hold circuit are used.

Usually, the reactive part of load current I_L includes only odd harmonic components. In this case, the value of B_1 can be calculated while one half cycle of line frequency is completed. From the left of Fig. 3, the product of the load current I_L and the supply voltage E_i is integrated during a half cycle of line frequency. The integration starts at a zero-crossing instant of the supply voltage and is over at the next zero-crossing instant of the supply voltage. When the integration is over, the output of the integrator is given to the sample-hold circuit, and then the output of the integrator

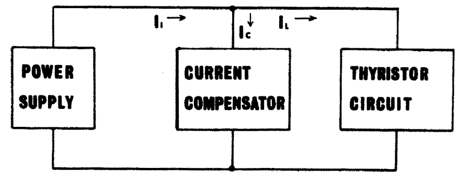

Fig. 1. Principle of operation.

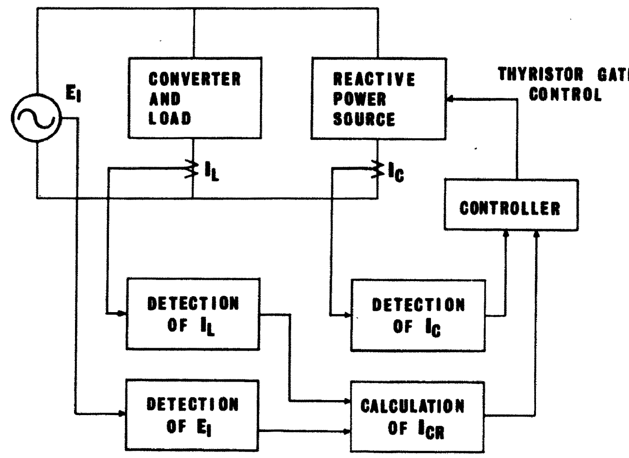

Fig. 2. Block diagram representation of the closed-loop system.

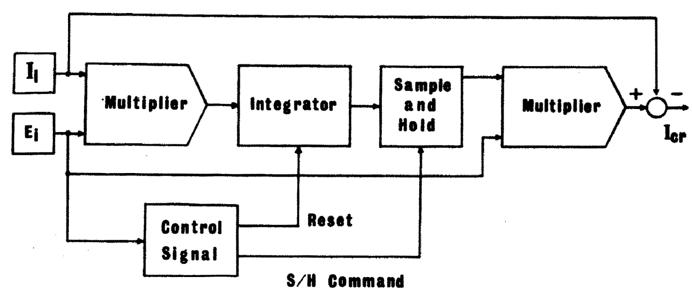

Fig. 3. Calculation of current reference.

is reset to zero. The output of the sample-hold circuit remains constant during the next half cycle of line frequency. The output of the sample-hold circuit corresponds to the value of B_1, since we have the following relation:

$$\begin{aligned} &\frac{\omega}{\pi} \int_0^{\pi/\omega} E_i \cdot I_L \, dt \\ &= \frac{\omega}{\pi} \int_0^{\pi/\omega} A \sin \omega t \\ &\quad \cdot \left[\sum_{n=1}^{\infty} B_{2n-1} \sin \{(2n-1)\omega t\} + \sum_{n=1}^{\infty} C_{2n-1} \cos \{(2n-1)\omega t\} \right] dt \\ &= \left(\frac{A}{2}\right) \cdot B_1 \end{aligned} \tag{4}$$

where A is the amplitude of the supply voltage and is constant. The output voltage of the sample-hold circuit is multiplied by the supply voltage waveform, and then the first term of (3), that is $B_1 \sin \omega t$, is obtained. At the right side of Fig. 3, the value of $B_1 \sin \omega t$ is subtracted by the value of load current I_L, and then we obtain the instantaneous value of reactive power, that is, I_{cr}. The calculation of I_{cr} is made at the end of every half cycle of line frequency. Thus, the real time computation of I_{cr} with computation time of a half cycle of line frequency is possible.

If the load current I_L includes even harmonics (such cases infrequently occur in practical circuits), the integration period should be extended to one cycle of line frequency in order to calculate the value of B_1. In such cases, we have the following relation:

$$\frac{\omega}{2\pi}\int_0^{2\pi/\omega} E_i \cdot I_L \, dt = \frac{\omega}{2\pi}\int_0^{2\pi/\omega} A \sin \omega t \cdot \left[\sum_{n=1}^{\infty} B_n \sin (n\omega t) + \sum_{n=1}^{\infty} C_n \cos (n\omega t)\right] dt = \left(\frac{A}{2}\right) \cdot B_1. \tag{5}$$

Regulated Reactive Power Source

The reactive power source used in our experiment consists of a dc choke, a forced-commutated inverter, and a filter (Fig. 4). The dc choke charges or discharges the reactive power. The forced-commutated inverter controls the reactive power flow. The technique of pulse-width modulation is used for this purpose. The modulation frequency should be higher than the maximum frequency of harmonic component to be compensated. The filter which is used in this circuit eliminates the modulation frequency component of the output current. The size of the filter can be a small one since the modulation frequency is relatively high.

By the gate control of the inverter, this reactive power source operates as a current source which is able to generate a current of arbitrary waveform. In order to keep the current flowing through the dc choke constant, the power corresponding to the loss in the dc choke and the inverter must be fed from the ac power supply. This power flow is also performed by the gate control of the inverter. The reference waveform of the output current of this reactive power source is given from the measuring circuit of the instantaneous reactive power which is mentioned above.

Control Circuit of Compensation Current

The generation of compensating current is performed by a closed-loop control. The gate signal of the inverter is given from a PWM controller. The block diagram of the control loop is shown in Fig. 5. The PWM controller consists of a delay element, a comparator with hysteresis, and a feedback loop. In Fig. 5, the difference of the reference I_{cr} and the detected value of I_c is applied to the modulator. The output of the modulator is used for the inverter gate control. The modulation frequency component of the inverter output current is eliminated by the filter, and then the compensating current is obtained. By the use of the closed-loop control, a wide bandwidth and a good linearity are secured.

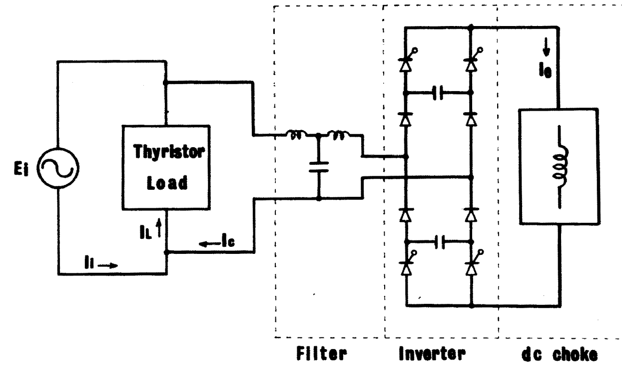

Fig. 4. Reactive power source connected parallel to the load.

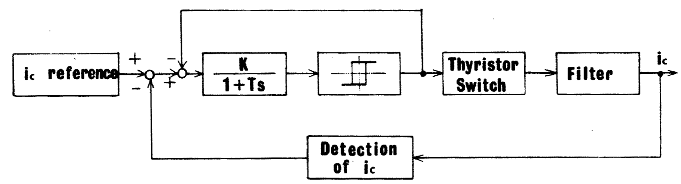

Fig. 5. Closed-loop control of compensating current.

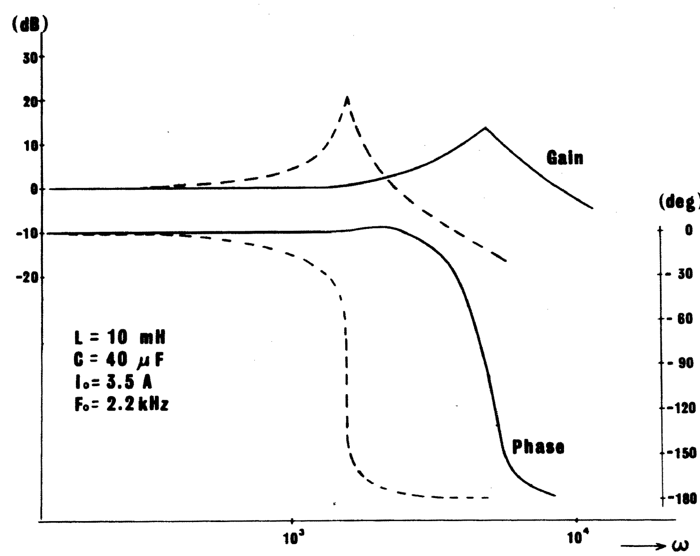

Fig. 6. Frequency response of closed-loop circuit.

The resonant frequency of the filter is determined by the modulation frequency. With higher modulation frequency, the bandwidth of the control loop becomes wider and the size of the filter becomes smaller. However, the commutation loss in the inverter becomes larger. The modulation frequency of 1–2.5 kHz is used in our experiment.

In Fig. 6, measured frequency response of the closed-loop circuit is shown. The modulation frequency of 2.2 kHz is used. The resonant frequency of the filter is selected as 220 Hz. Fig. 7 shows the step response of the circuit. For the step input, a square wave of 50 Hz is used.

Experimental Results

Fig. 8 is an example of experimental results. In this experiment, the frequency of power supply is 50 Hz and the thyristor load is a thyristor bridge rectifier circuit with a resistor and an inductance as the load. Fig. 8(a) shows the supply voltage (upper) and the load current (lower). The power factor (including both displacement of fundamental

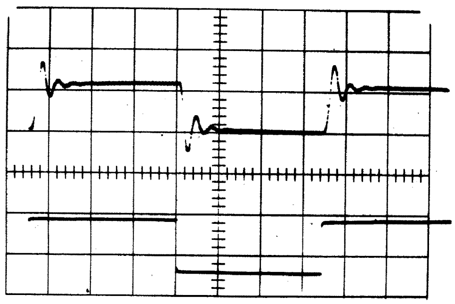

Fig. 7. Step response of closed-loop circuit. Upper: output current of the compensator. Lower: step input (50 Hz).

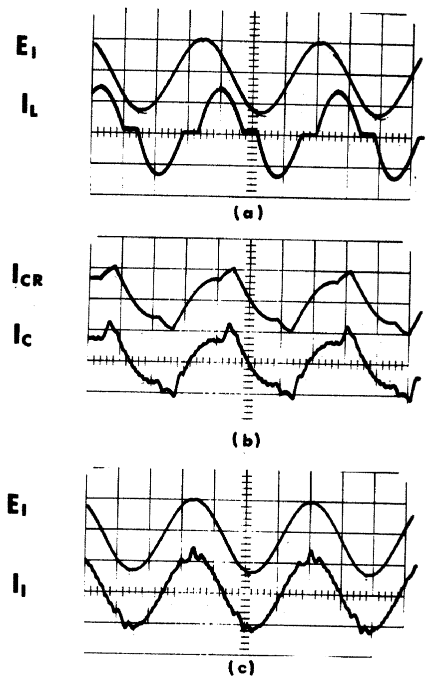

Fig. 8. Oscillograms. (a) Upper: line voltage (50 Hz). Lower: load current. (b) Upper: reference of the compensator. Lower: output current of the compensator. (c) Upper: line voltage. Lower: current from power line.

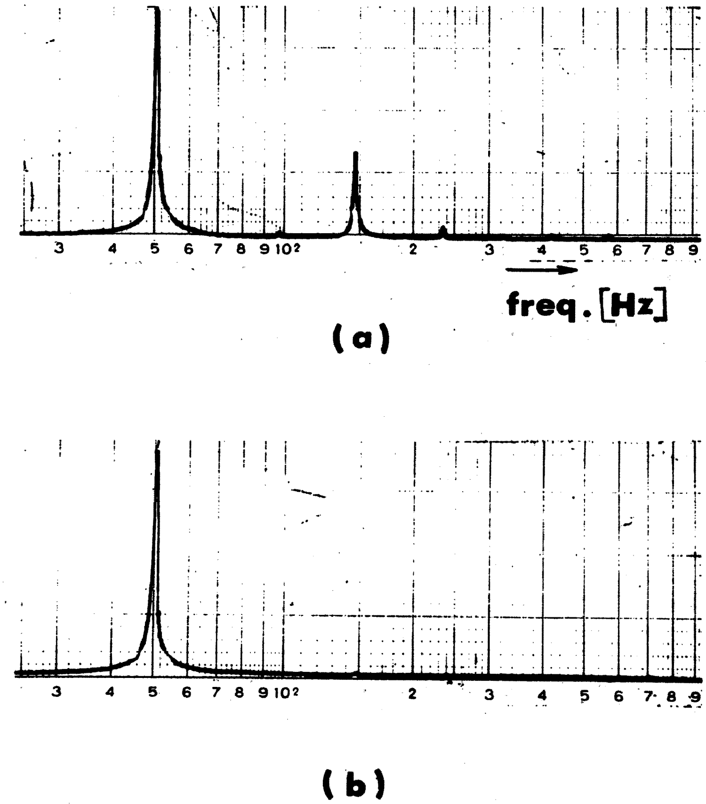

Fig. 9. Frequency analysis of supply current. (a) Load current. (b) Supply current.

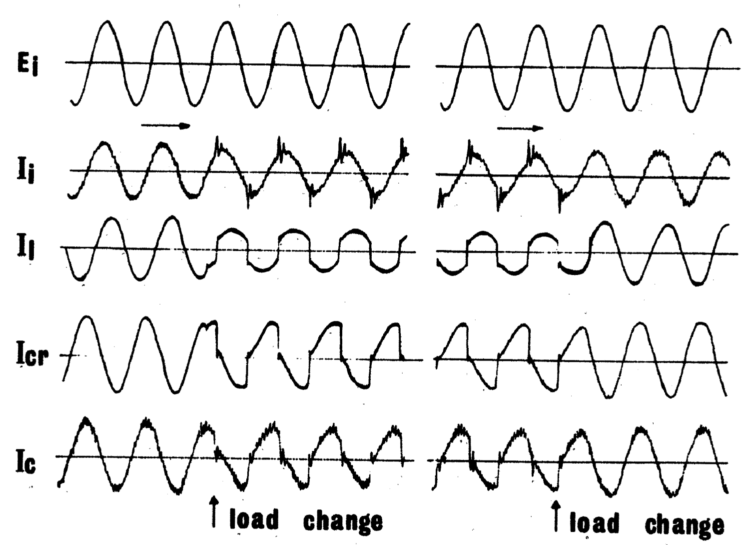

Fig. 10. Transient phenomena of the system.

current and harmonic distortion current) is 0.54. Fig. 8(b) shows the computed reference of compensating current (upper) and the actual compensating current. Fig. 8(c) shows the supply voltage (upper) and the current from the power supply, that is, the sum of the load current and the compensating current. This figure shows that the supply current is just in-phase with the supply voltage and includes slight harmonic components. The power factor is improved to 0.97. Fig. 9 is the result of frequency analysis of the load current (upper) and the supply current (lower). Fig. 10 is an example of measured transient response of the system. A response time of a half-cycle of line frequency is gained.

Conclusions

A closed-loop control system to reduce reactive power required by electronic converters has been presented.

The system proposed in this paper has the advantages and limitations shown below. The advantages are:

1) The reactive power including both displacement of fundamental current and harmonic distortion current can be eliminated. By the use of a closed-loop control, the accuracy of compensation is excellent.

2) Fast response for quick changes of the load can be attained.

3) The dc choke which stores the reactive power is of smaller size compared with the capacitor.

4) The voltage regulation of the power supply is not disturbed by the use of this system, because this apparatus is connected parallel to the power supply.

On the other hand, the limitations of this system are:

1) With higher modulation frequency, the commutation loss in the inverter is increased.

2) For high power applications, excellent ratings of thyristor voltage and (*di*/*dt*) characteristics are necessary.

Further investigations are necessary for the practical use of this system. They are:

1) Application to three-phase circuits. In this paper, an application to a signal-phase circuit is shown. Applications to three-phase circuits can be easily made. In this case, a dc choke and a three-phase bridge-inverter which consists of six thyristors are necessary for the reactive power source.

2) Improvement of efficiency. In order to reduce the commutation loss in the inverter, thyristors with higher rating of (di/dt) characteristics and shorter turn-off time are desirable.

In application to the circuits which generate relatively low frequency components of reactive power, such as cycloconverters, thyristors of ordinary ratings are sufficient.

By a proper choice of commutation angles of the inverter, the number of commutations during each half cycle of line frequency can be reduced. In this case, complicated calculations to determine the commutation angles become necessary. A computer should be used for this purpose.

3) Improvement of response time. The response time of a half-cycle of line frequency is not always sufficient for very quick change of the load, such as furnace flicker. In order to attain faster response, the prediction techniques must be introduced to estimate the instantaneous value of the reactive power.

Acknowledgment

The authors are grateful to Mr. Koyama who was with the Institute of Industrial Science, University of Tokyo, for his discussion and assistance to this research.

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Brushless Alternator with Optoelectronically Controlled Rotating Thyristors

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***Abstract*—The paper describes a brushless alternator arrangement in which the conventionally used rotating diodes are replaced by thyristors. To preserve the brushless principle, the firing signals are transmitted optically from a stationary source to a single shaft-mounted light-sensitive diode, which feeds a simple transistorized amplifier and a decoding circuit. Light pulses to the diode are coded in such a way that each thyristor is addressed in an appropriate sequence with a firing signal. The considerable improvement brought about by the new excitation system is illustrated by a comparison of the transient performance of a 10 kVA alternator, when excited by conventional and by rotating-thyristor means.**

Introduction

As normally understood, a brushless-alternator installation employs a rotating-armature ac exciter, carried on the same shaft as the main machine and supplying the field winding of this through a shaft-mounted diode-bridge rectifier. The output voltage of the alternator is controlled by an automatic voltage regulator (a.v.r.), fed from its output terminals and supplying the stationary field winding of the exciter. Although such sets have found widespread application, they have several inherent disadvantages, which may be summarized as:

a) The presence within the control loop of two machines, with somewhat similar time constants, may create a stability problem.

b) The recovery of the output voltage following the sudden application of load is slow, again due to the presence of the two time constants.

c) Following the removal of load, the alternator field current decays through the rectifier bridge at a rate which is not controlled by the voltage regulator. Dangerous output overvoltages may follow, for example, the removal of a short circuit.

The replacement of the shaft-mounted diodes by thyristors enables the exciter to be excluded from the control loop, and, with the above disadvantages overcome, a performance obtained which is comparable with that of a generator controlled by a direct-acting a.v.r. To preserve the brushless principle, the transfer of thyristor firing information can be accomplished in several ways [1]–[3], including the use of

Manuscript received August 22, 1975.
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