Universal Power Distortion Compensator* of Line Commutated Thyristor Converter

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A rapid control system of the active and reactive power with line commutated converters is presented. The system behaves like an active filter which compensates not only for the steplike change of the active and reactive power but also for the unbalanced currents and lower harmonics.

Instantaneous apparent current is newly defined to express the status of three-phase currents. A rapid current control method is proposed using the cascade thyristor converter which is triggered asymmetrically. An experimental converter system has been constructed which incorporates two stages of 24-phase thyristor converters controlled by one-chip micro-processor. The system has proved to be promising as a power active filter for distortional components under the 7-th harmonic.

Key word : Thyristor converter/ Reactive power control/ Power active filter/ Micro computer application/ Power distortion compensator

INTRODUCTION

As various types of loads are applied in industry, the flickering current sources such as today's thyristor Leonard and electric arc furnance systems have been increased. Under these circumstances there has been created a strong need for a distortional current compensator of large capacity with high efficiency and high speed. Recent progress in thyristor and electronic control technology has realized power distortion compensators of high response for the random fluctuating current. [1]

The high response compensators for distorted currents have been so far developed by using forced commutation. However large capacity compentation for power control could not be economically realized through conventional forced commutation techniques. [2]

This paper proposes a compensation scheme which controls instantaneous active and reactive power using high speed thyristor converters with line commutation. Although the scheme in conceptually simple, the proposed system operates like an active filter and compentates not only for rapid change in current of the active and reactive power but also for the unbalanced currents and harmonics. Therefore, the system might be designated as a universal power distortion compensator. [3]

VECTOR LOCUS OF INSTANTANEOUS CURRENT

The features of three-phase current are usually characterized an follows ;

a) Active and reactive (leading and lagging) currents.

b) Fundamental and harmonic currents.

c) Positive and negative sequence currents (unbalanced currents).

Since the relation among the above features has not yet been established, some skillful analysis techniques to describe them clearly are required for thyristor converter engineering. For this purpose, we propose two parameters, instantaneous active and instantaneous reactive currant to define the three-phase current.

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Consider three-phase voltages V_u, V_v and V_w of amplitude V_m with angular frequency ω, containing no harmonics, as given by the following equations:

$$V_u = V_m \cos\omega t$$
$$V_v = V_m \cos(\omega t - 2/3\pi) \quad (1)$$
$$V_w = V_m \cos(\omega t - 4/3\pi)$$

and let three-phase line currents be i_u, i_v and i_w, then instantaneous active power P_e is

$$P_e = V_u i_u + V_v i_v + V_w i_w$$

The instantaneous active current i_p which corresponds to P_e is, therefore, defined by the following expression:

$$i_p = \sqrt{2/3}\, p_e / V_m \quad (2)$$

Let the instantaneous reactive current i_q, newly designated in this paper, be with the component perpendicular to i_p. Then i_p and i_q are expressed in the matrix notation an follows:

$$\begin{bmatrix} 0 \\ i_p \\ i_q \end{bmatrix} = [C] \begin{bmatrix} i_u \\ i_v \\ i_w \end{bmatrix} \quad (3)$$

where

$$[C] = \sqrt{\frac{2}{3}} \begin{bmatrix} 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \\ \cos\omega t & \cos(\omega t - 2/3\pi) & \cos(\omega t - 4/3\pi) \\ \sin\omega t & \sin(\omega t - 2/3\pi) & \sin(\omega t - 4/3\pi) \end{bmatrix} \quad (4)$$

The first row of the coefficiet matrix $[C]$ shows that zero-sequence component is zero in the thyristor converter system. Factor $\sqrt{2/3}$ is given by power invariant transformation. Matrix $[C]$ is identical to the $d-q$ tansformation of rotating machine.

The reactive power has been conventionally denoted by the magnitude of alternating power flow. However, the component of alternating power flow is considered to be not reactive but active power in this paper ; we define that reactive power is associated with the circulating current of line to line through load. This means that reactive power is not always stored in the load system.

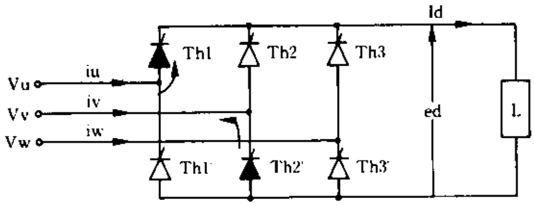


Fig. 1. Ideal thyristor converter.

Now we assume non-sinusoidal currents expressed as follows:

$$i_u = \sum_{k=1}^{\infty} \{I_{pk}\cos k\omega t + I_{nk}\cos k\omega t\}$$
$$i_v = \sum_{k=1}^{\infty} \{I_{pk}\cos k(\omega t - 2/3\pi) + I_{nk}\cos k(\omega t + 2/3\pi)\}$$
$$i_w = \sum_{k=1}^{\infty} \{I_{pk}\cos k(\omega t - 4/3\pi) + I_{nk}\cos k(\omega t + 4/3\pi)\} \quad (5)$$

Substituting Eq. (5) in Eqs. (3) and (4), we have

$$i_p = \sqrt{\frac{3}{2}} \sum_{k=1}^{\infty} \{I_{pk}\cos(k-1)\omega t + I_{nk}\cos(k+1)\omega t\}$$
$$i_q = \sqrt{\frac{3}{2}} \sum_{k=1}^{\infty} \{-I_{pk}\sin(k-1)\omega t + I_{nk}\sin(k+1)\omega t\} \quad (6)$$

Here we denote instantaneous apparent vector $\dot{i}_a$ as

$$\dot{i}_a = i_p + j i_q \quad (7)$$

The positive and negative sequence components of k-th harmonics, I_{pk} and I_{nk} in Eq. (5) correspond to the rotating vector of $\dot{i}_a$ with angular velocity $-(k-1)\omega$ and $(k+1)\omega$, respectively. The vector $\dot{i}_a$ is stationary with regard to the fundamental positive sequence currents.

If we vary the apparent vector $\dot{i}_a$ along the specified locus, we get three-phase currents with the correnponding waveforms. On the other hand, the waveforms of specified three-phase currents determine a correnponding locus of $\dot{i}_a$. This idea is employed to construct a three-phase current source which generates any desired waveform.

THREE-PHASE CURRENT CONTROL WITH THYRISTOR

In the calculation of vector locus $\dot{i}_a$ for a thyristor

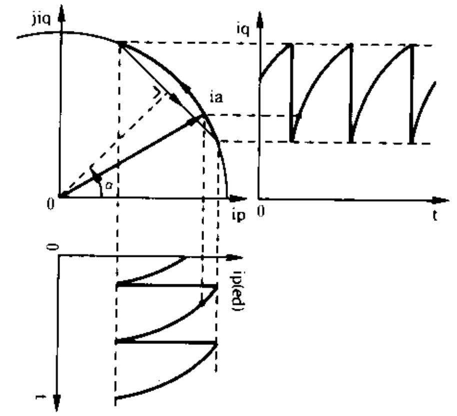


Fig. 2. Relation between i_p and i_q of ideal converter.

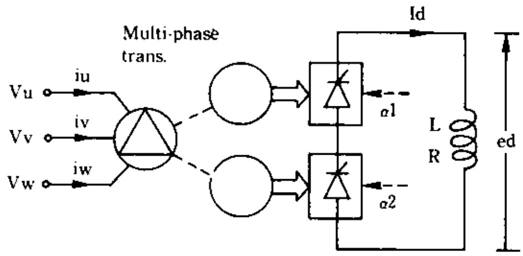


Fig. 3. Control of ip and iq using cascade converter.

converter, we assume an ideal converter with no energy consumption and storage as shown in Fig. 1. In the figure, the output energy $e_d I_d$ is instantaneously equal to input, considering the moment when both thyristors Th_1 and Th_2' are conducting. Then, from Eq. (2), the active current is given by

$$i_p=\sqrt{\frac{2}{3}}\frac{e_d}{V_m}I_d=\sqrt{2}I_d\cos(\omega t+\pi/6) \qquad (8)$$

Since the input current of phase u, i_u is I_d, and i_u is obtained from the inverse transformed equation of (3), we get

$$i_u=I_d=\sqrt{2/3}(i_p\cos\omega t+i_q\sin\omega t) \qquad (9)$$

Substituting Eq. (8) in Eq. (9), we obtain,

$$i_q=\sqrt{2}I_d\sin(\omega t+\pi/6) \qquad (10)$$

From Eqs. (8) and (10), we find that the apparent vector locus of the ideal converter is a circle of radius $\sqrt{2}I_d$ with angular velocity ω. Waveforms of e_d and i_p are the same under the condition of constant I_d and V_m as given by Eq. (8). Therefore, once the voltage waveform of the ideal converter output is given, the vector locus $\dot{i}_a$ and reactive current i_q are represented by the graphical solution as shown in Fig. 2.

From Fig. 2, we notice that the smaller is the ripple voltage of e_d, the smaller becomes the variation of $\dot{i}_a$ and i_q, and also notice that the larger gets the number of converter phases, the smaller becomes the ripple voltage, and ultimately active and reactive current become

$$i_p=K\ I_d\cos\alpha, \qquad i_q=K\ I_d\sin\alpha \qquad (11)$$

Where α is control angle of the converter, and K is a constant. Eq. (11) suggests that i_p and i_q cannot be controlled independently under the condition of constant I_d, and that rapid control of I_d, could not be obtained by using the conventional converter-reactor systems. In the following description it is shown that the above problems can be solved by emplying a multi-stage cascade converter.

Fig. 3 illustrates the basic circuit of a current source constructed as a two stage cacade converter plus a reactor. For an infinite number of converter phases, the output voltage e_d and current I_d at normal state is expressed as

$$e_d=E_{d0}(\cos\alpha_1+\cos\alpha_2)/2, \qquad I_d=E_d/R \qquad (12)$$

where α_1 and α_2 are control angles of respective converter of Fig.3, and E_d is the average value of e_d.

Corresponding to Eq. (11), for the cascade converter, we obtain i_p and i_q as follows:

$$i_p=KI_d(\cos\alpha_1+\cos\alpha_2)/2$$
$$i_q=KI_d(\sin\alpha_1+\sin\alpha_2)/2 \qquad (13)$$

Normalizing Eqs. (7) and (13), we denote $\dot{a}$, p, and q respectively, by the following expressions:

$$\dot{a}(\alpha_1,\alpha_2)=p(\alpha_1,\alpha_2)+jq(\alpha_1,\alpha_2)$$

$$p(\alpha_1,\alpha_2)=(\cos\alpha_1+\cos\alpha_2)/2$$

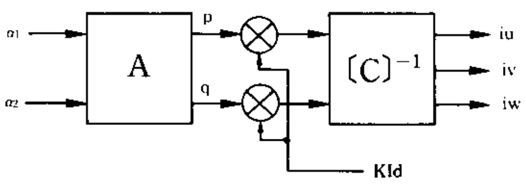


Fig. 4. Block diagram of cascade converter.

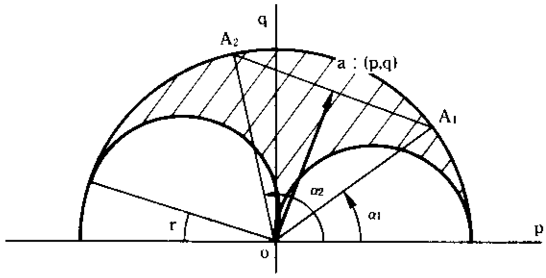


Fig. 5. Static limitation region.

$$q(\alpha_1,\alpha_2)=(\sin\alpha_1+\sin\alpha_2)/2 \tag{14}$$

Now, we represent Eq. (14) in the following form,

$$\begin{bmatrix} p \\ q \end{bmatrix}=A\left(\begin{bmatrix} \alpha_1 \\ \alpha_2 \end{bmatrix}\right) \tag{15}$$

The above cascade converter system is expressed by the block diagram shown in Fig. 4. In this diagram, $[C]^{-1}$ is the inverse to the coefficient matrix defined by Eq. (4), whereas A is the nonlinear element gives by Eq.(15).

Accordingly a control scheme for input currents i_p and i_q has been obtained under constant I_d by controlling α_1 and α_2.

CONTROL REGION OF THE SYSTEM

The control of the instantaneous vector $\dot{a}$ is restricted owing to the limitations of I_d and control angles α_1 and α_2 of the cascade thyristor converter. Two kinds of limitations are considered.

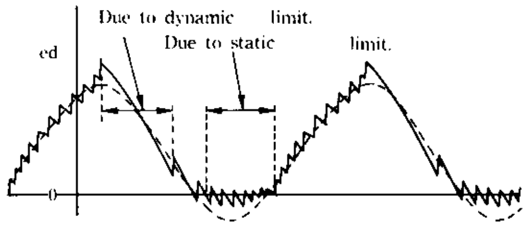


Fig. 6. Distorted waveform of ed.

The first limitation is the static state of the converter parameters. The relation between p and q in Eq. (14) and control anglen α_1 and α_2, is shown in Fig.5. The midpoint of the vectors A_1 and A_2 in Fig. 5 is coincident with the coordinates $(p,q)=((\cos\alpha_1+\cos\alpha_2)/2,\ (\sin\alpha_1+\sin\alpha_2)/2)$.When

$$0\leqq\alpha_1\leqq\pi-\gamma,\qquad 0\leqq\alpha_2\leqq\pi-\gamma \tag{16}$$

where γ is the minimum control angele of advance, then the point (p,q) is restricted to mapping onto the shaded region, as shown in Fig.5. The larger the number of the cascade converter stages gets, the wider this region becomes.

The other limitation is dynamic both the derivatives $d\alpha_1/dt$ and $d\alpha_2/dt$ must not exceed the angular frequency ω, corresponding to the rate of the line voltage decay. If the derivatives exceed this limitation, it is impossible for the output voltage e_d of the converter to follow the control signal.

Fig. 6 shows an example of the distorted waveform of e_d which is controlled by signals exceeding either the static or the dynamic limitation. The situation of the above example may be considered in terms of a saturated state of the system. Saturation in the system causes the distortion in the input current and generates undesirable harmonics. This tendency becomes more remarkable as either amplitude $|\dot{a}|$ or the changing rate $|d\dot{a}/dt|$ increases.

Assuming that the fundamental active and reactive components are p_0 and q_0, and the amplitude of the k-th harmonic in a_k, the locus of vector $\dot{a}$ is given by

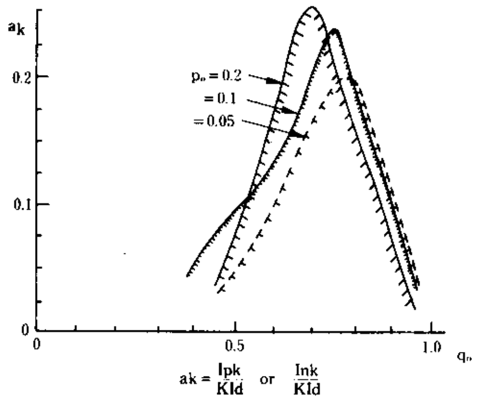


Fig. 7. Static limitation region.

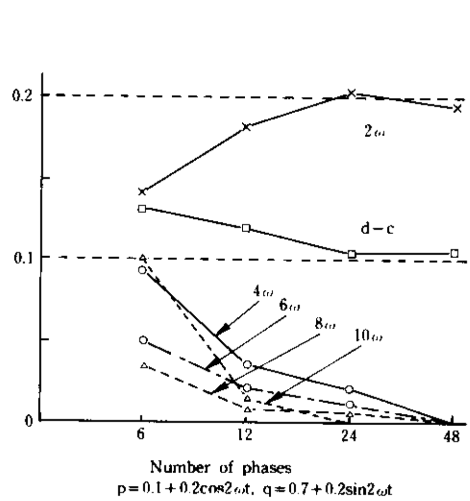


Fig. 9. Relation between phase number and amplitude of harmonics.

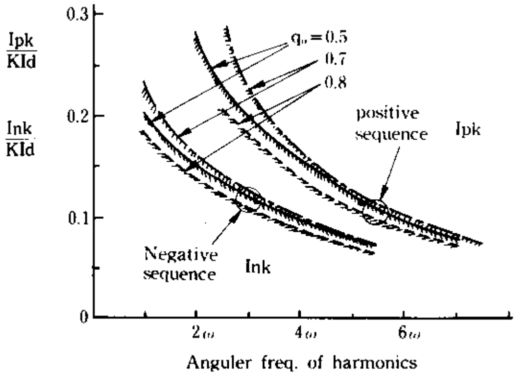


Fig. 8. Dynamical limitation region.

a circle with its center at $\dot{a}_0 = (p_0, q_0)$ and with radius of a_k, as expressed in Eq. (6).

With p_0 as a prameter, the relations between q_0 and a_k in the static limitation are illustrated in Fig. 7. In this case, vector $\dot{a}$ is in the shaded area of Fig.5. Fig. 7 shows the maximum value of a_k is 0.24 times that of the fundamental for component for any harmonic in the 2 stage cascade converter system. Whereas, the dynamical limitations for positive and negative sequence harmonics of the k-th order are shows in Fig.(8). As is clearly deducible from Eq. (6), Fig. 8 shows that each limitation curve of the positive sequence harmonics is shifted by 2ω to the rightside of the negative ones. From these figures, it might be concluded that the harmonics under 7ω are effectively conpensated by the proposed control scheme.

In the preceding analysis, we have assumed an infinite number of phases. But in practice, the number of phases is limited. The finite number of phases induces undesirable harmonics. As is shown in Fig.9, the phase number of at least 24 is required to eliminate the harmonic distortion.

Moreover, it is necessary to consider the rapping angle u of commutated currents in the practical system. But the effect of the rapping might be approximately removed by decreasing control angle α to $\alpha + u/2$. And it should be noted that even if we assume no rapping angle, the magitude of undesirable harmonics increases only 2 to 3 percents.

POWER DISTORTION COMPENSATOR SYSTEM

We shall try to compentate such distortional currents an follows;

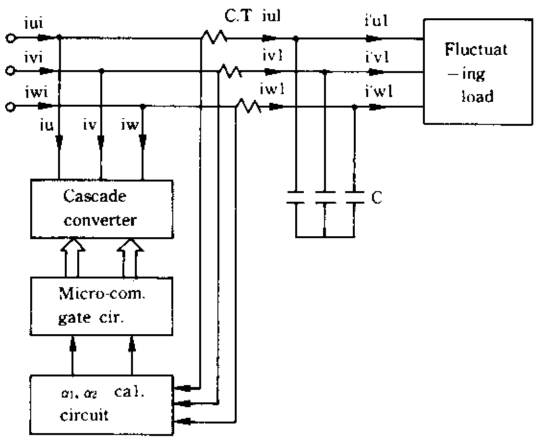


Fig. 10 Total system of power distortion compensator.

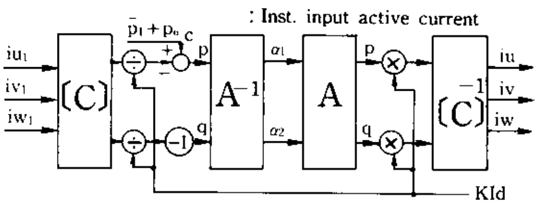


Fig. 11 Block diagram of cascade converter and control circuit.

a) Harmonic currents inculding flickering current.

b) Negative sequence current. (unbalanced current.)

c) Fundamental reactive current.

d) Rapid change components of fundamental active current.

The total system for a power distortion compensator using a thyristor converter in presented in Fig. 10. Because the thyristor converter in itself is unable to supply a leading current, it is necessary to connect a fixed capacitor bank C parallel with the load. Fig. 5 and Fig. 7 suggest that the capacitor bank requires about 70% of the KVA of the converter plus KVar of the load to obtain unity power factor and the lowest harmonics.

We will now consider how to decide on p and q for the total compensator system in Fig. 10. In the following consideration, let the distorted current be the sum of the load and capactior currents i_{u1}, i_{v1} and i_{w1} in Fig.10. The active and reactive components to be compensated by the converter are

$$p=-p_1+\bar{p}_1+p_{0c}, \quad q=-q_1, \qquad (17)$$

Where p_1 and q_1 are the instantaneous current components of the load. Both are given corresponding signs to p and q respectively so that the compensation current flow in in the opposite direction to the distorted current, and p_{0C} is the power loss of the total compensator system. $\bar{p}_1$ is the average active current over some duration. From Eq. (17), $\bar{p}_1+p_{0c}$

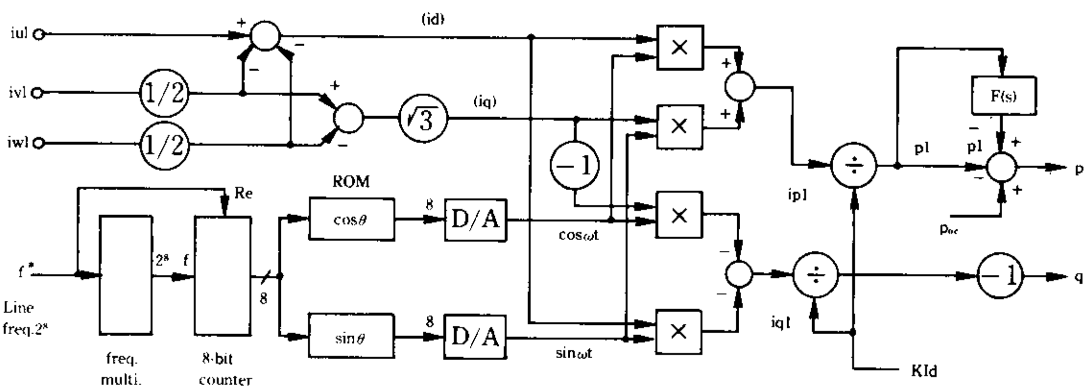


Fig. 12. Calculation circuit for [C].

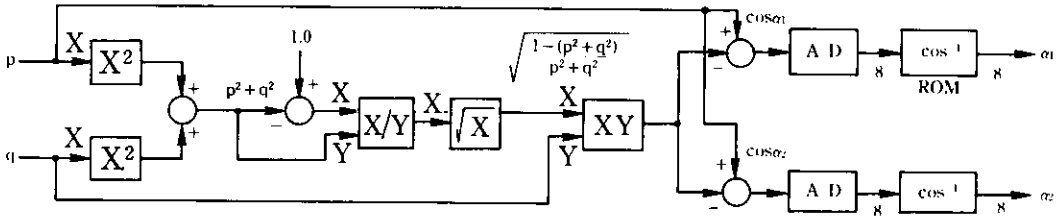


Fig. 13. Calculation circuit for A^{-1}.

equals to $p+p_1$ which in the instantaneous input active current component.

As was mentioned earlier, the transfer function of the cascade converter of Fig. 4 is $KI_d \cdot A \cdot [C]^{-1}$. T0 cancel the transferred signals, we multiply by its inverse function $[C] \cdot A^{-1}/KI_d$ as shown in the block diagram of Fig. 11. Fig. 12 and Fig. 13 give the calculation circuits for the $[C]$ matrix and A^{-1}, respectively.

In Fig.12, the load and capacitor currents i_{u1}, i_{v1} and i_{w1} are first transformed into two phase components $(i_{p1}),(iq_1)$ by the following matrix:

$$\begin{bmatrix}(i_{p1})\\(i_{q1})\end{bmatrix}=\begin{bmatrix}1 & -1/2 & -1/2\\0 & \sqrt{3}/2 & -\sqrt{3}/2\end{bmatrix}\begin{bmatrix}i_{u1}\\i_{v1}\\i_{w1}\end{bmatrix} \tag{18}$$

and then, transformed into i_{p1}, i_{q1} by the following rotaing matrix with algular velocity ω.

$$\begin{bmatrix}i_{p1}\\i_{q1}\end{bmatrix}=\begin{bmatrix}\cos\omega t & \sin\omega t\\-\sin\omega t & \cos\omega t\end{bmatrix}\begin{bmatrix}(i_{p1})\\(i_{q1})\end{bmatrix} \tag{19}$$

The sinusoidal signals in Eq. (19) are generated by using two D/A converters, two programmed ROMs, and an 8 bit counter clocked at 2^8 times the line freqency as shown in Fig. 12.

The calculating circuit for $\bar{p}_1$ consists of a first order lag filter. The transfer function F (s) of the low-pass filter is expressed by

$$F(s)=\frac{1}{1+sT_p} \tag{20}$$

The rate of active power change input to the total system is determined by time consant T_p of Eq. (20). In an actual power system, such a rapid change in the active power is undesirable.

However, the difference in the active powers between the input to the system and that consumed in the load is stored in the reactor. The bulky size of the reactor increases copper loss, and as a result, decreases the total system efficiency. In future, new energy storage systems such at super-conducting coil should be able to realize the distortion compensator with high capacity for active power storage.

P_{0c} o f Fig.12 is the normalized power loss of the system expressed in Eq. (17), and the loss in the reactor occupies its greater part. The reactor current should be regulated to be constant so as to obtain the widest control region with a reasonable time constant.

From Eq. (14), the inverse function $A^{-1}(\alpha_1,\alpha_2)$ of Eq. (15) is specifically expressed as follows:

$$\alpha_1=\cos^{-1}\{p+q\sqrt{1-p^2-q^2}/[p^2+q^2)\}$$

$$\alpha_2=\cos^{-1}\{p-q\sqrt{1-p^2-q^2}/(p^2+q^2)\} \tag{21}$$

We have construced the calculation circuit for Eq. (21) as shown in Fig.13, where the signals $\cos\alpha_1$ and $\sin\alpha_2$ are digitalized by A/D converters. Because the nonlinear element for the arc-cosine function is difficult to obtain by analog methods, we employed a digital arc-cosine table programmed into the ROM.

The use of a micro-computer (Z-80,2.5 MHz) makes the gate shifting circuit the 24-phase asymmetrical control of Fig. 14 remarkable simple. In a multiphase thyristor converter, the states of the gate signal of each thyristor is determined only by the magnitude of α-ωt. By using a table programmed with the gate sequences and a software counter to count ωt, 48 gate signals are controllable within 103 μsec. The memory requirement is 1 k bytes for ROM and 1/8 k bytes for RAM. In order to process rapidly, a timing pulse 192 times the line frequency is applied to the

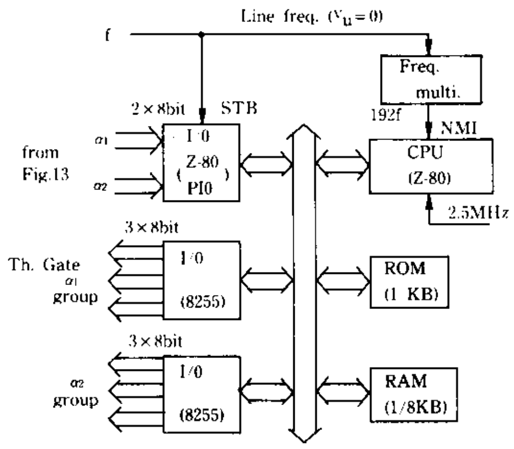


Fig. 14. Gate circuit controlled by micro-computer.

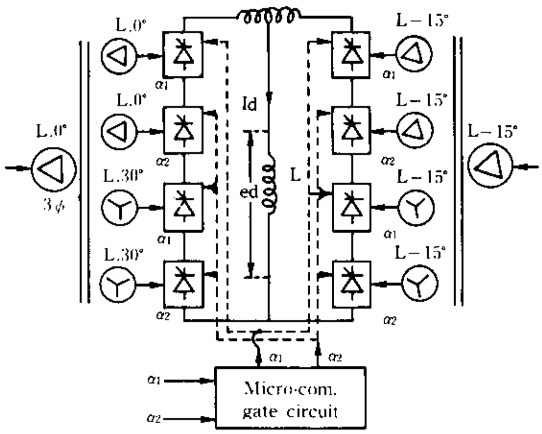


Fig. 15. Experimental converter system.

non-maskable-interrupt (N. M. I.) terminal of the C.P. U.

EXPERIMENTAL RESULTS OF COMPENTATOR

As was mentioned above, an almost ideal distortion compensator is obtained when a 24-phase asymmetrical converter is applied to the system. An experimental system with the capacity of 5 kVA at 200 V shown in Fig. 15 was constructed to examine the adaptability to the power distortion compensating

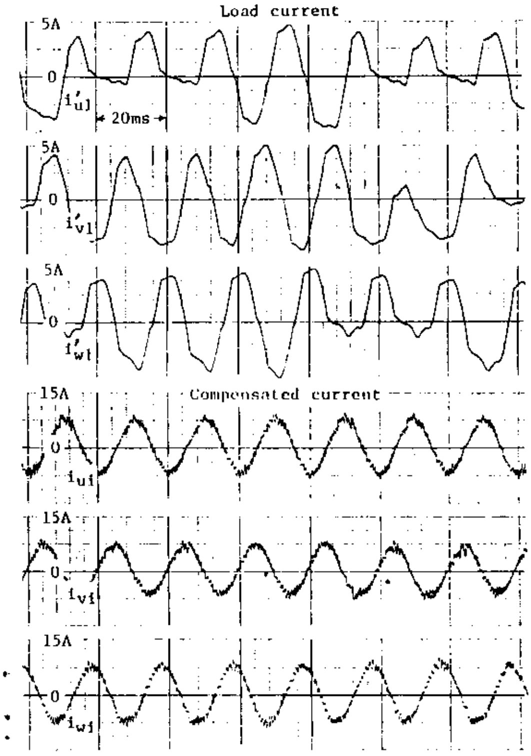
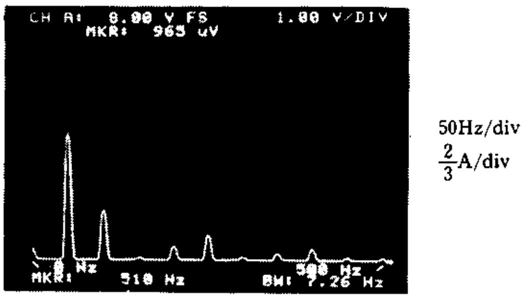
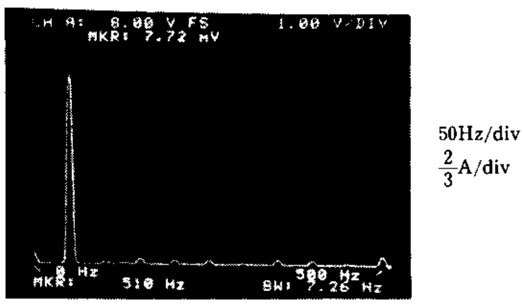


Fig. 16. Compensating characteristics for flickering current.



(a) Spectrum of load current.



(b) Spectrum of compensaced current.

Fig. 17 Filter characteristics of total system.

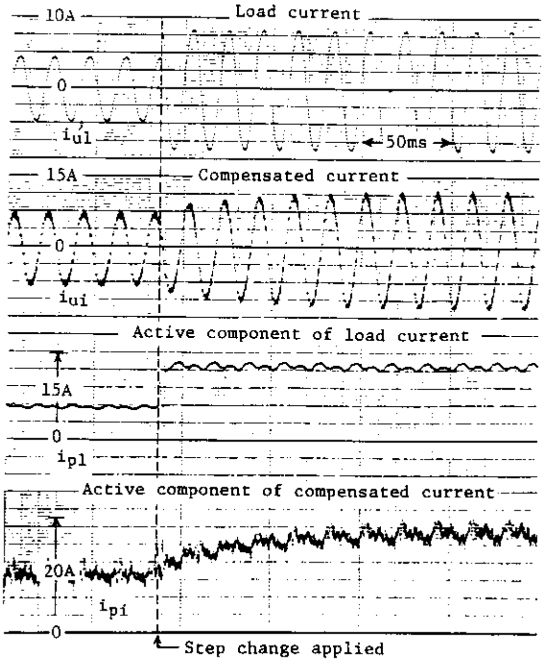


Fig. 18. Transient characteristics for rapid change of active current.

characteristics.

Fig 16 shows the compensating characteristics for the flickering currents. The high frequency component associated with the commutation of the converter are generated in the currents, but the flickering component are almost eliminated.

Fig.17 gives the active filter characteristics of the total compensating system, showing that the filtering ability of the system extends to at least the 7-th harmonics.

Fig.18 shows the transient characteristics for rapid change active current. The reactor with the capacity of 0.5 H and 20 A is used to the energy storage equepment. It shows the active current changes slowly over the several cycles.

These experiments show that the system has a fast response time of 1 msec and maintains unity power factor for any load current variation within the non-saturation region.

CONCLUSTONS

The idea of an instantaneous active and reactive current vector has been introduced, which is effective in the analysis of three-phase current control of the converter. In order to regulate the instantaneous currents, a new control scheme with line commutated converters has been presented. A compensating system with a capacity an large as a rectifier has also been proposed, using the control scheme presented. The effectiveness of the compensating characteristics of the proposed system has been confirmed experimentally.

In furure when the system might be applied to large energy storage equipment using super-conducting coils, the system will be more promising and could be designated as a universal power distortion compensator.

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