UNIVERSAL POWER DISTORTION COMPENSATOR OF LINE COMMUTATED THYRISTOR CONVERTER

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ABSTRACT

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

Instantaneous apparent current is defined to express the status of three-phase currents. A new 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 filter for distortional components under the 7-th harmonic.

INTRODUCTION

According as various types of loads are applied to industry, the flickering current sources such as today's thyristor Leonard and electric arc furnace systems have been increased. Under these circumstances there has been created a strong need for the 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 the compensator of large capacity for the purpose of power control could not be economically realized by the conventional forced commutation techniques. [2]

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

VECTOR LOCUS OF INSTANTANEOUS CURRENT

As is well known, the features of three-phase current are usually characterized as 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 strongly required for the recent thyristor converter engineering. For this purpose we propose two parameters, "instantaneous active and reactive current" which characterize three-phase current.

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

$$\begin{aligned} V_u &= V_m \cos \omega t \\ V_v &= V_m \cos(\omega t - 2/3\pi) \\ V_w &= V_m \cos(\omega t - 4/3\pi) \end{aligned} \qquad (1)$$

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:

$$i_p = \sqrt{2/3}\; p_e / V_m \qquad (2)$$

Whereas, 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 as follows:

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

where

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

The first row of the coefficient 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.

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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 reactive power is associated with the circulating current of line to line through load. This means that reactive power is not stored in the load system at any moment.

Now we assume non-sinusoidal currents expressed as follows:

$$\begin{aligned} i_u &= \sum_{k=1}^{\infty} \{ I_{pk}\cos k\omega t + I_{nk}\cos k\omega t \} \\ i_v &= \sum_{k=1}^{\infty} \{ I_{pk}\cos k(\omega t-2/3\pi) + I_{nk}\cos k(\omega t+2/3\pi) \} \\ i_w &= \sum_{k=1}^{\infty} \{ \underbrace{I_{pk}\cos k(\omega t-4/3\pi)}_{\text{Positive sequence}} + \underbrace{I_{nk}\cos k(\omega t+4/3\pi)}_{\text{Negative sequence}} \} \end{aligned} \quad (5)$$

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

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

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 corresponding waveforms. To the contrary the waveforms of specified three-phase currents determine a corresponding 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 converter, we assume an ideal converter with no energy consumption and storage as shown in Fig.1; the output energy $e_d I_d$ is instantaneously equal to the input. And, we consider the moment when both thyristors Th1 and Th2' are conducting. Then, from Eq.(2), the active current is given by

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

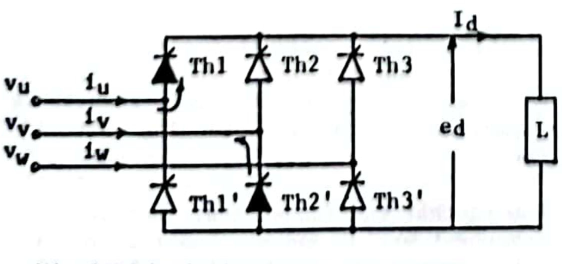


Fig.1. Ideal thyristor converter.

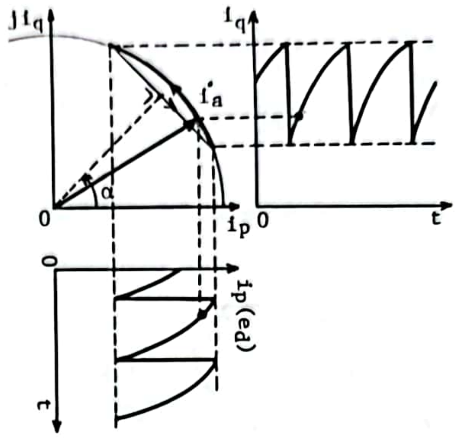


Fig.2. Relation between i_p and i_q of ideal converter.

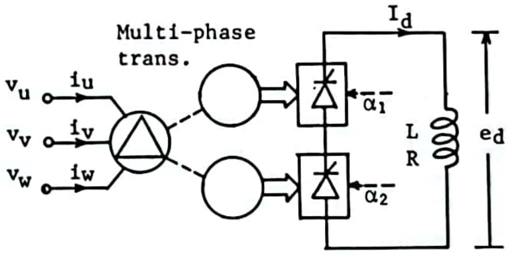


Fig.3. Control of i_p and i_q using cascade converter.

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

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

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

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

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 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

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

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 employing the conventional converter-reactor systems. In the following description it is shown that the above problems can be solved by employing the cascade converter of multi-stages.

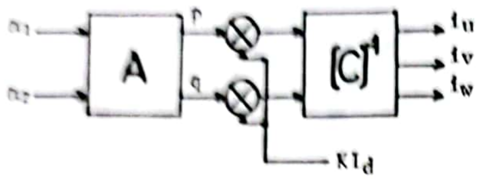


Fig.4. Block diagram of cascade converter..

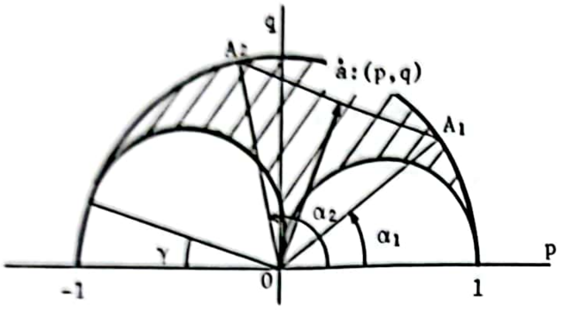


Fig.5. Statical limitation region.

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

$$e_d = E_d.(\cos\alpha_1+\cos\alpha_2)/2\ ,\ I_d = E_d/R \qquad (12)$$

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:

$$\begin{aligned} i_p &= KI_d(\cos\alpha_1+\cos\alpha_2)/2 \\ i_q &= KI_d(\sin\alpha_1+\sin\alpha_2)/2 \end{aligned} \qquad (13)$$

Normalizing Eqs.(7) and (13), we denote å, p, and q, respectively, by the following expressions:

$$\begin{aligned} \mathring{a}(\alpha_1,\alpha_2) &= p(\alpha_1,\alpha_2) + jq(\alpha_1,\alpha_2) \\ p(\alpha_1,\alpha_2) &= (\cos\alpha_1 + \cos\alpha_2)/2 \\ q(\alpha_1,\alpha_2) &= (\sin\alpha_1 + \sin\alpha_2)/2 \end{aligned} \qquad (14)$$

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

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

The system of the above cascade converter is expressed by the block diagram as shown in Fig.4. In this diagram, [C] is the inverse fo the coefficient matrix defined by Eq.(4), whereas A is the non-linerar element given 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 å 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 the limitations are considered in this control.

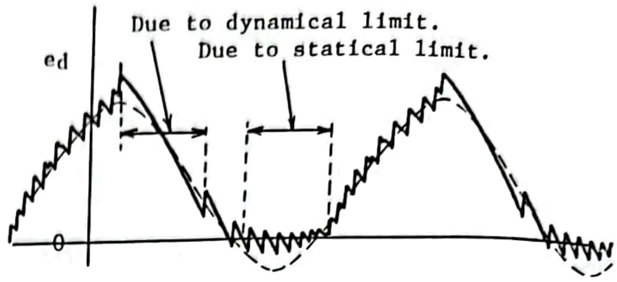
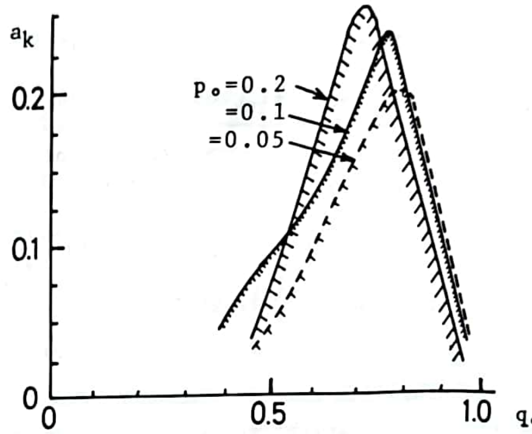


Fig.6. Distorted waveform of e_d.



$$a_k = \frac{I_{pk}}{KI_d} \quad \text{or} \quad \frac{I_{nk}}{KI_d}$$

Fig.7. Statical limitation region.

One is statical limitation for the parameters of the converter. The diagram of the relation between p,q of Eq.(14) and control angles α_1, α_2, is shown in Fig.5. The midpoint of the vectors A1 and A2 of Fig.5 is coincident to the coordinate of $(p,q)=((\cos\alpha_1+\cos\alpha_2)/2,\ (\sin\alpha_1+\sin\alpha_2)/2)$. When

$$0 \leqq \alpha_1 \leqq \pi-\gamma\ ,\quad 0 \leqq \alpha_2 \leqq \pi-\gamma \qquad (16)$$

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

The other limitation is dynamical one. Both of the derivatives $d\alpha_1/dt$ and $d\alpha_2/dt$ must not exceed angular frequency ω, corresponding to the rate of the line voltage decay. If the derivatives exceed the limitation,it is impossible for 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 the statical or dynamical 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 the undesirable harmonics. This tendency becomes more remarkable as either amplitude $|\mathring{a}|$ or the changing rate $|d\mathring{a}/dt|$ increases.

Assuming that the fundamental active and reactive component are p_o and q_o, and the amplitude of the k-th harmonic is a_k, the locus of vector å is

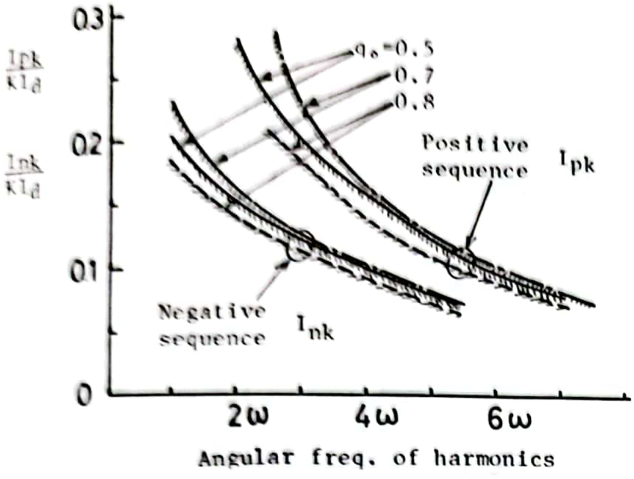
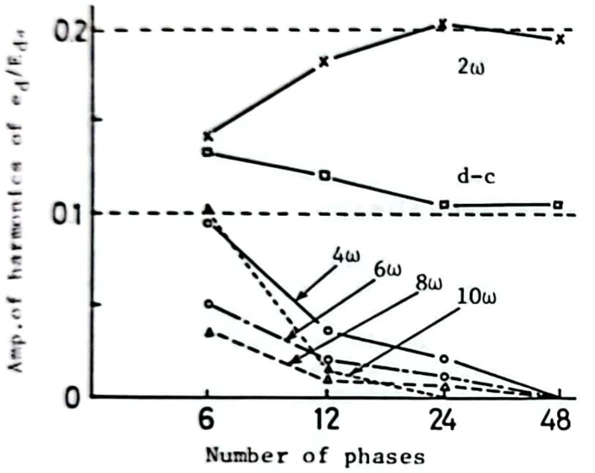


Fig.8. Dynamical limitation region.



P=0.1+0.2cos2ωt , q=0.7+0.2sin2ωt

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

given by a circle with center at $\dot{a}_o=(p_o,q_o)$ and with radius of a_k, as was expressed in Eq.(6). Letting p_o as a parameter, the relations between q_o and a_k in the statical limitation are illustrated 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 limitation for positive and negative sequence harmonics of the k-th order are shown in Fig.8. As is easily known by 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 compensated by the proposed control scheme.

In the preceding analysis of this paper, we have assumed the infinite number of phases. But in the 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.

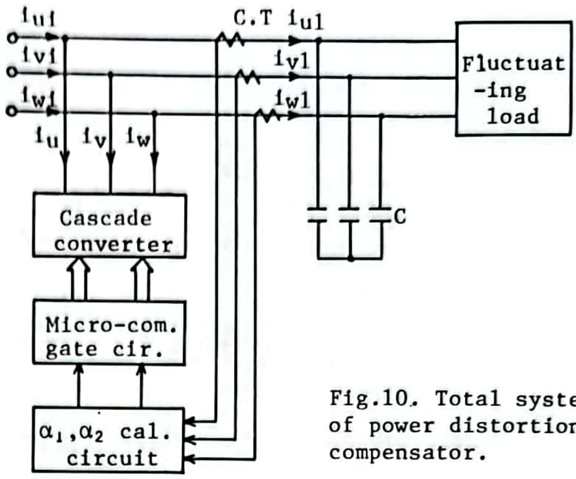


Fig.10. Total system of power distortion compensator.

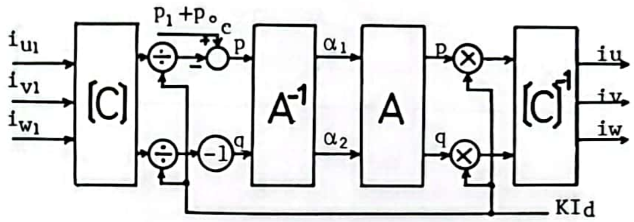


Fig.11. Block diagram of cascade converter and control circuit.

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 increasing control angle α to α+u/2. And it should be noted that even if we assume no rapping angle, the magnitude of undesirable harmonics increases only by 2 to 3 percents.

POWER DISTORTION COMPENSATOR SYSTEM

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

Now, we will consider the decision of p and q of the total compensator system of Fig.10. In the following consideration, let the distorted current be the sum of load and capacitor current i_{u1}, i_{v1} and i_{w1} of Fig.10. The active and reactive components to be compensated by the converter are

$$p = -p_1 + \bar{p}_1 + p_{oc}\ ,\ q = -q_1 \tag{17}$$

Where p and q are the instantaneous current components of the load. Both are given negative sign to p and q respectively to flow the compensation current to the opposit direction of the distorted current, and p_{oc} is the power loss of the total compensator system. $\bar{p}_1$ is the average active current for some duration.

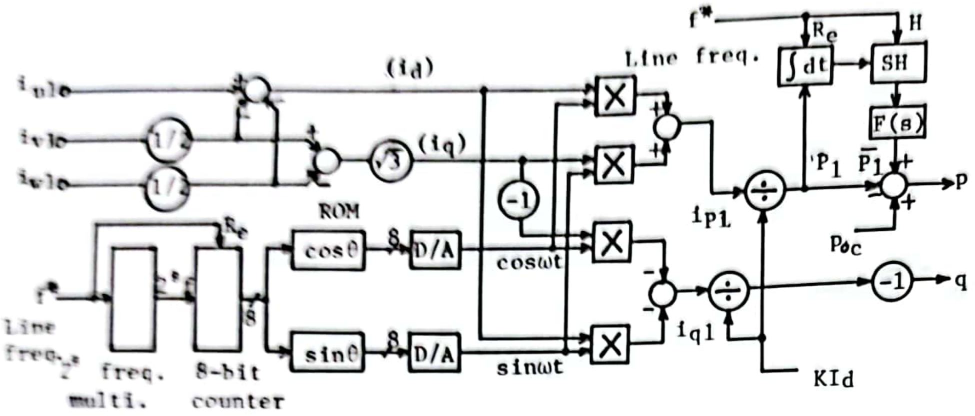


Fig.12. Calculating circuit for [C].

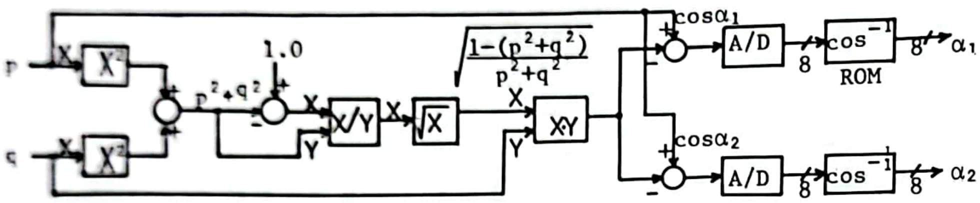


Fig.13. Calculating circuit for A^{-1}.

As was mentioned earlier, the transfer function of the cascade converter of Fig.4 is $KI_d \cdot A \cdot [C]^{-1}$. To cancel the transfered signals, we multiply 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 calculating circuits for [C] matrix and A^{-1}, respectively.

In Fig.12, the load and capacitor currents i_{ul}, i_{vl} and i_{wl} are first transformed into two phase components (i_{pl}), (i_{ql}) by the following matrix:

$$\begin{bmatrix}(i_{p1})\\(i_{q1})\end{bmatrix} = \begin{bmatrix}1 & -1/2 & -1/2\\ 0 & \sqrt{3}/2 & -\sqrt{3}/2\end{bmatrix}\begin{bmatrix}i_{ul}\\ i_{vl}\\ i_{wl}\end{bmatrix} \qquad (18)$$

and then, transformed into i_{pl}, i_{ql} by the following rotating matrix with angular velocity ω.

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

The sinusoidal signals of Eq.(19) are generated by using two D/A converters two programmed ROMs, and an 8 bit counter triggered by 2^8 multiplied line frequency as shown in Fig.12.

The calculating circuit of $\bar{p}_1$ consists of a resetable integrator, a sample-holder and a low-pass filter. To get low ripple voltage in $\bar{p}_1$, average value of p_1, for one period of the source, is calculated by the integrator and the value is held by the sample-holder. The transfer function F(s) of the low-pass filter is expressed by

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

The rate of active power change input to the total system is determined by time constant T_p of Eq.(20). In actual power system, so rapid change in the active power is undesirable. However the difference of active powers between input to the system and consumed in the load are 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 as super-conducting coil would realize the distortion compensator with high capacity for active power storage.

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

From Eq.(14), the inverse function A (α_1, α_2) of Eq.(15) is specifically expressed as follows:

$$\alpha_1 = \cos^{-1}\{p + q\sqrt{(1-p^2-q^2)/(p^2+q^2)}\}$$
$$\alpha_2 = \cos^{-1}\{p - q\sqrt{(1-p^2-q^2)/(p^2+q^2)}\} \qquad (21)$$

We have constructed the calculating circuit of Eq.(21) as shown in Fig.13, where the signals $\cos\alpha_1$ and $\sin\alpha_2$ are digitalized by A/D converters. Because nonlinear element of arc-cosine is diffecult

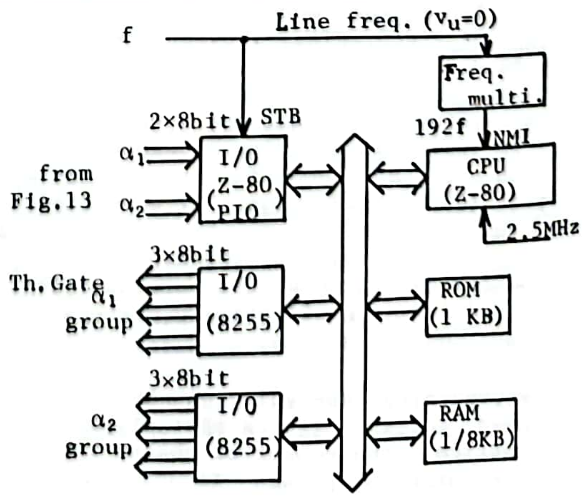


Fig.14. Gate circuit controlled by micro-computer.

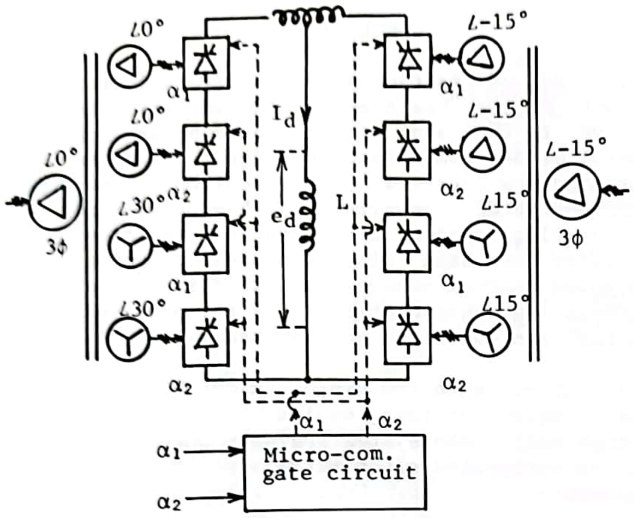


Fig.15. Experimental converter system.

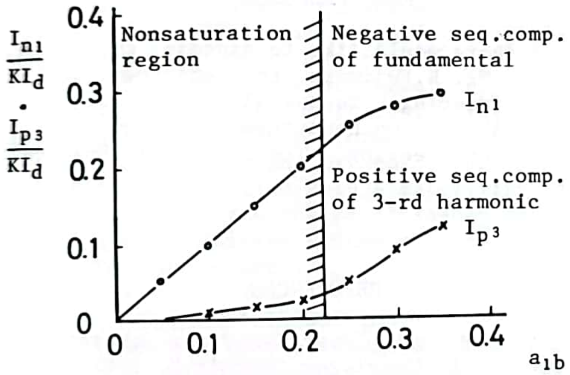


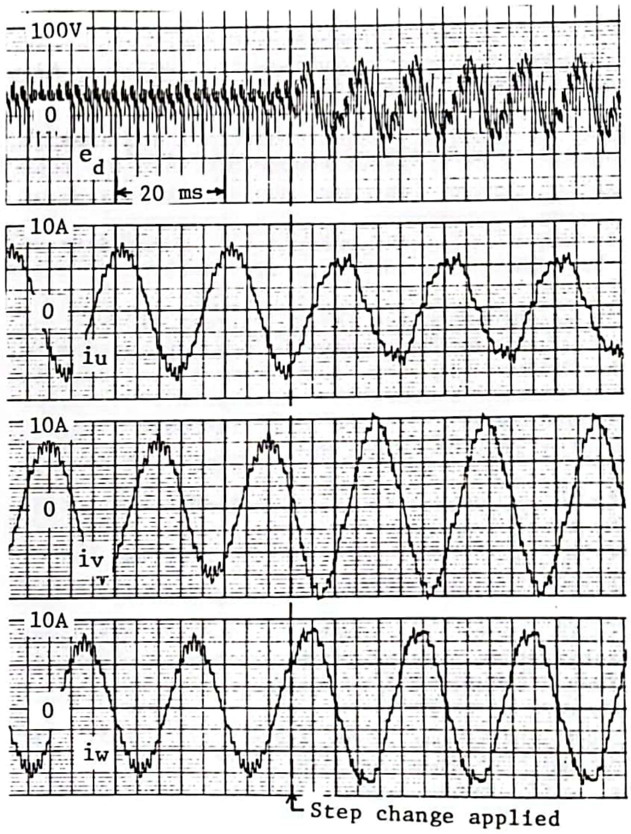
Fig.16. Negative sequence component versus its control variable a_{ib} .

to obtain by the analog method, we employed the digital arc-cosine table programmed in the ROM.

The use of a micro-computer (Z-80, 2.5MHz) remarkably makes simple the gate shifting circuit of the 24-phase asymmetrical control of Fig.14. In a multiphase thyristor converter, the status of the gate signal of each thyristor is determined only by the magnitude of $\alpha-\omega t$. By using the table programmed 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, the timing pulse of 192 times of line frequency is applied to non-maskable-interrupt (N M I) terminal of the C.P.U.

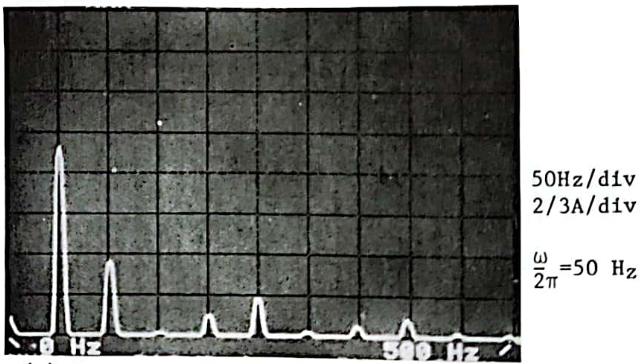
EXPERIMENTAL RESULTS OF COMPENSATOR

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



(p_o=0.19 , q_o=0.70 , a_{ib} : 0-0.18)

Fig.17. Step responses for negative sequence.



(a) Non-compensated current spectrum of load current.

(b) Compensated current spectrum.

Fig.18. Filter characteristics of total system.

Fig.16 gives one of the experimental results in case of control of the fundamental negative sequence component. The figure shows that the component increases approximately proportional to the control variable a_{1b} which controls the fundamental component of negative sequence within the non-saturation region, and also shows that outside of the region the component of the fundamental saturates gradually but the undesirable components of the third harmonies increases distinctly.

Fig.17 presents the input current of the converter when the step change in negative sequence of the fundamental component from zero to 0.18 is applyed under the condition that p_o=0.19,q_o=0.70. The figure shows that the step response time of the system is less than 1 msec.

Fig.18 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.19 shows the experiment on the transient characteristics of the total system in case of unbalanced current change applied.

It was proved by these experiments that the system has high response time of 1 msec and maintains unity power factor for any load current variation within the non-saturation region.

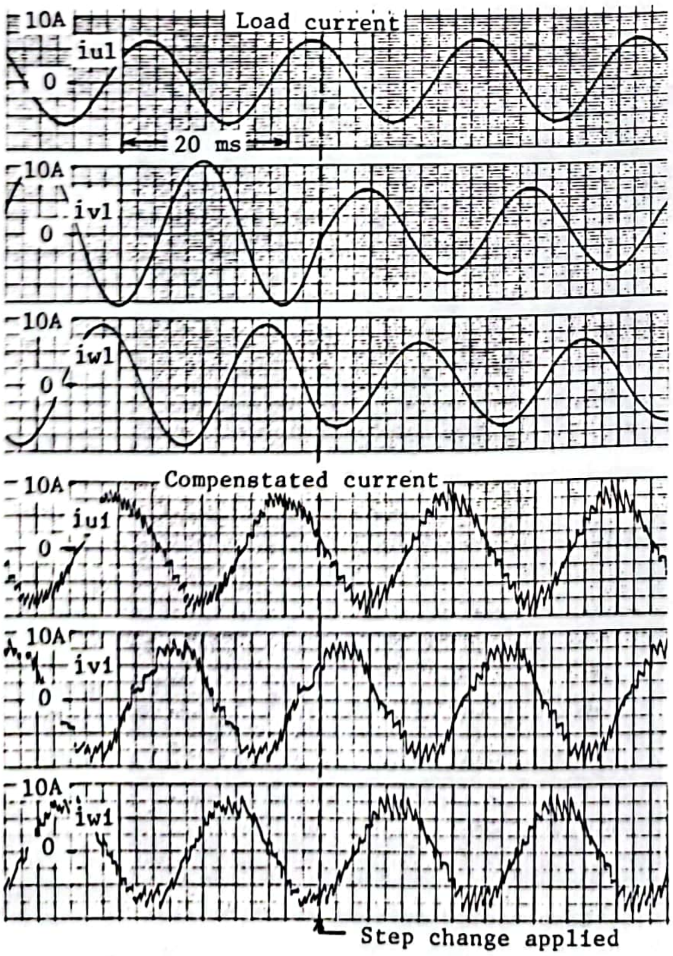


Fig.19. Transient characteristics of total system.

CONCLUSIONS

The idea of instantaneous active and reactive current vector has been introduced which is effective to 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 capacity as large as a rectifier has been also proposed by using the presented control scheme. The effectiveness of the compensating characteristics of the proposed system has been confirmed experimentally.

In future when the system might be applied to large energy storage equipment with super-conducting coil, the system would be more promising and be designated as universal power distortion compensator.

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