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REACTIVE POWER AND ITS COMPENSATION

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I. INTRODUCTION

"Reactive Power" is one of the principal concepts in the electrical engineering. Popularization of products of power electronics has caused the reactive power other than basic frequency components to appear in the power lines. Reactive power compensated converters have been developed, and reactive power compensators using power electronics are practically used. For example, for industrial use, they are used to eliminate flicker generated by fluctuated loads of an arc furnace, and in power network systems, they are used to control reactive power in power lines to supply stabilized power.

This special issue is to introduce features of technology and products on reactive power compensation of Fuji Electric. For this purpose, this paper, first reviews the concept of reactive power, then describes situations of reactive power generations due to electronic power converters and arc furnaces and reactive power reducing technique of power converter itself, and outlines various reactive power compensators including those being in the research and development stages.

II. CONCEPT AND CLASSIFICATION OF REACTIVE POWER

An electronic power converter or arc furnace produces not only the basic frequency component reactive power but also reactive powers due to distortion currents, load fluctuations and load asymmetry. Taking a positive or negative value, in a single phase alternative current system, the instantaneous value of the power produced by periodical voltage and current of a arbitrary waveform changes periodically. When components of current are classified into those which always produce positive power and the others which produce positive or negative power so that the value integrated toward one cycle becomes zero, the former is an active current and the latter is a reactive current. Voltages and currents in various cases and powers generated by them are described below.

2.1 Electrical power between sinusoidal voltage and sinusoidal current

As already known, voltage (e), current (i) and power (Pt) are expressed as follows;

$$\left.\begin{aligned} e &= \sqrt{2}\,E\cos(\omega t + \varphi e) \\ i &= \sqrt{2}\,I\cos(\omega t + \varphi i) \\ Pt &= ei = EI\cos(\varphi e - \varphi i) + EI\cos(2\,\omega t + \varphi e + \varphi i) \end{aligned}\right\} \quad \cdots\cdots (1)$$

And, putting them as

$P = EI\cos\varphi$, $Q = EI\sin\varphi$, and $\varphi = \varphi e - \varphi i$, the power is expressed as;

$$Pt = P\{1 + \cos(2\,\omega t + 2\,\varphi i)\} - Q\sin(2\omega t + 2\,\varphi i) \quad \cdots\cdots (2)$$

where, P represents active power and Q represents reactive power.

Fig. 1 shows the movements of instantaneous voltage,

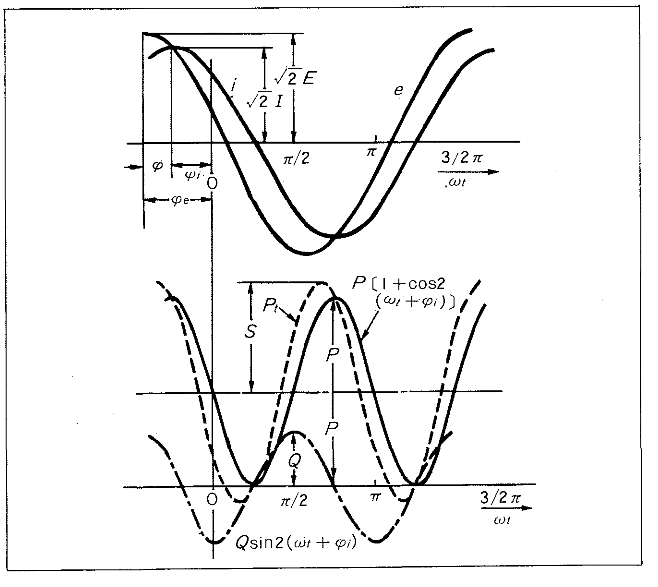


Fig. 1 Power movement due to sinusoidal voltage and current

current and power.

The first term of equation (2) always takes positive values, and for the second term, the integration of one period is zero. When current (i) is classified into active current (ip) and reactive current (i_Q), they are expressed as follows;

$$\left.\begin{aligned} ip &= \sqrt{2} I \cos\varphi \cos(\omega t + \varphi e) \\ i_Q &= i - ip = \sqrt{2} I \sin\varphi \sin(\omega t + \varphi e) \end{aligned}\right\} \quad \cdots\cdots (3)$$

Conductance (G) of load is expressed as follows;

$$G = \frac{P}{E^2} = \frac{I\cos\varphi}{E} = \frac{ip}{e} \quad \cdots\cdots (4)$$

2.2 Power at sinusoidal voltage and periodic nonsinusoidal current[1]

In this case, voltage (e) and current (i) are expressed as follows;

$$\left.\begin{aligned} e &= \sqrt{2} E \cos(\omega t + \varphi e) \\ i &= \sum_{l=1}^{\infty} \sqrt{2} I_l \cos(l\omega t + \varphi_{il}) \end{aligned}\right\} \quad \cdots\cdots (5)$$

Active power P and active current (ip) are expressed as follows as referred to 2.1 above;

$$P = EI_1 \cos(\varphi e - \varphi i_1) \quad \cdots\cdots (6)$$

$$\begin{aligned} ip &= Ge = \frac{P}{E^2} e \\ &= \sqrt{2} I_1 \cos(\varphi e - \varphi i_1) \cos(\omega t + \varphi e) \quad \cdots\cdots (7) \end{aligned}$$

Reactive current (i_Q) is expressed as follows;

$$\begin{aligned} i_Q &= i - ip = \sqrt{2} I_1 \sin(\varphi e - \varphi i_1) \sin(\omega t + \varphi e) \\ &+ \sum_{l=2}^{\infty} \sqrt{2} I_l \cos(l\omega t + \varphi_{il}) \quad \cdots\cdots (8) \end{aligned}$$

Where, the first term of i_Q changes to basic frequency component of reactive power.

$$Q_1 = EI_l \sin(\varphi e - \varphi i_1) \quad \cdots\cdots (9)$$

The effective value of total current (i) is;

$$I = \sqrt{\sum_{l=1}^{\infty} I_l^2} \quad \cdots\cdots (10)$$

The relationship among apparent power (S), reactive power (Q) and distorsion power (D) is expressed as follows;

$$\left.\begin{aligned} S &= EI \\ Q &= |\sqrt{S^2 - P^2}| \\ D &= |\sqrt{Q^2 - Q_1^2}| \end{aligned}\right\} \quad \cdots\cdots (11)$$

2.3 Power at periodic nonsinusoidal voltage and current[1]

Voltage (e) and current (i) are;

$$\left.\begin{aligned} e &= \sum_{k=1}^{\infty} \sqrt{2} E_K \cos(k\omega t + \varphi_{ek}) \\ i &= \sum_{l=1}^{\infty} \sqrt{2} I_l \cos(l\omega t + \varphi_{el}) \end{aligned}\right\} \quad \cdots\cdots (12)$$

Effective value of total voltage is;

$$E^2 = \sum_{k=1}^{\infty} E_k^2 \quad \cdots\cdots (13)$$

Effective value of total current is;

$$I^2 = \sum_{l=1}^{\infty} I_l^2 \quad \cdots\cdots (14)$$

The instantaneous power (Pt) is;

$$\begin{aligned} Pt &= \sum_{k=l=1}^{\infty} E_k I_l \cos(\varphi_{ek} - \varphi_{il}) + \sum_{k=1}^{\infty} \Big[\sum_{l=1}^{\infty} E_k I_k \cos \\ &\quad \{(k+l)\omega t + \varphi_{ek} + \varphi_{il}\} \Big] + \sum_{k=1}^{\infty} \Big[\sum_{\substack{l=1 \\ k\neq l}}^{\infty} E_k I_k \cos \\ &\quad \{(k-l)\omega t + \varphi_{ek} - \varphi_{il}\} \Big] \quad \cdots\cdots (15) \end{aligned}$$

From voltage (E) of equation (13) and first term (put as P) of equation (15), conductance (G) of the load is expressed as follows;

$$G = P/E^2 \quad \cdots\cdots (16)$$

Then, effective value of active current is;

$$Ip = GE = P/E \quad \cdots\cdots (17)$$

And, instantaneous value of active current is;

$$ip = Ge = (P/E^2)e \quad \cdots\cdots (18)$$

The current which produces active power is always in the waveform of the same phase similar to the voltage waveform.

Referring to the example described by *M.* Depenbrock[2], the instantaneous power, active and reactive powers are indicated for voltage and current which include basic wave and 3rd harmonic wave.

$e = \sqrt{2} E_1 (\sin\omega t + 0.9\sin 3\omega t)$
$i = \sqrt{2} I_1 (\sin\omega t + 0.1\sin 3\omega t)$

The active power (P), effective value of total voltage (E) and conductance (G) are;

$P = E_1 I_1 (1 + 0.09) = 1.09EI$
$E = E_1\sqrt{1 + 0.9^2} = 1.35E_1$
$G = P/E^2 = 0.602 I_1/E_1$

The active current (ip) is;

$ip = Ge = \sqrt{2} I_1 (0.602\sin\omega t + 0.542\sin 3\omega t)$

And, the reactive current (i_Q) is;

$i_Q = i - ip = \sqrt{2} I_1 (0.398\sin\omega t - 0.442\sin 3\omega t)$

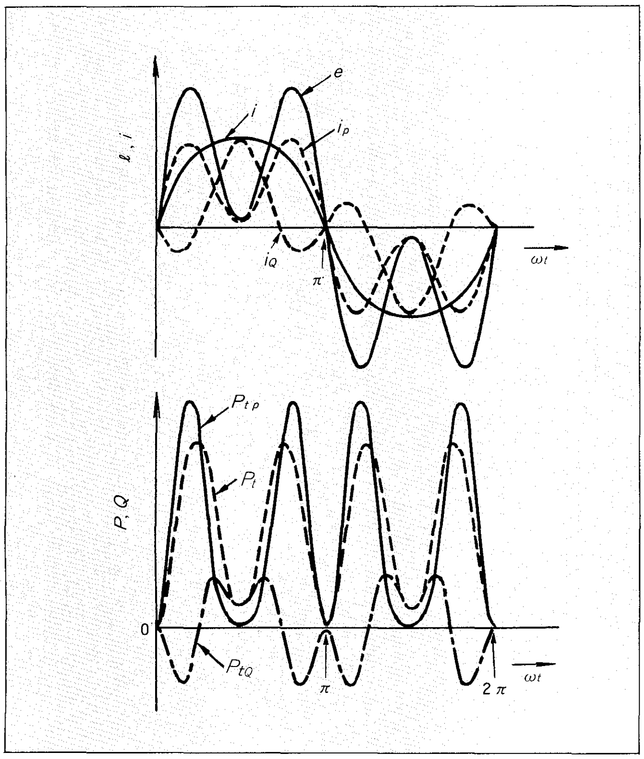


Fig. 2 Periodic nonsinusoidal voltage, current and power

Fig. 2 shows e, i, ip, i_Q. *Fig. 2* also shows instantaneous power $e{\cdot}i$, $e{\cdot}ip$ and $e{\cdot}i_Q$ as Pt, Ptp and Pt_Q respectively.

2.4 Reactive power at three-phase alternative current due to unsymmetrical load[3]

The definition for classification of reactive power has not been set up for polyphase systems. For such a simple case, where the voltage is of a symmetrical three-phase sinusoidal and current is of a sinusoidal, *G*. Moeltigen has defined as follows; When effective value of the phase voltage is expressed as E and effective value of each phase current and delayed phase angle are expressed as I_1, I_2, I_3, φ_1, φ_2, φ_3, the active power P, basic wave reactive power Q, apparent power S and power N which is based on the unsymmetrical load are defined as follows.

$$P = E\,(I_1\cos\varphi_1 + I_2\cos\varphi_2 + I_3\cos\varphi_3) = P_1 + P_2 + P_3 \quad \cdots\cdots (19)$$

$$Q = E\,(I_1\sin\varphi_1 + I_2\sin\varphi_2 + I_3\sin\varphi_3) = Q_1 + Q_2 + Q_3 \quad \cdots\cdots (20)$$

$$N = (P_1 - P_2)^2 + (P_2 - P_3)^2 + (P_3 - P_1)^2 + (Q_1 - Q_2)^2 + (Q_2 - Q_3)^2 + (Q_3 - Q_1)^2 \quad \cdots\cdots (21)$$

$$S^2 = \sqrt{3}\,E\,\sqrt{I_1^2 + I_2^2 + I_3^2} \quad \cdots\cdots (22)$$

$$= P^2 + Q^2 + N^2 \quad \cdots\cdots (23)$$

2.5 Decomposition of active and reactive current components

A method to extract the compensated current by decomposing current (i) of a line into ip, i_Q, i_{Q1} and i_D is described. Since active current (ip) produces an active current against voltage (e), the mean power can be obtained from the value derived by integrating the instantaneous power (which is the product of total current (i) and (e)) for a period of half cycle; and the value related to the amplitude of the active current can be obtained by dividing the mean power by the effective value of voltage toward the half cycle period. Then, by multiplying this with (e), the active current (ip) which is in the similar waveform to (e) can be obtained. Now, the reactive current i_Q can be obtained by subtracting (ip) from the total current (i).

Fig. 3[4] shows a circuit. This circuit produces a tolerance against the actual current (i) by feeding back the detected current, integrates and continues the instantaneous power obtained by multiplying this with voltage, takes out that value at each half cycle, and obtains the amplitude of the current components to be detected. In this figure, with the sine wave oscillator which is synchronized with the line voltage, $\cos\omega t$ signal which is in the same phase as the line voltage basic wave and $\sin\omega t$ signal used to obtain the reactive component of the basic wave are obtained. With these signals, basic wave active current (ip) and basic wave reactive current (i_{Q1}) are obtained, and high harmonic wave current i_D is obtained from the difference between these (ip and i_{Q1}) and total current (i).

With this method, the accuracy is enhanced, but one to two cycle detecting operation delay cannot be avoided.

III. FEATURE OF REACTIVE POWER PRODUCED BY LOAD

In addition to the basic wave reactive power due to

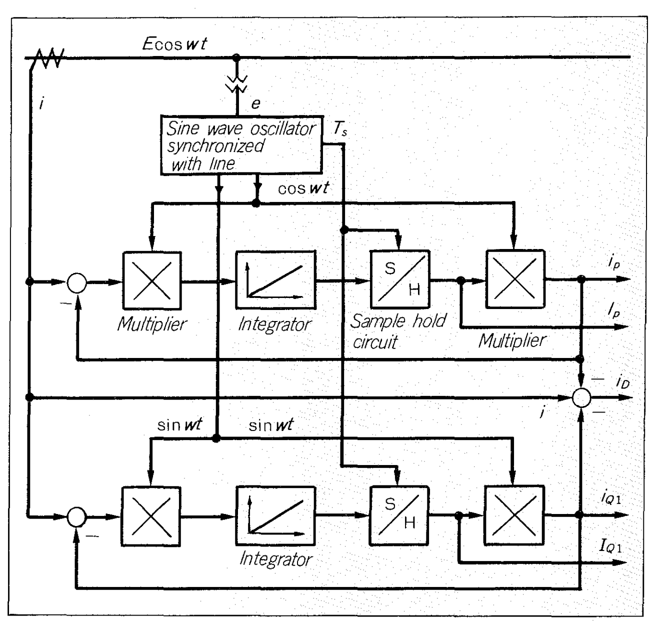


Fig. 3 Decomposition of current into active and reactive currents

loads of inductance and capacitance and basic wave reactive component and high harmonic wave reactive component due to line commutated converters, reactive power due to cychroconverter, self commuted AC-DC converter, etc. has appeared. Further, including the reactive power in the cycle control of alternative current power, reactive power produced by an arc furnace, etc., fluctuated load and unsymmetrical load can also be included in the reactive power. The reactive powers due to these loads are described below.

3.1 Reactive power of AC to DC converter

It has been well known that in a line commutated converter, the displacement factor is decided by the phase control almost completely and that in P-pulse connection, the ν^{th} $(\nu = np \pm 1)$ high harmonic wave current appears in an amplitude of $1/\nu$ of the basic component. Power factor and high harmonic wave can be improved by a self commutated converter. We made study for application of it to reactifiers for electric cars.

3.2 Fluctuated load and reactive current

For fluctuated load, the reactive power can be decided by assuming a certain interval as a cycle. As a simple case, a cycle control using thyristor a.c. power controller is examined. In this case, the load is assumed to be a pure resistance load. The switch on interval and repetitive interval are respectively expressed as Te and T.

Single phase voltage e is;

$$e = \sqrt{2}\, E \sin\omega t$$

When the switch on interval ratio is expressed as σ;

$$\sigma = Te/T$$

When current is applied from zero point of voltage wave, the current flowing during the switch on interval is;

$$i = \sqrt{2}\, I_0 \sin\omega t$$

Current for $(T - Te)$ is;

$$i = 0$$

Effective current over interval T is;

$$I = I_0 \sqrt{Te/T} = I_0 \sqrt{\sigma}$$

Apparent power S and active power P over interval T are;

$$S = EI = \sqrt{\sigma}\, EI_0,\ P = \sigma EI_0$$

Power factor λ is;

$$\lambda = P/S = \sqrt{\sigma}$$

Instantaneous value of active current is;

$$ip = \frac{P}{E^2} e = \sqrt{2}\, \sigma I_0 \sin\omega t$$

Reactive current (instantaneous value) is;

$i_Q = i - ip = \sqrt{2}\,(1 - \sigma) I_0 \sin\omega t$ over interval Te, and

$i_Q = -ip = -\sqrt{2}\, \sigma I_0 \sin\omega t$ over interval $(T - Te)$

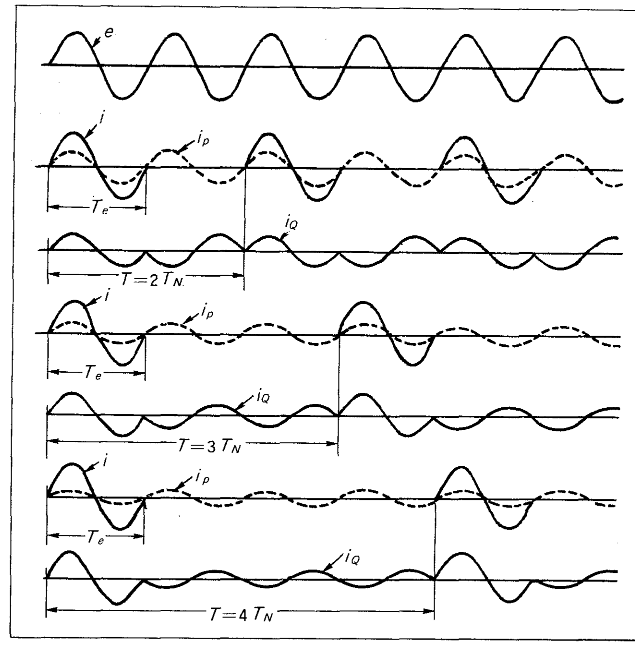


Fig. 4 Reactive power at alternative current on/off control

When cycle of voltage e is expressed as T_N $(= 2\pi/\omega)$, *Fig. 4* shows ip and i_Q obtained by assuming $Te = T_N$ and by assuming T to be $2T_N$, $3T_N$ and $4T_N$.

As it may be understood from the *Fig. 4*, when only interval Te is watched, even if the load is of power factor 1, reactive power is unvolved for interval T.

3.3 Reactive power at cychro-converter

A cychro-converter provides AC output of a frequency lower than the line frequency. When the output current of the *Fig. 4* is rectified and output as shown in *Fig. 5*, it becomes a cychro-converter as a principle.

When input line current is obtained by applying Fourier analysis to each harmonics, many subharmonics and higher harmonics appear. As it may be understood from this simple cychro-converter, order of harmonics is changed by changing output frequency f_A.

An actually used cychro-converter uses a polyphase converter to control the current so that the output waveform is similar to sine wave. Consequently, the front and tail parts of sinusoidal wave increases voltage control factor, and the power line indicates a low power factor. Since low frequency output is generally used for a large capacity equipment, the power supply line side is affected. Under the cooperative study with the Japanese National Railways, Fuji Electric developed a new system. This system combines an advanced angle control converter with a delay angle control converter, and makes the displacement factor to be 1. With this method, subharmonics and higher harmonics could be remarkably reduced at the power supply line side.

Fuji Electric manufactured a 5.4 MVA cychro-converter for thrust power supply of magnetic levitation

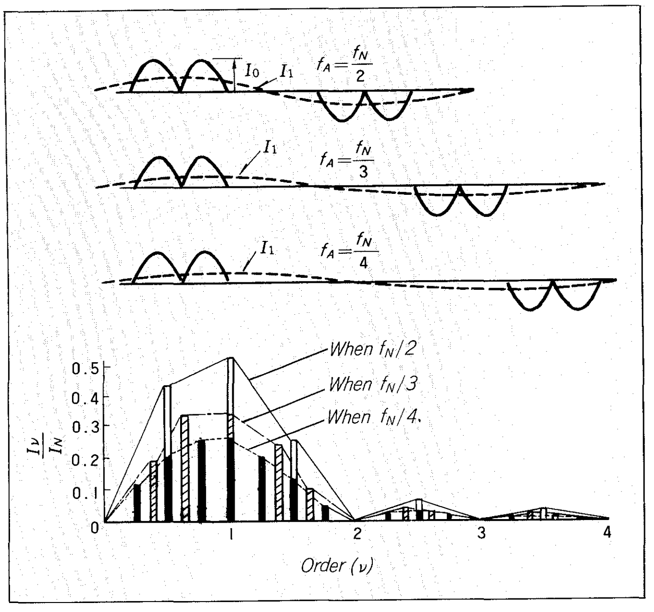


Fig. 5 Frequency spectrum of input current at a cychro-converter

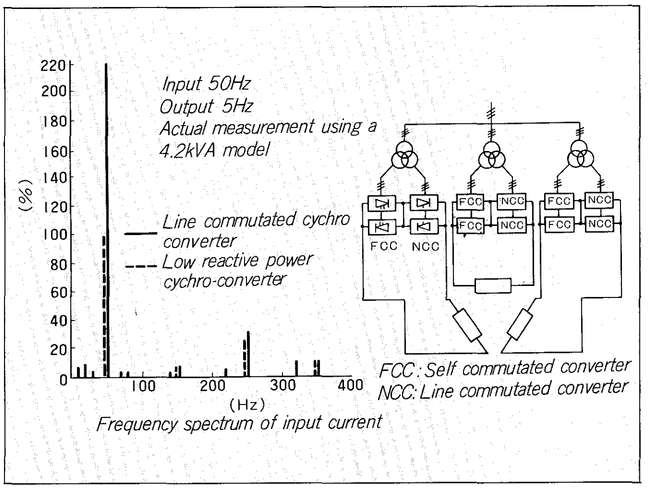


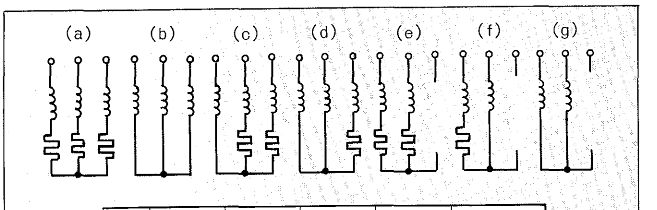
Fig. 6 Low reactive power cychro-converter

vehicles[5].

3.4 Load characteristics of arc furnace

When melting scrap, reduced iron, etc. with an arc furnace to make steel, the conditions inside the arc furnace rapidly change depending if arc is generated, not generated or the electrode contacts and shorts with the contents. This change appears every 1/2 cycle. In case of a electrode short-circuit, current is decided by a reactance of the transformer for the arc furnace, and this causes voltage to drop at the power receiving end. When the arc goes out, voltage drop at the power receiving end goes out all at once, and voltage jumps up. Depending this repeating frequency, a flicker occurs. To minimize voltage fluctuation and to eliminate flicker by controlling reactive power, synchronous-condenser was used conventionally. Recently, however, thyristor static var compensators (SVC) are like to be used because wide reactive power can be changed rapidly. Because each type has the individual features, Fuji Electric has delivered SVC or hybrid SVC combined with a synchronous-condensor depending on each line situation. The details are described in other paper in this special issue.

Simplifying load asymmetry, *Fig. 7* shows how relationships among various powers discussed in 2.4 above change depending on combinations of three conditions, namely electrode is opened, shorted and has an arc resistance (a constant value).



	P	S	Q	N	Power factor=P/S
(a)	3.00	4.24	3.0	0	0.707
(b)	0	6.0	6.0	0	0
(c)	2.40	5.02	4.20	1.34	0.478
(d)	1.38	5.52	5.08	1.66	0.251
(e)	1.50	3.0	1.50	2.12	0.50
(f)	1.20	3.79	2.40	2.68	0.316
(g)	0	4.24	3.0	3.0	0

Fig. 7 Various power values at load asymmetry

IV. REACTIVE POWER COMPENSATORS

For an intermittent load, the load is leveled by the use of an energy storage equipment. This special issue describes the compensation of reactive power for the line frequency. *Fig. 8* shows the presently suggested compensators. Out of these compensators, (a) uses a thyristor switch to control capacitor on/off (TSC), and (b) uses a thyristor to control reactor current (TRC). These two have been used practically for those of a large capacity.

The TSC compensates lagging reactive power only, and is operated a half cycle later to avoid inrush current. The TRC compensates leading current, and it can operated immediately by eliminating delay of the trigger signal. Reactive power can be compensated continuously from phase lagging to advancing by combining the TRC with a capacitor. (c) through (f) use power converters to control the systems so that reactive power can be mutually sent and received against the power line. At present, these types are under stages of research and development.

(c) controls phase and amplitude of voltage of voltage type inverter and flows reactive power to the line[6], and Fuji Electric conducted experiments using a 4 kVA model. (d) uses a power rectifier operated by extracting a voltage drop for the resistance of DC reactor only from DC voltage, and the line commutation (NCC)[7] and self commutation

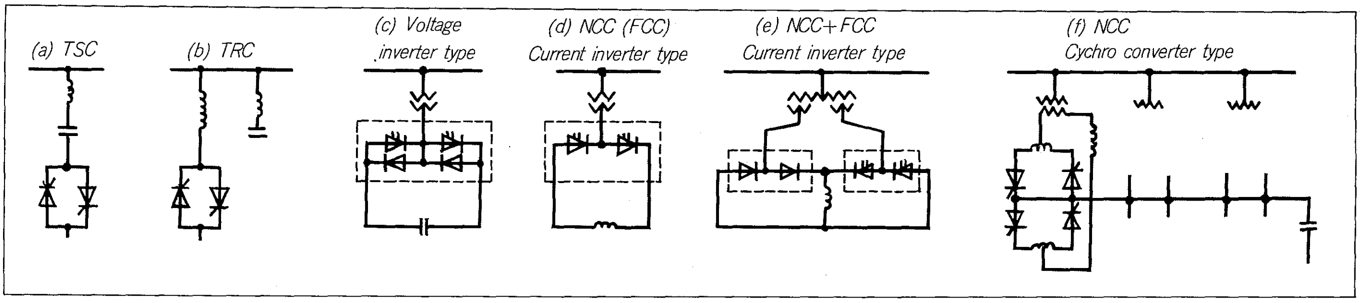


Fig. 8 Various type reactive power compensators

(FCC) respectively take lagging and leading. (e) flows direct current to the commonly used DC reactor by connecting the converter connection of NCC to converter connection of FCC in parallel. With the reactor current kept in a constant value, both leading and lagging vars can be compensated by changing direct current distributions to the NCC and FCC. (f) uses a cychro-converter while (c) uses an inverter[(8),(9)].

Types (c) through (f) are capable of compensating other frequency components than the basic reactive components by controlling power devices. For example, when the voltage type inverter of (c) distorts output voltage waveform from the sine wave, distorted wave current is caused by that voltage to go out. Also in the case of current type inverter of (d), waveform of the current sent to the line can be changed by controlling the power device. For these purposes, operating frequency of the power device must be increased to enhance resolution and a controller of higher response and operating accuracy must be realized. These compensators will be used practically in response to the performance required in applied fields.

V. POST SCRIPT

The importance of stabilized power supply and quality improvement increases more and more because high quality and stable power supply is the basis of the present society. As one of the methods, reactive power compensating technique will face to the development of devices having higher responsibility. Fuji Electric has surveyed and studied actual status of reactive powers in loads and lines, and to develope the suitable compensators, concentrated its effort together with the users to develop semiconductor power devices, var compensators, control technology and application-wares. Asking the users the continuous assistances, we are willing to further develop the technique.

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