New Type Automatic Power Factor Regulator

Yasuo Takasaki
Minoru Sato
Katsuhisa Uchida

1. Introduction

Major electrical devices such as motors, fluorescent lamps and mercury lamps are usually accompanied by lagging reactive power. As this lagging reactive power increases, line current will also increase, creating a drop in the line voltage and loss of power. Therefore it is necessary to increase power distribution capacity as lagging reactive power increases.

An automatic power factor regulator is a device that contributes to efficient electric energy utilization by connecting and disconnecting capacitors for phase advance to a power distribution system in response to load variation, to reduce the lagging reactive powere and to maintain the power distribution system at a high power factor.

Fuji Electric, which has previously supplied automatic power factor regulators models QC10 and QC02, has recently introduced the new type automatic power factor regulator model QC06N to the market. This paper summarizes the new type automatic power factor regulator model QC06N which uses a microcomputer (hereinafter referred to as CPU). **Figure 1** shows an external view of the automatic power factor regulator model QC06N. **Figure 2** shows line current and power loss reductions obtained by power factor improvement using the automatic power factor regulator model QC06N. The automatic power factor regulator model QC06N reduces line current to 60% and power loss to 36% (of prior values) by improving power factor from $\cos\theta_0$ of 0.6 up to $\cos\theta_1$ of 1.0 as shown in the figure.

2. Special Features

(1) Direct input of digital set values: no need for conversion of set values

Cumbersome set value conversion calculations are eliminated from the QC06N which allows direct input of digital set values from a touch-panel. Set values include Potential Transformer (PT) ratio, Current Transformer (CT) ratio, capacitance, and the target power factor necessary for power factor improvement.

(2) Common operating power supply voltage and input voltage detection for AC 100V or AC 200V systems

Fig. 1 New type automatic power factor regulator model QC06N

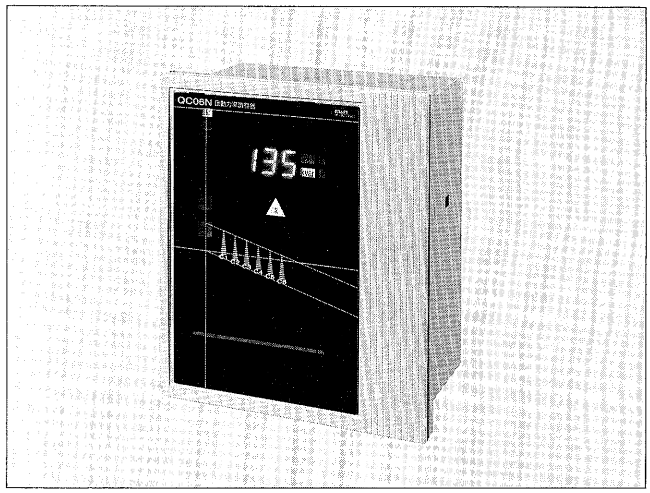
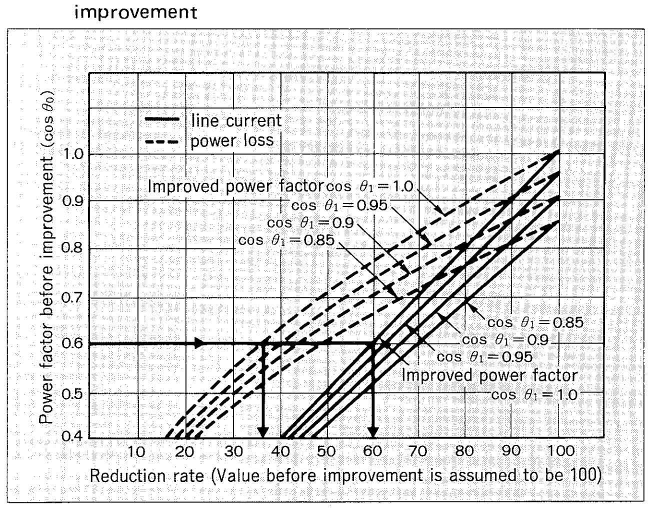


Fig. 2 Line current and power loss reductions by power factor improvement



The automatic power factor regulator model QC06N is very convenient since it is suitable for operating power supply voltage and input voltage detection in the AC 100 to 200V range.

(3) Input polarity diagnosis and input polarity inversion functions: eliminate need to re-wire for reversed input polarity

The QC06N signals an alarm with an LED and a buzzer when the PT input or CT input is connected in reserve polarity. In this case, after the power supply is disconnected, the conventional automatic power factor regulators would require re-wiring. However, the QC06N resumes its normal operation simply by flipping a polarity selection switch.

(4) Minimum on/off switching frequency of capacitors and equalization of on/off switching frequencies amongst capacitors

To control capacitors of different values, the QC06N automatically stores the input capacitance value of each capacitor in a capacitor bank and selectively switches on or off those capacitors to reach a value of capacitance which is the nearest to the reactive power caused by load variation. In controlling capacitors of the same capacitance, the QC06N cyclically changes the capacitor or capacitors to be switched on or switched off. Thus, the on/off switching frequencies of capacitors of different values are minimized and the on/off switching frequencies of the capacitors of the same values are equalized to the prolong life of capacitor bank contacts.

(5) Digital display facilitates recognizing power factor improvement

The QC06N facilitates recognizing power factor improvement in real time by displaying the digital instantaneous value of the power factor or the reactive power while in automatic operation mode. When this display function is not required, the QC06N can be set to "No display".

3. Characteristics

3.1 Ratings and specifications

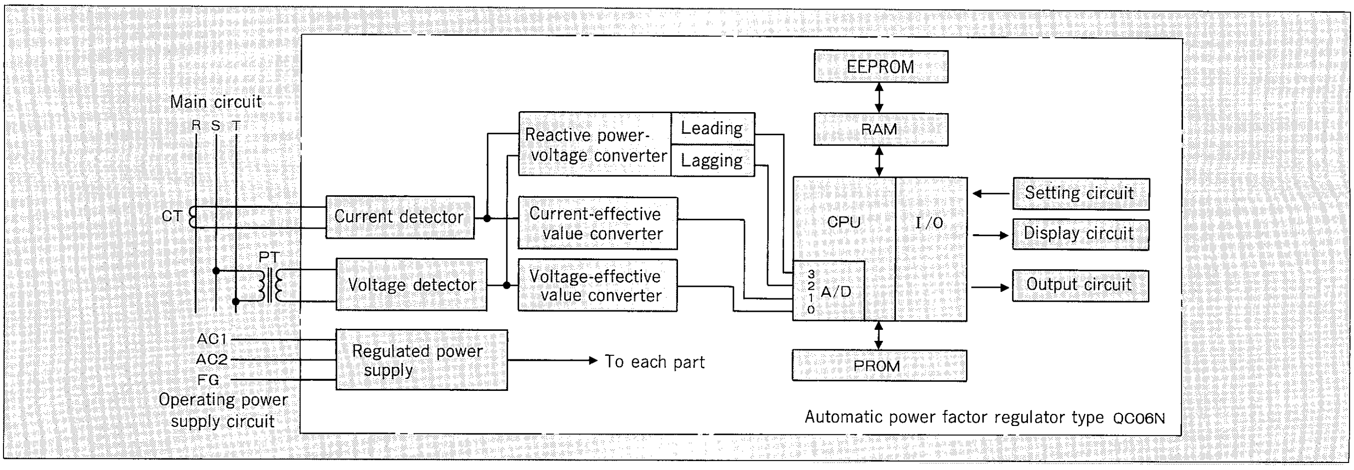
Table 1 lists ratings and specifications of the automatic power factor regulator model QC06N.

Table 1 Ratings and specifications

Item		Specification
Detection input	Frequency	45 to 65Hz
	Rated voltage	100 to 240V (1PT or direct input on low-voltage side)
	Rated current	5A (1CT input)
Operating power	Frequency	45 to 65Hz
	Rated voltage	100 to 240V
	Permissible voltage variation	85 to 264V
Reactive power control range	Switch-on control level (Lag) [kvar]	Automatically set by target power factor entered. (After measurements during delay time, a capacitor of optimum value is switched on. A constant control level of 1A for CT input is maintained.
	Switch-off control level (Lead) [kvar]	(Minimum switch-on capacitance x 1.2) – (switch-on control level) (If value obtained from equation is negative, switch-off control level is automatically set to 0.)
	Correct control range [kvar]	1.2 times Min. capacitor capacitance to be switched on is set automatically
	Operating precision (Total)	±0.04 kvar x PT ratio x CT ratio
Capacitor control output	Connectable No. of banks	Max. of 6 circuits (Contact "a" common on one side)
	On/off switching capacity	250V AC 5A, 30V DC 5A, 100V DC 0.5A
	Service life	Approx. 100,000 operating times under 220V AC (inductive load) closed circuit 20A, power factor 0.7, opened circuit 2A, power factor 0.3 to 0.4
Controlling method		Same value capacitors: cyclic control/Different value capacitors: optimum on/off switching time controlled automatically
Current consumption		Voltage detection curcuit: Max. 4VA, Current detection circuit: Max. 4VA, Operating power circuit: Max. 15VA
Light-load switch-off control value [kW]		When effective power is reduced to the min. load value, capacitors already on are switched off in order of greatest capacitor bank (at intervals of the delayed switch-off time.) For same value capacitors, switch-off is in cyclic order.
	Operation precision	±0.04kW x PT ratio x CT ratio
Switch-on delay time [minutes]		Switching delay time of 1 min., 5 min.* or 10 min. selected by switch
Switch-off delay time [%]		100% or 600% of delayed switch-on time can be selected by switch
Digital display	Power factor [%] display precision	±5% (at CT input is 1A or more and power factor at LEAD or LAG is 60% or more)
	Reactive power [kvar] display precision	±0.04kvar x PT ratio x CT ratio
Incorrect input polarity diagonosis function		Alarm display (7 seg. LED) and Buzzer
Input polarity invert function		Equipped with polarity invert"+*/–" switch
ON-AUTO-OFF switch		"ON-AUTO-OFF" switch is equipped
Operation testing function		Pressing a test button forms a delay circuit, regardless of the input status, and turns on capacitors in order from the smallest capacitance. Same valued capacitors are turned on in cyclic order.
Operating power circuit Over-load protector on PT circuit		Fuse (φ5.2 x 20mm, 3A) Rush-proof or ordinary melting type should be used
Dielectric strength		2,000V AC, 1 minute (between terminals and case, terminal E is excluded)
Mass		2.5kg

Set value marked with the * symbol is set at shipment.

Fig. 3 Circuit configuration



3.2 Configuration and operation

The QC06N detects reactive power in a three phase circuit from the current of one phase and the voltage between the other two phases. An output circuit switches capacitors on and off in response to the detected reactive power. **Figure 3** is a block diagram of the QC06N circuit configuration.

As **Fig. 3** shows, voltage and current values input from a PT and CT pass through detection circuits, effective value converter circuits, and reactive power-voltage converter circuits, before reaching the A-D converter circuit of the CPU, where they are converted to DC values.

The voltage detector, current detector, voltage—effective value converter, current-effective value converter, and reactive power-voltage converter circuits are immune to noise and operate stably because there is a filter in each of the current and voltage detector circuits and the voltage-effective value converter, current-effective value converter, and reactive power-voltage converter are constructed from integrated circuits.

Data necessary for automatic operation such as PT ratio, CT ratio, value of capacitance, and target power factor is set from a setting circuit. This set data is stored in an EEPROM and is not erased even when the operating power supply is disconnected. The CPU is a one-chip microcomputer that calculates the switch-on or switch-off control level in response to load variation, and outputs control signals from its I/O port to output circuit relays and display circuit LEDs. A RAM is use for data storage memory and a PROM for program memory.

3.3 Setting and operation methods

Table 2 lists items which are specified by the setting keys and **Table 3** lists modes of operation set by the function keys. The setting keys are used to switch between modes and to input numerical parameters for each mode. Since a default value of 98% is pre-set as the target power factor in the automatic power factor regulator model QC06N, automatic operation may begin with minimum inputs of capacitance for each capacitor bank, PT ratio and CT ratio. In addition to these keys, the QC06N has inherited useful features from prior automatic power factor regulators such as auto/manual selection switches for capacitor control signals, an operation test button,, a switch-on/

Table 2 Assignment of setting keys

Key name	Mode symbol	Content	Default value *
C1	1	Set capacity of 1st capacitor	0
C2	2	Set capacity of 2nd capacitor	0
C3	3	Set capacity of 3rd capacitor	0
C4	4	Set capacity of 4th capacitor	0
C5	5	Set capacity of 5th capacitor	0
C6	6	Set capacity of 6th capacitor	0
PT	P	Set ratio of PT primary and secondary voltage	0
CT	C	Set ratio of CT primary and secondary voltage	0
Power factor	F	Set target power factor	98%
Light load	L	Set minimum load value of system	0

* The default values are set at shipment.

Table 3 Assignment of function keys

Key name	Description
AUTO/SET	Switches mode to AUTO or SET
ENTER	Enters set value of mode. The set value is stored in the internal memory area and the value indicator will blink while setting. When switching AUTO operation mode to SET mode, set status of 1st capacitors will change. Accordingly, if modifying any other capacitors content or consecutive conformation of set contents, press the ENT. key to switch the blinking display of C1 set value to a steady lit display and go on to the next operation.
DISPLAY	In automatic operation, displays instrumentation values in order from "No display", "Power factor" to "Reactive power". In set mode, press the key to display values such as capacity of 1st capacitor, minimum load value and etc. continueusly for 1 second that is set by the SET button.
RESET	Resets the set value to 0 by pressing this button while the value indicator is blinking. Furthermore, presets set values of all modes as default values by pressing it while blinking for 5 seconds and will notify the operator by sounding a buzzer.

switch-off delay time setting switch and a polarity selection switch. The QC06N is configured to facilitate easy setting of the operation parameters and greater operational functionality.

3.4 Selection of switch-on/switch-off capacitors

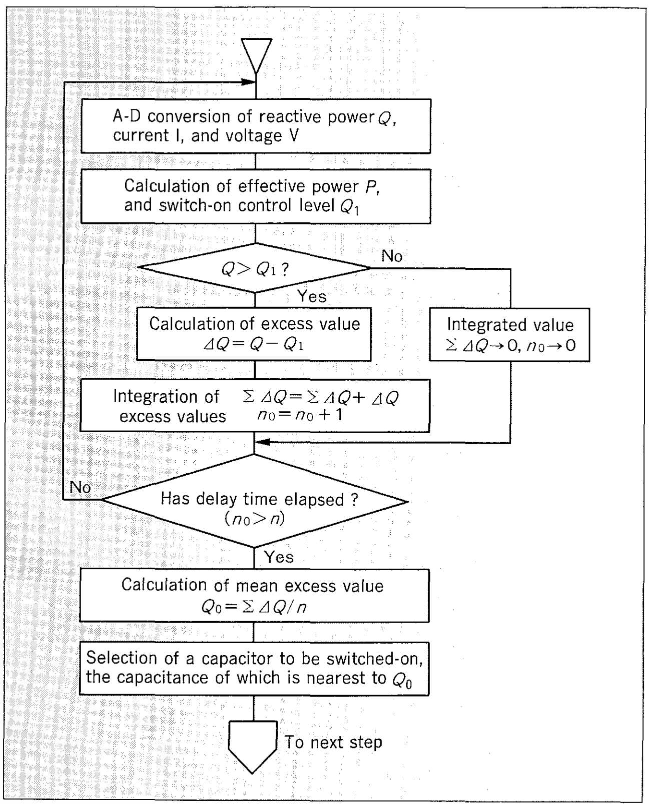
The automatic power factor regulator QC06N evaluates set capacitance values and cyclically selects different capacitors cyclically whose values are equal. When capacitor values differ, the QC06N selects the most appropriate capacitor or capacitors to minimize on/off switching frequencies in response to increase or decrease of reactive power caused by load variation. More specifically, when several capacitors have the same value, which differ from other capacitors in a capacitor bank, the QC06N will cyclically select a capacitor from among the equal valued capacitors.

Figure 4 is a flow chart explaining the switch-on process of the capacitor. The CPU calculates effective power P(kW) and a switch-on control level Q_1 (kvar) based on detected and calculated voltage and current values, a reactive power value, and the set target power factor. However, when the value of current is less than 1 A, the QC06N calculates the switch-on control level by fixing the value of current to 1 A so as to prevent an advance in phase when there is a light load. If the detected reactive power exceeds the switch-on control level Q_1, excess values ΔQs are integrated over a pre-set delay time. After the delay time is over, the integrated value $\Sigma \Delta Q$ is divided by the number of samples, n, to calculate a mean value Q_0. The QC06N then selects a capacitor not yet switched on, the capacitance of which is nearest to Q_0, and outputs an "ON" control signal to the selected capacitor. If the detected reactive power is less than the switch-on control level Q_1, the integrated value $\Sigma \Delta Q$ is cleared to zero. When selecting a capacitor to be switched off, the QC06N calculates a switch-off control level Q_2 in place of Q_1 and selects an appropriate capacitor in accordance with the flowchart of **Fig. 4**. The QC06N calculates the switch-off control level Q_2 from the following equation which considers the switch-on control level Q_1 and the minimum capacitance $C_{\text{ON-MIN}}$(kvar) from among the capacitors which are already switched on.

$$Q_2(\text{kvar}) = 1.2C_{\text{ON-MIN}} - Q_1 \quad \cdots\cdots\cdots\cdots \quad (1)$$

When equation (1) calculates a negative switch-off control level Q_2, the QC06N sets Q_2 at zero so as to switch off the capacitors only when the power factor is leading since it is unnecessary to switch off capacitors when the power factor is lagging. In a manner similar to the case of switch-on, the QC06N calculates the switch-off control level from a mean value of integrated excess leading reactive power. A capacitor which is already switched on and has a value nearest to the calculated switch-off control level is selected, and an "OFF" control signal is output to the selected capacitor. When the detected reactive power is less than the switch-off control level, the integrated excess reactive power value is cleared to zero.

Fig. 4 Flow chart of capacitor switch-on



3.5 Example of capacitor switch-on/switch-off

The on/off switching of capacitors with load variation in electrical equipment consisting of different valued capacitors is explained in the example load pattern of **Fig. 5**.

(1) Switch-on operation

Figure 6 shows an example switch-on operation for the capacitors of different values. When load exceeds the set minimum load value and the reactive power exceeds the switch-on control level on the lagging side, the power factor regulator QC06N indicates this condition with a lagging LED. Next the QC06N samples excess values of lagging

Fig. 5 Example of load pattern

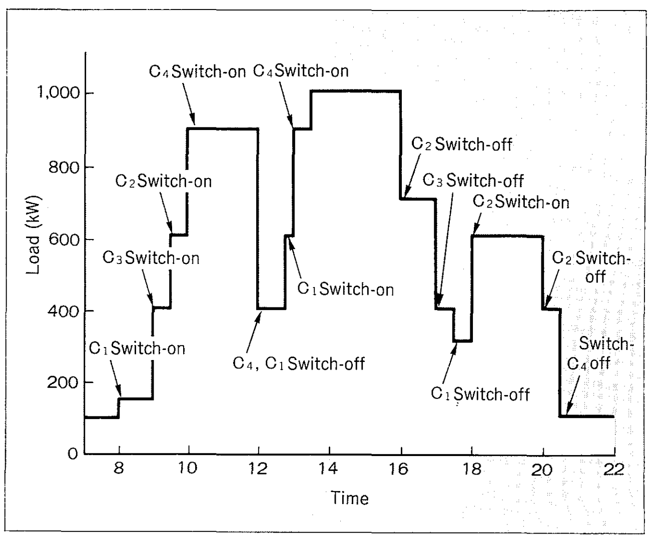


Fig. 6 Example of different valued capacitors being switched on

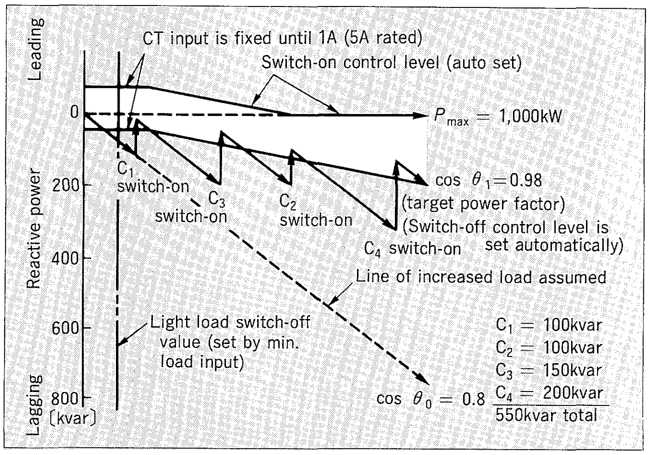
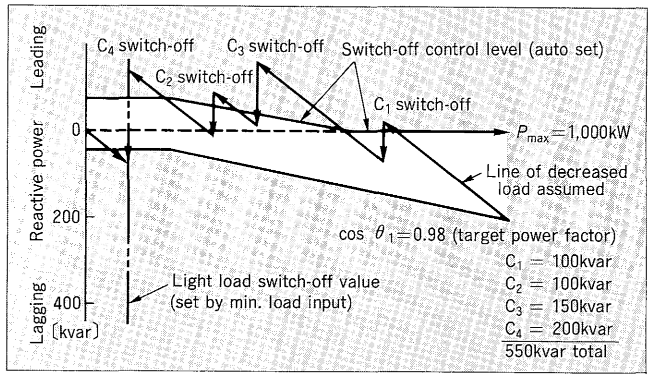


Fig. 7 Example of different valued capacitors being switched off



reactive power during the switch-on delay time and calculates a mean value of the lagging reactive power as soon as 90% of the switch-on delay time has elapsed. The QC06N then selects a capacitor with a value nearest to the calculated mean value, flashes the output indicator LED corresponding to the selected capacitor and then designates a capacitor bank to be switched on. After the switch-on delay time, the QC06N switches on an output relay for capacitor control and changes the output indicator LED from flashing continuously lit. When the reactive power falls below the switch-on control value or when the load is less than the set minimum load value, the integrated value of the excess lagging reactive power is cleared. This value is cleared even if a capacitor has already been selected after 90% of the delay time has elapsed. When the value is cleared, the output indicator LED which is flashing will turn off.

In **Fig. 6**, the capacitors having values nearest to the first load increase (150 kW) are capacitors C_1 and C_2 with values of 100 kvar. Capacitor C_1 is selected to be switched on in accordance with the aforementioned cyclic operation. Then C_3, C_2, and C_4 are sequentially selected to be switched-on since they have the nearest capacitance to the load increase in order to maintain the power factor at the target value of 0.98 or more. When the capacitance of a single capacitor is insufficient to cover the excess lagging reactive power value and the reactive power still exceeds the switch-on control level, the switch-on operation will be repeated.

(2) Switch-off operation

Figure 7 shows an example of switch-off operation for capacitors of different values. When the load decreases and the leading reactive power is increased by the switched-on capacitor to exceed the switch-off control level on the leading side, the power factor regulator QC06N indicates this condition with a leading LED. The QC06N selects a capacitor, from among the already switched on capacitors, whose value is nearest to the excess reactive power value corresponding to the switch-off control level. After 90% of the switch-off delay time has elapsed, the QC06N will flash the output indicator LED corresponding to the selected capacitor, and then designate the bank to which the selected capacitor belongs. When the switch-off delay time has elapsed, the QC06N switches off the corresponding capacitor control output relay and turns off the flashing LED. In **Fig. 7**, capacitors C_1, C_3 and C_2 are sequentially selected for switch-off in response to load decreases.

If the load further decreases below the light load switch-off value, the QC06N illuminates the light load indicator LED and switches off, in order of decreasing capacitance, all switched on capacitors at every set switch-off delay time interval. In **Fig. 7**, only C_4 is subject to the light load switch-off operation.

4. Conclusion

As described above, the new type automatic power factor regulator model QC06N controls the power factor with a minimum of on/off capacitors switching frequency. Conventional power factor regulator controlled the power factor with capacitor control signals in a fixed on/off order. An appropriate value of capacitance was obtained after several on/off switching operations.

The need for automatic control devices to control capacitance for power factor improvement, the so-called automatic power factor regulator, is increasing rapidly due to power and energy savings. Fuji Electric is continuing its effort to develop and improve the automatic power factor regulator.