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(54) Title: A REACTIVE POWER COMPENSATION SYSTEM AND A METHOD OF CONTROLLING A REACTIVE POWER COMPENSATION SYSTEM

(57) Abstract: A reactive power compensation system of the type having thyristor-switched capacitors, in which a thyristor and a diode are connected in anti-parallel configuration, wherein the or each capacitor has a discharge resistor connected in parallel therewith.

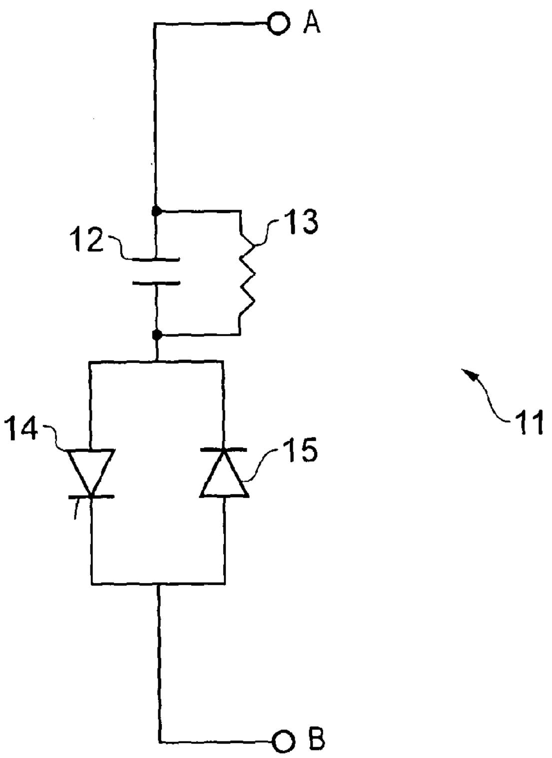

FIG. 1

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A REACTIVE POWER COMPENSATION SYSTEM AND
A METHOD OF CONTROLLING A REACTIVE POWER COMPENSATION SYSTEM

The present invention relates generally to a reactive power compensation system suitable for application to single phase or multi-phase electrical networks.

The power factor of an AC electric power system having loads with resistance, inductance and capacitance is the ratio of the real power and the apparent power in the circuit, and is a dimensionless number between 0 and 1. The real power is the capacity of the circuit to perform work and the apparent power is the vector sum of real and reactive power; it is measured as the product of the root mean square of current and voltage in the circuit. Due to energy stored in the load and returned to the source, or due to a non-linear load that distorts the wave shape of the current drawn from the source, the apparent power may be greater than the real power so that, in an electric power system, a load with a low power factor draws more current than a load with a high power factor for the same amount of useful power transferred. Even though the current associated with reactive power does no work at the load, it heats the wires, wasting energy. Conductors, transformers and generators thus have to be dimensioned to carry the total current, not just the current that does useful work. At higher currents the energy lost in the distribution system is greater and a distribution network supplier typically charges more to industrial or commercial users if their equipment has a lower power factor.

Power factor correction is intended to bring the power factor of an AC power circuit as close as possible to unity by supplying reactive power of opposite sign. This usually involves switching in capacitors which act to cancel the inductive or capacitive effects of the load. An automatic power factor correction unit has blocks of capacitors in steps which are switched to ensure that the power factor stays at the highest possible level despite variations in the load. In addition to this, non-linear loads change the shape of the current wave form from a sine wave to some other form having harmonic components in addition to the original fundamental frequency. Filters in the form of inductors or capacitive/inductive circuits are then necessary to prevent harmonic currents entering the supply system and degrading the power factor.

One prior art power factor correction system is described in US patent application 2010/0109616 which describes a thyristor switched capacitor system comprising at least one diode and thyristor set connected in parallel in each phase for a multi-phase system, with the diode being in an anti-parallel configuration with the thyristor and at least one capacitor being connected in series with the diode and thyristor set in each phase for a multi-phase system. There is at least one surge current controlling reactor in each phase of a multi-phase system. Thyristors allow an almost transient free fast switching of the capacitor, which is essential to achieve efficient reactive power compensation. The surge current controlling reactor is required in order to protect the thyristor by preventing the rate of change of current in the thyristor exceeding its maximum rated level. The presence of such a reactor, however, increases the cost of the power factor corrector system and also involves an introduction of varying delays in the switching of the capacitor to compensate for distortions in the timing, which complicates the calculation of the triggering points for the thyristor control system.

Moreover, if the capacitor banks are installed in harmonic rich networks harmonic amplification takes place and hazardous resonance conditions can arise due to the slow response and delayed external switching command of a reactive power compensation system.

The present invention seeks to provide a reactive power compensation system, and a method of controlling a reactive power compensation system, in which it is possible to influence the power factor of a consumer load to a point approaching unity, whilst at the same time enabling utilisation in the system of components of lower power rating by optimization of switching times in capacitor banks and minimisation of heating effect by appropriate configuration of the system. This makes it possible to achieve an effectively continuous VAR utilising fast thyristor switched capacitors incorporated with a fast reactive power control relay. Embodiments of the invention provide fine controlled delta-connected thyristor switched capacitor banks usable in industrial and commercial reactive power compensation systems. This provides a fast response to load variations, and provides continuous capacitor current in consecutive switchings, thereby overcoming power quality and safety issues such as slow response, long transients and increased harmonics.

The reactive power compensation system of the present invention is therefore optimized in terms of fast response to sudden load variations, providing continuous reactive power required by varying loads, and reducing the amount of heat dissipation and unwanted harmonics.

In prior art reactive power compensation systems the on/off command signal has to be delayed in order to compensate for potential hazardous resonance conditions and as a consequence of the slow response of the capacitor banks. The present invention provides means by which these problems are overcome.

According to one aspect of the present invention, therefore, there is provided a reactive power compensation system of the type having thyristor-switched capacitors, in which the connection and disconnection of the capacitors to the load is determined by a reactive power control unit whereby to supply substantially continuous reactive power to the load in response to the load variation.

The means by which this is achieved constitute the fundamental features of the present invention. In practice, capacitor banks may be connected to the bus of the low voltage main distribution board from where the loads are fed and/or at the load centres within the installation. The number of capacitor banks in a compensation system, and their rated values, is determined according to the total installed inductive load of the system.

In another aspect, the present invention provides a reactive power compensation system of the type having thyristor switched capacitors, in which a thyristor and a diode are connected in anti-parallel configuration, wherein the or each capacitor has a discharge resistor connected in parallel therewith.

In one embodiment; a reactive power compensation system of the invention further includes a micro controller acting to correct phase displacement caused by hysteresis and the discharge resistors whereby to obtain optimum capacitor switching times from the detected zero volt crossing instants.

It is preferred that the switching of the capacitors is triggered without the introduction of delay from the detection of the zero crossing instants.

The present invention is applicable to single phase or multi-phase systems.

According to a particular aspect of the present invention, a multi-phase reactive power compensation system of the type having thyristor-switched capacitors has harmonic filters connected in series with the thyristor-switched capacitors in respective arms of a delta type connection configuration.

A preferred embodiment of the invention comprises a multi-phase reactive power compensation system in which the harmonic filters are inductors.

In such a multi-phase reactive power compensation system the capacitors preferably have discharge resistors connected in parallel thereto and it is likewise preferred that the thyristors form part of a thyristor-diode set with the thyristors and diodes connected in anti-parallel with one another.

The present invention also comprehends a method of controlling a reactive power compensation system of the type having thyristor-switched capacitors, preferably with discharge resistors, in which the phase angle during load variation is detected and switching commands are delivered to the tyristors without any delay, whereby to deliver substantially continuous reactive power to the load.

In a preferred method according to the invention the phase displacement caused by hysteresis and by the discharge resistors is corrected by a micro controller to obtain zero volt crossing instants.

Prior art thyristor-switched capacitor-type reactive power compensation systems have required the presence of surge reactors to limit the surge current due to false triggering to protect the thyristor in order not to exceed the rate of change of current of the thyristor in its maximum rating.

Embodiments of the present invention will now be more particularly described, by way of example, with reference to the accompanying drawings in which:

Figure 1 is a circuit diagram illustrating a single phase thyristor-switched capacitor reactive power compensation system acting between two network points A and B between which the operating voltage of the network appears;

Figure 2a illustrates the supply voltage across the capacitor bank;

Figure 2b illustrates the peak value of the trapped charge voltage in the capacitor bank;

Figure 3 illustrates the currents through respective capacitor switching banks assigned as 5 kVAR and 10 kVAR;

Figure 4 illustrates a multi-phase reactive power compensation system formed as an embodiment of the present invention;

Figure 5 is another embodiment of the invention having three reactive power compensation banks; and

Figure 6 is a functional control scheme for achieving continuous VAR in a reactive power compensation system having thyristor-switched capacitors.

Referring now to Figure 1, a single phase reactive power compensation system employing thyristors as switching elements for capacitors is illustrated. As mentioned above, the system is connected between points A and B of a network, and comprises a capacitor 12 having a parallel-connected discharge resistor 13 in series with a switching thyristor set comprising a thyristor 14 and diode 15 in anti-parallel.

As is known, thyristors allow almost transient free fast switching of the capacitor. The discharge resistor 13 makes it possible to form a circuit as described in relation to Figure 1 without requiring a surge reactor as used, for example, in prior art reactive power compensation systems such as that described in US patent application 2010/0109616, and which are necessary in that prior art system in order to ensure that the maximum rate of change of current rated for the thyristor is not exceeded. The function of the discharge resistor 13 is to bring the stored charge in the capacitor 12 to a safe level when the capacitor 12 is de-energized. Of course, although illustrated as a single capacitor in Figure 1, it will be appreciated that in a practical system the capacitor 12 may, in fact, be a bank of capacitors. The reactive power compensation system illustrated in Figure 1 employs a gate control scheme which takes the hysteresis into account for zero volt crossing detection due to electrical noise present in AC power networks and provides precise pulses to eliminate false triggering of the thyristors. Phase displacement caused by hysteresis, and the discharge resistors, is again corrected by means of a micro controller (not illustrated) to obtain the optimum zero volt crossing instants. This explains why the large size surge reactor required in the prior art systems can be eliminated. Of course, in other embodiments (not shown) a surge reactor of much smaller size than required by the prior art may be utilised in certain circumstances.

The anti-parallel connection of the thyristor 14 and the diode 15 ensures that the trapped charge in the capacitors is always of a given polarity and, as will be explained below, the capacitor 12 can be switched on with minimum transients at the instant when the supply voltage is having its peak value providing it was initially charged to that peak value of the supply voltage. Thus, if:

$v(t)= V_{max}\sin(\omega t)$,	where v(t) is AC supply voltage,
V_{ci},	is the trapped capacitor initial voltage,
$v_{th}(t)$	is the voltage across thyristor anode and cathode.

then for transient free switching $v_{th}(t)$ must be zero, $v_{th}(t)=0$ at the switching instant which is:

$v_{th}(t) = V_{max}\sin(\omega t) - V_{ci},$ (1)

but due to trapped voltage,

$V_{ci} = -V_{max}$ and $v_{th}(t) = V_{max}(1 + \sin(\omega t)).$ (2)

If the firing pulse is applied at the instant when $\omega t = 3\pi/2$ then $v_{th}(t)=0$. Capacitor begins to discharge. The capacitor voltage for $\omega t>270$ will be:

$Vc(t) = -V_{max}\cos(\omega t)$ (3)

and the capacitor current will be:

$i_c = C\,V_{max}\sin(\omega t)$ (4)

from which it will be seen that the current delivered by the capacitor 12 commences from zero without any transient and without capacitive current being interrupted.

Because the charge in the capacitor 12 is always trapped in the capacitor bank at the same polarity, in consecutive capacitor bank switching the capacitor currents start from zero and increase sinusoidally in consecutive switching instants. This can be seen from Figure 2a which shows the supply voltage across the capacitor 72, whilst Figure 2b shows the peak value of the trapped charge voltage. The total capacitor bank currents are therefore continuous. Figure 3 illustrates this graphically with the rated values of the consecutive switching banks being assigned as 5 kVAR and 10 kVAR and their respective bank currents illustrated as switching instants t1, t2, t3 are passed. As will be appreciated from the lower line in Figure 3, the currents sum continuously with no singularity, for example at t2 or t3 where switching in of the 10 kVAR or at t3 where switching out of the 5 kVAR capacitive bank occurs.

In Figure 4, which illustrates a three-phase delta-configuration reactive power compensation system, the reference numerals for components corresponding to those in Figure 1 will be used, with $_{R,S}$ and $_{T}$ identifying those related to the individual phases R, S and T of the network. *Here, each arm of the delta configuration has a capacitor 12 with parallel connected discharge resistor 13 in series with a thyristor/diode set 14, 15. Between the nodes of the delta and the reactive power compensation system in the* arm are connected respective harmonic filters 16_R, 16_S, 16_T. Connection in the delta arms minimizes the heat dissipation in the case of harmonic reduction. The average heat dissipation within a thyristor is related to thyristor current. Since the thyristor-switched capacitors are connected in delta configuration, the RMS current through the thyristor-switched capacitor is 1.73 times less than the line current, thereby reducing the heat dissipation significantly. In a conventional reactive power control system the external signal from the reactive power control relay (not shown) applied to the thyristor control gate has to be delayed to prevent resonant oscillations, and this makes the process inefficient. In Figure 5 there is shown a fast reactive power control relay 90, the function of which is to detect the phase angle during load variations and supply the external on/off commands to the control gates of the thyristor switched capacitors without any delay. This improves the reactive power compensation process significantly.

The system illustrated in Figure 5 has three sets of reactive power compensation banks 17, 18, 19 connected to the network lines RST to accommodate different power levels. In practice, the number of capacitor banks in a compensation system and their rated values are determined according to the total installed inductive load.

Figure 6 illustrates a functional control scheme by which the signals for triggering the thyristors can be generated. Here, a thyristor-switched capacitor reactive power compensation system generally indicated 18 follows the same pattern as that described in relation to Figure 1, but with the addition of a harmonic filter 16. Again, the same reference numerals are used to identify the same or corresponding components as in the embodiment illustrated in Figure 1. In comparison with Figure 4, the network 18 of Figure 6 corresponds to one arm of the delta configuration, in this case between phases R and S.

The three phases R, S, T of the network are applied to a three-phase signal processing circuit 20, the output of which is fed to a zero crossings detector 21 which, upon triggering at zero crossings, feeds a signal to a timing calculation circuit 22 driven by a timing control unit 23. In order to avoid transients upon switching of the thryistors the system aims to ensure that switching takes place when the initial charge voltage across the capacitor bank units is equal to the AC supply voltage across them. This occurs when the AC supply voltage reaches a peak value due to the trapped charge in the capacitor banks. As is known, the peak value of the AC supply occurs half way through the half-cycle from the zero crossing point. In a 50Hz supply this amounts to 5ms whereas at 60Hz the time interval is 4.16ms.

The timing calculation circuit 22 thus calculates from the zero volt crossing information from the detector 21 exactly when the supply voltage reaches a peak value. The microcontroller of the timing calculation circuit 22 has a 16 Bit timing resolution.

In order to eliminate the effect of noise, which can cause false zerocrossing detection, the zero crossing instants are offset by between about 200µs and 300µs by use of a hysteresis effect in the crossings detector 21. This offset is taken into account by the microcontroller of the crossings detector 21 in order to determine the precise peak value instants of the AC supply voltage.

External on/off request signals are generated by a unit 24 in response to the load variations, and this feeds a signal to the on/off control unit 25 which receives its input from the timing unit 22 and which provides an output signal to a triggering pulse generation unit 26 which generates triggering pulses of appropriate magnitude and polarity to apply to the gate of the thyristor 14. This avoids creation of oscillations since its switching instant takes place when the capacitor current is zero.

As described above, optimization of the reactive power compensation system described means that a cost-effective way of achieving substantially continuous VAR has been developed utilising fast thyristor-switched capacitors incorporated in a unit having a fast reactive power control relay. Conventional power factor control units known until now cannot generate the output signal to switch on or off the capacitor banks *without a minimum delay of the one second, although in practice this delay is often chosen to be as much as five seconds in order to prevent oscillations in the AC power network.* As a consequence there are often moments when the reactive power compensation is interrupted. By contrast, in the system of the present invention the load driven fast reactive power control unit 25 generates the output signal without any delay both when turning on and when turning off. Thus, at all times when the load is connected to the network one or more capacitor bank is connected and stays connected as long as the load is not disconnected.

CLAIMS

1. A reactive power compensation system of the type having thyristor-switched capacitors, in which a thyristor and a diode are connected in anti-parallel configuration, wherein the or each capacitor has a discharge resistor connected in parallel therewith.

2. A reactive power compensation system as claimed in claim 1, further including a microcontroller acting to correct phase displacement caused by hysteresis and the discharge resistors whereby to determine from the zero volt crossing instants the optimum switching instant.

3. A reactive power compensation system as claimed in claim 1 or claim 2, in which the switching of the capacitors is triggered without delay from the determination of the optimum switching instants after detection of the zero crossing instants.

4. A reactive power compensation system of the type having thyristor-switched capacitors, in which the connection and disconnection of the capacitors to the load is determined by a reactive power control unit whereby to supply substantially continuous reactive power to the load in response to load variation.

5. A multiphase reactive power compensation system of the type having thyristor-switched capacitors, in which harmonic filters are connected in series with the thyristor-switched capacitors in respective arms of a delta type connection configuration.

6. A multiphase reactive power compensation system as claimed in claim 5, in which the harmonic filters are inductors.

7. A multiphase reactive power compensation system as claimed in claim 5 or claim 6, in which the capacitors have discharge resistors connected in parallel thereto.

8. A method of controlling a reactive power compensation system of the type having thyristor-switched capacitors having discharge resistors, in which the phase angle during load variation is detected and switching commands are

delivered to the thyristors without any delay whereby to deliver substantially continuous reactive power to the load.

9. A method as claimed in claim 8, in which phase displacement caused by hysteresis and the discharge resistors is corrected by a microcontroller to obtain optimum capacitor switching times from the zero volt crossing instants.

10. A reactive power compensation system substantially as hereinbefore described with reference to, and as shown in, the accompanying drawings.

11. A method of controlling a reactive power compensation system substantially as hereinbefore described with reference to the accompanying drawings.

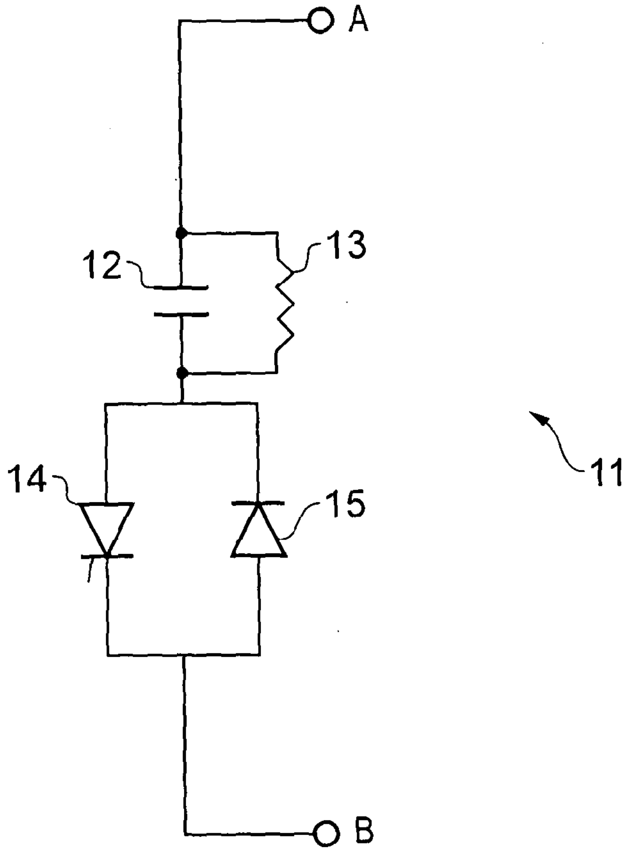

FIG. 1

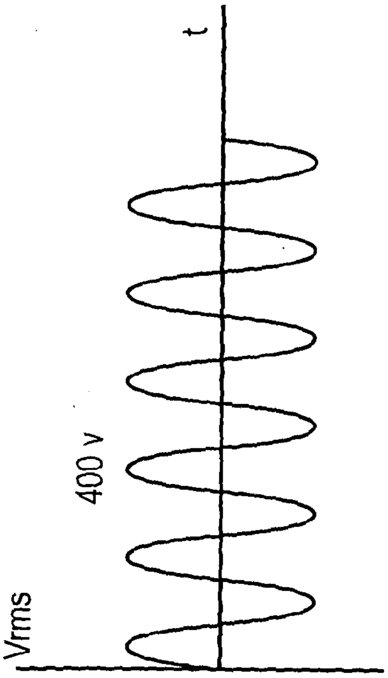

FIG. 2A

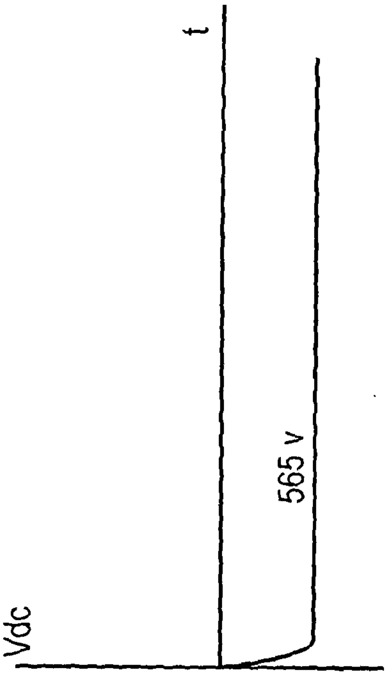

FIG. 2B

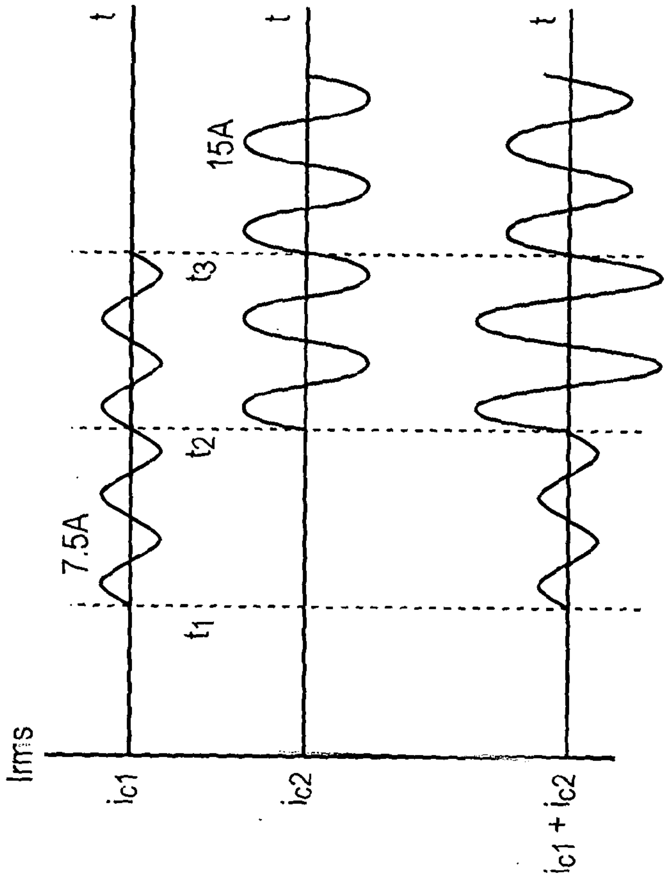

FIG. 3

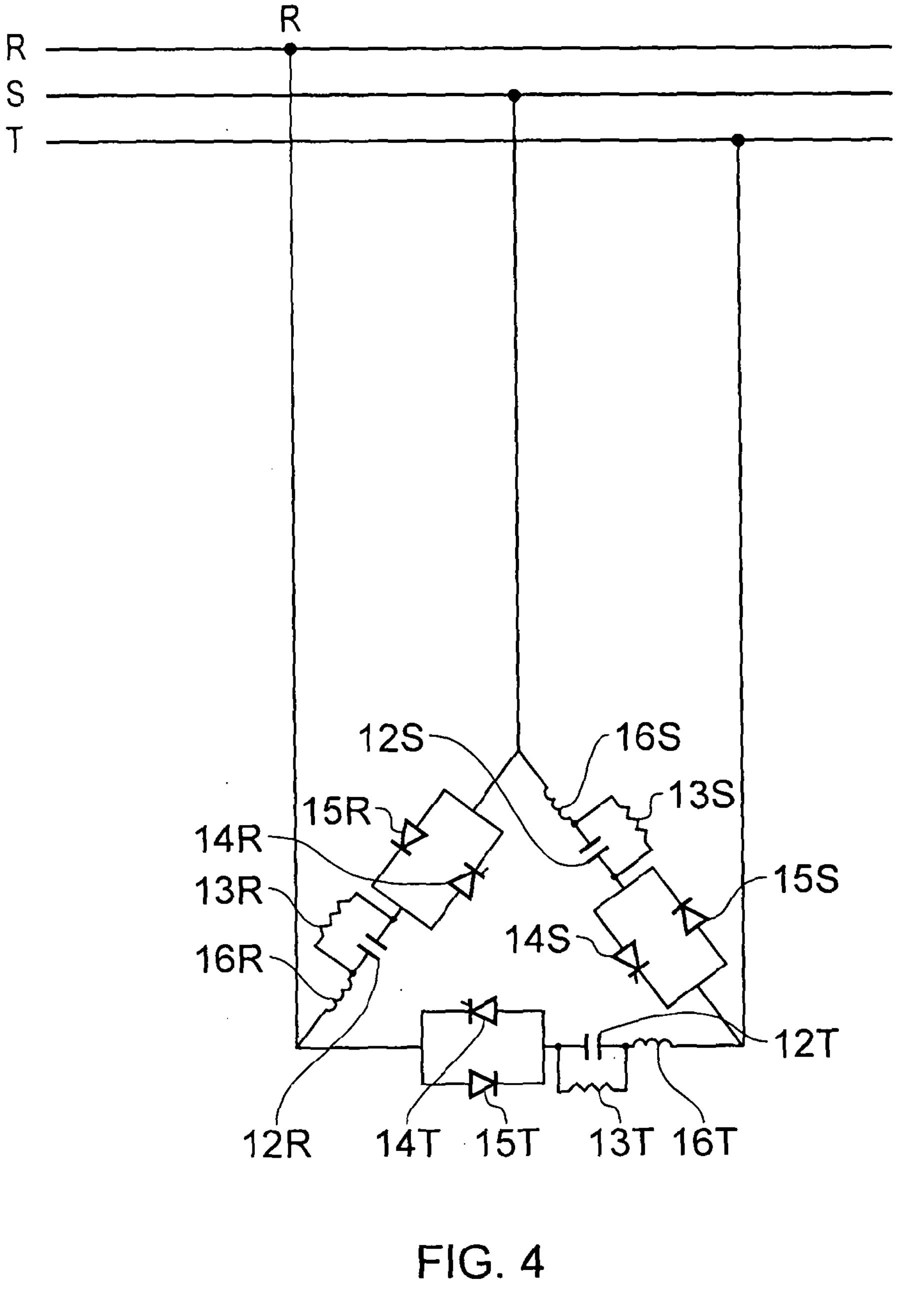

FIG. 4

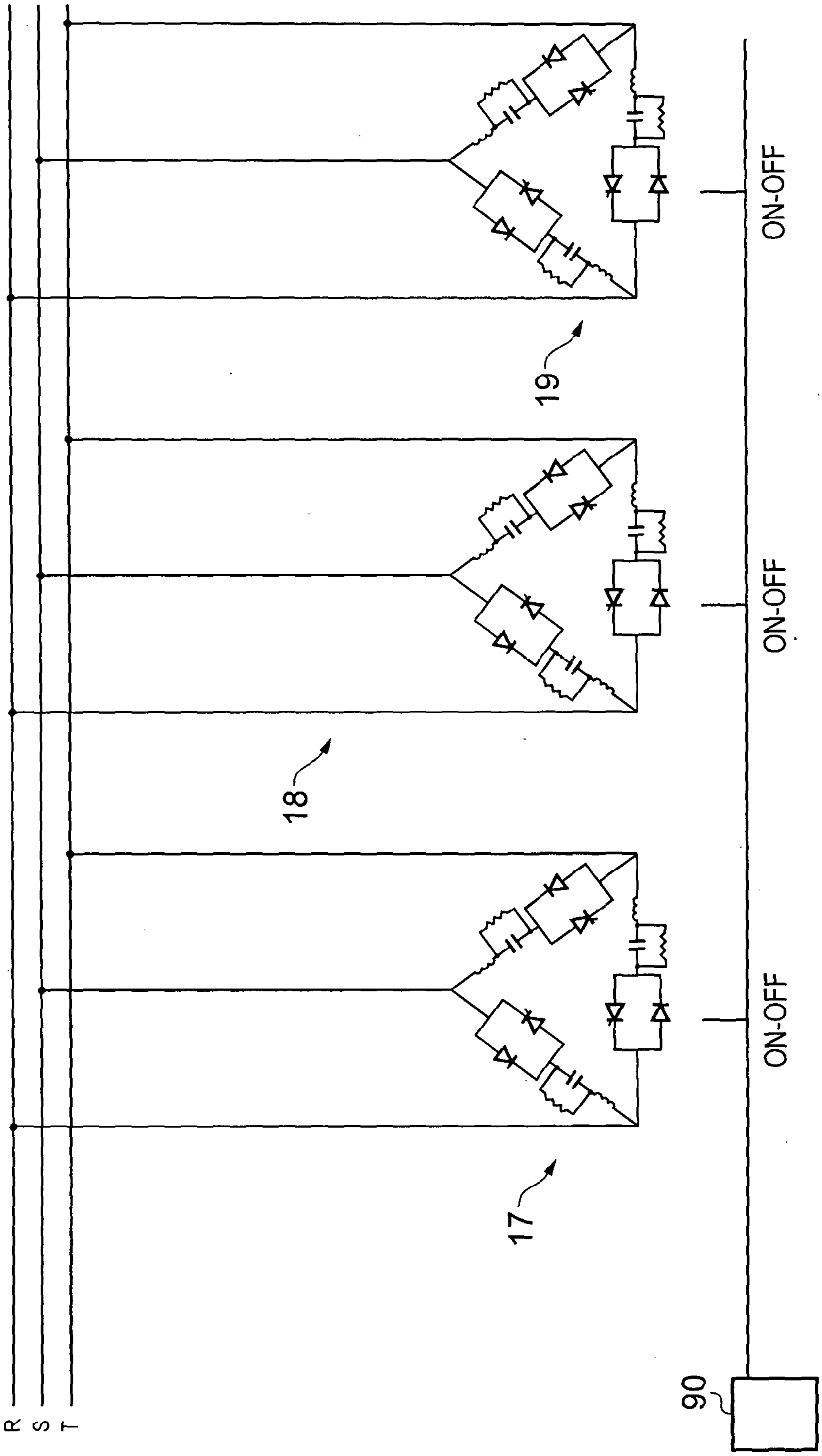

FIG. 5

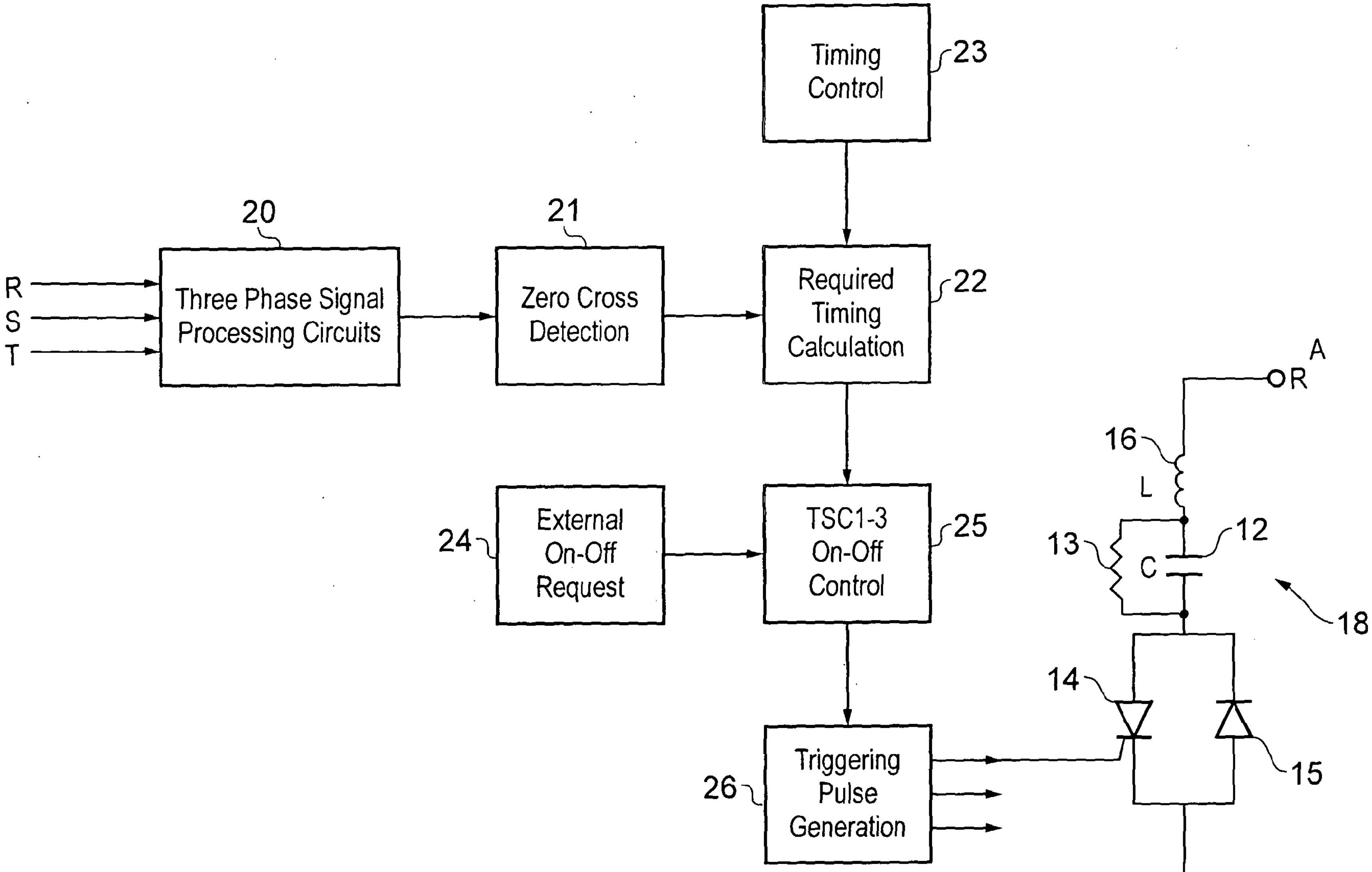
R
S
T
20
Three Phase Signal Processing Circuits
21
Zero Cross Detection
23
Timing Control
22
Required Timing Calculation
24
External On-Off Request
25
TSC1-3 On-Off Control
26
Triggering Pulse Generation
A
R
16
L
13
C
12
18
14
15
B
S

FIG. 6