

June 8, 1954

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SYNCHRONOUS ELECTRIC SWITCHING APPARATUS

Filed Dec. 4, 1950

2 Sheets-Sheet 1

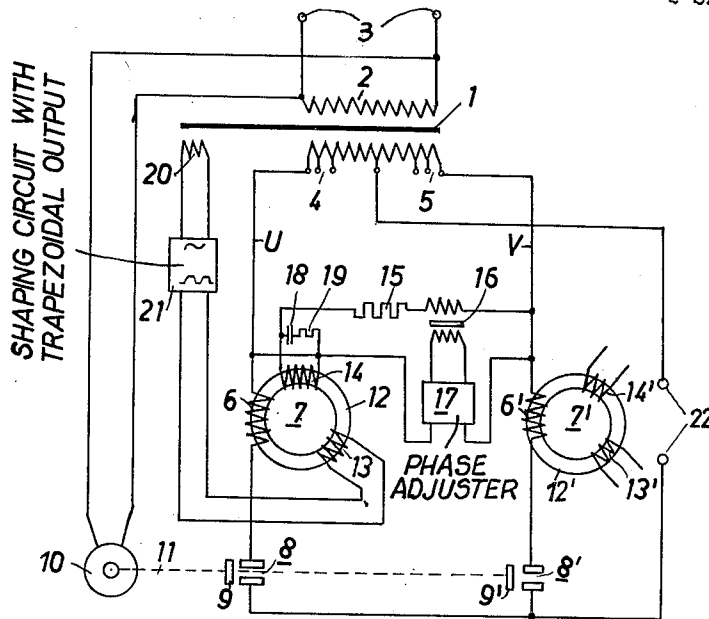


Fig. 1

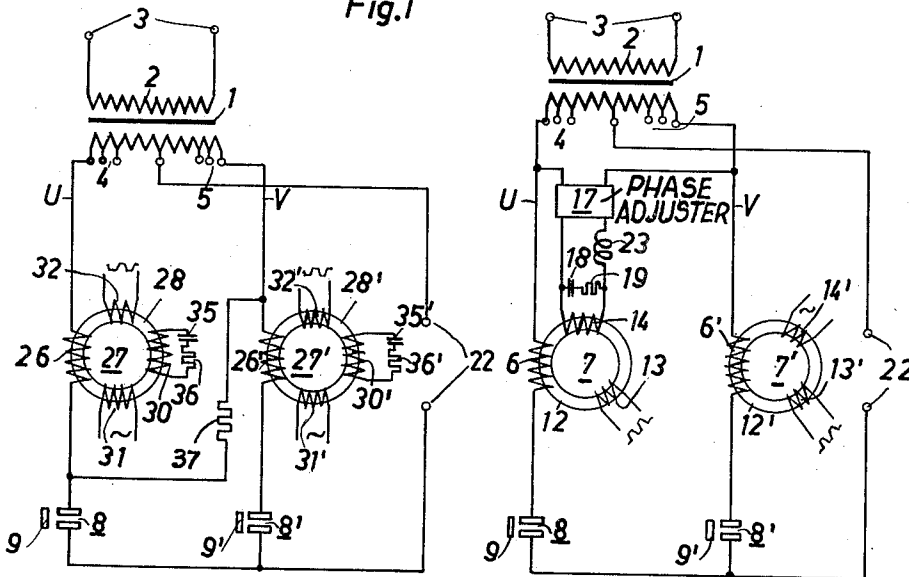


Fig. 3

Fig. 2

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FIG. 4

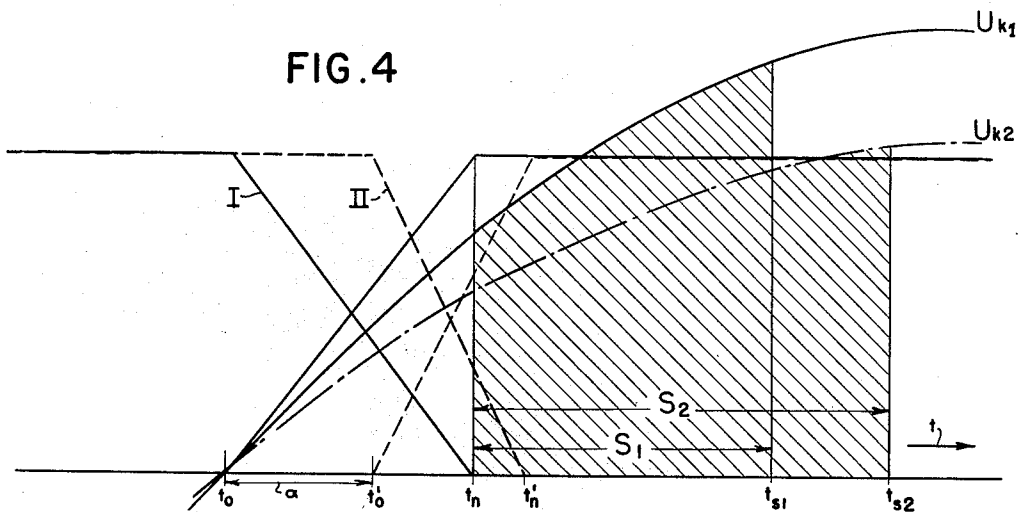
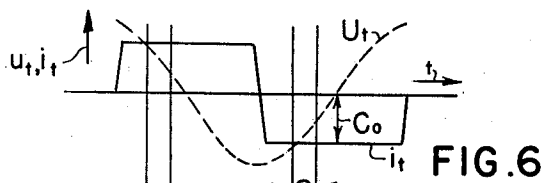
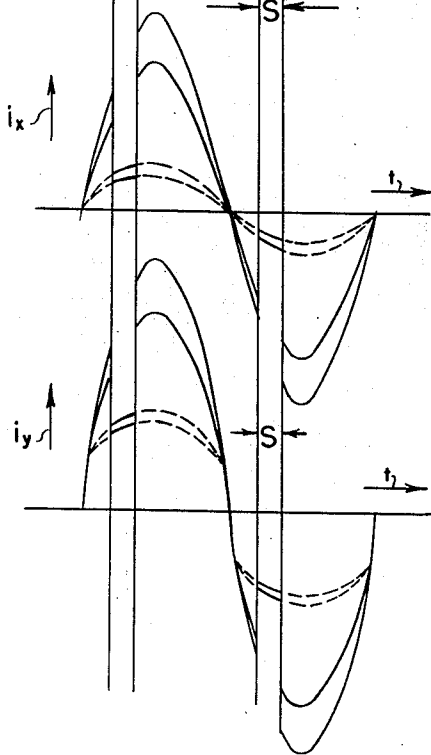
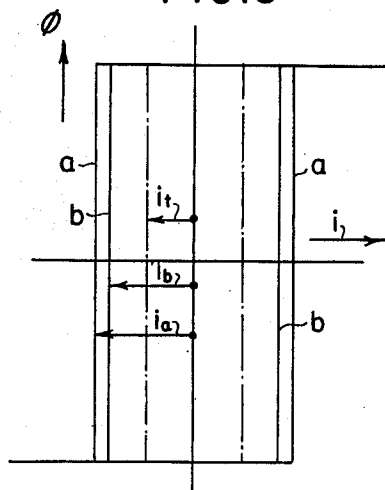


FIG. 5



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SYNCHRONOUS ELECTRIC SWITCHING
APPARATUS

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My invention relates to apparatus for switching alternating-current circuits by means of synchronously operating contacts which open and close at moments near the current zero passages and are series connected with saturable commutating reactors whose periodic, desaturation-responsive increase in reactance minimizes the current-carrying duty of the contacts at these moments. The saturable commutating reactors in such apparatus have been premagnetized by separate bias excitation in order to reduce to substantially zero the residual current, i. e. the reactance-reduced current flowing at the contact opening and closing moments.

Difficulties may be encountered with such apparatus, especially periodic multiphase converting apparatus such as contact rectifiers, if the operating voltage is adjustable or controllable, for instance, by means of a stepped input transformer. These difficulties are due to the fact that a change in operating voltage causes a corresponding change in commutating voltage. That is, the magnetization speed of the commutating reactor changes and so does the width of its hysteresis loop so that a different premagnetizing current would be required to keep the residual contact current at zero during the circuit opening interval. As a result, the residual current flowing through the contact at the opening moment is not constant but varies with changes in operating voltage and may exceed the limit at which a migration of contact material between the separating contact pieces will occur, thus reducing the useful life of the apparatus.

It is an object of my invention to eliminate these difficulties and to provide synchronous contact apparatus with premagnetized commutating reactors that automatically and elastically adjust their premagnetization to optimum conditions regardless of changes in input voltage.

To this end, and in accordance with a feature of my invention, I provide the commutating reactor with two pre-excitation circuits and apply to these circuits a sinusoidal current and a trapezoidal current respectively so that the reactor premagnetization is the resultant of these two mutually superimposed currents, both being synchronous with the voltage of the current to be controlled or translated by the apparatus.

The foregoing and more specific objects and features of the invention will be apparent from the drawings, in which Figs. 1, 2 and 3 show the schematic circuit diagrams of three respective bi-phase rectifying apparatus according to the invention; and in which Figs. 4, 5, and 6, are co-

ordinate diagrams illustrating the operation of the invention.

The contact rectifier according to Fig. 1 has a power transformer 1 whose primary 2 is energized from terminals 3 for connection to an alternating-current supply line. The transformer has secondary windings 4 and 5 connected to the phase circuits U and V of the rectifying equipment proper. As shown, the power transformer may have tapped or stepped windings in order to permit adjusting or controlling the voltage to be rectified. Connected in the phase circuit U is the main reactance winding 6 of a commutating reactor 7 in series with a contact device 8 whose movable contact member 9 is periodically actuated by a synchronous motor 10 with which it is connected by a suitable transmission here schematically indicated by a broken line 11. The motor 10 is connected with the supply terminals 3 and operates in synchronism with the line current. The phase position of the movable contact 9 is such that it opens and closes the phase circuit U at moments in the neighborhood of the current zero passages. The commutating reactor 7 has a saturable core 12 with two premagnetizing bias windings 13 and 14. Winding 14 is connected in a cross-phase circuit which extends across the phase circuits U and V and includes in series with winding 14 a resistor 15 and the secondary of an auxiliary transformer 16. The primary winding of the transformer 16 is impressed by the same phase-to-phase voltage which is also effective across the main reactance winding 6 of the commutating reactor. To this end, the primary of transformer 16 is connected across the phase leads U and V, if necessary through phase adjusting means as schematically represented at 17. A shunt circuit of a capacitor 18 and a series resistor 19 is preferably connected across the bias winding 14. The sinusoidal current flowing through the winding 14 is produced by the sum of the interphase voltage between phases U, V and the auxiliary voltage impressed through the transformer 16. Its phase coincides approximately with that of the voltage across the phase leads.

The bias winding 13 of the commutating reactor is supplied with a trapezoidal or approximately square wave shaped current. Various circuits and the like means for producing trapezoidal currents are well known as such and are applicable for the purposes of the invention. Such circuits, for instance, may be primarily energized by sinusoidal voltage and may contain pulse shaping or wave clipping members to produce a

trapezoidal output current. For instance, as shown in Fig. 1, coil 13 may be connected to the alternating-current supply by an auxiliary secondary winding 20 of the power transformer 1, and an amplitude limiting or otherwise wave shaping device as schematically indicated at 21 may be interposed. It will be recognized that the voltage of the secondary winding 20 is substantially constant and does not participate in the changes of rectifier voltage due to a change in the tap setting of the transformer windings 4 and 5. In this manner winding 13 is excited by a trapezoidal current wave having the same frequency as the sinusoidal current that flows through the winding 14 but having a substantially constant amplitude for all available rectifier input voltages. The possibility of producing and applying trapezoidal currents has been mentioned previously (see the article by Dr. W. Schilling, in the German periodical *Electrotechnik und Maschinenbau*, 1941, page 397) so that a description of other applicable circuit means appears unnecessary.

The phase circuit V includes in series the main reactance winding 6' of a commutating reactor 7' in series with a contact device 8' whose movable contact member 9' is actuated by the motor 10 in the necessary phase relation to the contact device of phase U to provide for proper commutation and rectification. The output terminals 22 of the apparatus are connected to the mid-point of the secondaries 4, 5 and to a mid-point between the contact devices 8 and 8', respectively. The core of commutating reactor 7' has two bias windings 13' and 14' which are energized in the same manner as the corresponding windings 13, 14 of reactor 7, the necessary circuit connections being not shown because they are a duplicate of those already described. It will be understood that in circuits with three or more phases each phase is equipped with a commutating reactor with two premagnetizing coils connected and energized as described in the foregoing, the various cross-phase circuits being arranged in a cyclical relation to one another.

The modified contact rectifier apparatus shown in Figs. 2 and 3 are to some extent similar to the above-described apparatus of Fig. 1, corresponding elements being denoted in all figures by the same respective reference numerals. In distinction from the apparatus of Fig. 1, however, the modification of Fig. 2 is equipped with reactor-stabilized premagnetizing circuits, instead of the cross-phase circuit of Fig. 1, for providing the sinusoidal premagnetizing current for windings 14 and 14'. As shown, the winding 14 of the commutating reactor 7 is excited in series connection with a reactor 23 which enforces a practically sinusoidal wave shape of the current flowing through winding 14. This current must be approximately in phase with the voltage across the phase conductors U and V. Since the stabilizing reactor 23 produces a large phase displacement between current and driving voltage, suitable phase shift means 17 must therefore be interposed between the reactor-stabilized circuit and the energizing transformer or current supply line. The winding 14' of the commutating reactor 7' is energized in the same manner. In all other respects the apparatus is designed and operative in the manner described with reference to Fig. 1.

The modification shown in Fig. 3 has in its phase U the main reactance coil 26 of a commutating reactor 27 whose core 28 is equipped with three additional windings 30, 31 and 32. The

auxiliary circuit connected to winding 30 comprising a capacitor 35 and a resistor 36, is a damped oscillatory circuit and serves to improve the shape of the step in the wave of the main current flowing through the coil 26. The effect of this oscillatory circuit is to reduce or virtually eliminate the inclination of this step relative to the zero axis of the current wave. Winding 31 is excited by sinusoidal current supplied, for instance, from an auxiliary transformer or from an auxiliary secondary winding of the main power transformer. Winding 32 is supplied with trapezoidal current in substantially the same manner as the winding 13 in Fig. 1.

In addition, a cross-phase circuit is provided which contains an ohmic resistor 37 and extends from a point between winding 26 and contact device 8 of phase U to a point at the transformer side of the main reactance winding 26 in phase V. The cross-phase circuit is as free of inductance as possible, for instance, by a bifilar design of the resistor 37. The commutating reactor 27' appertaining to the phase V is designed in accordance with reactor 27 and the appertaining circuit connections (not shown) are also similar to those of reactor 27.

Operation

In Fig. 4, I shows the time curve of the full load current during the commutation interval. This current curve I may result, for instance, when the contact of the incipient phase (V) is closed at the moment t_0 at which the time curve of the commutation voltage (U_{K1}) intersects the zero line (time axis). The contact in the decaying phase (U) opens at the moment t_N . Hence the commutation interval commences at t_0 and terminates at t_N .

The broken-line curve II in Fig. 4 applies to a different operating condition in which the magnitude of the load current is the same as before but the closing of the contact is delayed by a phase angle α and occurs at the moment t'_0 . In the latter case, the commutation interval from moment t'_0 to moment t'_N is shorter than the corresponding commutation interval t_0-t_N for curve I because the instantaneous values of the commutation voltage U_{K1} are larger during the interval t_0-t_N . Since the moment t'_N occurs later than the moment t_N , the commutating reactor, when operating with current curve II, commences at moment t'_N to produce the current step at a higher instantaneous value of the commutation voltage; and all instantaneous voltage values during the further course of the current step are also higher than for curve I. These instantaneous voltage values are responsible for the reversing of the saturating magnetization of the commutating reactor along the flanks of the magnetic characteristic. Since the velocity (rate of change) of the reversal in magnetization is directly proportional to the voltage that produces the reversal, it follows that the break step for the operating conditions of curve II is shorter than the break step obtaining under the operating conditions of curve I. For the relatively small phase difference α assumed in Fig. 4, this difference in the duration of the respective break steps is not very large. However, when the phase angle α is increased, for instance, in order to reduce the converter output voltage by delayed-commutation control, then the difference may assume considerable values because then the step commences much later and hence closer to the crest of the commutation voltage than when

operating under full voltage, so that the reversal in reactor magnetization occurs at considerably higher instantaneous values of the commutation voltage.

Still more noticeable is the effect of the different values of the magnetization reversing voltage when the primary voltage supplied to the apparatus is changed. Such a change may be inadvertent, for instance, caused by extraneous phenomena acting upon the power line, or it may be introduced purposely by adjusting the supply voltage, for instance, with the aid of a tapped power transformer as shown at 1 in Figs. 1, 2, and 3.

Consider two different operating conditions with respectively different energizing voltages. The corresponding commutating voltages are also different and may be represented by curves U_{K1} and U_{K2} in Fig. 4. Assume that the apparatus operates at full load and under full voltage as represented by current curve I. Under these conditions, the differences of the instantaneous values of the respective commutation voltages U_{K1} and U_{K2} are relatively small during the commutation interval from moment t_0 to moment t_N . For simplicity, therefore, it is assumed in Fig. 4 that this commutation interval t_0 to t_N applies equally to both voltage conditions (U_{K1} , U_{K2}), although the interval is actually somewhat longer for the lower commutating voltage U_{K2} than for the higher voltage U_{K1} . With the higher voltage U_{K1} , the break step S_1 lasts from moment t_N to moment t_{S1} . This interval of time corresponds to the cross-hatched area under the curve U_{K1} representing the voltage-time integral required for reversing the magnetization of the commutating reactor from positive saturation to negative saturation. This integral, or the corresponding area, is a constant magnitude definitely determined by the dimensions of the magnet core of the commutating reactor and by its number of winding turns. With a reduced supply voltage and the correspondingly smaller commutating voltage U_{K2} , the reversal in magnetization takes place at a slower rate. The required voltage-time integral is then reached only at the later time point t_{S2} . The cross-hatched area from t_N to t_{S2} beneath curve U_{K2} has the same magnitude as the aforementioned area beneath curve U_{K1} from t_N to t_{S1} . As a result, the break step S_2 for the lower voltage U_{K2} is decidedly longer than the corresponding break step S_1 for the higher voltage U_{K1} .

In accordance with the different velocities of magnetization reversal, the hysteresis loop of the reactor core assumes respectively different widths as indicated in Fig. 5. Fig. 5 shows an idealized representation of different hysteresis loops of one and the same core for respectively different velocities of magnetization reversal. With a high velocity or rate of reversal, the hysteresis loop passes along the flank portions a and hence has a large width corresponding to a larger magnetizing current i_a . At a lower rate of reversal in magnetization, the hysteresis loop extends along flanks b corresponding to a smaller magnetizing current i_b . However, the magnetizing current is not directly proportional to the rate of change in magnetization but, within the practically useful voltage range, corresponds to an equation of the type $y=c_0+cx$ in which y denotes the magnetizing current, x the rate of change in magnetization, and c_0 and c are constants.

This equation can be graphically represented in a coordinate diagram by a straight line which

intersects the y axis at the constant value c_0 . If the premagnetization of the commutating reactor can be chosen so that it always just furnishes the magnetizing current required at the obtaining voltage by the reactor core for reversing its magnetization from saturation of one polarity to saturation of the other polarity, then no current at all can flow through the main winding of the commutator reactor during the interval of time in which the magnetization reversal is taking place. That is, the step would then accurately coincide with the zero line and the step current to be interrupted would have the desired zero value when the contact is opened at any moment within the step interval.

It will be clear from the foregoing that this advantageous result can neither be attained by a constant premagnetization nor by a load-responsive premagnetization or a superposition of both, because both kinds of premagnetization fail to involve any dependency upon the operating voltage. It is further apparent that this aim can likewise not be attained with a voltage-dependent premagnetization alone, because this would require a linear proportionality between the rate of saturation reversal or voltage on the one hand, and the width of the hysteresis loop or the magnitude of the required magnetizing current on the other hand; but such a linear dependency does not exist.

The desired achievement, however, is attained by the present invention involving the superposition of a voltage-dependent premagnetization by sinusoidal current and a completely independent premagnetization by a trapezoidal current of constant amplitude. The result of this particular superposition is that any conceivable changes in magnitude of the commutation voltage, no matter whether resulting from voltage regulation or from a change in the supply voltage, are always compensated as to their effects upon the step current. Variations in magnitude of the load current have no effect upon the step current because such variations are compensated by the above-mentioned auxiliary circuit.

The resultant effects of the sinusoidal current i_x (in winding 13, Fig. 1) and the trapezoidal current i_t (in winding 14, Fig. 1) will be explained with reference to Figs. 5 and 6. The amplitude of the trapezoidal current i_t is completely independent from any operating conditions so that this current supplies, during the break step, an absolutely constant component of the premagnetization according to the value c_0 in the above-mentioned equation. Fig. 5 shows the magnetizing current i and the corresponding width of the hysteresis loop by dot-and-dash lines.

The time curve of the trapezoidal premagnetizing current i_t is shown in the top diagram of Fig. 6. The broken-line curve indicates the voltage U_t driving this current. It is apparent that the current i_t is essentially wattless. The trapezoidal shape of the current offers a sufficient range for a phase displacement of the break step S , such a displacement being caused by load currents of different magnitude, or by different phase displacement of voltage control, for instance, according to Fig. 4.

The middle diagram of Fig. 6 shows the time curve of the sinusoidal premagnetizing current $i_x=cx$, the magnitude x in the present case being identical with the commutation voltage (U_K). The current i_x follows a sinusoidal curve of a relatively high peak value in those intervals in which the commutating reactor is saturated.

During those intervals in which the saturation of the reactor reverses its polarity and in which the reactor, then being unsaturated, has a much higher reactive resistance than in the saturated condition, the sinusoidal current i_x follows a sinusoidal curve of a much lower peak value, the latter curve being shown by broken lines in the middle diagram of Fig. 6. The diagram shows two individual curves for each of the high-peak and low-peak current conditions corresponding to respectively different values of the supply voltage or commutating voltage. If the current step S is given a different phase position, the sinusoidal currents maintain their original phase position and the premagnetizing current i_x assumes different instantaneous values derivable from the diagram.

The bottom diagram in Fig. 6 shows the superposition of the two premagnetizing currents $i_x + i_y = i_z$. The resultant premagnetizing current i_z has during the break step S, regardless of the time position of this step relative to the current half wave, always just those instantaneous current values which are needed by the commutating reactor at the given voltage to pass from saturation of one polarity to saturation of the other polarity. Consequently, the break step always coincides virtually with the zero line, and the contact interruption is always effected at zero current for any operating condition of the converting apparatus.

Fig. 6 reveals another advantage of the trapezoidal premagnetizing current. Since this current flows in the reversed direction at the contact closing moment occurring during the period of the other half wave, it contributes to the return magnetization which places the commutating reactor back to saturation of the original polarity in the direction of the main current before the contact is reclosed. This secures definite closing conditions at the make moment of the contact and prevents the break reactor from imposing disturbing effects upon any make reactor or make core with which the apparatus may be equipped. Besides, the trapezoidal premagnetizing current may also usefully contribute to properly premagnetizing the make reactor.

While in the foregoing reference is made to Fig. 1, the embodiments according to Figs. 2 and 3 operate basically in the same manner. In the embodiment of Fig. 1, the premagnetizing circuit that applies sinusoidal current to the winding 14 includes a resistor 15 which imparts to the circuit a predominantly ohmic character. This has the result that the premagnetizing current i_x will instantaneously follow any sudden changes in supply voltage.

In contrast, the premagnetizing circuit of the corresponding winding 14 in Fig. 2 is stabilized by a reactor coil 23. Due to the predominantly inductive character of this premagnetizing circuit, the sinusoidal current in winding 14 lags the voltage by almost 90° and is not subjected to sudden variations. The required phase angle between voltage and current is adjusted by means of the phase adjuster 17. Such an inductive circuit reacts to change in supply voltage only during a period of several cycles. This is permissible especially when the above-mentioned voltage changes occur only rarely and has the advantage of lower losses as compared with a predominantly ohmic premagnetizing circuit according to Fig. 1.

The embodiment of Fig. 3 adds a cross-phase circuit with a resistor 37 to an apparatus other-

wise designed in accordance with Fig. 1 or Fig. 2. The cross-phase circuit acts essentially like a shunt path across the contact 2. That is, the cross-phase circuit, due to its negligible reactance, absorbs any residual current that may remain flowing in the main circuit when the contact 8 opens.

In all three embodiments, the step current can always be kept below the value critical for the occurrence of migration of contact material, regardless of any changes in operating voltage, thus securing a reliability of operation and a voltage-independent period of useful life not achieved by heretofore existing devices.

I claim:

1. Synchronous electric switching apparatus, having supply means providing alternating current of substantially sinusoidal wave shape and having a plurality of phase circuits, each of said phase circuits having a synchronous contact device adapted to alternately make and break its circuit in synchronism with the cycle of said alternating current and a saturable commutating reactor series-connected with each other, said reactor having two premagnetizing bias windings, a cross-phase circuit extending across different ones of said phase circuits and including one of said bias windings to pass substantially sinusoidal current through said one bias winding, and trapezoidal-current supply means connected between said alternating-current supply means and said other bias winding and having a constant current amplitude during the break interval of said make and break cycle to pass through said other bias winding a trapezoidal current of the frequency of said alternating current.

2. Synchronous electric switching apparatus, comprising a power input transformer of adjustable voltage having multi-phase secondary windings, a plurality of phase circuits connected to said respective windings, each of said phase circuits having synchronous contact means to alternately make and break its circuit in synchronism with the cycle of said respective phase circuit and a saturable commutating reactor series connected with each other, said reactor having premagnetizing bias means, two excitation circuits connected with said bias means, current supply means of sinusoidal current characteristic connected to one of said circuits, and current supply means of trapezoidal current characteristic connected to said other circuit and having a constant current amplitude during the break interval of said make and break cycle.

3. Synchronous electric switching apparatus, comprising power input transformer means having multi-phase secondary windings of adjustable voltage and another secondary winding of normally constant voltage, a plurality of phase circuits connected to said respective multi-phase windings, each of said phase circuits having synchronous contact means to alternately make and break its circuit in synchronism with the cycle of said respective phase circuit and a saturable commutating reactor series connected with each other, said reactor having two premagnetizing bias windings, a cross-phase circuit extending across different ones of said phase circuits and including one of said bias windings to pass substantially sinusoidal current through said one bias winding, and trapezoidal-current supply means having a constant current amplitude during the break interval of said make and break cycle and being connected between said other secondary winding and said other bias winding to

pass through said other bias winding a trapezoidal current of the frequency of said alternating current.

4. Synchronous electric switching apparatus, comprising power supply means providing alternating current of substantially sinusoidal wave shape having a plurality of phase circuits of adjustable input voltage, each of said phase circuits having a synchronous contact device to alternately make and break its circuit in synchronism with the cycle of said respective phase circuit and a saturable commutating reactor series-connected with each other, said reactor having two premagnetizing bias windings, a sinusoidal-current circuit connecting one of said bias windings with said supply means and having a current stabilizing reactor series connected with said one winding, phase shift means interposed between said latter circuit and said supply means, and trapezoidal-current supply means connecting said other bias winding with said power supply means and having a constant current amplitude during the break interval of said make and break cycle, whereby said commutating reactor is premagnetized by mutually superimposed sinusoidal and trapezoidal currents.

5. Synchronous electric switching apparatus, comprising a main circuit having alternating-current power supply means, synchronous contact means for making and breaking said main circuit in synchronism with the cycle of said power supply means, a saturable reactor series-connected with said contact means in said main circuit for temporarily flattening the current wave in said main circuit to a break step during which said contact means break said main circuit, said reactor having premagnetizing bias means, two

excitation circuits connected with said bias means, circuit means connecting one of said two excitation circuits with said supply means and having a voltage dependent upon that of said main circuit, and current supply means of a trapezoidal current characteristic connected to said other excitation circuit and having a constant current amplitude during said break step.

6. Synchronous electric switching apparatus, comprising a multi-phase circuit having in each of its phases a synchronous contact device and a saturable commutating reactor series-connected with said device for flattening the current wave in said circuit near each current zero passage to a break step during which said device breaks said circuit, said reactor having two premagnetizing bias windings, a cross-phase circuit extending across different ones of said phases of said multi-phase circuit and including one of said bias windings, and trapezoidal-current supply means connected with said other bias winding and having a constant current amplitude during said break step.

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