

Nov. 2, 1954

E. J. DIEBOLD
COMMUTATING REACTOR

2,693,569

Filed Feb. 21, 1951

5 Sheets-Sheet 1

FIG. 1

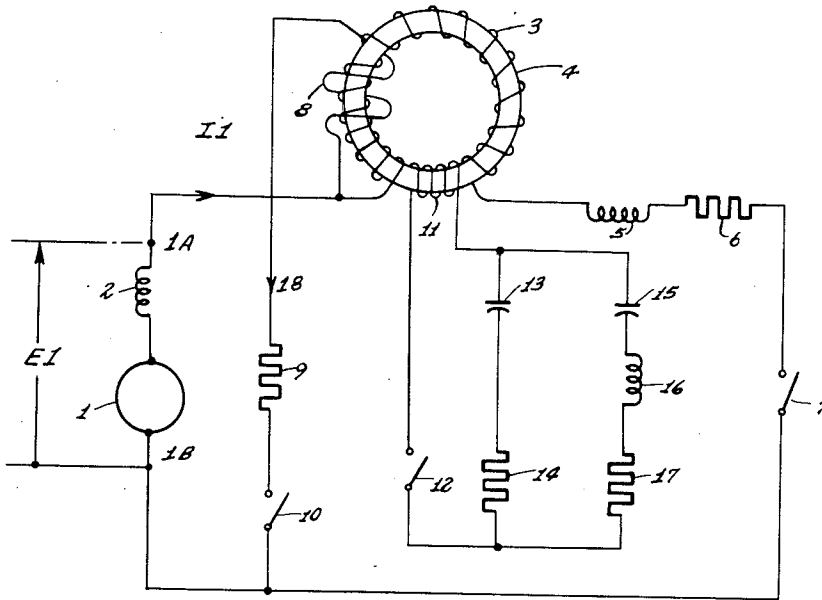
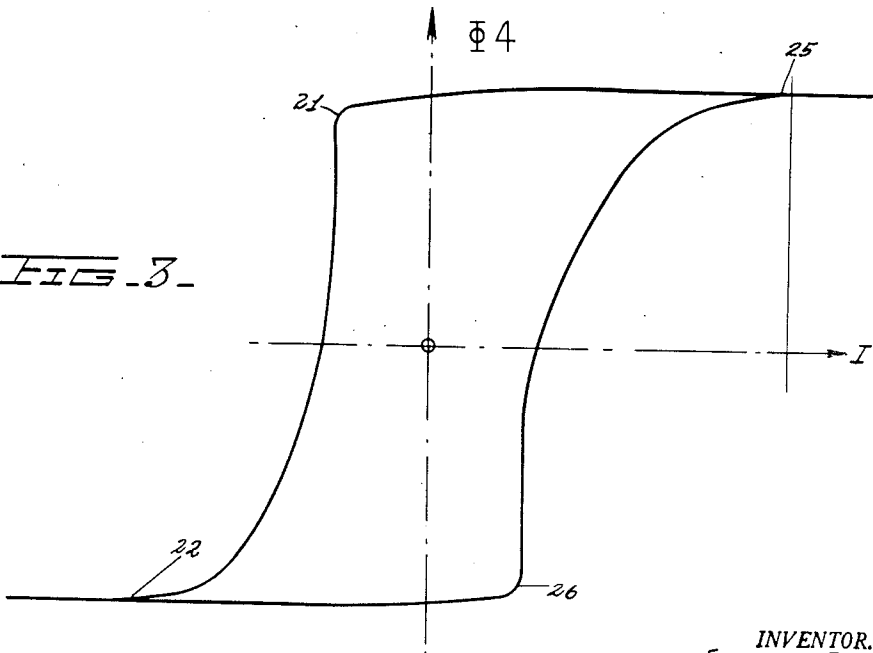


FIG. 3



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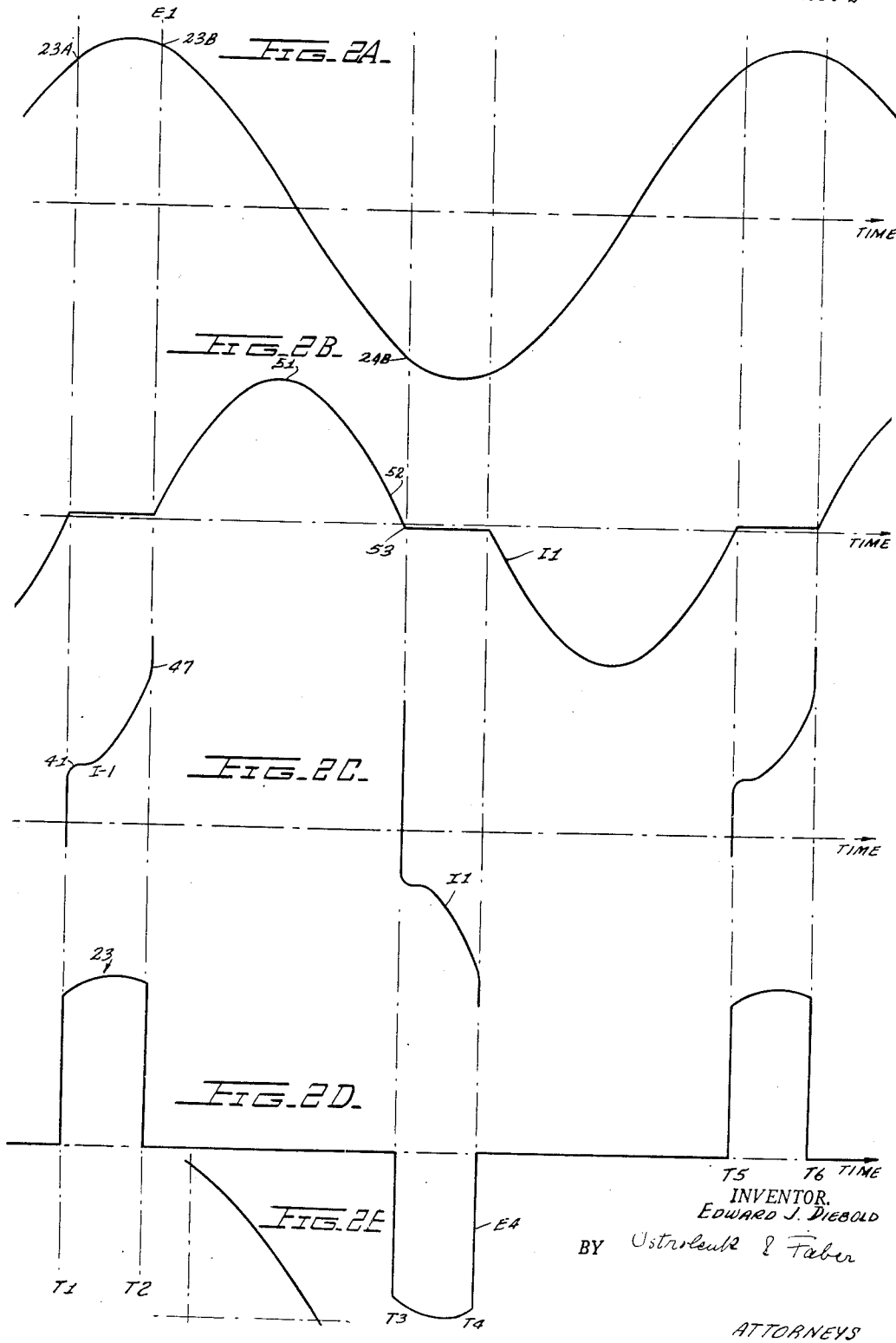
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5 Sheets-Sheet 2



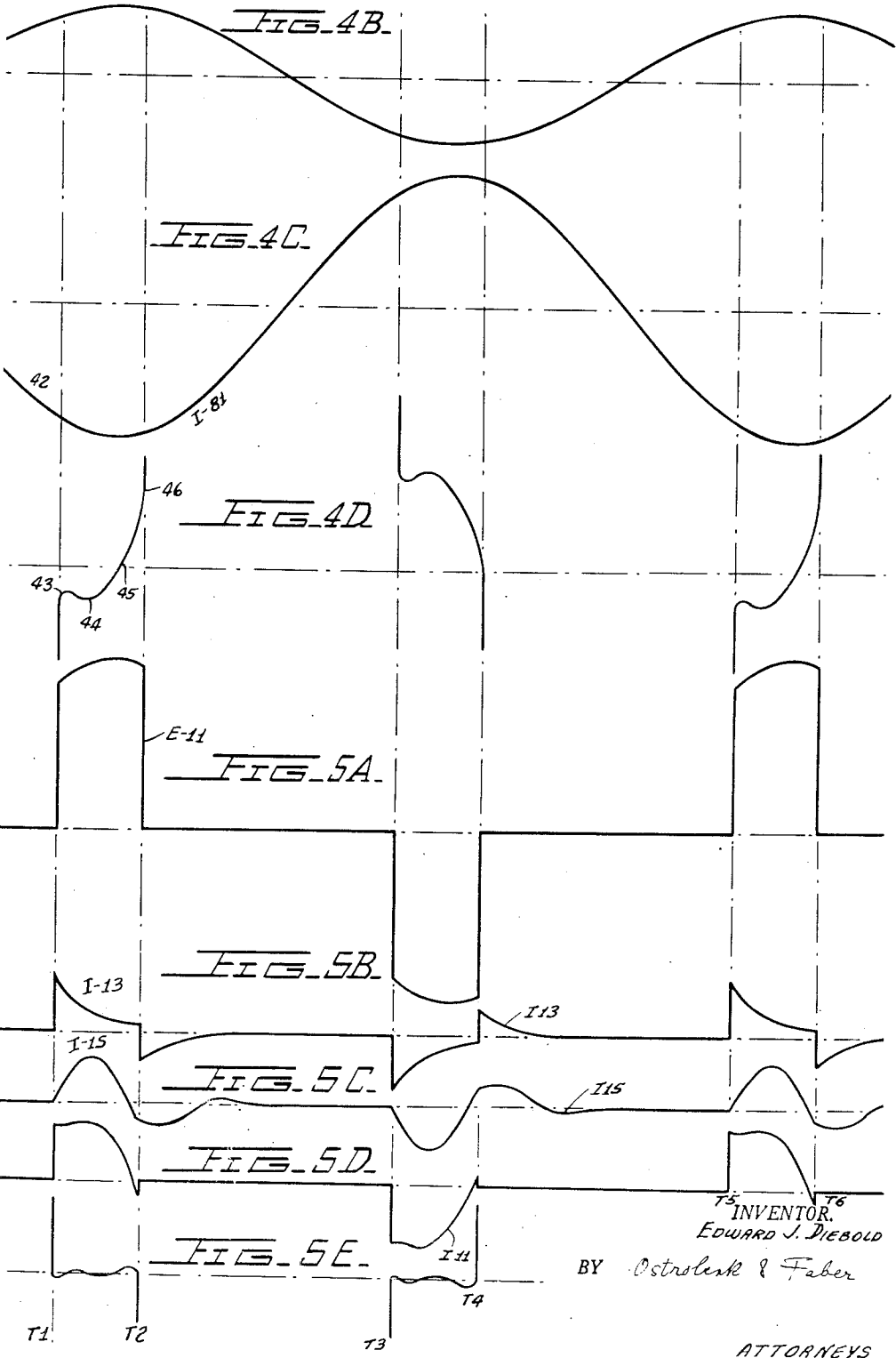
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5 Sheets-Sheet 3



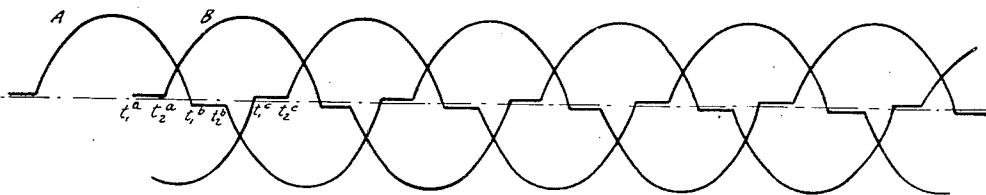
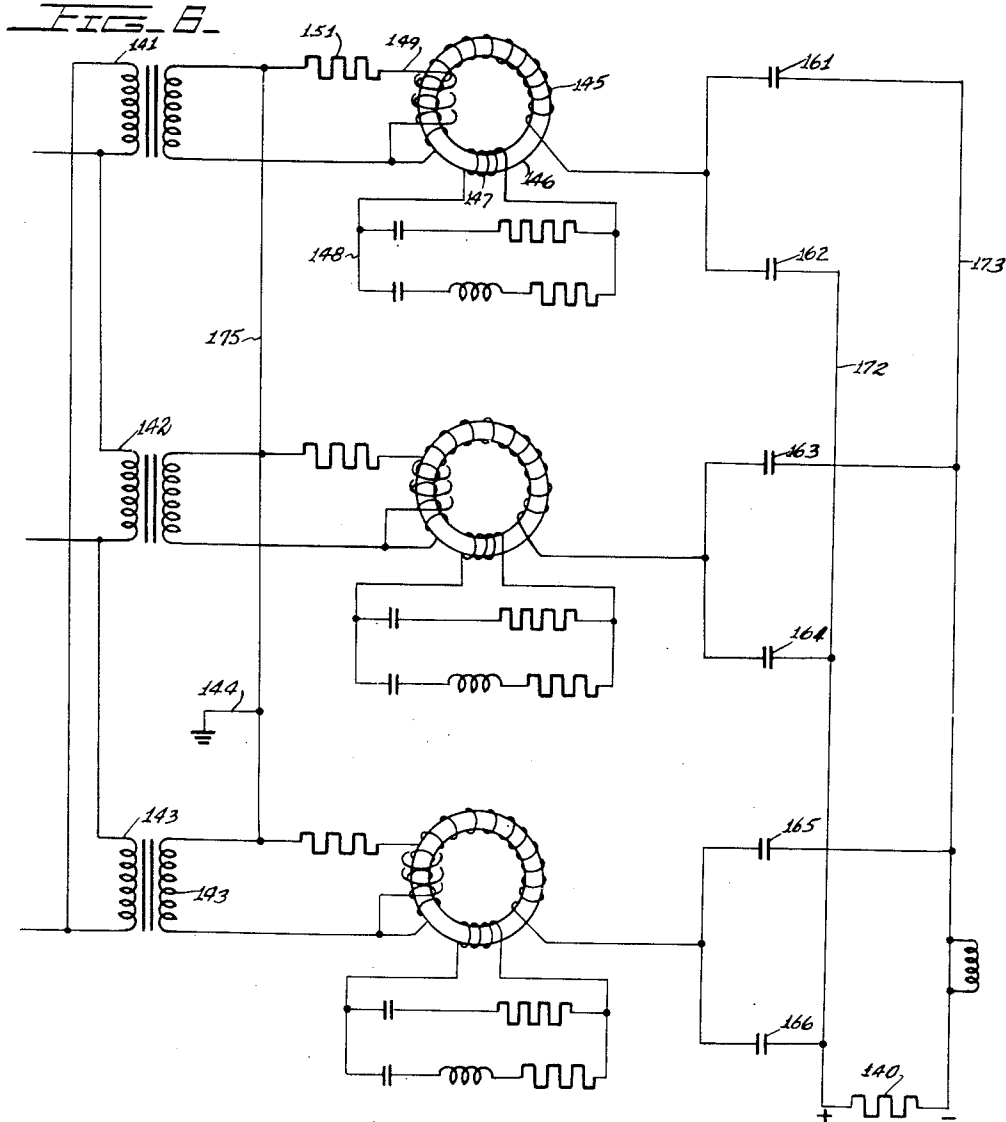
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2,693,569

Filed Feb. 21, 1951

5 Sheets-Sheet 4



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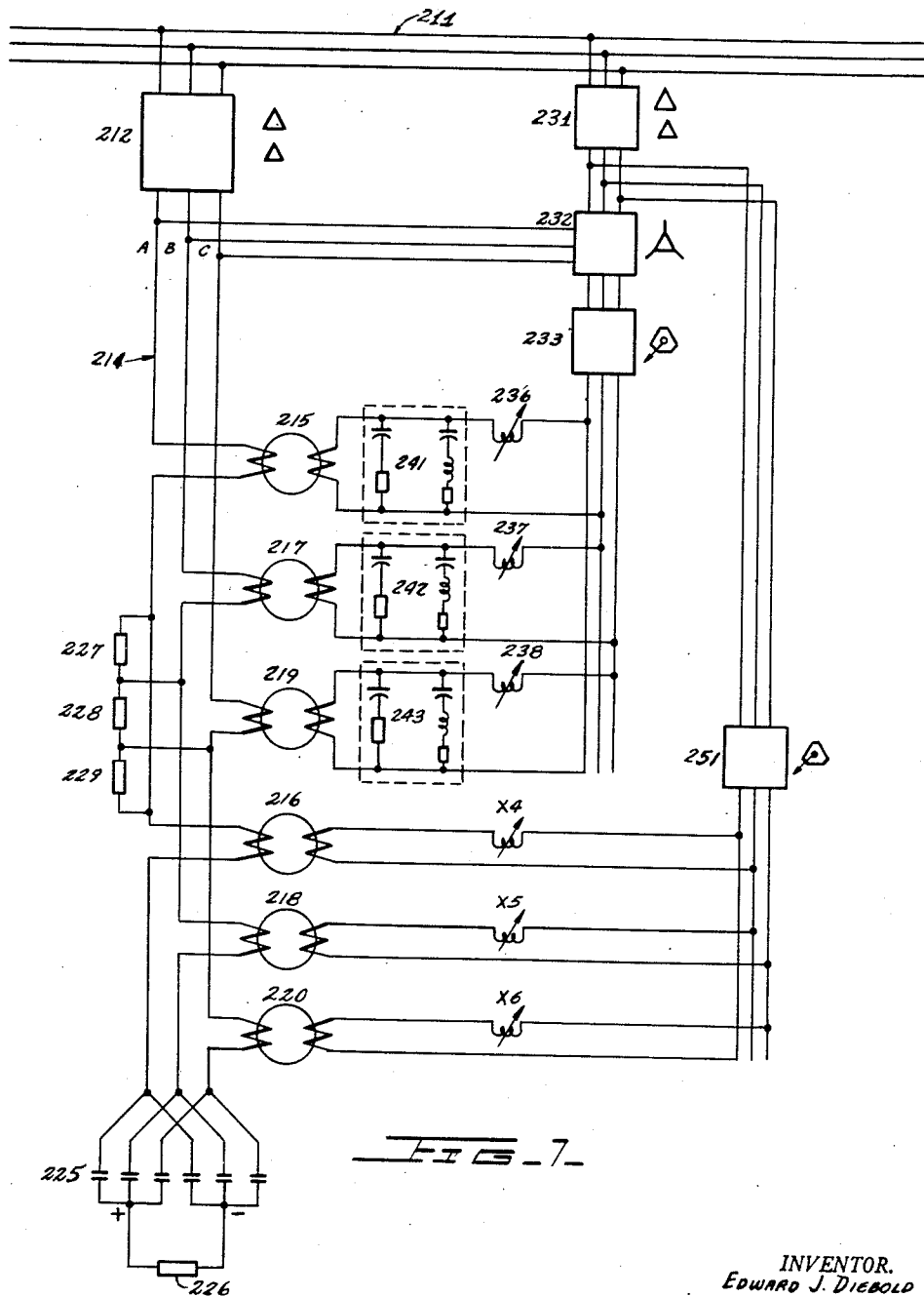
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2,693,569

Filed Feb. 21, 1951

5 Sheets-Sheet 5



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2,693,569

COMMUTATING REACTOR

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Application February 21, 1951, Serial No. 212,017

10 Claims. (Cl. 321-48)

My invention relates to electrical circuits for compensating for the non-ideal shape of the dynamic hysteresis loop of a saturable reactor made of a ferromagnetic material and more particularly relates to reducing the commutation current due to such a saturable reactor used in a mechanical rectifier.

A mechanical rectifier produces direct voltage by making metallic contact between a proper phase of an A. C. system and the associated D. C. system during the time interval the particular phase of the A. C. system is capable of delivering energy in the desired direction and breaking the metallic contact when the A. C. phase reverses its voltage in relationship to the D. C. voltage. This operation is performed sequentially and repeatedly in synchronism with the A. C. frequency.

The metallic contacts which perform the switching are switches which are able to carry the full current which flows through the rectifier. These contacts, when open, are able to withstand the full inverse voltage, when the alternate voltage is opposed to the direct voltage. But they cannot interrupt a current greater than a fraction of one ampere without suffering a slight damage. Due to the periodical operation of the switches (they must each operate 60 times per second in a 60 cycle system), the slight damage to the contact, if they are called upon to interrupt any substantial current soon accumulates to a total destruction of the contact surface.

Another limitation is the inrush current after closing the contact. A contact does not close instantly. During closing the contacts touch very lightly over a small area thus providing a high resistance. As the contacting area and pressure increases, the contact resistance is correspondingly reduced. The time required for this phenomenon is twenty to thirty microseconds. If a high current is permitted during this interval, the narrow contact area will melt and thus be the cause of transfer of metal. Furthermore, the contact might rebound partially or totally after approximately one hundred microseconds. If the reverse motion is strong enough to reduce the contact pressure appreciably, some more transfer of metal will ensue. The transfer of metal will again be the cause of destruction because it is cumulative. To use such a switch as a mechanical rectifier, without any additional protective equipment will immediately result in its destruction.

To prevent such damage, saturable commutating reactors are inserted in series with the contacts. These reactors have a substantially square shaped, so-called hysteresis loop which present high resistance at low current and thus limit the inrush current after closing, and the residual current before opening, to a sufficiently low value to warrant a satisfactory performance for many billion operations.

The rectifier contacts are arranged to open during the interval just after the current passes through zero. At this time, the hysteresis loop is very steep, the rate of change of flux very large and accordingly the reactance of the saturable reactor very large compared to a normal load. The amplitude of the current flowing in the system instead of changing in accordance with the normal sine-wave is, therefore, held at a comparatively low value during the switching interval.

However, due to inevitable imperfections of the core material the hysteresis loop at the switching interval is not absolutely vertical but instead has an angle of slope, which cannot be neglected inasmuch as it tends to produce a current of a variable value to be interrupted. Dur-

2

ing the time that the make coil or the break coil are blocking the current, the coil in question assumes the full value of the short circuit voltage of the two phases of the transformer.

The variable magnetizing current that is carried during this period must be carried and interrupted by the switching contacts of the mechanical rectifier or be furnished by an auxiliary means.

Accordingly an object of my invention is to provide an auxiliary supply of magnetizing current for the commutating reactors and especially for the break coils, such that the remaining current that is to be carried by the contacts of the mechanical rectifier becomes negligible.

The solution involves the application of a transient by-pass to the commutating reactor, such as to straighten out the nearly vertical and linear part of the hysteresis loop. The resulting current is constant, although higher than the initial magnetizing current; it is then compensated entirely by a small portion of a sine-wave shaped current flowing in an auxiliary winding.

The above method has the following advantages:

1. The current that must actually be interrupted by the contacts of the mechanical rectifier is reduced to about 5% of what it would be by applying the same commutating reactors without using this auxiliary supply of magnetizing current.

2. Inversely, as the current that can be opened without damage is limited by a physical law, I can build a rectifier for a 20 times higher magnetizing current of the reactors than without this method.

3. The recovery voltage at the contact, immediately after opening it, will depend upon the amount of magnetizing current which will be carried after the opening. Without any compensation, the recovery voltage assumes the full interphase voltage because the full magnetizing current is interrupted. Using my current to provide the magnetizing current by an auxiliary means, maintains it after the opening of the contact; hence the interphase voltage will still be applied in full to the break coil etc. after opening the contact. The voltage will recover to its full value only at the end of the step, providing thus a time interval to de-ionize any eventually existing arc at the opening moment.

Accordingly, an object of my invention is to provide a novel straightening circuit for saturable reactors.

Still another object of my invention is to provide a novel saturable reactor operating as an interacting transformer.

Still a further object of my invention is to provide a novel saturable reactor in which a secondary current is set up during the switching interval to reduce the excitation current for the saturable reactor.

A further object of my invention is to provide a novel circuit arrangement for controlling the reactors.

These and other objects of my invention will appear more fully in the detailed description of my invention in connection with the drawings in which:

Figure 1 is a schematic of a circuit diagram of one simple form of my invention;

Figure 2A is a voltage curve of the voltage applied at the alternating current end of the system shown in Figure 1;

Figure 2B shows the corresponding current curve in the system;

Figure 2C is a curve showing a magnification of the current flowing in the saturable reactor during switching;

Figure 2D shows the voltage across the saturable reactor during switching;

Figure 2E shows the voltage across the load during the remainder of the cycle;

Figure 3 is a hysteresis loop for the saturable reactor used in my invention;

Figure 4B shows the current flowing in one of the auxiliary windings wound around the saturable reactor core;

Figure 4C shows the induced current in Figure 4B;

Figure 4D shows the resulting current due to the sum of the current of curve Figures 2C and 4C;

Figure 5A shows the voltage induced in a second auxiliary winding of my reactor;

Figure 5B shows the current flowing in one portion

of the transient circuit as a result of the voltage of Figure 5A;

Figure 5C shows the current flowing in a second portion of the transient circuit as a result of the voltage in Figure 5A;

Figure 5D shows the current flowing in the main winding of the reactor as a result of the currents of Figures 5B and 5C;

Figure 5E shows the final summation of the currents in the main reactor winding which is to be switched; and

Figure 6 shows a circuit diagram of one practical application of my invention.

Figure 6C is a curve versus time representation and illustrates make and break steps in each phase of the three phase circuit.

Figure 7 shows a circuit diagram of a more elaborate practical application of my invention.

Referring to Figure 1, I have shown an alternating current generator 1 connected in series with its leakage reactance 2 across a line 1A—1B applying a voltage E_1 thereto as illustrated in Figure 2A.

Energy from the generator is fed through the winding 3 of a saturable reactor 4 to a load here represented by the air inductor 5 and resistance 6 when rectifying switch 7 is closed. Inductor 5 is the main load. The resistor 6 is merely illustrative of the distributed resistance of all the elements of this main circuit and is in practice much smaller than the impedance of reactor 5.

The saturable reactor 4 consists of a coil of conducting material which is saturable at relatively low current values. The core is made of wound tape and therefore has no air gap. By reason of the use of a tape, the magnetic flux flows in the circumferential direction of the wound tape. Accordingly, the flux does not cross any air gaps. In order to reduce eddy currents, the tape is made extremely thin, being usually of the order from 0.001 to 0.002 inch thick.

The coil around the core should be wound as tightly as possible. This permits the use of a small core for a predetermined amount of wire that must be used; it also reduces the reactance of the core when the core is saturated and the coil assumes the properties of an air reactor of the same dimensions.

The best core material for commutating reactors known up to now is vacuum fused 50% iron, 50% nickel alloy, and must not contain any impurities such as oxygen, carbon, other metals, etc. In order to maintain its crystalline structure, it should not be deformed after annealing. Insulation such as magnesium oxide is provided between the layers of the tape of the property to withstand the annealing temperature. The tape is cold rolled down to the final thickness and annealed at 1950° F. in electrolytic hydrogen with no water vapors present.

The outstanding property of a commutatory reactor is the great variation in physical behavior it affords at different currents. Whenever the total ampere-turns around the reactor core are higher than a predetermined minimum, the reactor behaves exactly as if it were a copper coil wound around a non-magnetic core. It has a predetermined resistance and reactance of relatively low value.

As soon as the total ampere-turns are reduced to near zero and changed into the opposite direction, the reactor suddenly assumes a reactance which is 50,000 to 100,000 times higher than at the larger currents. This transition happens always at the same current value and is instantaneous.

A high voltage must now be applied to the winding of the coil which carries only a very small current, i. e., the so-called magnetizing current. This current is almost constant and is almost independent of the voltage applied. This period of high reactance lasts for a relatively short time interval in each cycle with the exactly defined condition that the voltage applied to the coil, times this time interval is always constant. After the end of the time interval, the coil has again the properties of an air core reactor, the core reactance becomes negligibly small and the current suddenly rises again to a value which is limited only by external means, such as a load.

The portion of the abnormal behavior of the commutating reactor is usually described by its flux-current curve shown in Figure 3, inappropriately called hysteresis loop. This curve (Figure 3) resembles a rectangle with the horizontal parts (extending to the infinite)

indicating the normal low reactance behavior and the almost vertical parts indicating the high reactance part.

This latter portion is characterized by the low current which cannot be allowed to increase during the above mentioned time interval. This current is called magnetizing current, or step current, and the time interval the step length, i. e., the time during which the current is actually frozen, to the small value of the step current. The step current of practically used commutating reactors is less than one thousandths of the peak current, the step length approximately one one-thousandths second and the rise of the flux after the end of the step is less than 4% of the step length.

From the above, it will now be clear that during most of the current cycle, as for example, current values from 25 (Figure 3) and higher, the reactor is saturated. Accordingly, as shown, there is no flux change, and the reactor presents substantially no impedance to the circuit. Accordingly during this portion of the cycle, all or almost all of the voltage of the generator 1 appears across the load illustrated by reactor 5.

However, during a relative small part of the cycle when the current has just passed through zero value reversing its polarity from positive to negative as at 21 (Figure 3) and is increasing to 22, reactor 4 is unsaturated. At this low current value, due to rapid change in flux from 21 to 22 (Figure 3) the reactor 4 presents a very much higher reactance than the load. Due to this high impedance, the current is held low and all or substantially all the voltage of the generator appears across the reactor.

During this portion of the cycle, the current is very small. The rectifier switch opens and must interrupt this small current.

The present invention resides in the provision of winding 8 on the saturable reactor 4 and its circuit connection to resistor 9 and straightener winding 11, and its circuit connection to resistor 14 and 17, capacitors 13, 15 and inductor 16, the function and operation of which will be described hereinafter.

For the purpose of illustrating the operations of the present invention, it will be assumed first that the switches 10 and 12 connected in the individual circuits of windings 8 and 11 on the reactor 4 are open. In such a case and with only the load circuit including the switch 7 closed, current in winding 3 will flow as shown in Figure 2B.

It will be noted from Figure 2B that during the intervals following current polarity reversals T_1 — T_2 , T_3 — T_4 , and T_5 — T_6 , the load circuit current is very small and in fact, as will be shown hereinafter, consists only of the magnetizing current required to apply the full generator voltage in winding 3. This is, as explained hereinbefore, the interval when the flux (ordinate Figure 3) is changing from 21 to 22 or from 26 to 25. Accordingly the winding 3 presents very high reactance which in actual practice is considerably greater than the reactance of load winding 5.

Inasmuch as the reactance of the winding 3 during these intervals is so much greater than that of inductor 5, the current will be kept small and substantially all of the voltage of the generator will appear across the reactor 4. Accordingly during these intervals T_1 — T_2 , T_3 — T_4 , and T_5 — T_6 , the voltage across the reactor is substantially the voltage of the generator as shown by the portions 23, Fig. 2D, which corresponds to the portion between 23A and 23B, Figure 2A.

At point 22 (Figure 3), the core 4 again becomes saturated, there is no further change in flux during the remainder of the current cycle, and reactor 4 now again presents almost zero impedance to the system.

During these intervals T_2 — T_3 and T_4 — T_5 , the core 4 due to the rise in the current flowing through the winding 3 continues to be saturated. The reactance of the core 4 accordingly continues very small compared to the reactance of load inductance 5. Accordingly, substantially the full generator voltage of 1 will now appear across the inductor 5 as illustrated at 24 in Fig. 2E which corresponds to 23B to 24B, Fig. 2A.

As a result of all this, the current drawn by the inductor 5 is a sine wave-shape current distorted near zero and lagging in the present illustration by about 90° as shown in Fig. 2B. This current at the extreme left reduces from negative polarity to zero and then becomes slightly positive at interval T_1 . At this instant,

the reactor 4 reactance becomes large and the current is held small in value between T_1 and T_2 . Thereafter the shape is again a sine wave.

In Figure 3, the magnetizing current is shown in the dynamic hysteresis loop of the core material of core 4. As will now be clear, the abscissa of Figure 3 corresponds to the ordinate of Figure 2C. Fig. 2C is a magnification of the line current of Figure 2B during interval T_1 — T_2 and illustrates the positive and negative current values as at 21, 22 and 25, 26, respectively, of Fig. 3 and constitutes the switching current to be corrected in accordance with my invention. It will be noted that at 26, the magnetizing current is at its minimum value. The magnetizing current stays at this value while the flux almost instantaneously changes from 26 to 25; then no further exchange occurs as this current increases. In Fig. 2C magnification of this same current is shown at 41 first as a substantially constant value; then increasing to value at 47.

The law of induction for the winding 3 of the core 4 is expressed by the equation

$$E_4 = -N \frac{d\Phi_4}{dt} \times 10^{-8} \quad (1)$$

and therefore

$$d\Phi_4 = -\frac{10^8 E_4}{N} dt \quad (2)$$

From Figure 2D it will be noted that the voltage 23 over the switching interval T_1 — T_2 and the other corresponding intervals is the same as the peak portions 23A to 23B of the generator voltage at which period the voltage E_4 rate of change is relatively small and may for the present purpose be considered as a constant.

Inasmuch as N , the number of turns in the winding 3, is also a constant, Equation 2 becomes

$$d\Phi_4 = K dt \quad (3)$$

Accordingly, during the switching step, according to Equation 3, the flux Φ_4 is approximately proportional to the time t . Therefore, the current-flux curve (Fig. 3) is about the same as the current time curve I — t time of Figure 2C.

Thus further comparing Fig. 2B and Fig. 3, it will be noted that the current curve Fig. 2B over the positive range of values corresponds to the current value which is to the right of 25 (Fig. 3) during which the reactor core 4 is saturated and therefore presents little or no resistance. As the current, after reaching its peak value, decreases to a point approximately corresponding to 25 (Fig. 3), the flux in the saturable reactor remains substantially constant. As the current is reversed in polarity at the time T_3 (Fig. 2B) corresponding to 21, Fig. 3, this saturated flux condition is still maintained. During this period of current reversal from 25 to 21, Fig. 3, corresponding to a point just above zero in Fig. 2B to point 53, as explained above, substantially the full generator voltage appears across the load reactance 5. At point 53 (Fig. 2B) corresponding to point 21 (Fig. 3), the flux in reactor 4 experiences a sudden drop—the reactance of reactor 4 suddenly rises to an excessively high value compared to the load reactance and all the voltage of the generator appears across reactor 4. At this time only so much current flows as is necessary to produce the full voltage across reactor 4.

The current flowing during the time intervals T_1 — T_2 , T_3 — T_4 , T_5 — T_6 , is, as pointed out in the above, the switching current or the current which must be interrupted. As also pointed out in the above, this current is the magnetizing current of core 4; it depends on the shape of the dynamic hysteresis loop and consists of the hysteresis and eddy currents in the magnetic core 4.

In actual practice, that is, the practical application of the present invention, the switch corresponding to switch 7 is opened during the switching interval T_1 — T_2 , T_3 — T_4 , T_5 — T_6 , of Fig. 2 and will have to interrupt this magnetizing current at the time when the generator voltage is at peak value, Fig. 2A. As has already also been pointed out above, this magnetizing current in reactor 4 is necessary because substantially all of the voltage of the generator must appear across the reactor 4. But while this current is necessary in reactor 4, it is harmful to the remainder of the circuit and particularly at switch 7, which must interrupt this current.

It will accordingly be apparent that so long as sub-

stantially the full voltage appears across the reactor 4 during this switching interval, a means for eliminating or substantially reducing the current in the main winding 3 will reduce the current to be interrupted by switch 7. A switch opening at substantially zero current with a recovery voltage of zero volts, however short, even during a possible time ranging over the interval between T_1 — T_2 , or T_3 — T_4 , or T_5 — T_6 , will thus be the result.

In order to reduce the switching current, I propose to furnish the full amount of the magnetic current in auxiliary windings and therefore reducing the current in the winding 3. To this end, I provide an auxiliary winding 8 in inductive coupling relationship with the winding 3 of core 4 and connected in a circuit including the resistor 9 of very large resistance and switch 10 across the generator 1.

Assuming now that the switch 10 is closed with switch 12 in the second auxiliary circuit, to be described hereinafter, still open. The current and voltage curves, Fig. 2A, will not experience any substantial change.

A comparatively small alternating current I_8 will flow through the winding 8 and resistor 9 due to the relative high resistance of resistor 9. Inasmuch as this is a substantially pure resistive circuit, this current will be in phase with the voltage E_1 , Fig. 2A, as shown.

The current I_8 flowing in the winding 8 will induce a transformer current I_{81} , shown in Fig. 4C, in the winding 3. This current, as is well known in connection with transformers, will be 180° out of phase with the voltage E_1 , Fig. 2, as shown in Fig. 4C.

Accordingly the current I_1 , Fig. 2C, which was the magnetizing current originally described as flowing through the winding 3 plus the current I_{81} , Fig. 4C, and will assume the resultant shape shown in Fig. 4D, it being understood that the scale of Fig. 4C and 4D are drawn to the same magnified scale as Fig. 2C.

As shown in Fig. 4D at interval T_1 , the sum of the positive current of value 41, Fig. 2C, plus the negative current value 42 of Figure 4C produces a resultant negative current value at 43, Fig. 4D. As the negative current of Fig. 4C increases faster than the positive current of Fig. 2C, the resultant first shows a negative increase to 44. Thereafter as the negative current value of Fig. 4C remains substantially constant while the positive current of Fig. 2C increases, the resultant of Fig. 4D gradually decreases to zero value at 45 and then to a positive value at 46 at time T_2 .

Comparing Figures 4D and 2C, it will be obvious that the area between 43, 44, 45, 46 of Fig. 4D and its reference line, which is a function of the average current to be interrupted, has been reduced over the area under 41, 47 of Fig. 2C and its reference line, by the application of the described resistive bias circuit 9 just described. It will also now be apparent that by varying the resistance 9 of Fig. 1, the switching current of Fig. 4D can be varied to possibly still further reduce the average current value to be interrupted.

However, with the resistive circuit 9 alone, there is still a resultant interrupting current during the switching interval. It will be noted that if the switch 7 is opened at the beginning of the step T_1 , or near that beginning where the switching current is the highest, an arc current will follow but the current will still go through zero at 45 before flowing in the reverse direction and accordingly can be quenched.

However, in order to still further reduce this current value, I have provided a so-called straightening circuit which includes the winding 11 on the core 4 having a capacitive resistive circuit 13, 14 and a second parallel capacitive inductive resistive circuit 15, 16 and 17, controlled by a switch 12.

One of the results of the voltage appearing in the winding 3 of the reactor 4 is to induce a voltage E_{11} across the winding 11 mounted on the same core. This voltage E_{11} is, of course, related to the voltage in the reactor winding 3 in direct ratio to the number of turns in each of the windings 3 and 11 respectively.

Thus voltage E_{11} is shown, of the wave shape, Fig. 5A. As will be noted, the induced voltage E_{11} is generated only during the intervals T_1 — T_2 ; T_3 — T_4 ; T_5 — T_6 since it is only during these intervals that any voltage appears across the winding 3.

When the switch 12 is closed, the induced voltage E will generate a current I_{11} in the winding 11 which will flow through the parallel circuits including the

capacitor 13 and resistor 14 and the second circuit including the capacitor 15, reactor 16 and resistor 17. As is well known, the current I_{11} will be composed of the two transient currents I_{13} and I_{15} flowing through the two parallel circuits.

The current I_{13} flowing in the circuit including the capacitor 13 and the resistor 14 is shown by the usual capacitor discharging current curve Fig. 5B. The current I_{15} flowing in the circuit including capacitor 15, reactor 16 and resistor 17 is the usual oscillatory discharge current shown by the curve Fig. 5C.

As illustrated in Fig. 5B at the time T_1 when the voltage E_{11} suddenly reaches a high value, the current I_{13} is large and thereafter decays until the time T_2 . Correspondingly, by the proper selection of the capacitor 15, inductor 16 and resistor 17, the oscillatory current I_{15} may be caused to assume the shape as shown by the curve Fig. 5C, in which the current I_{15} is at zero value at the interval T_1 , reaches its peak value between T_1 and T_2 and drops to zero and reverses itself by interval T_2 .

Adding the currents I_{13} and I_{15} will produce the current I_{11} shown in Fig. 5D. In the above no account has been taken of the 180° phase shift of these currents in the secondary winding 11 with respect to the current in the primary winding 3. This is because the current in winding 3 required to produce the current I_{11} is primary of interest here.

The current now flowing in the winding 3 may be considered as composed of the current of Fig. 5D and the current of Fig. 4C and of 2C, or of Fig. 5D and 4D. These currents added together will produce the current shown in Fig. 5E. Since in all of these figures the magnification employed has been the same, it will be found that the resultant magnetizing current which must be opened by the mechanical rectifier contacts has now been reduced from that shown in Fig. 2C to that in Fig. 5E in which the same calibration scale has been employed.

Thus, in accordance with my invention, I have reduced the current to be interrupted by the switch during the interval T_1 — T_2 substantially to a zero value.

In the above I have described my invention in connection with a simple single phase circuit and which for purpose of illustration I have first assumed switches 10 and 12 to be open so as to describe the problem that exists in opening switch 7, and then have illustrated the operations that occur when the circuits controlled by switches 10 and 12 have been inserted into the switching system.

Obviously, a circuit arrangement such as shown in Fig. 1 may be employed where it is desired to open and close an auxiliary current circuit. In Fig. 6, I have illustrated my principle applied to a three phase alternating current system in which a mechanical rectifier is employed extending to a load 140. As here shown, three transformers 141, 142, 143 having a primary winding connected in delta and to a three phase alternating current system and having the secondaries connected in star with the mid-point grounded as at 144. Each of these secondaries is connected to its individual reactor winding 145 of the saturable reactor 146. Each of these reactors consists of an iron core of readily saturable permiron material, as described hereinbefore. Around the core of each winding is a winding made of small wire 147 fitting closely to the core so as not to have much leakage reactance and connected directly to the straightening circuit 148.

A resistance stabilizing alternating current bias is provided by the winding 149 in which the current is limited by the resistor 151 in a manner which has already been described in detail hereinbefore. This alternating current bias, though here shown provided from the main source of alternating current, may, if desired, be provided from some other source and be maintained constant by means of a reactor.

The contacts 161—166 are arranged to commutate synchronously within the intervals T_1 — T_2 ; T_3 — T_4 ; T_5 — T_6 by any well known manner as by a synchronous motor operated from the main supply. The motor drives a cam which in turn operates the contacts. For example, contacts 161 and 166 are closed simultaneously with the current in phase 1 being positive and the current in phase 3 being negative. The reactors are saturated by these high currents.

The operation of the mechanical rectifier with commutating reactors is based on the so-called commutation by means of short-circuiting the phases of the A. C. network. The transition of the current from one contact to another is called commutation. Consider two contacts connected to two different phases of the A. C. supply, each in series with two commutating reactors, one make coil and one break coil. In the first phase carrying the current, both reactors are saturated by the current. In the second phase there is no current. The make coil is saturated (from the previous operation) in the opposite direction of the one to be achieved by the current which will have to flow through it. Hence, it will present its period of high reactance as soon as a current will be forced through it. The break coil is already saturated in the right direction and does not represent any obstacle.

Closing the second circuit parallel to the first one, will short circuit the two phases. The short circuit current, however, is blocked by the make coil of the second contact. Therefore, the inrush current of the second contact is limited to the magnetizing current of its make coil. After saturation of the make coil, the short circuit current pushes the main current from the first contact to the second contact. When the current in the first contact reaches zero, its break coil will become unsaturated and assumes an almost infinite reactance and thus blocking any further change of current. This contact now opens with the current zero.

Assuming the interval when the voltage of phase 1 decreases and the voltage of phase 2 increases. Contact 163 is now also closed. Therefore, transformers 141 and 142 are short circuited. The short circuit current is limited only by the leakage reactance of the transformers 141 and 142 and the air resistance of the commutating reactors. Hence the current in phase 1 decreases rapidly and the current in phase 2 increases rapidly. When the current in phase 1 approaches zero, reactor 146 unsaturates and prevents further change of current. The reactor 146 now assumes the full short circuit voltage. The extremely small reactance current flowing (Fig. 5E) through 146 must now be interrupted by contact 161.

Circuit for three-phase rectifier

Fig. 7 shows a schematic diagram of a three phase bridge rectifier, similar to the one shown in Fig. 6. The primary line 211 of the supplying A. C. system is connected through the transformer 212 to the secondary line 214. In series with the secondary line are the reactors 215 and 216 in phase A; 217 and 218 in phase B; 219 and 220 in phase C. The A. C. lines are connected to the switch 225 which connects them to the D. C. load 226.

The reactors 215, 217 and 219 are break coils for reducing the opening current of the switch contacts. The reactors 216, 218 and 220 are make coils and are used to reduce the closing current at the switch contacts.

The resistors 227, 228 and 229 are connected between the lines after the break coils and before the make coils. These resistors provide a high resistance by-pass for the contacts of the mechanical rectifier 225 to provide a passage for the very small rest currents remaining after the contacts of S open.

The operation of the auxiliary circuits in Fig. 7 is the same described before on hand of Fig. 6. The only difference is the bias supply which is replaced by an inductive supply using phase shifters. The reason for this change over from resistive to inductive circuit is simply a consideration of losses in the resistor. The reactors used, introduce a phase by 90° which can easily be overcome by an equivalent phase shift in the opposite direction of the bias voltage.

The bias voltage supply is from the primary system 211 through transformer 231. As the main transformer 212 is supposed to have a tap changer, an auxiliary series transformer 232 is inserted in the bias voltage supply introducing an additional voltage component which varies with the transformer voltage. The resulting voltage is phase shifted in an adjustable phase shifter 233. As mentioned before, the magnetizing current of the coils 215, 217 and 219 is not constant but depends on the voltage applied to the reactors. This voltage, however, depends only on the ratio of transformer 212 and on the moment at which the commutation occurs. Delaying the commutation in order to reduce the D. C. voltage will increase the commutatory voltage and thus the magnetizing current. The bias current being a sine

wave, it is easy to adjust (by means of transformer 233) the respective angle between the bias current and the commutating voltage so that the magnetizing current and the bias current are always proportional. Furthermore, the variable addition which is introduced by means of the series transformer 232 compensates the bias current for the variations of the ratio in 212.

The variable reactors 236, 237 and 238 are inserted in the bias circuit to maintain the sine wave shape of the bias current and to permit the individual adjustment of the bias current of each phase in order to compensate for individual differences in the magnetic cores.

The transient circuits 241, 242, 243 are the exact replica of the circuits on winding 11 in Fig. 1, except that they are now inserted in the bias circuit. As their operation is only needed during the step and as the reactors 215, 217 and 219 are good transformers, during that time, the transient circuits 241, 242 and 243 can be connected to the secondary of these coils without any change in their operation.

The make coils 216, 218 and 220 are inserted after the by-pass resistors 227, 228 and 229 in order to block any inrush current through the switch 225. They are also provided with a bias. Fig. 7 shows an arrangement to obtain such a bias by means of a phase shifter transformer 251 and adjustable reactors X4, X5 and X6. By adjusting 251, the bias voltage can be adapted to the variations of the commutatory voltage (and therefore the magnetizing current) due to the variable delay angle and for regulating the D. C. voltage.

The elements needed for these control circuits on an actual rectifier are very small compared to the main parts (power transformer, buses, reactors, etc.). This comes from the fact that they carry only currents of the magnitude of the magnetizing current of the reactors which is less than one thousandth of the main current.

In one practical application of my invention, the D. C. current which is switched by the contacts may have a peak value of about 6000 amperes; the non-compensated interrupting current has a maximum value of 10 amperes, whereas the actual current to be interrupted has, in accordance with experimentation, been found to be at all times less than one-half an ampere, and an average value of about one-tenth of an ampere, thus reducing the current to be interrupted to $\frac{1}{20}$ to $\frac{1}{100}$ of its initial value.

Although I have shown my invention as applied to a mechanical rectifier, it will be obvious that it may have other applications and it will also be apparent that I may utilize other means for achieving the biasing current of the winding 8 or for achieving the phase relation of windings 11.

Thus while I have shown magnetizing current compensations achieved by windings on the saturable core, it will now be apparent that through the use of a separate source applying energy to the oscillating currents 13 to 17 of such values with relation to the elements of the oscillating circuits that the current in winding 11 will induce the required compensating current in winding 3 for its magnetizing current. In fact, the oscillating circuits with proper values may be directly in circuit with the main winding. It will now be apparent that there are numerous combinations for compensating for this magnetizing current all within the scope of my inventive concept and I do not wish to be limited except as in the appended claims.

I claim:

1. In a rectifier system connectible to a source of alternating current and to a load make and break contact rectifying means, a saturable magnetic core carrying a main winding connected in series between said make and break contact rectifying means and said source and a straightening winding mounted on said core and having a capacitor, inductor and resistor in series connected thereto for controlling the current in said main winding.

2. In a rectifier system connectible to a source of alternating current and to a load make and break contact rectifying means, a saturable magnetic core carrying a main winding connected in series between said make and break contact rectifying means and said source and a straightening winding member on said core and having a capacitor, inductor and resistor in series connected thereto and a capacitor and resistor in parallel with said first mentioned capacitor, inductor and resistor for generating compensating current in said main winding.

3. In a rectifier system connectible to a source of alternating current and to a load make and break contact rec-

tifying means, a saturable magnetic core carrying a main winding connected in series between said make and break contact rectifying means and said source, a resistor, an auxiliary winding mounted on said core and connected in series with said resistor across said source, said main winding carrying a magnetizing current during the switching operation of said contact rectifying means and said auxiliary winding having a resistive current for producing a compensating current in said main winding for a substantial portion of said magnetizing current to reduce the value of said magnetizing current to be interrupted by said contacts, and a straightening winding mounted on said core and having an oscillating current for controlling the current flow therein induced by the current in said main winding, said straightening winding being connected in series with a parallel circuit comprising capacitors and an inductor.

4. In a rectifier system connectible to a source of alternating current and to a load make and break contact rectifying means, a saturable magnetic core carrying a main winding connected in series between said make and break contact rectifying means and said source, a resistor, an auxiliary winding mounted on said core and connected in series with said resistor across said source, said main winding carrying a magnetizing current during the switching operation of said contact rectifying means and said auxiliary winding having a resistive current for producing a compensating current in said main winding for a substantial portion of said magnetizing current to reduce the value of said magnetizing current to be interrupted by said contacts, and a straightening winding mounted on said core, a capacitor-resistor circuit and a capacitor-inductance-resistor circuit connected in parallel with each other and in series with said straightening winding.

5. In a rectifier system connectible to a source of alternating current and to a load make and break contact rectifying means, a saturable magnetic core carrying a main winding connected in series between said make and break contact rectifying means and said source, a resistor, an auxiliary winding mounted on said core and connected in series with said resistor across said source, said main winding carrying a magnetizing current during the switching operation of said contact rectifying means and said second winding having a resistive current for producing in said main winding compensating currents for a substantial portion of said magnetizing current to reduce the value of said magnetizing current to be interrupted by said contacts, and a straightening winding mounted on said core and having a circuit including a capacitor, inductor and resistor connected thereto for controlling the current in said main winding.

6. In a rectifier system connectible to a source of alternating current and to a load make and break contact rectifying means, a saturable magnetic core carrying a main winding connected in series between said make and break contact rectifying means and said source, a resistor, an auxiliary winding mounted on said core and connected in series with said resistor across said source, said main winding carrying a magnetizing current during the switching operation of said contact rectifying means and said second winding having a resistive current for producing in said main winding compensating currents for a substantial portion of said magnetizing current to reduce the value of said magnetizing current to be interrupted by said contacts, and a straightening winding mounted on said core and having a circuit including a capacitor and resistor connected thereto and a capacitor, inductor and resistor connected thereto for controlling the current in said main winding.

7. A rectifying system comprising a saturable core reactor and a switching means, said reactor including a first load winding connectible in series between a source and a load for carrying the load currents flowing in the system, said switching means being in series with said first load winding, said source and said load; said reactor providing maximum reactance during a portion of each cycle during which full voltage from the source appears across the said first winding and only the switching current flows in said first winding and said reactor providing minimum reactance during which substantially no voltage from the source appears across said first winding, said reactor further comprising means for reducing said switching current in inductive coupling relation with said first winding including, an auxiliary winding, a substantially pure resistive circuit for said auxiliary winding including a resistor connectible across the source for generating currents in

said load winding substantially 180° out of phase with the switching currents flowing in said load winding, said switching current reducing means further including a third straightening winding on said reactor core, a first capacitor and resistor in series connection with said straightening winding for producing a capacitor discharging current and a capacitor, inductor and resistor connected in parallel with said first capacitor and resistor for producing an oscillatory discharge current, the capacitor discharge current and the oscillatory discharge current in said straightening winding generating currents in said load winding which together with the generated current in said load winding from said auxiliary winding substantially balance out the switching currents normally flowing in said load winding.

8. A rectifying system comprising a saturable core reactor and a switching means, said reactor including a first load winding connectible in series between a source and a load for carrying the load currents flowing in the system, said switching means being in series with said first load winding, said source and said load; said reactor providing maximum reactance during a portion of each cycle during which full voltage from the source appears across the said first winding and only the switching current flows in said first winding and said reactor providing minimum reactance during which substantially no voltage from the source appears across said first winding, said reactor further comprising means for reducing said switching current including a second auxiliary winding on said reactor core in inductive coupling relation with said first winding, a substantially pure resistive circuit for said auxiliary winding including a resistor connectible across the source for generating currents in said load winding substantially 180° out of phase with the switching currents flowing in said load winding, said switching current reducing means further including a third straightening winding on said reactor core, a capacitor, inductor and resistor connected to said straightening winding for producing an oscillatory discharge current and generating currents in said load winding which together with the generated current in said load winding from said first auxiliary winding substantially balance out the switching currents normally flowing in said load winding.

9. A rectifying system comprising a saturable core reactor and a switching means, said reactor including a first load winding connectible in series between a source and a load for carrying the load currents flowing in the system, said switching means being in series with said first load winding, said source and said load; said reactor providing maximum reactance during a portion of each

cycle during which full voltage from the source appears across the said first winding and only the switching current flows in said first winding and said reactor providing minimum reactance during which substantially no voltage from the source appears across said first winding, said reactor further comprising means for reducing said switching current including a second auxiliary winding on said reactor core in inductive coupling relation with said first winding, a substantially pure resistive circuit for said auxiliary winding including a resistor connectible across the source for generating currents in said load winding substantially 180° out of phase with the switching currents flowing in said load winding, said switching current reducing means further including a third straightening winding on said reactor core, a capacitor resistor in series connection with said straightening winding and a capacitor-inductor-resistor in parallel with said capacitor-resistor for producing a capacitor discharging current generating currents in said load winding which together with the generated current in said load winding from said first auxiliary winding substantially balance out the switching currents normally flowing in said load winding.

10. In a rectifier system connectible to a source of alternating current and to a load make and break contact rectifying means, a saturable magnetic core carrying a main winding connected in series between said make and break contact rectifying means and said source and a straightening winding mounted on said core and an oscillatory circuit including an inductor and capacitor connected to said straightening winding for producing oscillating current in said straightening winding for controlling the current flow therein induced by the current in said main winding.

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