Dec. 14, 1943. H. A. PETERSON 2,336,886

ELECTRIC CIRCUIT

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Fig. 1.

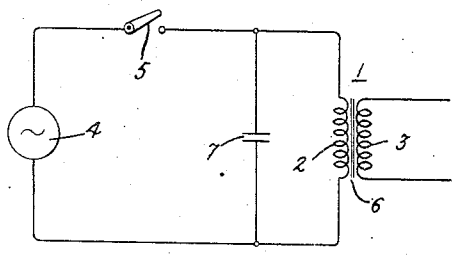
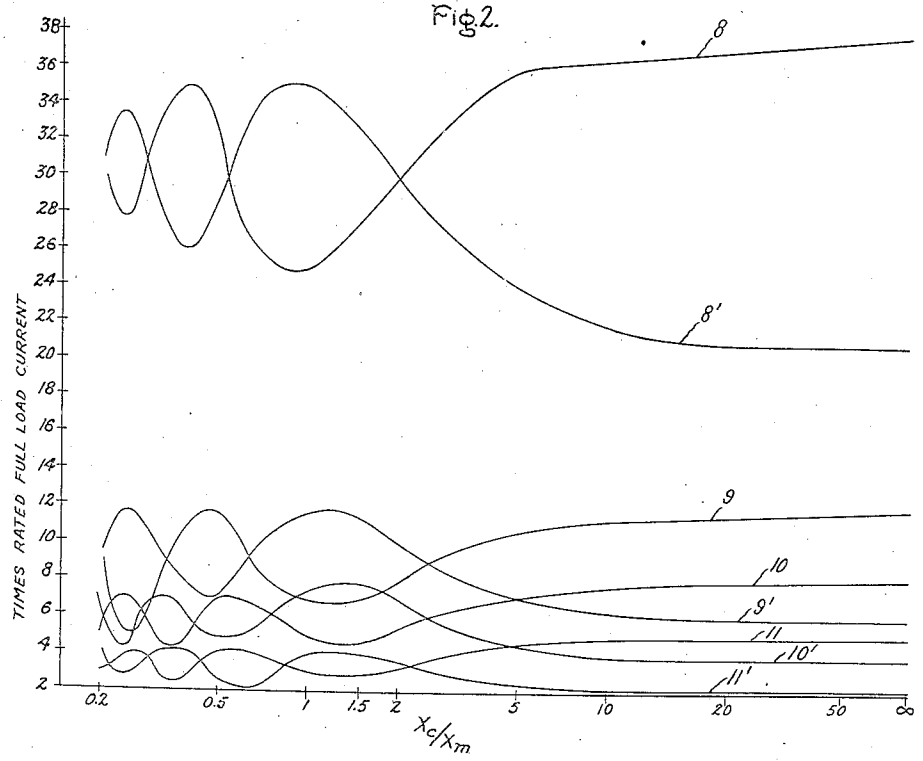



Fig. 2.




Inventor

Harold A. Peterson,

by Harry E. Dunham

His Attorney.

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# UNITED STATES PATENT OFFICE

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## ELECTRIC CIRCUIT

Harold A. Peterson, Scotia, N. Y., assignor to General Electric Company, a corporation of New York

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7 Claims. (Cl. 171—97)

This invention relates to electric circuits and has for an object the reduction of the inrush current of alternating-current inductive power apparatus.

Transformers, motors, reactors and solenoids are among the better known examples of such apparatus. It has long been known that when the switch, or its equivalent, for connecting such devices to their normal source of alternating voltage excitation is closed there is an initial, so-called inrush, magnetizing current which is often many times larger than the normal load current. These high values of inrush current are caused by saturation of the magnetic core of the apparatus and they are damped out in a short time by the effect of resistance in the circuit.

Ordinarily the occurrence and magnitude of these inrush currents is a random phenomenon which depends primarily on the point on the applied voltage wave at which the switch is closed and the amount of residual flux in the core at that instant. The worst possible conditions are maximum residual flux in the core and closing of the switch at the zero point of a half cycle of voltage whose polarity is such as to cause the flux to increase. This is because the flux must then continue to increase from a relatively high initial value for the maximum possible length of time, namely one-half a cycle. It is therefore carried to its maximum possible value at the end of this half cycle. As most cores are designed so as to operate at normal or steady state peak values of flux which are just below core saturation, that is, just below the knee of the magnetization curve, the above described maximum possible flux value will be far beyond the knee of the magnetization curve so that the accompanying inrush magnetizing current will reach its maximum possible value. If the residual flux is zero and the switch is closed at the zero point of the applied voltage wave the flux will reach a peak value of twice its normal steady state peak value, if the resistance of the circuit is neglected.

Improvements in core materials are continually increasing the permeability and decreasing the width of the hysteresis loop. Increase in the permeability means that the size, and hence the cost, of a given piece of apparatus may be reduced, while decreasing the width of the hysteresis loop means reducing the core losses and hence increasing the efficiency of the apparatus. Unfortunately, however, the increase in permeability is often accompanied by an increased abruptness of saturation, that is to say, it is accompanied by a sharper bend of the knee of the magnetization curve. Furthermore, it is also often accompanied by an increase in the residual flux when the magnetizing current is reduced to zero. These latter properties both contribute to a material increase in the maximum possible value of inrush current because it has been shown above that the value of the inrush current depends upon the value of residual flux and the shape of the magnetization curve. Furthermore, the reduction in core loss in the newer core materials is equivalent to a reduction in resistance in the circuit so that the damping effect which tends to bring down the value of the inrush current to the normal steady state value of the magnetizing current is decreased with the result that the duration of the high initial values of magnetizing current is increased. Thus, both factors of the $i^2T$ effect are increased and it is this $i^2T$ which causes the melting of fuses. It is therefore becoming increasingly difficult to provide automatic overcurrent protection which will provide adequate protection against the occurrence of overloads but which will not be actuated by inrush currents.

In accordance with the present invention the maximum possible inrush current value is materially reduced by connecting a capacitor in parallel circuit relation with the exciting or magnetizing winding of the device whose inrush current is to be controlled. The function of the capacitor is to discharge through the winding when the switch is opened, thus reducing the residual flux in the core. Alternating-current interruption ordinarily takes place at normal current zero so that in an inductive circuit the voltage is ordinarily near its maximum value at the instant of current interruption. Consequently, the voltage across the capacitor will be near its maximum value and the energy stored in the capacitor will therefore reverse the current in the winding so as in effect to knock the residual flux down to near its zero value. It can even produce a damped oscillatory discharge and as is well known, such a damped oscillation will also demagnetize the core. Unexpectedly, however, it has been discovered that the smaller values of capacitance which will reduce the residual flux substantially to zero are quite critical and that for certain other values of capacitance there is very little reduction in residual flux so that with such other capacitance values the peak value of inrush current will not be materially reduced. By means of this invention the peak value of

inrush current can be positively so controlled that it will never exceed a value corresponding to twice the peak steady state value of flux.

Another object of the invention is to provide a new and improved capacitive circuit arrangement for controlling the inrush current to inductive apparatus.

The invention will be better understood from the following description taken in connection with the accompanying drawing and its scope will be pointed out in the appended claims.

In the drawing, Fig. 1 illustrates diagrammatically an embodiment of the invention applied to a transformer and Fig. 2 is a set of curves showing the values of inrush current for various ratios of capacitive reactance to the inductive reactance of apparatus having cores with different magnetic properties.

Referring now to the drawing and more particularly to Fig. 1, there is shown therein by way of example an inductive device in the form of a power transformer 1 having a primary winding 2 and a secondary winding 3. The primary winding is normally energized from a conventional source of alternating potential 4 (whose frequency is preferably a standard commercial frequency, such as 25, 50, or 60 cycles per second) under the control of any suitable circuit maker and breaker, shown by way of example as a simple single-pole single-throw switch 5.

The transformer is provided with a magnetic core 6 which is preferably of the high-permeability low-loss type characterized by a hysteresis loop showing high residual flux and low coercive force. As has been previously explained, when the exciting circuit of such a transformer is closed, as by the closing of the switch 5, the inrush current has a maximum possible value which is many times the normal magnetizing current and which, in fact, is also many times the full load current of the transformer itself.

In order to reduce this inrush current and substantially reduce its heating and mechanical effects a capacitor 7 is connected in shunt circuit relation with the primary winding 2. This capacitor is preferably a relatively small device having a reactance of the order of twice the magnetizing reactance of the primary winding 2. Such a capacitor is very much smaller than conventional power factor correcting capacitors whose reactance is normally very much less, such, for example, as of the order of one-tenth of the magnetizing reactance of the transformer, because it should be remembered that those capacitors must neutralize not only the transformer magnetizing current but also the relatively very much larger reactive load current.

The operation of the circuit is as follows: When the switch 5 is closed the voltage of the capacitor 7 and the voltage of the primary winding 2 are in phase with each other. If now the switch 5 is opened, the current is interrupted at substantially the zero point of its wave, which due to the normally substantially ninety-degree phase displacement between current and voltage in an inductive circuit means that the voltage across the primary winding 2 and across the capacitor 7 are substantially at their maximum values. Furthermore, because of this ninety-degree phase displacement the magnetizing current is passing through zero at the instant of maximum voltage. Therefore, at this instant the flux in the core is the residual flux and the polarity of the voltage on the capacitor will be such as to cause the flux to continue to change in the same direction as it was changing at the instant the switch opened. In other words, the discharge of the capacitor will tend to demagnetize the core by reducing the residual flux toward zero. As will be explained below, certain optimum capacitor values have been found which will produce 100 per cent reduction of the transformer residual magnetism to zero.

If now the switch 5 is reclosed, the maximum possible value to which the flux can build up in the first half cycle is twice the normal crest or peak value of flux during steady state conditions and this will only occur if the switch is closed at the zero point of its voltage wave. Consequently, the maximum possible magnetizing current is the value of current corresponding to twice the normal steady state crest value of magnetizing flux.

In Fig. 2 are a number of sets of curves showing the relationship between inrush current plotted as ordinates and the ratio of the reactance ($X_c$) of capacitor 7 to the magnetizing reactance ($X_m$) of the primary winding 2 plotted as abscissae. The current values are per unit values in which unity represents normal 100 per cent load current. Curve 8 shows the relation between inrush current and

$$\frac{X_c}{X_m}$$

when the last half cycle of current in the primary winding 2 before switch 5 was opened and of the same polarity as the first half cycle of inrush current. In other words, the residual flux in the core 6 is in the same direction as the flux produced by the inrush current. As shown, this produces the highest values of inrush current, the value being approximately 37 times the normal load current for an infinite ratio of

$$\frac{X_c}{X_m}$$

which is equivalent to not having the capacitor 7 present. Curve 8' differs from curve 8 in that the last half cycle of current in the primary winding 2 before the switch 5 was opened was of opposite polarity to the first half cycle of inrush current. As shown, this produces materially lower values of inrush current when no capacitor is present, the value in that case being 21 times normal full load current. As the size and hence the capacitance of the capacitor 7 is increased its capacitive reactance decreases, thus decreasing the ratio of $X_c$ to $X_m$. This causes the inrush current shown by curve 8 to decrease and the inrush current shown by curve 8' to increase because in each case the increase in the amount of capacitance means a greater reduction in the residual flux when the switch is opened. This continues until the value of

$$\frac{X_c}{X_m}=2$$

at which point the curves cross each other. Therefore, at this point the effect of residual flux has been reduced to zero showing that the residual flux has been completely cancelled at this value of

$$\frac{X_c}{X_m}$$

This means that at this particular ratio the energy stored in the capacitor is just sufficient to neutralize the energy represented by the re-

sidual flux. It will be seen that at this critical value of $X_c$ corresponding to the ratio of

$$X_c:X_m=2$$

the inrush current has a value of thirty times normal full load current. This represents a reduction in the $I^2$ effect of the current of substantially 33 per cent from the peak value obtained when no capacitor is present.

The reason values of

$$\frac{X_c}{X_m}$$

substantially larger than 2 are not effective is because the damping of the capacitor discharge current oscillation is so great at the higher frequencies. The discharge current must be of sufficient magnitude to reduce the residual flux to zero and this is not possible at the higher ratios of $X_c$ to $X_m$ because of the iron loss (not $I^2R$).

Further decreases in the ratio of $X_c$ to $X_m$ corresponding to further increases in the size of the capacitor cause the inrush current for curve 8' to increase and for curve 8 to decrease. This is because the capacitor is now large enough to more than neutralize the residual flux so that the flux passes through zero and is left with a residual value in the opposite direction. Thus the residual flux for curve 8' is now in the same direction as the flux produced by the inrush current and is in the opposite direction to the flux produced by the inrush current with respect to curve 8. As the size of capacitor 7 is increased still further the inrush currents will again tend to converge because of the oscillatory nature of the circuit consisting of the capacitor 7 and the winding 2 in parallel and at a value of

$$\frac{X_c}{X_m}$$

of approximately .525 the circuit will oscillate through one cycle instead of one-half cycle as was the case for the value of

$$\frac{X_c}{X_m}=2$$

Therefore, at this .525 the residual flux is all removed but the size of the capacitor has been materially increased. Further increases in the size of the capacitor will cause a repetition of this cycle so that the residual flux may be reduced to zero by numerous other predetermined but larger and larger size capacitors.

Curves 8 and 8' were produced with a transformer having a high permeability, high residual flux core material. Curves 9 and 9' correspond to 8 and 8' but were taken on a transformer having a core with lower permeability and lower residual flux. Similarly, curves 10 and 10', 11 and 11' show the effect of different core materials. It will be noted, however, that for all these four different core materials the flux is reduced to zero when

$$\frac{X_c}{X_m}$$

is within the range of 2 to 2½ inclusive. For the lower ratios of $X_c$ to $X_m$ the range in per cent of the value necessary to reduce the residual flux to zero is very much greater, for example, in the case of the next lower ratio the range will be from .525 in the case of curves 8 and 8' to .86 in the case of curves 11 and 11'.

It has also been found that the value

$$\frac{X_c}{X_m}$$

required to eliminate the residual is relatively independent of the amount of that residual.

While there has been shown and described a particular embodiment of this invention, it will be obvious to those skilled in the art that various modifications can be made therein without departing from the invention and, therefore, it is aimed in the appended claims to cover all such changes and modifications as fall within the true spirit and scope of the invention.

What I claim as new and desire to secure by Letters Patent of the United States, is:

1. In combination, a source of alternating potential, an inductive device having a maximum possible inrush magnetizing current several times higher than the crest value of its rated full load current, a circuit maker and breaker for controlling the application of said potential to said device, and means for substantially reducing the maximum possible inrush magnetizing current comprising capacitive reactance of predetermined size connected in shunt circuit relation to said device, said capacitive reactance producing a unidirectional non-oscillating discharge current through said device when said circuit maker and breaker is opened.

2. In combination, a source of alternating potential, an inductive device having a maximum possible inrush magnetizing current several times higher than the crest value of its rated full load current, a circuit maker and breaker for controlling the application of said potential to said device, and means for substantially reducing the maximum possible inrush magnetizing current comprising capacitive reactance of predetermined size connected in shunt circuit relation to said device, said capacitive reactance being greater than the magnetizing reactance of said device at the frequency of said potential.

3. In combination, a source of alternating potential, an inductive device having a maximum possible inrush magnetizing current several times higher than the crest value of its rated full load current, a circuit maker and breaker for controlling the application of said potential to said device, and means for substantially reducing the maximum possible inrush magnetizing current comprising capacitive reactance of predetermined size connected in shunt circuit relation to said device, said capacitive reactance being between 1½ and 2½ times the magnetizing reactance of said device at the frequency of said potential.

4. In combination, a source of alternating potential, an inductive device having a maximum possible inrush magnetizing current several times higher than the crest value of its rated full load current, a circuit maker and breaker for controlling the application of said potential to said device, and means for substantially reducing the maximum possible inrush magnetizing current comprising capacitive reactance of predetermined size connected in shunt circuit relation to said device, said capacitive reactance being of the order of twice the magnetizing reactance of said device at the frequency of said potential.

5. In combination, a source of alternating potential, an inductive device having a maximum possible inrush magnetizing current several times higher than the crest value of its full load current, a circuit maker and breaker for controlling the application of said potential to said device, and capacitive reactance which reduces the residual flux of said device substantially to zero when said circuit breaker is opened connected in

shunt circuit relation with said device, said capacitive reactance having such a low value of capacitance that its discharge current through said device is dead beat when said circuit maker and breaker is opened.

6. In combination, a source of alternating potential, an inductive device having a maximum possible inrush magnetizing current several times higher than the crest value of its full load current, a circuit maker and breaker for controlling the application of said potential to said device, and means for automatically reducing the residual flux of said device substantially to zero when said circuit breaker is opened so as substantially to reduce the squared value of the maximm inrush current of said device, said reduction in residual flux being accomplished without reversing its direction.

7. In combination, an alternating-current potential power source of commercial frequency, a power transformer having a high permeability core with an abrupt saturation characteristic, a switch for selectively connecting the primary winding of said transformer to said source and disconnecting it therefrom, and a small capacitor having an effective reactance of the order of 2 to 2½ times the normal magnetizing reactance of said primary winding connected in shunt circuit relation with said primary winding so as substantially to reduce the squared value of the maximum inrush magnetizing current of said primary winding when said switch is opened.

HAROLD A. PETERSON.