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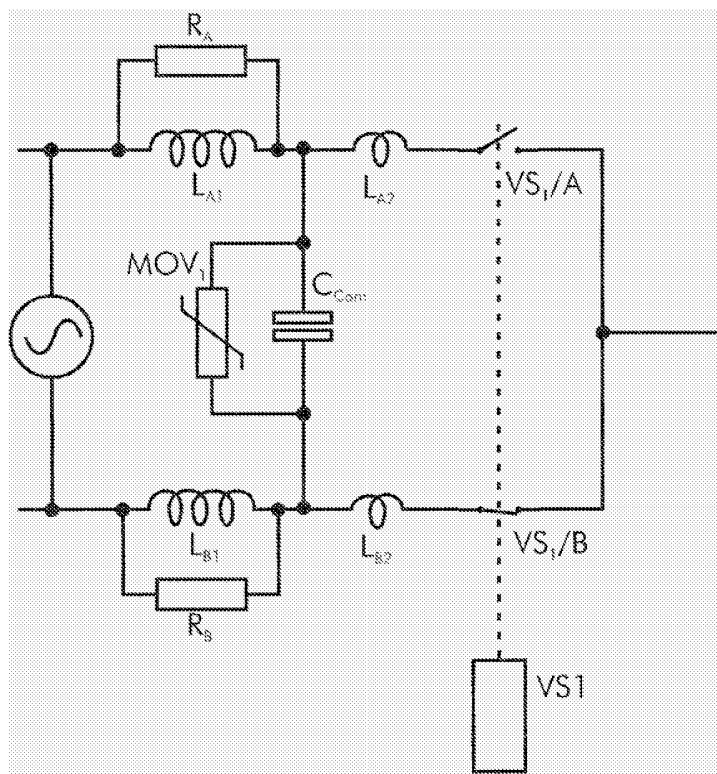
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(54) Title: AN ON-LOAD TAP CHANGER



(57) Abstract: The invention relates to commutation in on-load tap changers and in particular to the utilisation of arcing at the contacts of one of a pair of opposed switch elements. The invention provides a commutation circuit being connectable to a pair of opposed switch elements in the tap changer and a tap winding of the transformer, the commutation circuit being operable to establish a resonant current upon closure of a non-conducting switch element to commutate off an arcing switch element. The commutation circuit may be incorporated into a diverter for use with a conventional Selector or may form part of a complete tap changer.



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AN ON-LOAD TAP CHANGER

The invention relates to on-load tap changers, and in particular to commutation in on-load tap changers.

5 A tap changer is a device fitted to a transformer for regulating the output voltage of the transformer to a required level. Such regulation is normally achieved by selectively connecting to particular taps of the transformer, thereby controlling the number of turns in
10 the active portion of the primary or secondary winding (ref. 1).

An on-load tap changer is designed to operate when conducting current and requires that the circuit must
15 not be opened even momentarily during tap changing.

A simplified example of a conventional tap changer is shown in Figure 1A. The tap changer includes a selector, having two output current paths to select one
20 of a number of taps in the primary winding of the transformer; and a diverter with a "make-before-break" action to divert current from one current path to another without interrupting current flow. Figure 1B illustrates the level of complexity that is common
25 within tap changers for power transmission.

Conventional tap changers achieve the "make-before-break" action by connecting resistors across the tap winding during the moment of changeover to limit
30 circulating current that would otherwise develop. The breaking of this combined load current and circulating

current using conventional high voltage electrical switch contacts leads to a high level of arcing occurring. This both degrades the insulating property of the oil in which the switch is placed and
5 occasionally leads to the mechanism "sticking". The former of these conditions requires that the oil is segregated from the main transformer oil and that it must be replaced on a regular basis, while the latter can lead to catastrophic failure of the whole
10 transformer system. Modern systems include a vacuum switch to contain the arc but this adds complexity and the vacuum switch requires regular replacement (ref. 2).

The selector and diverter for a conventional on-load
15 tap changer rely on oil insulation to achieve the contact-to-contact insulation levels required for the highest rated transformer voltage. The selector only operates relatively slowly, taking several seconds to change the tap connection, while the diverter must
20 provide a rapid changeover when the selector has made the tap connection in order to limit the level of circulating current. However, this still takes several cycles of power frequency to complete.

25 A conventional power network may be described as a network of power stations that provide power to a grid network from which power is then dispersed to consumers through a distribution network. There is a trend towards more localised generation, supported by
30 national and international legislation, which will require much more flexibility in the manner in which

the power is managed at a local level. This will require tap changers that are smaller, cheaper and easier to install and maintain and that will operate with a wider range of current flow and power factors than existing tap changers. Moreover there is a requirement for tap changers with significantly higher performance to be applied to more novel applications such as phase shifting transformers where the requirement would be to cover the full range of 25 taps within the same time that it presently takes to do one tap change.

An object of the invention is to overcome the problems described above and to meet the foreseen demands of applying distributed generation to localised power distribution.

Another object of the invention is to provide a tap changer with better properties than those described above, providing a faster change in tap connection without breaking the transformer circuit.

The invention may be used either to replace the diverter or to replace the complete on-load tap changer system. The latter option would require a sufficiently small number of electrical power switches to make it competitive in size and cost to prior art on-load tap changers described above.

According to a first aspect of the invention, there is provided an on-load tap changer comprising a selector

and a diverter, the diverter comprising a pair of opposed switch elements and a commutation circuit, the commutation circuit being operable to establish a resonant current upon closure of a non-conducting
5 switch element to commute off an arcing switch element.

The tap changer is intended for association with a transformer for connection to a power system having one
10 or more phases.

The opposed switch elements may be arranged to provide a "break before make" change over in which opening the switch contacts on current draws an arc between the
15 contacts maintaining conduction past the first break action. The concept is that the closure of the second switch will invoke the commutation circuit to quench the arc in the first switch contacts. With a sufficiently fast acting commutation circuit the result
20 is to give an ideal instantaneous change over between the switches.

According to a second aspect of the invention, there is provided an on-load tap changer comprising one or more
25 pairs of opposed switch elements for connection to respective tap windings of a transformer, the tap changer including a commutation circuit being operable to establish a resonant current upon closure of a non-conducting switch element to commute off an arcing
30 switch element.

The commutation circuit is included with each opposing switch element to provide an ideal changeover of current in which the closed switch contact opened on load and maintains conduction by drawing an arc between its contacts. Closing the second switch contacts invokes the commutation circuit commutating off the arc across the first switch contacts. By using an array of electrically isolated transformer taps as part of a network of such opposing switch elements, a complete tap changer can be assembled, with no requirement to distinguish between a selector and diverter. Furthermore, by employing isolated tap windings with turns values that vary one to another according to a set sequence, for example binary, the required number of windings and switch elements can be significantly reduced over that of a conventional tap changer.

The operation of the commutation circuit should be very rapid making the changeover of current in the opposing switch element a matter related to the values of voltage and current at the instant of the changeover rather than the conventional consideration of load power factor. Thus the changeover scheme provides for a fast reliable switchover, allowing operation at high speed making the resulting tap changer suitable for high performance applications such as in power transmission phase shifting, high voltage D.C. transmission transformers and arc furnace transformers.

A range of different types of electrical contact could be employed and it is possible to use a semiconductor

switch such as a thyristor, for which the term "arcing" should be substituted by "non-gated conduction".

However, in a preferred embodiment, each switch element
5 is a vacuum switch. A vacuum switch will readily arc between the contacts when opened on current, maintaining conduction until the arcing is quenched. Vacuum switches require little armature movement to obtain high levels of electrical isolation between
10 contacts so the armature action can be very rapid. The small contact gap also means that they arc very readily when being opened on current and several aspects of their design have been introduced to permit arcing to take place without deteriorating their performance such
15 as special contact metals being used that have advantageous properties under arcing. Being plasma in nature, contact arcing is prone to instability under certain conditions. Vacuum switches are designed to maintain a high level of arc stability to very low
20 levels of current and voltage (0.5A to 2.5A and 60V being quoted). Unlike arcing that takes place in air, the time to recover the full breakdown voltage for the gap between the contacts is very short. Also, the containment of the arc within the vacuum chamber means
25 that the possibility of contaminating the transformer oil in which it is placed is not possible.

The tap changer may include a network of opposed switch elements for connection to tap windings with weighted
30 numbers of turns, such that a complete range of integer tap values can be obtained by the tap voltages being

caused to subtract or add. The network may include a difference winding arrangement, a sum winding arrangement, or a sum-difference winding arrangement. The tap windings may have numbers of turns of equal
5 value or weighted as a numerical sequence, which may be binary.

There are several different ways in which transformer taps with unequal values can be combined to produce a
10 range of tap values using a minimum of opposing switch elements. Because all the tap winding voltages have the same polarity, passing load current through them in one direction means the tap windings add to the main transformer winding, while passing current in the
15 opposite direction means they subtract from the main transformer winding. The simplest scheme is the "difference scheme" in which current passes alternately up and down through the windings as illustrated in Figure 3A. The winding values increase as $3N$, in a
20 sequence 1, 3, 6, 9.... For example to obtain a tap winding value of 2 the windings are arranged as 3-1, and for 7 the arrangement is 9-3+1. A more complex scheme is the "summation scheme" which is illustrated in Figure 3B and uses true binary windings. Here the
25 switches bypass windings that are not required. To illustrate the degree of reduction possible in the numbers of switches it is well known that binary arrangements rise as 2^N . Thus with 5 opposing switch elements it should be possible to obtain 32 different
30 tap combinations. With the circuit shown in Figure 3B a reversing function has been added that requires an

extra opposing switch pair, so to cover a typical range of -12 to +12 would require six sets of opposing switch combinations and five tap windings. Figure 3C shows a scheme that combines the sum and difference schemes to
5 reduce the numbers of windings to a minimum. Unfortunately this is at the expense of increased numbers of switches.

The commutation circuit may include an LC circuit
10 having a capacitor arranged to discharge upon closure of the non-conducting switch element to create the resonant current, the polarity of the resonant current opposing that of the arcing current.

15 Depending on the polarity of the transformer load current, the resonant current will cancel the transformer load current either before the first resonant peak of the commutation circuit, or at or before the second resonant peak.

20

The capacitor may store sufficient charge for the magnitude of the resonant current to sufficiently cancel the transformer load current during at least one cycle such that the combined current through an arcing
25 switch element reduces to less than the chopping current for the switch element. The chopping current is set by the properties of the switch used, but will be considered to be approximately zero amperes.

30 The commutation circuit must reverse the potential due to the arcing across the contacts of the open switch

element on the closure of the opposing switch element in order to quench the arc. The reversal of this potential requires that all the current passing through the switch element contacts must be driven to below the chopping current quoted for the switch element. Once the arc is extinguished the time for the switch element to recover is exceptionally short.

One proposed method utilises the property of capacitors to provide low impedance at high frequency and high impedance at low frequency in contrast with the property of inductors to give high impedance at high frequency and low impedance at low frequency. Thus with the conducting switch element contacts open and arcing to maintain conduction the action of closing the opposing switch element contacts applies a step voltage through a pair of capacitors which momentarily reverses the voltage on the arcing contacts. This is allowed to occur due to the presence of two inductors. The time constant of this action is very short so these components would not interfere with the normal operation of the tap changer.

A capacitor placed within a network of inductors and capacitors (LC network) can be arranged to charge to the tap voltage and to then discharge upon the closure of the non-conducting switch element to create a resonant current.

The commutation circuit may be balanced. By "balanced" is meant that two or more conduction paths of the commutation circuit have identical impedance.

- 5 The advantage of such a scheme is that all the resonant current circulates around the LC network and does not disturb the load current. Also, the extent of the resonance is determined by the polarity of the load current, so a full resonance will not occur when the
- 10 circulating current due to the capacitor discharge already opposes the direction of the load current. When this initial circulating current is in the same direction as the load current the capacitor needs to have available sufficient charge to drive the resonance
- 15 through, for example, a positive peak current and back to a negative peak current, the negative peak current having sufficient magnitude to drive the combined load and resonant current within the arcing contacts through zero, so commutating the arc. This process will result
- 20 in a reliable commutation process.

In a first embodiment, a first load current path has connected in series first and second inductors and a first switch element of an opposed pair. A second load

25 current path has connected in series third and fourth inductors and a second switch element of an opposed pair. The input connections to the first and third inductors are placed on either side of an isolated transformer tap winding. A capacitor bridges a point

30 between the first and second inductors with a point between the third and fourth inductors.

A first resistor may be connected in shunt with the first inductor, and a second resistor may be connected in shunt with the third inductor, to damp out resonance
 5 between these inductors and the resonant capacitance once the arc has been commutated off and the voltage on the capacitor returns to being the tap voltage. A voltage-limiting resistor may be connected in shunt with the capacitor.

10

To provide a balanced circuit the inductance values of the first and third inductors (L_1 and L_3 respectively) must be equal and similarly the inductance values of the second and fourth inductors (L_2 and L_4 respectively)
 15 must also be equal.

The inductances of the first and second inductors (and hence the third and fourth inductors) should be related

by the equation: $L_2 < \frac{2}{3\pi} L_1$, and preferably $L_2 \approx 0.1 \cdot L_1$.

20 This ensures that the first and third inductors may present a sufficiently large impedance to the resonant current to substantially decouple the capacitor during commutation.

25 Finally $\frac{V_0}{I_0} > \frac{0.481}{\omega \cdot L_1}$, where V_0 is the resonant capacitor voltage and I_0 the load current at the instant of commutation and ω is the natural frequency of the commutation circuit. These conditions ensure that the magnitude of the resonant current will be sufficient to

be able to cancel the load current and that the resonant current is contained within the commutation circuit, the load current remaining unaffected. They also ensure that neither the capacitance nor the blocking inductor has too large a value.

In a second embodiment, a first load current path has a first switch element of an opposed pair. A second load current path has connected in series an inductor and a second switch element of the opposed pair. A capacitor is connected in shunt with the inductor and the second switch element.

In a third embodiment, a first current path has connected in series a first inductor, a second inductor, a first switch element of an opposed pair, and a third inductor. First and second resistors are connected in shunt with the first and third inductors respectively. A second current path has connected in series a fourth inductor, a fifth inductor, a second switch element of the opposed pair, and a sixth inductor. Third and fourth resistors are connected in shunt with the fourth and sixth inductors respectively. A first capacitor bridges a point between the first and second inductors and the fourth and fifth inductors. A second capacitor bridges a point between the first switch element and the third inductor with a point between the second switch element and sixth inductor.

According to a third aspect of the invention, there is provided a commutation circuit for an on-load tap

changer, the commutation circuit being connectable to a pair of opposed switch elements in the tap changer and a tap winding of a transformer, the commutation circuit being operable to establish a resonant current upon
5 closure of a non-conducting switch element to commute off an arcing switch element.

The commutation circuit may include any of the features of the tap changers of the first and second aspects of
10 the invention.

In order that the invention may be more readily understood, a description is now given, by way of example only, reference being made to the accompanying
15 drawings, in which:-

Figure 1A is a schematic diagram of a simplified example of a conventional on-load tap changer;

Figure 1B is a schematic diagram illustrating a more typical selector arrangement for a power
20 transmission transformer to obtain a tap range of ± 12 (ref. 1);

Figure 2 is a schematic diagram of a pair of opposed switch elements operated using a common actuator;

25 Figures 3A to 3C are schematic diagrams of opposed pairs of switch elements in a difference winding arrangement; a sum winding arrangement; and a sum-difference winding arrangement, respectively;

Figures 4A to 4D are schematic diagrams showing
30 circulating current flow and various permutations of load current through opposed pairs of switch elements;

Figure 5 is a schematic diagram of a commutation circuit according to a first embodiment of the invention;

Figure 6 is a schematic diagram of a modification
5 to the circuit of Figure 5 so that it can act in place of a conventional diverter;

Figure 7 is a schematic diagram of a complete tap changer having a difference winding arrangement giving ± 12 taps and incorporating the circuit of Figure 6;

10 Figure 8A is a schematic diagram of a complete tap changer having a sum winding arrangement giving ± 15 taps and incorporating the circuit of Figure 6;

Figure 8B is a schematic diagram of a complete tap changer having a sum winding arrangement giving +31
15 taps and incorporating the circuit of Figure 6 (note $N_p^* = N_p - 16.N_t$);

Figure 9 is a schematic diagram of a commutation circuit according to a second embodiment of the invention;

20 Figure 10 is a schematic diagram of a commutation circuit according to a third embodiment of the invention;

Figure 11A is a schematic diagram of a commutation circuit according to a fourth embodiment of the
25 invention;

Figure 11B is a schematic diagram of the circuit of Figure 11A applied to a derivative of the difference tap changer form, rather than a distribution transformer;

Figure 12A is a schematic diagram of a split tapped primary winding with which the circuit of Figure 11 is used;

Figure 12B illustrates how the circuit of Figure 11 might be connected to the winding of Figure 12A;

Figure 13 is a MATLAB/SimPower Systems representation of a 70MVA power transmission transformer with a 227kV r.m.s. nominal primary rating used to simulate the operation of a tap changer according to the invention;

Figure 14 illustrates the results for the load current and voltage waveforms of the simulation of Figure 13 when undergoing a tap change;

Figure 15 illustrates the results for the currents in the opposed pair of switch elements (top trace) and the commutation capacitor voltage (bottom trace);

Figure 16 shows an expansion of Figure 15 to show the commutation process.

The invention is based on a pair of opposed switch elements 14, 16, as shown in Figure 2.

When used in an on-load tap changer, the switch elements 14, 16 are arranged to have a momentary "break before make" action. A common actuator 18 provides a mechanical drive assembly to produce the required action. Alternatively, the switch elements 14, 16 can be driven by individual actuators with electronic timing to provide the required action.

Such a pair of opposed switch elements can be used to replace the conventional diverter within a conventional on-load tap changer described above.

- 5 Alternatively, one or more pairs of opposed switch elements can be arranged in conjunction with isolated transformer taps to form a complete tap changer, replacing both the selector and the diverter.
- 10 The tap values may be identical. For example, the circuit of Figure 3B could be utilised with identical tap winding values. However, by using tap windings with individual winding values, the number of taps and opposing switch elements can be significantly reduced.
- 15 Figures 3A, 3B and 3C show simple examples of such tap changers. In Figure 3A, three sets of opposed switch elements are connected so that the intermediate tap values are obtained by subtracting tap voltages, the
20 "difference winding" arrangement. In Figure 3B, four sets of opposed switch elements are connected so that the intermediate tap values are obtained by adding tap voltages, the "sum winding" arrangement. Figure 3C shows a further arrangement that combines these two
25 schemes to give intermediate values by both adding and subtracting the tap voltages, the "sum-difference" arrangement. In the proposed arrangements, the sequence defining the tap winding values vary. For the difference scheme, the number of turns (N_i) for the i^{th}
30 tap winding is given as: $N_i = 3 \cdot i$. For the sum scheme, the number of turns (N_i) for the i^{th} tap winding is

given as: $N_i = 2^i$. For the sum-difference scheme, the number of turns (N_i) for the i^{th} tap winding is given as: $N_i = 3^i$.

- 5 Figures 4A to 4D show the four possible permutations of current flow through opposed switch elements 14,16 when connected to a tap winding 12 as in Figures 3A, 3B and 3C. In all these diagrams, it has been assumed that the conducting switch has commenced opening on current and
10 is now remaining in conduction as a result of drawing an arc between the contacts. This is represented by the voltage source symbol in the load current path, whose polarity is defined by the direction of flow if the load current, I_L . This arcing will be sustained until
15 the current passing between the switch contacts reduces to the "chopping current" for the contacts, which for a vacuum switch can be as low as 0.5A. In the context of the normal load current this is negligible, and in the following argument will be treated as zero. Closing the
20 opposing switch element causes a circulating current I_C to develop, driven by the voltage source representing the transformer tap winding 12 and limited in its rate of rise by inductance within the current loop.
- 25 In Figures 4A and 4C the circulating current I_C opposes the load current I_L . Thus I_C will continually rise until it reaches the value of I_L and cancels it, quenching the arc. This will be referred to as the "cancellation condition".

In Figures 4B and 4D, the circulating current I_C adds to the load current I_L . I_C reinforces I_L , and it is possible that it can then rise to a level that is large enough to cause damage to the transformer due to the
5 low impedance of the transformer tap winding. This will be referred to as the "reinforcement condition" and is a problem that is overcome by the invention, as will be described.

10 Figure 5 shows part of a tap changer according to a first embodiment of the invention. The tap changer includes a commutation circuit and is intended for use with a power transmission transformer to replace the diverter.

15

The commutation circuit is connected to first and second opposed switch elements operated by an actuator, and to a tap winding, represented in Figure 5 by a voltage source.

20

The commutation circuit has two load current paths. A first load current path has connected in series first and second inductors and a first switch element of an opposed pair. A second load current path has connected
25 in series third and fourth inductors and a second switch element of the opposed pair. A capacitor bridges a point between the first and second inductors with a point between the third and fourth inductors.

In use, the capacitor charges to near the instantaneous voltage of the voltage source representing the tap winding.

- 5 In the cancellation condition, closing the non-conducting switch element results in the arc being quenched naturally, as described above.

- 10 In the reinforcement condition, closing the non-conducting switch element creates a discharge path for the capacitor, while the second and fourth inductors create a sinusoidal resonant current. This current will initially rise in the same sense as the load current. However, it will then swing back to oppose the load
15 current in the arcing switch element with sufficient magnitude to quench the arc.

In this way, the arc is quenched for all permutations of load current flow.

20

- Values of inductance and capacitance are chosen such that, on closing the non conducting switch element, the magnitude of the second peak of the resonant current exceeds that of the load current, causing the current
25 in the arcing switch element to pass through zero, thereby commutating off the arcing switch element.

- The natural frequency for the commutation circuit is a matter of design choice and will normally be greater
30 than 1kHz and may be as high as 100kHz. A higher frequency requires smaller components, but too high a

frequency result in damping effects due to eddy currents in the circuit and particularly within the switch element. In particular the capacitor needs to have a very high rated voltage and must have a
5 relatively low value of self-resonance that should not be permitted to conflict with the selected resonant frequency.

The inductance values of the first and third inductors
10 are chosen to present sufficiently large impedance to the resonant current for the capacitor to substantially decouple the voltage source. Significantly, this ensures that the resonant current is contained within the commutation circuit, with the load current
15 remaining unaffected.

The inductance values of the first to fourth inductors are L_1 , L_2 , L_3 and L_4 . In this embodiment, $L_1 = L_3$ and $L_2 = L_4$, i.e. the commutation circuit is balanced having
20 equal impedance in both current paths. This mitigates 'ringing' on the load current after a switchover with any ringing being contained within the loop.

The inductor values L_1 and L_2 (and hence L_3 and L_4) must
25 be related by the equation: $L_2 < \frac{2}{3\pi} \cdot L_1$. This ensures that the magnitude of the resonant current will be sufficient to be able to cancel the load current.

For the relationship $L_2 = \frac{2}{3\pi} \cdot L_1$ the value of the resonant
30 capacitor becomes excessively large so an optimum

balance between the values of the inductors L_1 and the resonant capacitor is nominally $L_2 = 0.1 \cdot L_1$.

The design value of L_2 is found by selecting the
 5 desired resonant frequency (ω radians per second) and substituting it into the expression $L_2 = \frac{0.481 \cdot V_0}{\omega \cdot I_0}$, where

V_0 is the minimum instantaneous voltage required for commutation and I_0 is the maximum instantaneous value of load current. The value of the capacitance is then
 10 found from the expression for the resonant frequency

$$\omega = \sqrt{\frac{1.1}{L_2 \cdot C}}.$$

The damping resistor is then selected to give minimum damping of the initial commutation resonance while
 15 providing a minimum number of resonant cycles after commutation. The non-linear resistance placed across the capacitance must limit the capacitor voltage to a value less than the capacitor rated voltage but more than the worst case maximum peak voltage to be
 20 expected. Hence all the component values in the circuit can be found. In practice some adjustment may be required to account for effects such as damping due to eddy currents within the vacuum switch or stray circuit inductance.

25

The maximum peak resonant current will be very high for the commutation at maximum peak voltage. None of the inductors must saturate and the capacitor must be rated for this current. Similarly after commutation has

occurred the current built up within the "blocking" inductor L_1 , must now pass directly through the resonant capacitor, causing this to reverse in potential and to reach a voltage several times the
 5 normal supply voltage if it is not suppressed. The following give derived expressions to provide an approximate indication of the magnitudes of the various voltages and currents that affect the component design.

10 The current in L_1 at commutation is given as:

$$I_{L1c} = \frac{(3\pi+2)}{2} \cdot \frac{V_0}{\omega \cdot (L_1 + L_2)} + I_0$$

And the current in L_2 at commutation is given as:

$$I_{L2c} = -\frac{(\pi+22)}{22} \cdot \frac{V_0}{\omega \cdot L_2} + I_0$$

15

The voltage at commutation is $V_{cc} = \frac{0.1}{1.1} \cdot V_0$, however the voltage by which the capacitor has deviated from the steady state is $\Delta V_c = -\frac{1}{1.1} \cdot V_0$

The peak capacitor voltage after commutation has taken

20 place is given as: $V_{cc} = \sqrt{I_{L1c}^2 \cdot \frac{L_1}{C} + \Delta V_c^2}$

The size of the components can be significant compared to the size of the switch assembly. Since the commutation process employs current that wholly
 25 circulates through the capacitor the two pairs of inductors L_1/L_3 and L_2/L_4 may be combined as mutually coupled inductors on a common magnetic core. This

exploits the phenomena that inductance is proportional to the number of turns squared. Thus two identical coils which have a common current passing through them in the same direction will develop a total inductance
5 of four times that of the individual inductors. However, if the current flows in opposing directions through the coils, the flux cancels resulting in no net inductance being present. Thus the pair of coils can be placed on a single core of the same size as for each of
10 the previous coils, where the number of turns for each coil winding is reduced in value by the square root of two.

The circuit presented in Figure 5 may be directly
15 applied as a replacement to a diverter in a conventional on-load tap changer. In doing this it, should be noted that the connection of the capacitance in parallel with the tap windings might present a problem with selectors that switch in oil. In this
20 case, it may be necessary to introduce two additional auxiliary contacts as in Figure 6, so that this capacitance can be isolated while the selector is being operated.

25 The commutation circuit can be applied directly or may need to be modified to allow it to be incorporated into different forms of tap changers such as those shown in Figures 3A, 3B and 3C.

The low values of L_2 and L_4 means that stray terms within the current path may provide sufficient inductance without the need for those inductors.

5 Figure 7 shows a complete tap changer having a difference winding arrangement and incorporating a modified form of the commutation circuit of the first embodiment. Note that the inductors L_1 , L_3 and the resonant capacitor are associated with the tap winding,
10 while the inductors L_2 and L_4 are associated with the opposed switch pair. In this L_1 and L_3 have been designed as mutually coupled inductors but cannot be applied to this configuration to L_2 and L_4 . Note that opposing switch element S5 uses pairs of switches in
15 series with voltage sharing Metal Oxide Varistors (MOVs) in order to obtain the required breakdown insulation voltage (BIL) for the highest tap voltage.

Figure 8A shows a complete tap changer having a sum
20 winding arrangement and directly incorporating the commutation circuit of the first embodiment. In this example, L_2 and L_4 have been implemented as mutually coupled inductors to reduce their size and cost. In this example, opposing switch pair S5 needs to form a
25 full bridge circuit to provide a voltage reversal. Since the BIL is above that for the individual switches, series connected pairs of switches have had to be used as with Figure 7. Figure 8B shows how separating out part of the primary winding to give an
30 additional 16.Nt tap winding may reduce the complexity of this circuit.

Any of the commutation circuits herein may be used in such a way as to form a complete tap changer.

- 5 Alternatively, any embodiment shown and described may be used to replace a conventional diverter simply by omitting the tap winding and instead connecting the two resulting free points to the selector such that the two load current paths of the circuit connect respectively
10 to the two current paths of the selector.

Figure 9 shows part of a tap changer according to a second embodiment of the invention. The tap changer includes a commutation circuit 400.

15

- The commutation circuit 400 has two load current paths. A first load current path has a first switch contact 414 of an opposed switch pair. A second load current path has connected in series an inductor 401 and a
20 second electrical contact 416 of the opposed switch pair. A capacitor 410 is connected in shunt with the inductor 401 and second switch contact 416.

- Figure 10 shows part of a tap changer according to a
25 third embodiment of the invention. The tap changer includes a commutation circuit 500 and is intended for use with a distribution transformer.

- The commutation circuit essentially mirrors that of the
30 first embodiment. The principle is the same except that

the resonant current passes through the second 502 and fifth 505 inductors and both capacitors 510, 511.

The commutation circuit 500 has two load current paths.

5 A first current path has connected in series a first inductor 501, a second inductor 502, a first electrical switch contact 514 of an opposed switch pair, and a third inductor 503. First 521 and second 522 resistors are connected in shunt with the first 501 and third 503
10 inductors respectively. A second current path has connected in series a fourth inductor 504, a fifth inductor 505, a second electrical switch contact 516 of the opposed switch pair, and a sixth inductor 506. Third 523 and fourth 524 resistors are connected in
15 shunt with the fourth 504 and sixth 506 inductors respectively. A first capacitor 510 bridges a point between the first 501 and second 502 inductors with a point between the fourth 504 and fifth 505 inductors. A second capacitor 511 bridges a point between the first
20 electrical switch contact 514 and third inductor 503 with a point between the second electrical switch contact 516 and sixth inductor 506.

The four resistors 521-524 connected in shunt
25 respectively with the first, second, fifth and sixth inductors 501, 502, 505, 506 damp the resonant voltage that that develops after the arc has been quenched. The quenching of the arc means that the capacitor voltage is now significantly different from its steady state
30 value of equalling the tap voltage. Similarly the current in the two outer inductors (i.e. 501 and 503 or

504 and 506) in load current path that has now been disconnected still have current present in them that must be dissipated. The presence of the inductor currents actually causes the resonant capacitor to swing further away from its steady state voltage leading to a large resonance that must be suppressed to prevent re-strike on the open electrical switch contacts.

10 Figure 12A shows a tap arrangement of a distribution transformer, with which the tap changer of Figure 11A may be used. The required tap setting is obtained by shorting between any two of the adjacent tap connections. In practice, a rack and pinion assembly is used, the shorting link being attached to the rack and a winding handle being attached to the pinion. This form of tap change can only be used with the tap changer off-load and isolated. Figure 12B illustrates how the on-load tap changer given in Figure 11A might be coupled into the distribution transformer to provide the ability to switch between two pre-selected tap settings.

The first embodiment of the invention provides the most straightforward implementation of the invention, providing symmetry and balance. This can be used directly as either a diverter or as part of a tap changer. When used as a diverter, the presence of the capacitor directly across the transformer winding may present problems for the switchgear providing the selector function. The relatively high value of this

means that arcing may well take place on closing and opening contacts and so using "switching-in-oil" techniques may cause degradation of the selector contacts and the insulation properties of the oil in which it is placed. In this event, auxiliary contacts will need to be included within the diverter, for example as indicated in Figure 6. The auxiliary contact in the non-conducting path would be opened prior to any operation to change state taking place within the selector. The auxiliary contacts would use vacuum switches to contain any arcing that might take place.

The second and third embodiments of the invention are not symmetrical or balanced although they might be developed to this. Thus they will only function for a restricted load power factor and their operation disrupts the load current during the commutation operation.

The fourth embodiment has been shown in operation within a distribution transformer. However, it may also be applied to derivatives of the difference tap changer form, although this can lead to an increase in the component count. By associating the resonant capacitors and the blocking inductors with specific windings as in Figure 11B and applied in Figure 7, the component count is reduced.

There is a possibility that stray EMC coupling, including capacitance between the tap winding and the core, may disturb the predicted operation of the

scheme. If this is neglected, for the summation scheme, the predicted disturbance for each element on the load current is minimal so it is reasonable that a tap change might be carried out by changing all the
5 actuators that are required to make the change simultaneously. The functioning of the difference scheme as shown in Figure 7 is different in that it uses a common capacitor in two possible resonant commutation circuits. Thus it is advised that the tap
10 change is carried out sequentially.

Arcing relies on ionised particles being drawn across the contact gap, so once the arc has been extinguished there must be sufficient time for the particles
15 remaining in the gap to condense. Thus, although the use of vacuum switches means this time is very short and there is a risk that if this process occurs too rapidly the arc might re-strike with the risk that the circulating current might commence developing in the
20 opposite polarity. This is particularly so if the "chopping current" level is high and the inductance in series with the switch contacts is relatively high.

Comparing the three proposed tap-changing schemes, the
25 sum, difference and sum-difference, they all have the restriction that the optimal number of tap changes available for any one scheme might not coincide with the number of tap changes required. Thus extra components are required. This also applies to the
30 amount of copper required for extra transformer windings that might be required. Most significantly,

the difference scheme does not fully utilise the windings available, making this scheme less economic.

Figure 13 shows a simulation of the electrical circuit shown in Figure 5 using the SimPower Systems Blockset within MATLAB to represent a 70MVA transformer with a 227kV primary supply voltage and a 1% tap winding. The transformer is fully loaded with a 0.8 power factor. The commutation components have been calculated on the basis of a commutation frequency of 50kHz.

This method of representing the transformer is only approximate since in the model to switch from the bottom conduction path to the top conduction path reduces the load voltage whereas in practice it would reduce the transformer turns ratio and increase the load voltage. However, since this change in load voltage is small, the model presents a satisfactory indication of the operation of the tap changer.

20

The Mayr Arc model has been used for the arcing switch as provided by Delft University (ref. 3). This model uses a controlled current source for output which requires defined initial impedance, so all the inductors associated with this element require parallel connected resistors. These have all been given a nominal $1k\Omega$ value and are not listed below.

25

Component Description	Component Reference	Component Value
Primary Inductance		0.84H
Primary Resistance		1.946 Ω
Tap Inductance		0.376mH
Tap Resistance		42m Ω
Load Resistance		736 Ω
Load Inductance		1.4H
Magnetising Inductance		4059H
Magnetising Resistance		1.571M Ω
Primary Voltage		227kV r.m.s.
Tap Winding Voltage		3.017kV r.m.s
	L1 & L3	50 μ H
	L2 & L4	5 μ H
	C	2.2 μ F
L1 & L3 Damping Resistors		1 Ω
Surge arrestor voltage		4kV

Table 1

The values of the components are presented in Table 1. Table 2 shows the calculated design parameters around which the component design would be based.

Parameter Description	Value
Steady state capacitor current	1.2A rms
Steady state inductor impedance	16m Ω
Peak L2/L4 commutation current	1.19kA
Peak L1/L3 commutation current	704A Ω
Capacitor voltage at commutation	112V
Capacitor deviation from steady state	-1.12kV
Unsuppressed peak capacitor voltage after commutation (in addition to voltage at instant of commutation)	3.5kV

Table 2

The model shows five cycles of operation with the opening contact commencing to arc at 35ms into the simulation. The closing contact is then closed 36ms into the simulation. Figure 14 shows the load current and voltage indicating that no disturbance is created during the tap change process. Figure 15 shows the currents in the opposing pair contacts, and the capacitor voltage, with no apparent deviation in the 50Hz nature of the waveform until the instant of contact closure, when the commutation resonance occurs. For the opposing pair currents there appears to be a clean transfer of current between the contacts, shown expanded in Figure 16. However, the capacitor voltage would swing to a negative voltage in excess of 8kV without the presence of the surge arrestor. This is due to the surplus energy built up in the inductors L1 & L3 during the commutation process. Additional over-voltage suppression will clearly be necessary.

20 References

1.	Axel Kramer	On-Load Tap-Changers for Power Transformers, MR Publication, ISBN 3-00-005948-2, 2000
2.	MR Publication	VacutapVV, Maintenance free up to 150 operations
3.	P H Shavemaker L Van Der Sluis	The Arc Model Blockset, Proceedings of the Second IASTED International Conference, Power and Energy Systems (EuroPES), Crete, Greece, June 25-28, 2002

CLAIMS

1. An on-load tap changer comprising a selector and a diverter, the diverter comprising a pair of opposed switch elements and a commutation circuit, the
5 commutation circuit being operable to establish a resonant current upon closure of a non-conducting switch element to commute off an arcing switch element.
- 10 2. An on-load tap changer comprising one or more pairs of opposed switch elements for connection to respective tap windings of a transformer, the tap changer including a commutation circuit being operable to establish a resonant current upon closure of a non-
15 conducting switch element to commute off an arcing switch element.
3. The tap changer of any preceding claim wherein each switch element is a vacuum switch.
- 20 4. The tap changer of Claim 2 including a network of opposed switch elements for connection to tap windings with weighted numbers of turns, such that a complete range of integer tap values can be obtained by the tap
25 voltages being caused to subtract or add.
5. The tap changer of Claim 4 wherein the network includes a difference winding arrangement, a sum winding arrangement, or a sum-difference winding
30 arrangement.

6. The tap changer of any preceding claim wherein the commutation circuit includes an LC circuit having a capacitor arranged to discharge upon closure of the non-conducting switch element to create the resonant
5 current, the polarity of the resonant current opposing that of the arcing current.

7. The tap changer of Claim 6 wherein the capacitor stores sufficient charge for the magnitude of the
10 resonant current to sufficiently cancel the transformer load current during at least one cycle such that the combined current through an arcing switch element reduces to less than the chopping current for the switch element.

15

8. The tap changer of any preceding claim wherein the commutation circuit is balanced.

9. The tap changer of any preceding claim including a
20 first load current path having connected in series first and second inductors and a first switch element of an opposed pair, and a second load current path having connected in series third and fourth inductors and a second switch element of the opposed pair, a
25 capacitor bridging a point between the first and second inductors with a point between the third and fourth inductors.

10. The tap changer of Claim 9 including a first
30 resistor connected in shunt with the first inductor, a second resistor connected in shunt with the third

inductor, and a voltage-limiting resistor connected in shunt with the capacitor.

11. The tap changer of Claim 9 or 10 wherein the
5 inductances of the first and second inductors are

related by the equation: $L_2 < \frac{2}{3\pi} L_1$.

12. The tap changer of Claim 11 wherein the relationship is $L_2 \approx 0.1L_1$.

10

13. The tap changer of any of Claims 9 to 12 wherein the inductances of the third and fourth inductors are

related by the equation: $L_4 < \frac{2}{3\pi} L_3$.

14. The tap changer of Claim 13 wherein the
15 relationship is $L_4 \approx 0.1L_3$.

15. The tap changer of any of the Claims 9 to 14 wherein the first and third inductors present a
20 sufficiently large impedance to the resonant current to substantially decouple the capacitor.

16. The tap changer of any of Claims 1 to 7 including a first load current path having a first switch element
25 of an opposed pair, and a second load current path having connected in series an inductor and a second switch element of the opposed pair, a capacitor being connected in shunt with the inductor and the second switch element.

17. The tap changer of any of Claims 1 to 8 including
a first current path having connected in series a first
inductor, a second inductor, a first switch element of
5 an opposed pair, and a third inductor, first and second
resistors being connected in shunt with the first and
third inductors respectively; and a second current path
having connected in series a fourth inductor, a fifth
inductor, a second switch element of the opposed pair,
10 and a sixth inductor, third and fourth resistors being
connected in shunt with the fourth and sixth inductors
respectively; a first capacitor bridging a point
between the first and second inductors with a point
between the fourth and fifth inductors; and a second
15 capacitor bridging a point between the first switch
element and third inductor with a point between the
second switch element and sixth inductor.

18. The tap changer of any preceding claim wherein the
20 resonant frequency of the commutation circuit is
selected to be compatible with the inherent properties
of the components making up the commutation circuit.

19. The tap changer of any of Claims 6 to 18 wherein
25 the resonant frequency of the commutation circuit is
lower than a self-resonant frequency of the capacitor.

20. A commutation circuit for an on-load tap changer,
the commutation circuit being connectable to a pair of
30 opposed switch elements in the tap changer and a tap
winding of a transformer, the commutation circuit being

operable to establish a resonant current upon closure of a non-conducting switch element to commutate off an arcing switch element.

- 5 21. The commutation circuit of Claim 20 including the features of any of Claims 6 to 19.

22. An on-load tap changer substantially as herein before described with reference to, and/or as
10 illustrated in, any one or more of Figures 5 to 16 of the accompanying drawings.

23. A commutation circuit substantially as herein before described with reference to, and/or as
15 illustrated in, any one or more of Figures 5 to 16 of the accompanying drawings.

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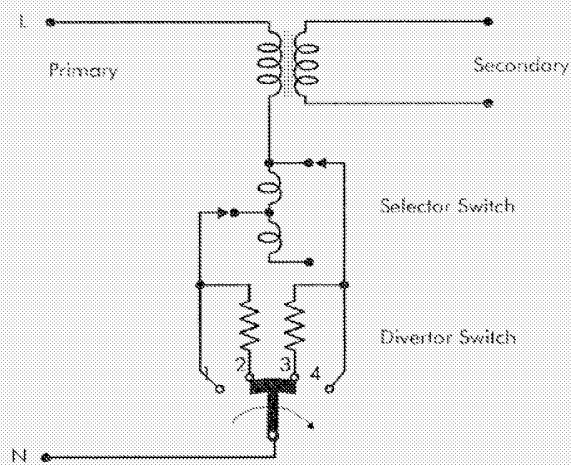


Figure 1A

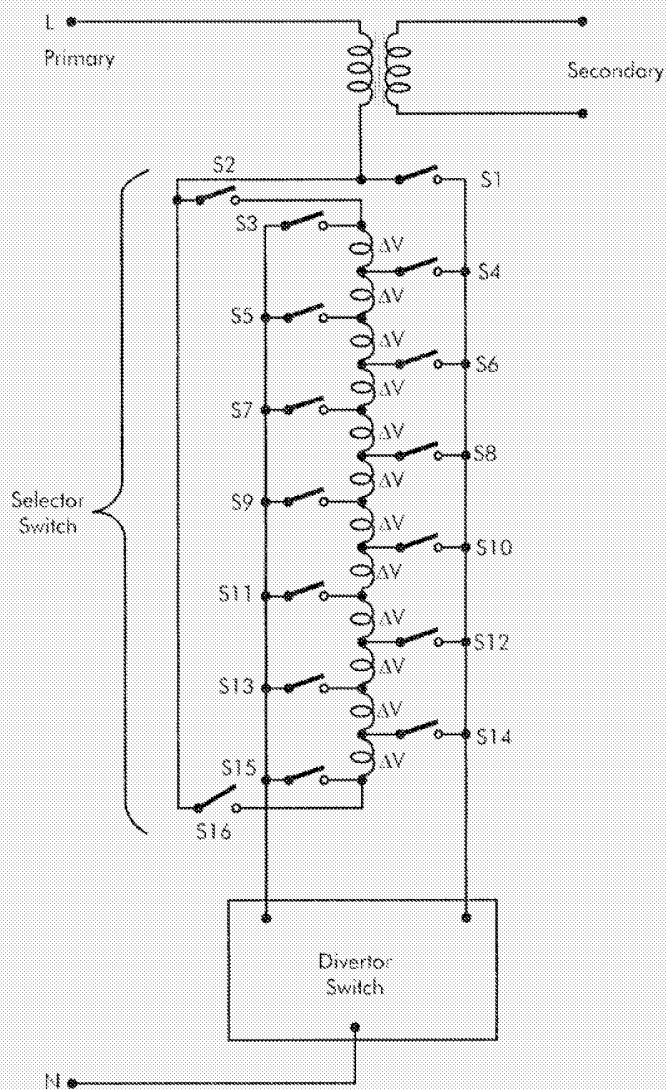


Figure 1B

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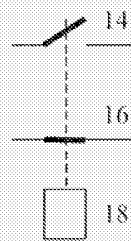


Figure 2

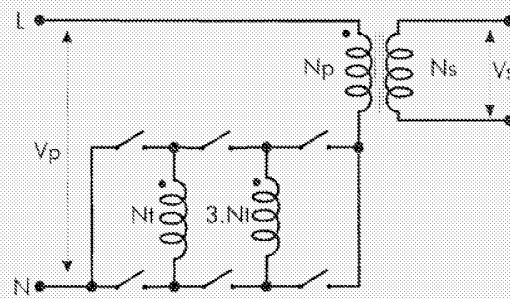


Figure 3A

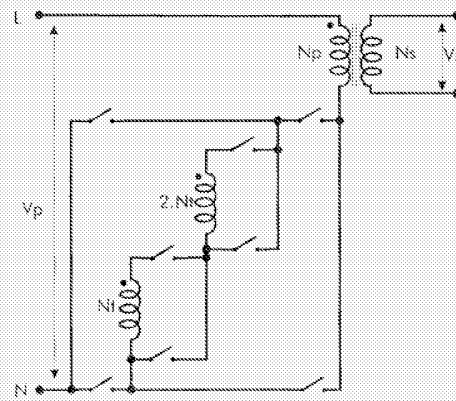
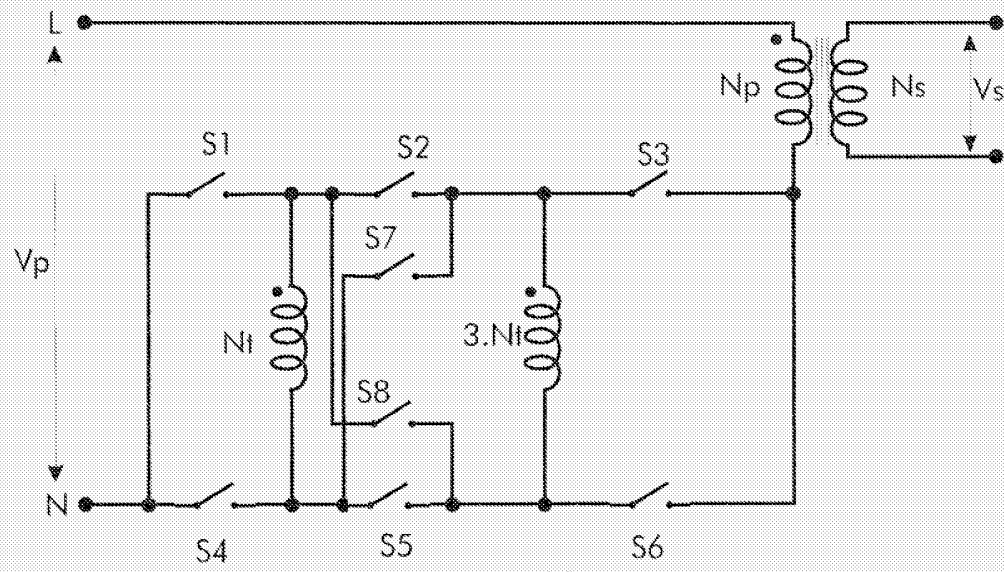


Figure 3B

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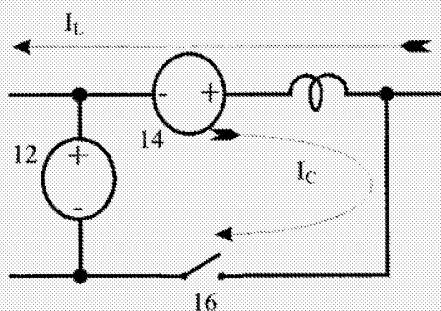


Figure 4A

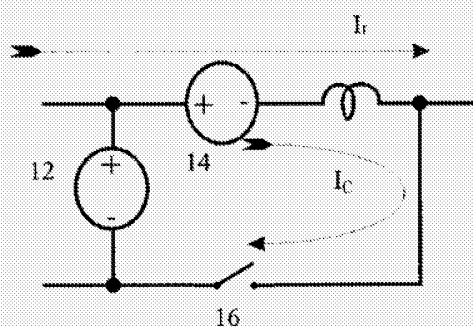


Figure 4B

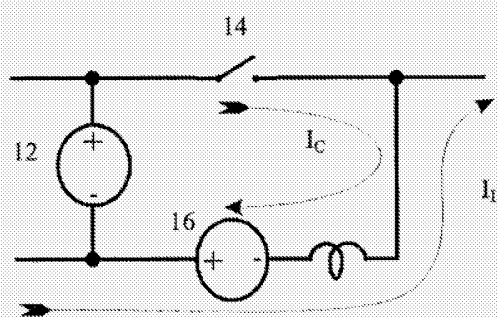


Figure 4C

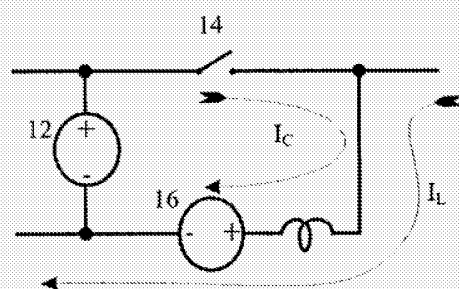


Figure 4D

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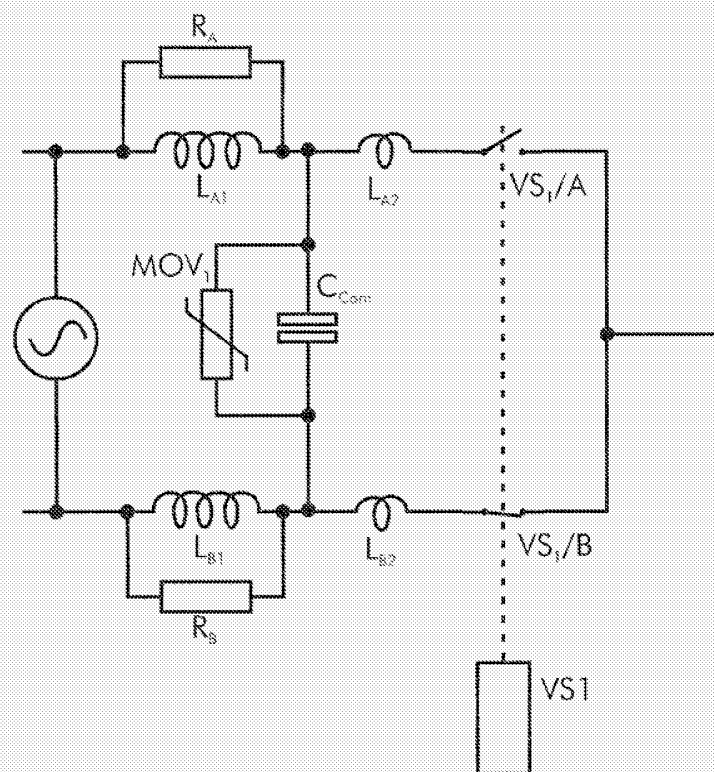


Figure 5

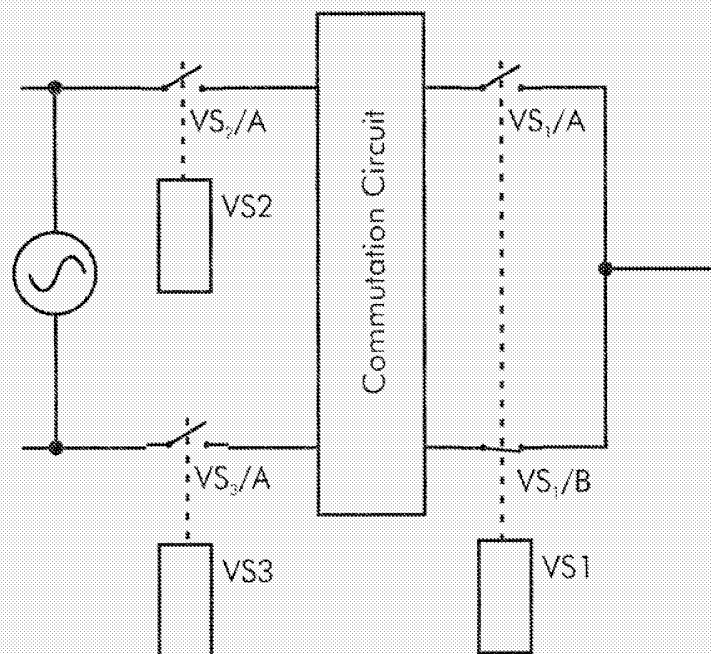


Figure 6

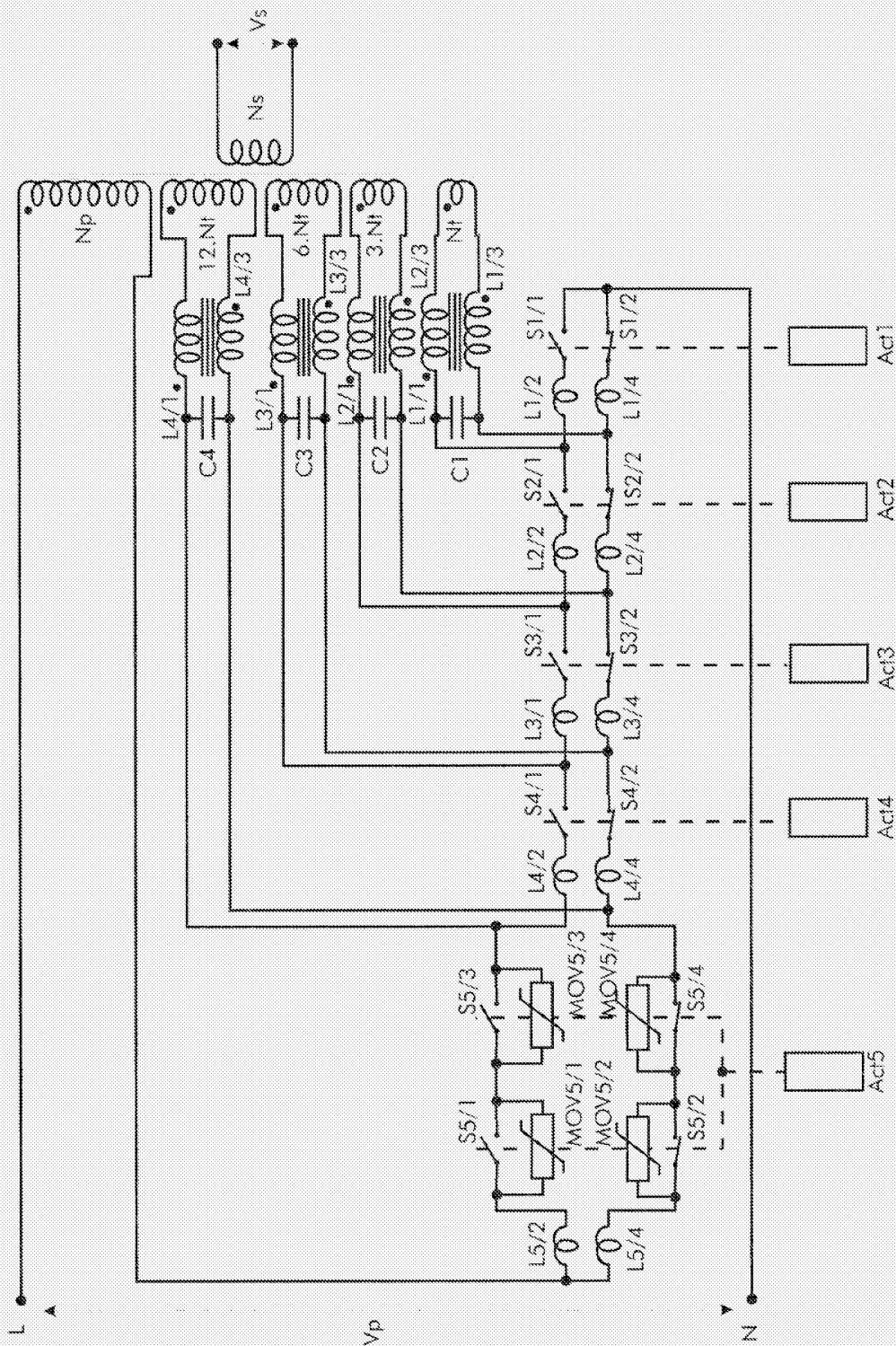


Figure 7

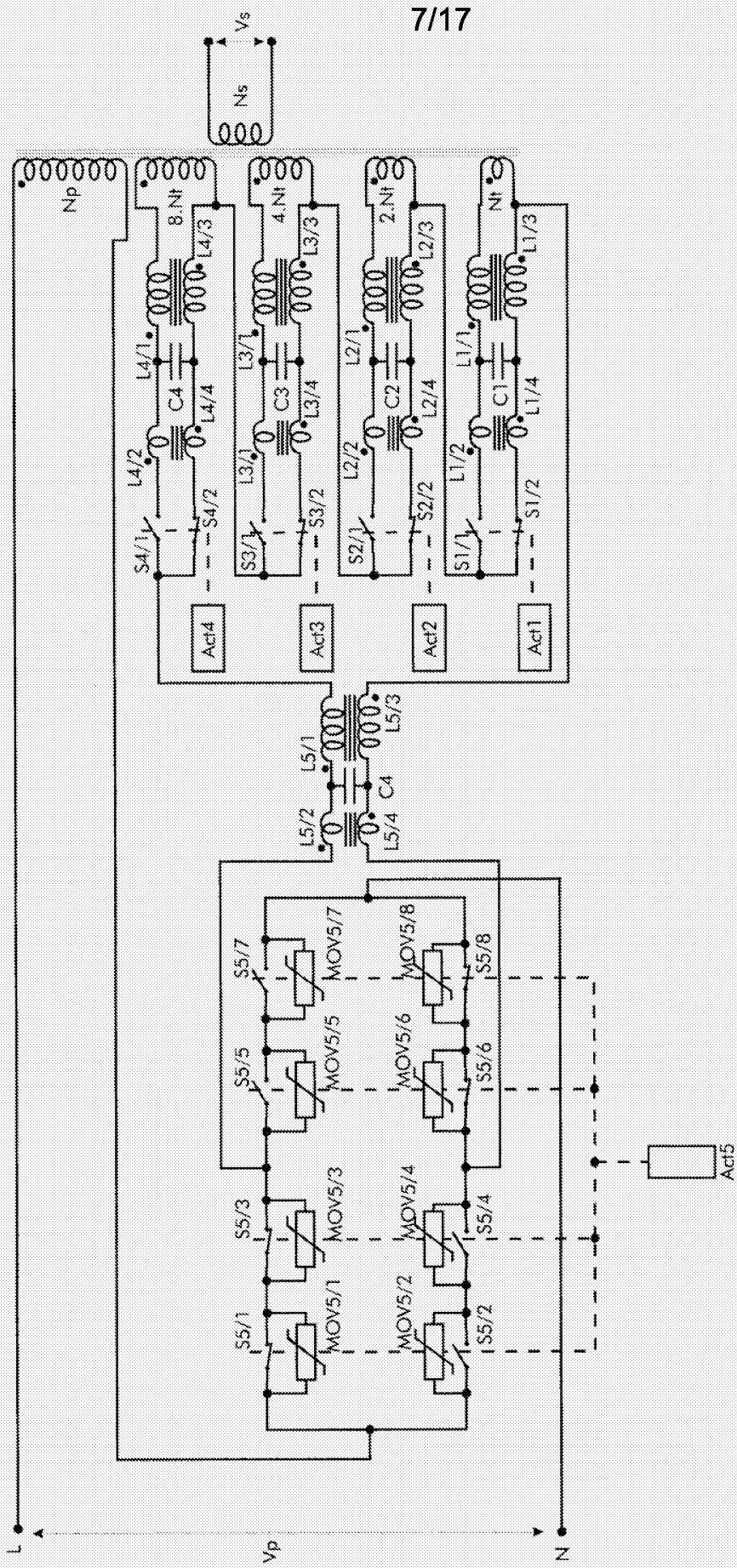


Figure 8A

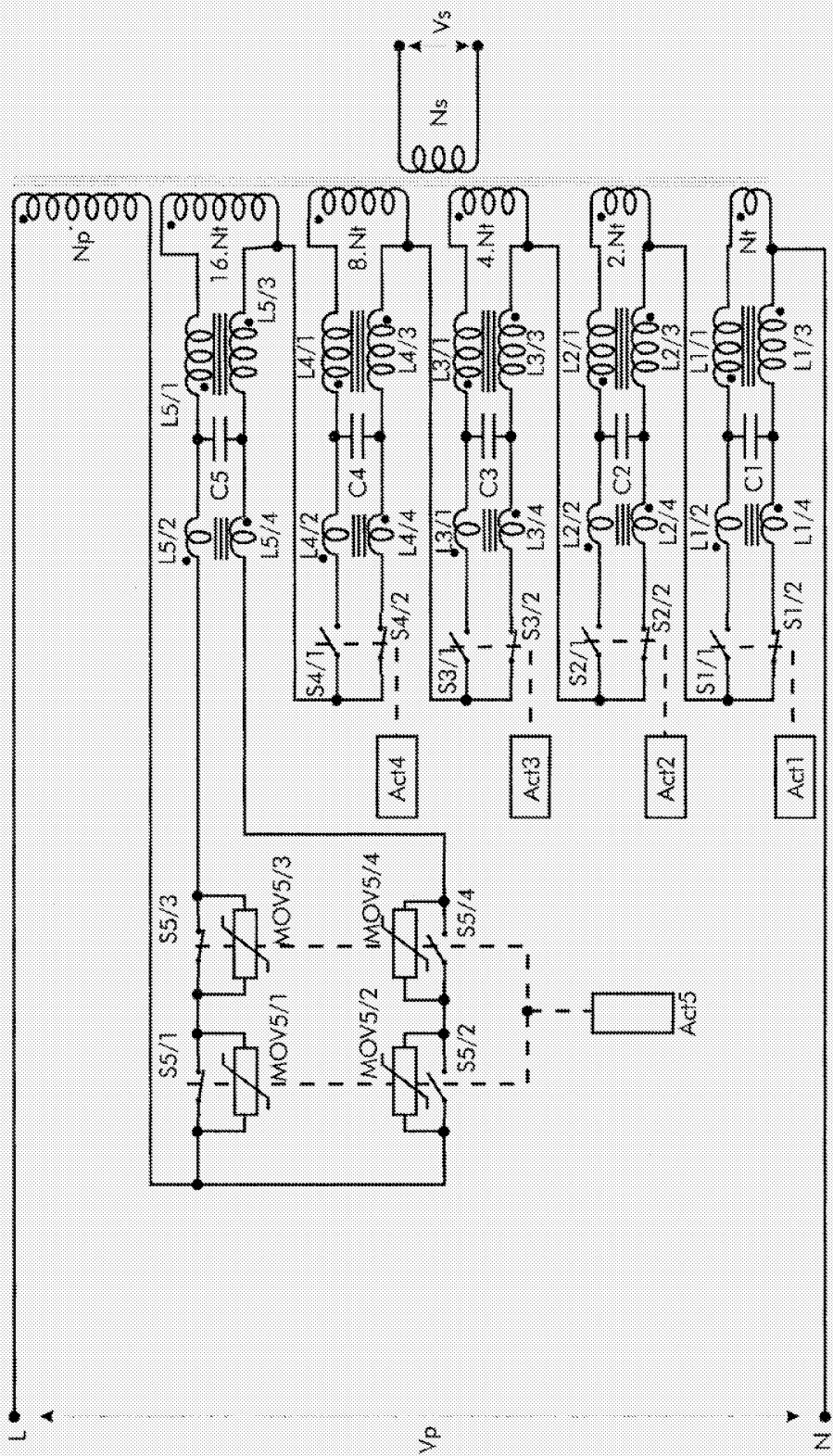


Figure 8B

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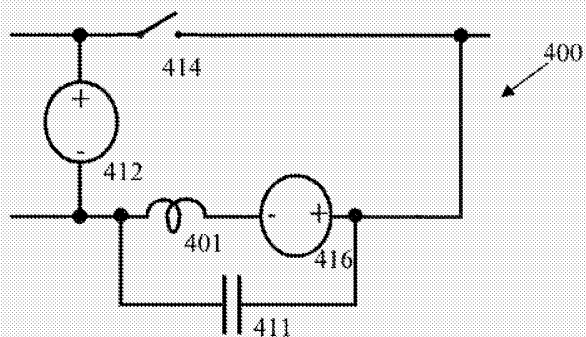


Figure 9

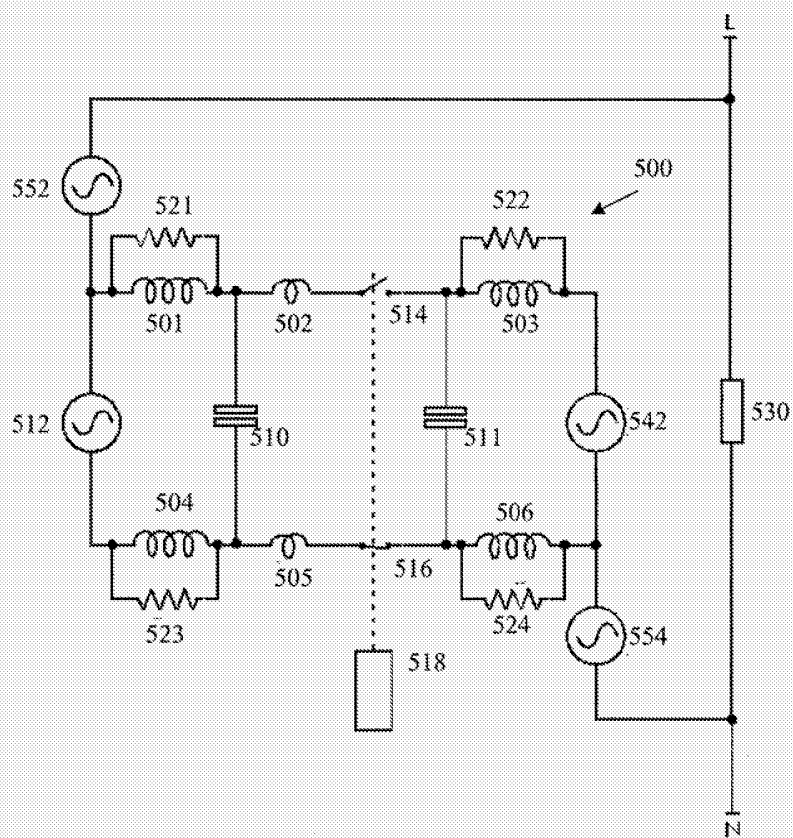


Figure 10

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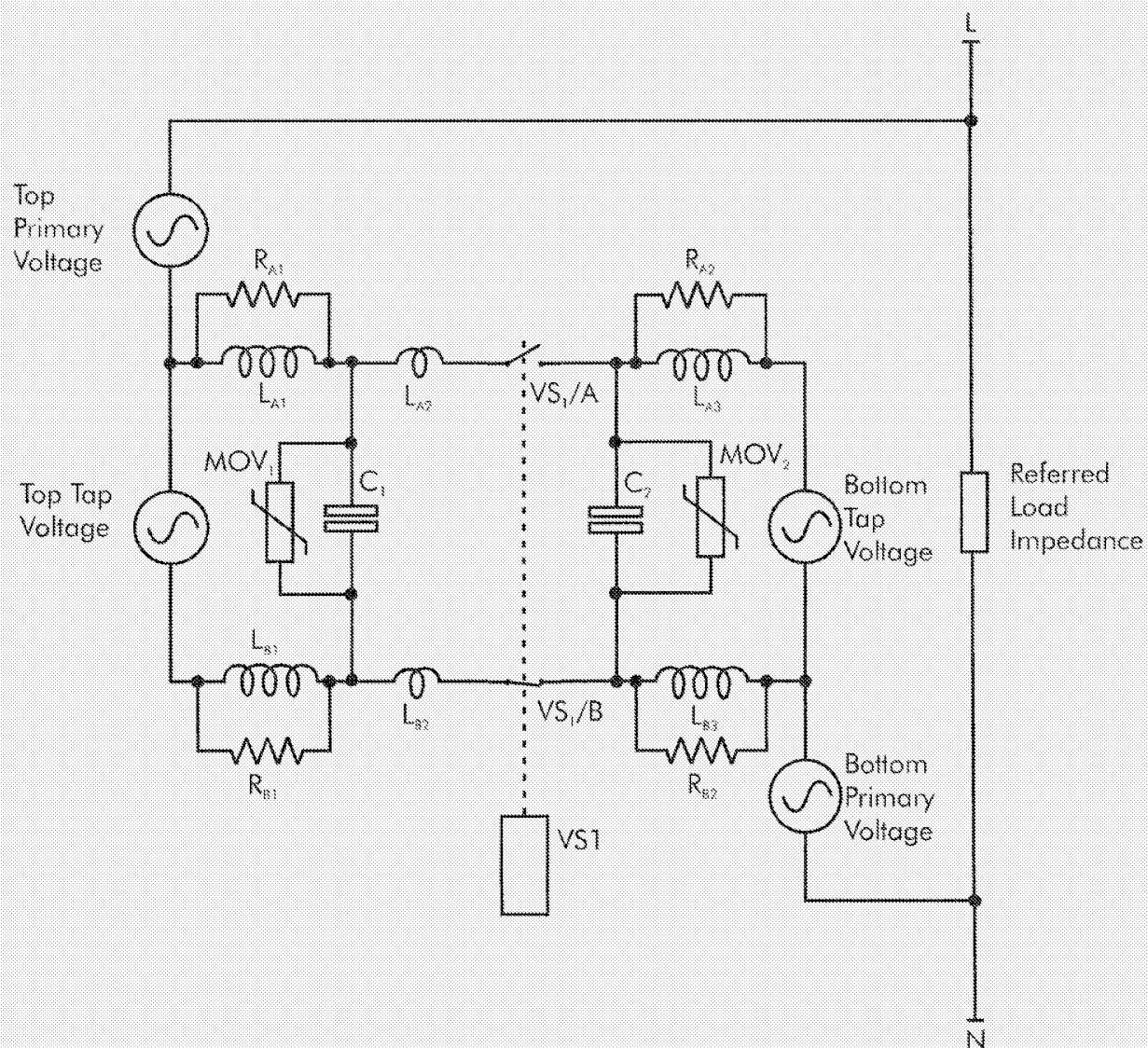


Figure 11A

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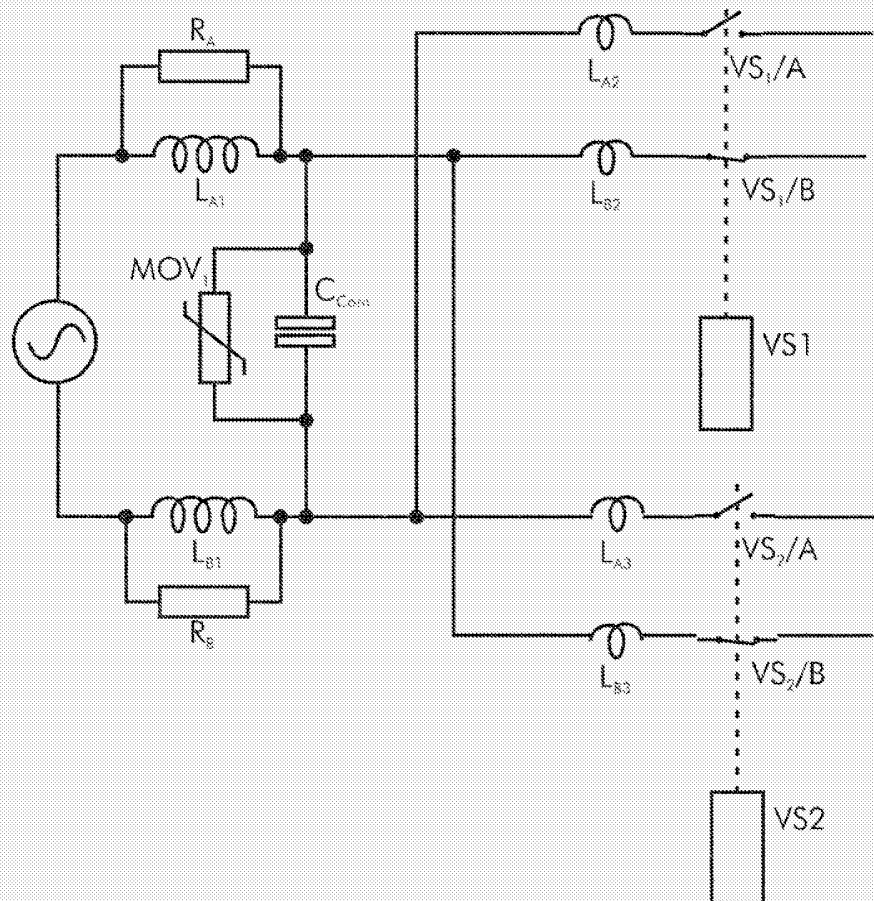


Figure 11B

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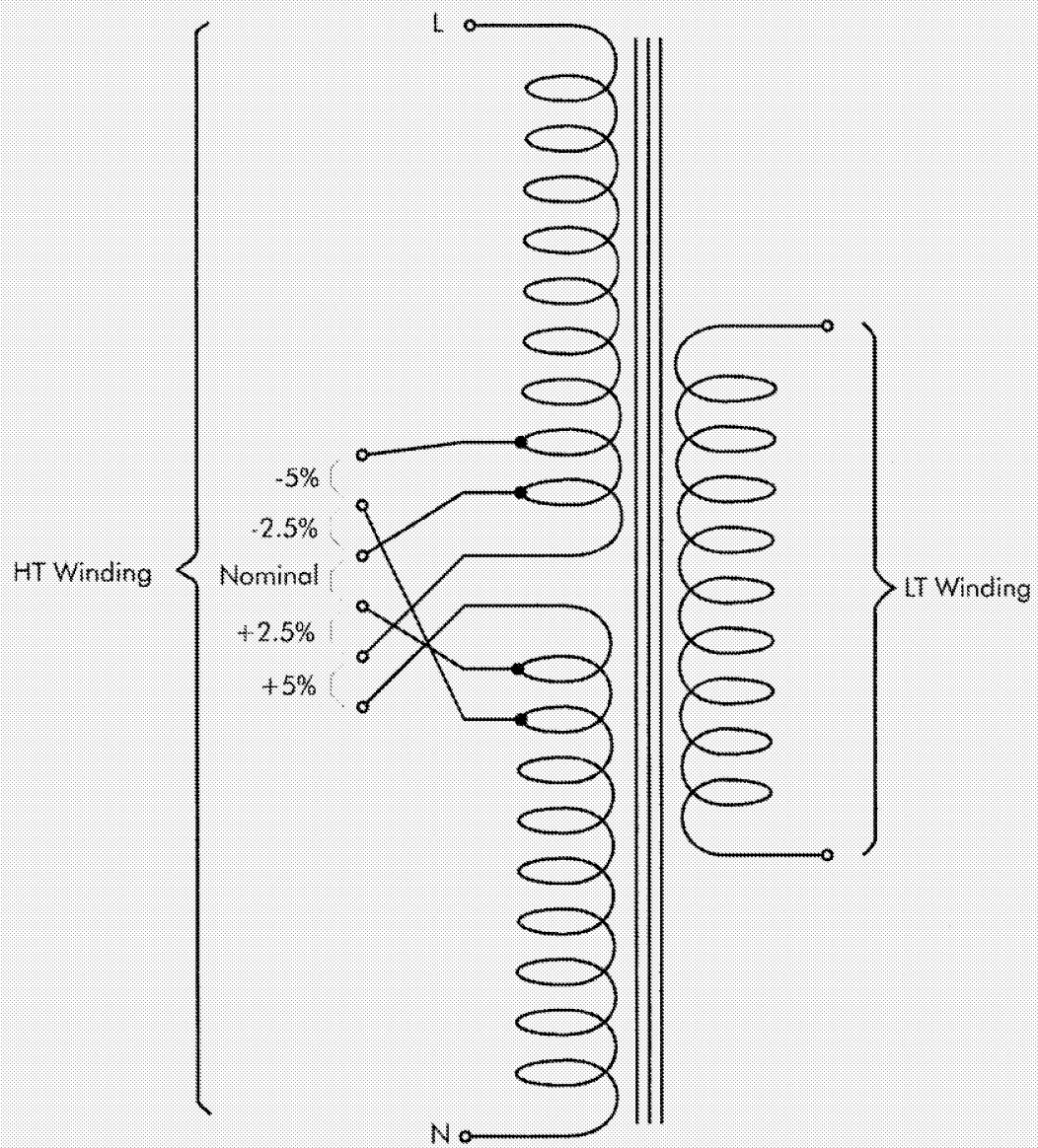


Figure 12A

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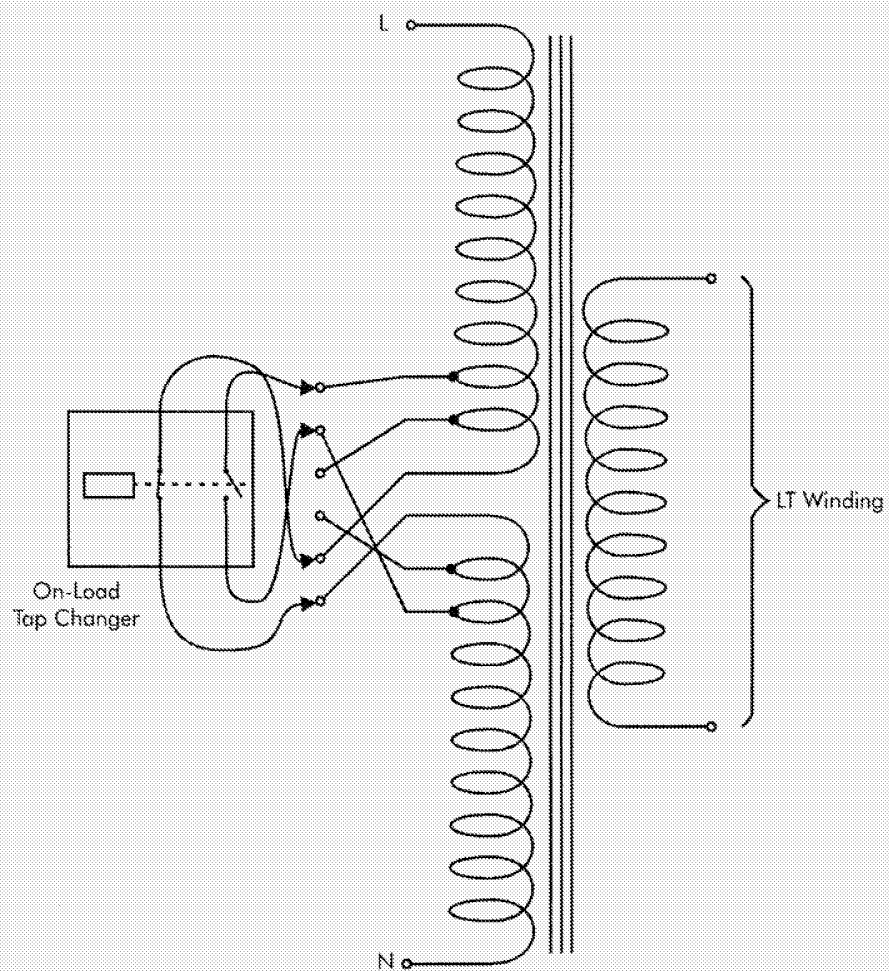


Figure 12B.

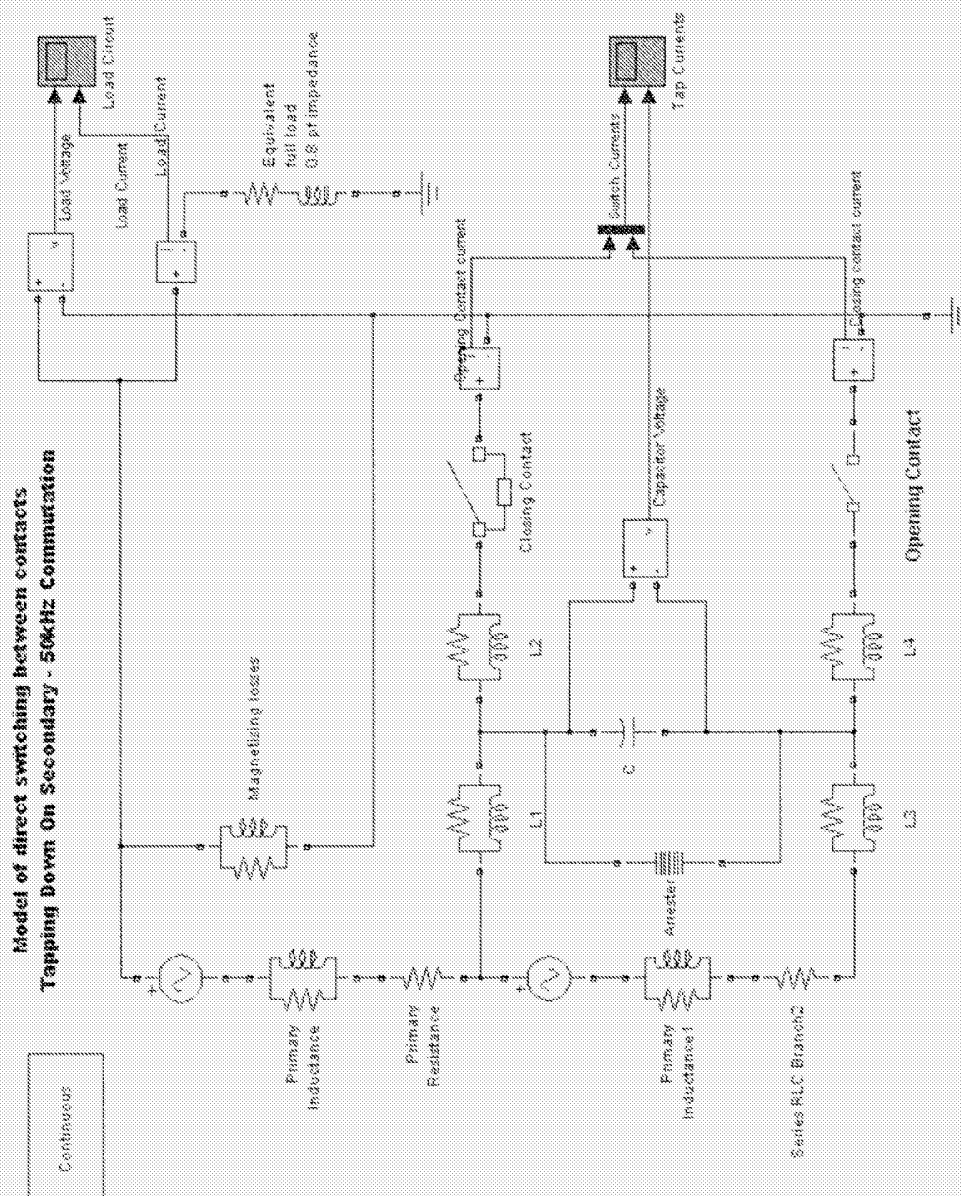


Figure 13

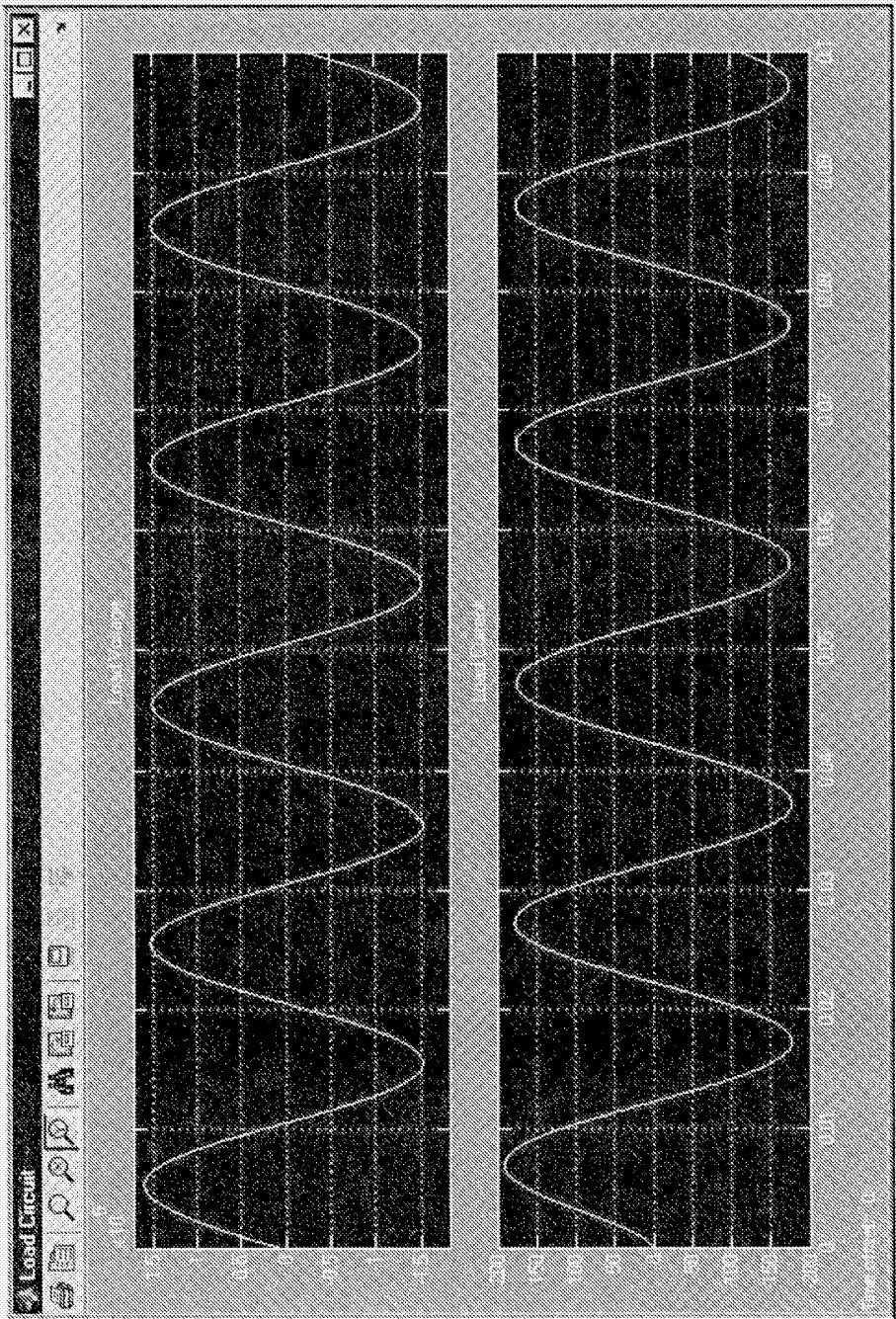


Figure 14

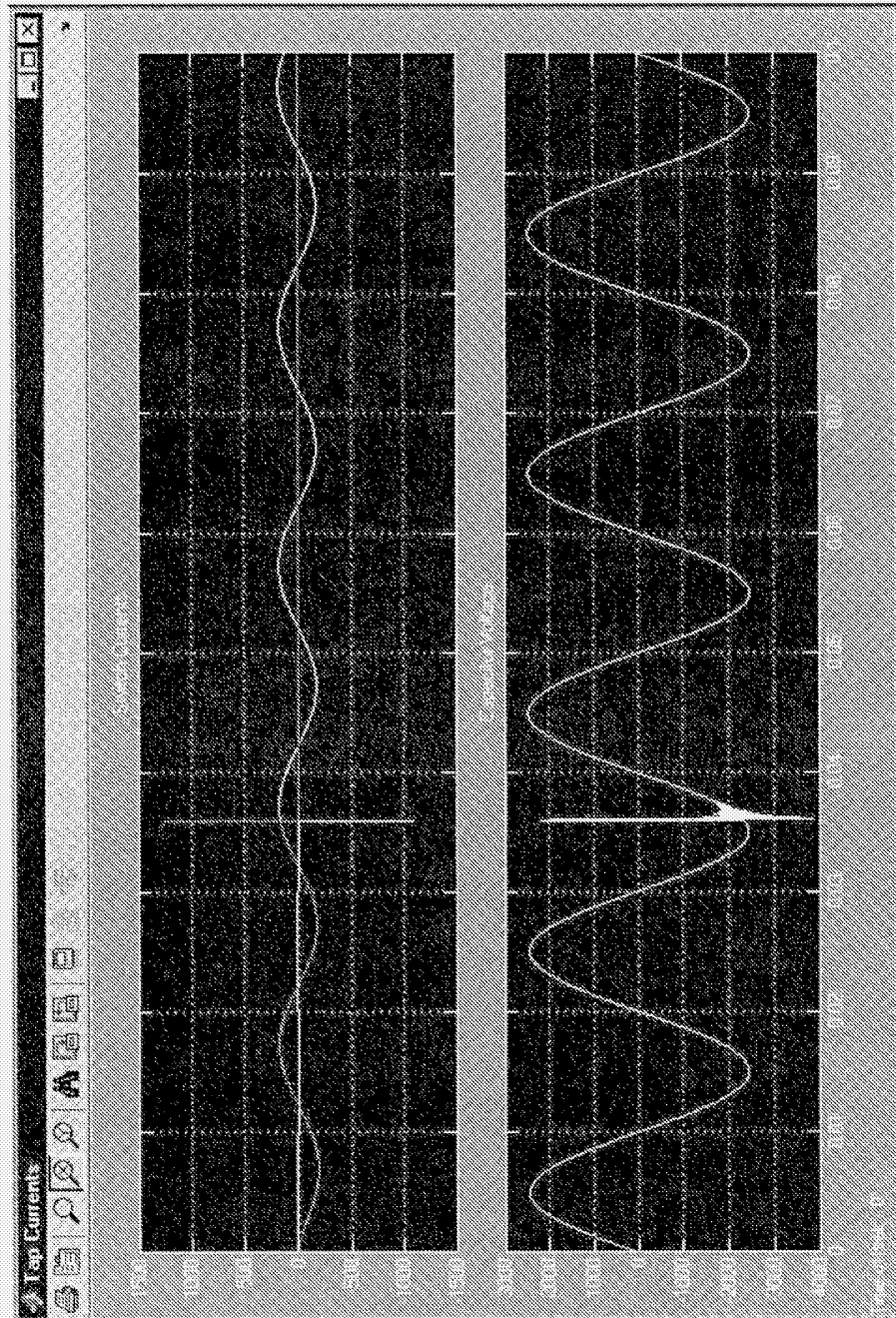


Figure 15

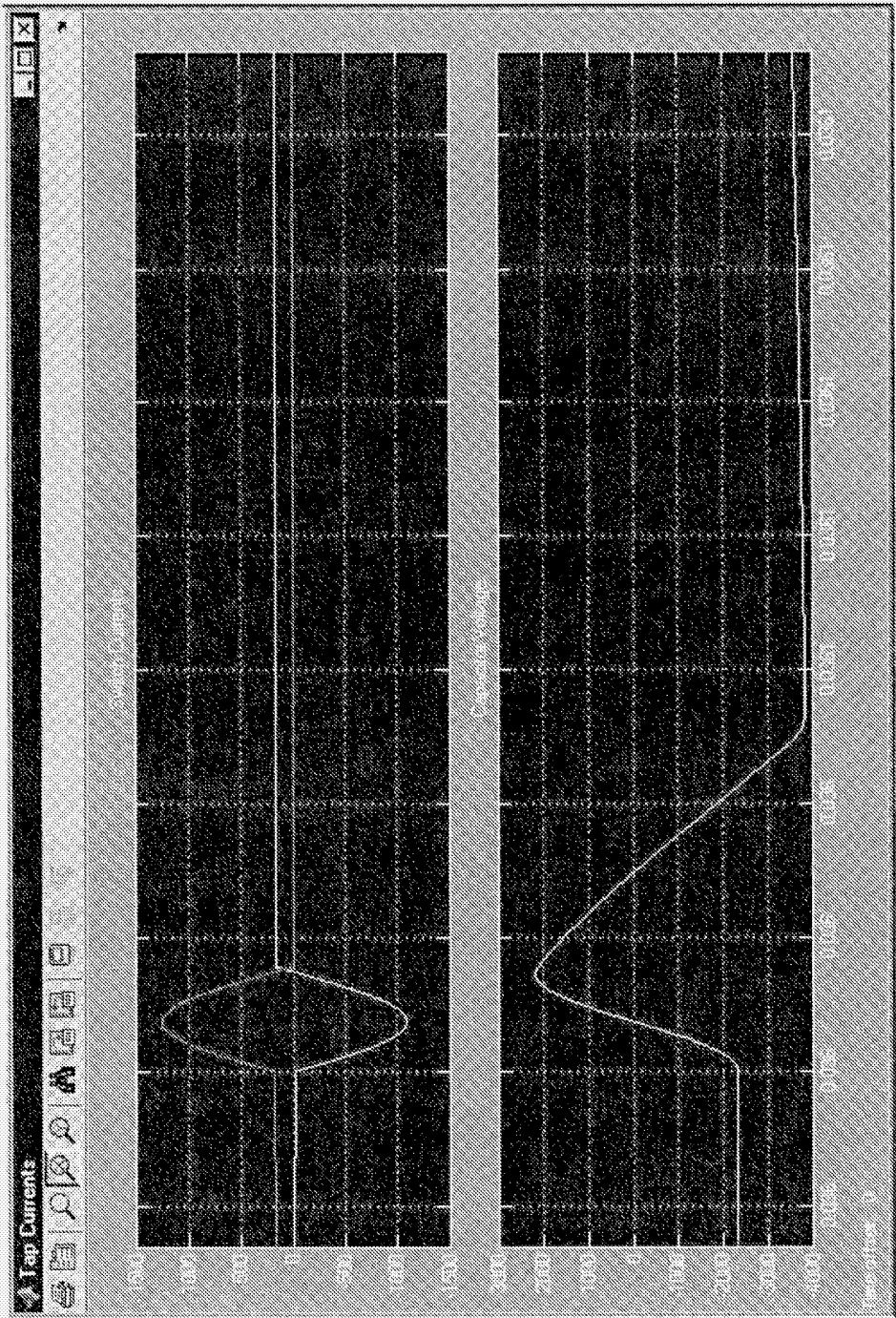


Figure 16