CONTROLLED SWITCHING SYSTEM AND METHOD FOR TAP CHANGER POWER TRANSFORMERS

A system and method for controlling energization of a tap changer power transformer. A first status of the tap changer, and accordingly a value of a remanent flux remaining in the transformer, is determined after opening of a switching arrangement for disconnecting the transformer from a source and de-energizing the transformer. A second status of the tap changer, and accordingly a value of a dynamic magnetic flux generated by the transformer, is determined before closing of the switching arrangement for connecting the transformer to the source, thereby energizing the transformer. A closing angle at which to close the switching arrangement is determined, the remanent flux value substantially equal to the dynamic magnetic flux value at the closing angle. A control signal is output for causing the switching arrangement to be closed at the closing angle, thereby energizing the transformer.
CONTROLLED SWITCHING SYSTEM AND METHOD FOR TAP CHANGER

POWER TRANSFORMERS

CROSS-REFERENCE TO RELATED APPLICATIONS
[0001] This patent application claims priority of US provisional Application Serial No. 61/915,568, filed on December 13, 2013, the contents of which are hereby incorporated by reference.

TECHNICAL FIELD
[0002] The present invention relates to mitigation techniques for energization of tap changer power transformers.

BACKGROUND OF THE ART
[0003] Strong inrush currents and temporary overvoltage surges may occur on an electrical network when first energizing a power transformer. These undesired phenomena reduce network power quality and cause network exploitation problems. This may also lead to mechanical and dielectric constraints on the transformer's winding, thereby reducing the operating life of the transformer and of neighboring equipment. Furthermore, these phenomena may also activate protection circuits.

[0004] Transformers, including tap changer power transformers, are one of the more expensive pieces of equipment used in a power system and the potential consequences of failure can be dramatic. In order to overcome these issues, a variety of mitigation techniques may be used. One such technique is controlled switching, where the most suitable moment for energizing each one of the transformer's phases is chosen, taking into account the transformer's remanent flux (i.e. the magnetic flux density remaining in the transformer core after the transformer is de-energized). However, for tap changer power transformers, optimal controlled switching may be difficult to achieve due to the various parameters that come into play.
[0005] There is therefore a need for an improved controlled switching technique for tap changer power transformers.

SUMMARY

[0006] In accordance with a first broad aspect, there is provided a method for controlling energization of a tap changer power transformer, the tap changer power transformer having a first winding and a second winding and a tap changer connected to a given one of the first and the second winding, the tap changer configured to adjust positions of a plurality of taps of the given winding for modifying a number of turns of the given winding, the given winding connected to a voltage source through a switching arrangement moveable between a closed position for connecting the tap changer power transformer to the source, thereby energizing the tap changer power transformer, and an open position for disconnecting the tap changer power transformer from the source, thereby de-energizing the tap changer power transformer. The method comprises determining a first status of the tap changer, and accordingly a value of a remanent flux remaining in the tap changer power transformer, after the switching arrangement is placed in the open position, determining a second status of the tap changer, and accordingly a value of a dynamic magnetic flux generated by the tap changer power transformer, before the switching arrangement is moved from the open position to the closed position, determining from the remanent flux value and the dynamic magnetic flux value a closing angle at which to place the switching arrangement to the closed position, the remanent flux value substantially equal to the dynamic magnetic flux value at the closing angle, and outputting a control signal for causing the switching arrangement to be moved from the open position to the closed position at the closing angle, thereby energizing the tap changer power transformer.

[0007] In some embodiments, determining the first status of the tap changer comprises determining a first difference between a nominal value of the number of turns of the given winding and a first value of the number of turns, the first value
determined after the switching arrangement is placed in the open position and before the tap changer adjusts the positions of the plurality of taps in response to the switching arrangement being placed in the open position, the remanent flux value determined on the basis of the first difference.

[0008] In some embodiments, determining the second status of the tap changer comprises obtaining a most recent status of the tap changer before the switching arrangement is moved from the open position to the closed position, the most recent status obtained by determining a second difference between the nominal value and a second value of the number of turns of the given winding, the second value determined a predetermined time period before the switching arrangement is moved from the open position to the closed position, the dynamic magnetic flux value determined on the basis of the second difference.

[0009] In some embodiments, the remanent flux value is determined as:

\[
\phi_r = \left( \text{constant} \times \frac{N \pm \Delta N_0}{N} \times \left[ (\int_{O-a}^E E \times \partial t) - (\int_{O-b}^E E \times \partial t) \right] \right)
\]

[0010] where \( \phi_r \) is the remanent flux value, \( E \) is an alternating voltage originating from the voltage source, \( O \) is an opening time at which the switching arrangement is placed in the open position, \( a \) is a first predetermined number of full cycles after the opening time, \( b \) is a second predetermined number of full cycles before the opening time, \( N \) is the nominal value of the number of turns of the given winding, \( \Delta N_0 \) is the first difference, and constant is calibration constant.

[0011] In some embodiments, the dynamic magnetic flux value is determined as:

\[
\phi = \left( \text{constant} \times \frac{N \pm \Delta N_C}{N} \times \int E \times \partial t \right) + \phi_r
\]

[0012] where \( \phi \) is the dynamic magnetic flux value and \( \Delta N_C \) is the second difference.
In some embodiments, the remanent flux value is determined on the basis of data received from at least one sensing device connected to one of the tap changer power transformer and a potential transformer connected to one of the first and the second winding, the at least one sensing device configured to measure a voltage at terminals of the tap changer power transformer and compute therefrom the remanent flux value.

In some embodiments, the remanent flux value is determined on the basis of a voltage measured at a potential transformer connected to another one of the first and the second winding, a number of turns of the other winding not controlled by the tap changer.

In some embodiments, the remanent flux value is determined on the basis of a ratio between a first voltage measured at a first potential transformer connected to the first winding and a second voltage measured at a second potential transformer connected to the second winding.

In some embodiments, the remanent flux value is determined from a first measurement received from a tap changer control unit, the tap changer control unit connected to the tap changer for controlling operation thereof and configured to measure the remanent flux value; and/or the dynamic magnetic flux value is determined from a second measurement received from the tap changer control unit, the tap changer control unit configured to measure the dynamic magnetic flux value.

In some embodiments, the remanent flux value is determined on the basis of a first voltage measured at a potential transformer connected to the given winding and the first difference obtained from a result of a simulation model performed to emulate operation of the tap changer; and/or the dynamic magnetic flux value is determined on the basis of a second voltage measured at the potential transformer and the second difference obtained from the result of the simulation model.
[0018] In some embodiments, the remanent flux value is determined by querying a memory with a voltage measured at a potential transformer connected to the given winding, the memory having stored therein a plurality of voltage values, a plurality of values for the first difference, and a first correspondence between each one of the plurality of voltage values and each one of the plurality of values for the first difference, determining a selected one of the plurality of values for the first difference corresponding to the measured voltage, and computing the remanent flux accordingly; and/or the dynamic magnetic flux value is determined by querying the memory with the voltage, the memory having stored therein a plurality of values for the second difference and a second correspondence between each one of the plurality of voltage values and each one of the plurality of values for the second difference, determining a selected one of the plurality of values for the second difference corresponding to the measured voltage, and computing the dynamic magnetic flux accordingly.

[0019] In some embodiments, the closing angle is determined for each one of at least one phase of the tap changer power transformer and the control signal is output for causing the switching arrangement to be moved to the closed position at the closing angle for each one of the at least one phase.

[0020] In some embodiments, the method may further comprise selecting a first phase of the tap changer power transformer having a highest remanent flux value, generating the control signal for energizing the first phase, and, a predetermined number of half-cycles after a voltage signal of the first phase crosses zero, generating the control signal for energizing at least one remaining phase of the tap changer power transformer.

[0021] In accordance with a second broad aspect, there is provided a system for controlling energization of a tap changer power transformer, the tap changer power transformer having a first winding and a second winding and a tap changer connected to a given one of the first and the second winding, the tap changer configured to adjust positions of a plurality of taps of the given winding for
modifying a number of turns of the given winding, the given winding connected to a voltage source through a switching arrangement moveable between a closed position for connecting the tap changer power transformer to the source, thereby energizing the tap changer power transformer, and an open position for disconnecting the tap changer power transformer from the source, thereby de-energizing the tap changer power transformer. The system comprises a remanent flux determination unit configured to determine a first status of the tap changer, and accordingly a value of a remanent flux remaining in the tap changer power transformer, after the switching arrangement is placed in the open position; a dynamic flux determination unit configured to determine a second status of the tap changer, and accordingly a value of a dynamic magnetic flux generated by the tap changer power transformer, before the switching arrangement is moved from the open position to the closed position; and a switching arrangement closing unit configured to determine from the remanent flux value and the dynamic magnetic flux value a closing angle at which to place the switching arrangement to the closed position, the remanent flux value substantially equal to the dynamic magnetic flux value at the closing angle, and output a control signal for causing the switching arrangement to be moved from the open position to the closed position at the closing angle, thereby energizing the tap changer power transformer.

[0022] In some embodiments, the remanent flux determination unit is configured to determine a first difference between a nominal value of the number of turns of the given winding and a first value of the number of turns, the first value determined after the switching arrangement is placed in the open position and before the tap changer adjusts the positions of the plurality of taps in response to the switching arrangement being placed in the open position, and determine the remanent flux value on the basis of the first difference.

[0023] In some embodiments, dynamic flux determination unit is configured to determine a second difference between the nominal value and a second value of the number of turns of the given winding, the second value determined a
predetermined time period before the switching arrangement is moved from the open position to the closed position, and determine the dynamic magnetic flux value on the basis of the second difference.

[0024] In some embodiments, the remanent flux determination unit is configured to determine the remanent flux value as:

$$\varphi_r = \left( \frac{\text{constant}}{N \pm \Delta N} \right) \times \left[ \left( \int_{2-b}^{2-a} E \times \partial t \right) - \left( \int_{2-a}^{2-a} E \times \partial t \right) \right]$$

[0025] where $\varphi_r$ is the remanent flux value, $E$ is an alternating voltage originating from the voltage source, $O$ is an opening time at which the switching arrangement is placed in the open position, a is a first predetermined number of full cycles after the opening time, b is a second predetermined number of full cycles before the opening time, $N$ is the nominal value of the number of turns of the given winding, $\Delta N_o$ is the first difference, and constant is calibration constant.

[0026] In some embodiments, the dynamic flux determination unit is configured to determine the dynamic magnetic flux value as:

$$\phi = \left( \frac{\text{constant}}{N \pm \Delta N_c} \right) \times \int E \times \partial t + \varphi_r$$

[0027] where $\Phi$ is the dynamic magnetic flux value and $\Delta N_c$ is the second difference.

[0028] In some embodiments, the remanent flux determination unit is configured to determine the remanent flux value on the basis of data received from at least one sensing device connected to one of the tap changer power transformer and a potential transformer connected to one of the first and the second winding, the at least one sensing device configured to measure a voltage at terminals of the tap changer power transformer and compute therefrom the remanent flux value.

[0029] In some embodiments, the remanent flux determination unit is configured to determine the remanent flux value on the basis of a voltage measured at a
potential transformer connected to another one of the first and the second winding, a number of turns of the other winding not controlled by the tap changer.

[0030] In some embodiments, the remanent flux determination unit is configured to determine the remanent flux value on the basis of a ratio between a first voltage measured at a first potential transformer connected to the first winding and a second voltage measured at a second potential transformer connected to the second winding.

[0031] In some embodiments, the remanent flux determination unit is connected to a tap changer control unit, the tap changer control unit connected to the tap changer for controlling operation thereof and configured to measure the remanent flux value, the remanent flux determination unit configured to determine the remanent flux value from a first measurement received a from the tap changer control unit; and/or the dynamic flux determination unit is connected to the tap changer control unit and configured to determine the dynamic magnetic flux value from a second measurement received from the tap changer control unit, the tap changer control unit configured to measure the dynamic magnetic flux value.

[0032] In some embodiments, the remanent flux determination unit is configured to determine the remanent flux value on the basis of a first voltage measured at a potential transformer connected to the given winding and the first difference obtained from a result of a simulation model performed to emulate operation of the tap changer; and/or the dynamic flux determination unit is configured to determine the dynamic magnetic flux value on the basis of a second voltage measured at the potential transformer and the second difference obtained from the result of the simulation model.

[0033] In some embodiments, the remanent flux determination unit is configured to determine the remanent flux value by querying a memory with a voltage measured at a potential transformer connected to the given winding, the memory having stored therein a plurality of voltage values, a plurality of values for the first
difference, and a first correspondence between each one of the plurality of voltage values and each one of the plurality of values for the first difference, determining a selected one of the plurality of values for the first difference corresponding to the measured voltage, and computing the remanent flux accordingly; and/or the dynamic flux determination unit is configured to determine dynamic magnetic flux value by querying the memory with the voltage, the memory having stored therein a plurality of values for the second difference and a second correspondence between each one of the plurality of voltage values and each one of the plurality of values for the second difference, determining a selected one of the plurality of values for the second difference corresponding to the measured voltage, and computing the dynamic magnetic flux accordingly.

[0034] In some embodiments, the switching arrangement closing unit is configured to determine the closing angle for each one of at least one phase of the tap changer power transformer and to output the control signal for causing the switching arrangement to be moved to the closed position at the closing angle for each one of the at least one phase.

[0035] In some embodiments, the switching arrangement closing unit is configured to select a first phase of the tap changer power transformer having a highest remanent flux value, generate the control signal for energizing the first phase, and, a predetermined number of half-cycles after a voltage signal of the first phase crosses zero, generate the control signal for energizing at least one remaining phase of the tap changer power transformer.

[0036] In accordance with a third broad aspect, there is provided a tap changer power transformer comprising a power transformer comprising a first winding and a second winding, a given one of the first and the second winding having a plurality of taps, each one of the plurality taps providing a tap voltage; a tap changer connected to the given winding, the tap changer configured to adjust positions of the plurality of taps for modifying a number of turns of the given winding; a voltage source; a switching arrangement connecting the tap changer to the voltage source,
the switching arrangement moveable between a closed position for connecting the
tap changer power transformer to the source, thereby energizing the tap changer
power transformer, and an open position for disconnecting the tap changer power
transformer from the source, thereby de-energizing the tap changer power
transformer; and a control unit. The control unit is configured to determine a first
status of the tap changer, and accordingly a value of a remanent flux remaining in
the tap changer power transformer, after the switching arrangement is placed in
the open position; determine a second status of the tap changer, and accordingly
a value of a dynamic magnetic flux generated by the tap changer power
transformer, before the switching arrangement is moved from the open position to
the closed position; determine from the remanent flux value and the dynamic
magnetic flux value a closing angle at which to place the switching arrangement to
the closed position, the remanent flux value substantially equal to the dynamic
magnetic flux value at the closing angle; and output a control signal for causing the
switching arrangement to be moved from the open position to the closed position at
the closing angle, thereby energizing the tap changer power transformer.

BRIEF DESCRIPTION OF THE DRAWINGS

[0037] Further features and advantages of the present invention will become
apparent from the following detailed description, taken in combination with the
appended drawings, in which:

[0038] Figure 1a is a schematic diagram of a controlled switching system for a tap
changer power transformer, in accordance with an illustrative embodiment of the
present invention;

[0039] Figure 1b is a schematic diagram of the controlled switching module of
Figure 1a, in accordance with an illustrative embodiment of the present invention;

[0040] Figure 2a is a flowchart of a controlled switching method for a tap changer
power transformer, in accordance with an illustrative embodiment of the present
invention;
[0041] Figure 2b is a flowchart of the step of Figure 2a of obtaining remanent flux value;

[0042] Figure 2c is a flowchart of the step of Figure 2a of adjusting closing angles;

[0043] Figure 3 is a plot of a result of control of a tap changer using standard regulation in steady state;

[0044] Figure 4 is a plot of an example of erroneous magnetic flux calculation values using various source voltage amplitudes without taking into account the position of the tap changer, in accordance with an illustrative embodiment of the present invention; and

[0045] Figure 5 is a plot of an example of the absolute error in the remanent flux calculation for different flux values, when the calculation is not performed in accordance with an illustrative embodiment of the present invention.

[0046] It will be noted that throughout the appended drawings, like features are identified by like reference numerals.

DETAILED DESCRIPTION

[0047] Referring to Figure 1a, a controlled switching system 100 for a tap changer power transformer will now be described. The system 100 shown in Figure 1a illustratively comprises a single phase of a power transformer 102 having a core 103, a low voltage winding 104a, and a high voltage winding 104b. In one embodiment, regulation of the power transformer 102 is performed at the high voltage winding 104b but it should be understood that the power transformer 102 may be regulated at either the low voltage winding 104a or the high voltage winding 104b. Although a single phase power transformer 102 has been shown for illustrative purposes, it should be also understood that the power transformer 102 may be a three-phase power transformer, an autotransformer, or any other suitable power transformer known to those skilled in the art.
[0048] The system 100 further comprises a voltage source 106 (illustratively providing an AC voltage having a plurality of repeating cycles) coupled to the high voltage winding 104b through a switching arrangement, such as a source circuit breaker 108a, and a load 110 coupled to the low voltage winding 104a. A tap changer 112 is further provided (e.g. between the high voltage winding 104b and the circuit breaker 108a) to enable stepped regulation of the power transformer's output voltage in order to achieve required levels. For this purpose, the tap changer 112 may vary the turns ratio of the power transformer 102 by selecting in discrete steps the number of turns of the transformer winding 104b (as illustrated) or 104a to which the tap changer 112 is connected. The tap changer 112 may add turns to or subtract turns from either the low voltage winding 104a or the high voltage winding 104b. For this purpose, a tap changer control unit 114 may be used to autonomously determine whether current should be transferred by the tap changer 112 from one voltage tap to the next, thereby ensuring that the voltage is maintained at a predetermined set point. As known to those skilled in the art, most tap changer power transformers as in 102 have taps (not shown) on either the low voltage winding 104a or the high voltage winding 104b to vary the number of turns thereof. By changing positions (or settings) of the taps and thus varying the number of turns, the output voltage of the tap changer power transformer, and accordingly the magnetic flux thereof, may in turn be varied.

[0049] In the embodiment of Figure 1a, the tap changer control unit 114 is connected to the tap changer 112 as well as to the low voltage winding 104a through a potential (or voltage) transformer 116. For simplification purposes, no circuit breaker has been illustrated in Figure 1a to disconnect the load 110 from the tap changer power transformer 102 although it should be understood that such a circuit breaker may be present in the system 100. For the same reason, the connections from the potential (or voltage) transformer 120a and/or 120b to the tap changer control unit 114 are not shown. As known to those skilled in the art, the tap changer control unit 114 may be computer-implemented or may comprise
purely mechanical components configured to control operation of the tap changer 112.

[0050] A controlled switching module (or unit) 118 may further be provided for controlling energization of the tap changer power transformer 102. The controlled switching module 118 may comprise one or more computing devices including, but not limited to, a digital computer, a processor (e.g. a microprocessor), and a memory. In the embodiment of Figure 1a, the controlled switching module 118 is connected to a first terminal (not shown) of the source circuit breaker 108a through a first potential transformer 120a and to a second terminal (not shown) of the source circuit breaker 108a through a second potential transformer 120b. The first terminal of the source circuit breaker 108a is further connected to the tap changer 112 and the second terminal of the source circuit breaker 108a to the source 106. Also, the controlled switching module 118 is illustratively connected to, and therefore in communication with, the tap changer control unit 114 and adapted to receive therefrom signals used to obtain the position of the tap changer 112. It will be understood that the controlled switching module 118 may also be configured to send signals to the tap changer control unit 114 and/or receive signals from the potential transformer 116. For simplification purposes, no direct connection is shown between the potential transformer 116 and the controller switching module 118, although it should be understood that such a connection may be present. Although the controlled switching module 118 is illustrated as separate from the tap changer control unit 114, it should be understood that in embodiments where the tap changer control unit 114 is computer-implemented, the controlled switching module 118 may be integrated with the tap changer control unit 114.

[0051] The controlled switching module 118 may be used to delay the closing and/or opening of the circuit breaker 108a by a predetermined amount of time. For instance, rather than immediately performing a circuit breaker closing operation in response to a closing command received at the system 100 from an operator, the controlled switching module 118 may be used (as will be discussed further below)
to continuously assess a general state of the tap changer power transformer 120 and determine a suitable (e.g. delayed) time for closing the circuit breaker 108a such that unwanted switching transients (e.g. strong inrush currents and temporary overvoltage surges) are avoided. In one embodiment, the controlled switching module 118 loops indefinitely until a command is received from the operator and/or a change in tap settings occurs.

[0052] The amount of time by which the closing and/or opening is delayed may depend on the application, equipment characteristics, and operating conditions. In particular, upon energization of the tap changer power transformer 102 having a remanent flux $\phi_r$, the contribution of the flux generated by the inflow of the voltage depends on the moment at which the tap changer power transformer 102 is energized as well as on the voltage's waveform seen by the tap changer power transformer 102. The controlled switching module 118 may then be used to synchronize the closing and/or opening of the circuit breaker 108a with a voltage or current reference so as to energize/de-energize the tap changer power transformer 102 at an optimum moment, characterized by the circuit breaker closing angle. The closing angle is illustratively representative of a given time or moment in the cycle (measured in degrees, with one full cycle being represented by 360 degrees and each cycle corresponding to one (1) second) at which to close the circuit breaker 108a. For a given remanent flux $\phi_r$, energization of the tap changer power transformer 102 at the optimum moment in turn allows to achieve a symmetrical magnetic flux through the tap changer power transformer 102 and generation of unwanted switching transients can be avoided. The optimum moment for closing the circuit breaker 108a illustratively depends on a variety of factors. One such factor includes the value of the residual magnetic flux, i.e. the magnetic flux remaining in the power transformer's magnetic core 103 when the tap changer power transformer 102 is de-energized. Other factors (e.g. temperature, delays in circuit breaker operation, or the like) known to those skilled in the art may apply.
As shown in Figure 1b, the controlled switching module 118 illustratively comprises a remanent flux determination unit 120, a dynamic flux determination unit 122, and a switching arrangement closing unit 124, whose operation will be discussed further below.

The typical remanent flux $\phi_r$ is illustratively obtained by applying the Lenz Faraday law as follows:

$$E = -N \frac{d\phi_r}{dt} \quad (1)$$

where $E$ is an alternating voltage whose peak-to-peak amplitude varies, e.g. a source voltage generated by the source 106 and applied to the tap changer power transformer 102 (when considering the closing of the circuit breaker 108a) or a voltage measured at terminals of the tap changer power transformer 102 (when considering the opening of the circuit breaker 108a), $N$ is the nominal number of turns of the transformer's winding 104b (determined by the transformer manufacturer, as known by those skilled in the art), and $\phi$ is the magnetic flux generated by the tap changer power transformer 102.

The controlled switching module 118 illustratively ensures that the circuit breaker 108a is closed at the optimum moment, such a moment depending in part on the value of the remanent flux $\phi_r$ of the tap changer power transformer 102. As such, the closing strategy is implemented by the controlled switching module 118 (and more particularly the remanent flux determination unit 120) may first determine the remanent flux $\phi_r$ of the tap changer power transformer 102 at de-energization thereof (e.g. upon opening of the circuit breaker 108a). The remanent flux $\phi_r$ calculation of a power transformer without a tap changer as in 112 is mainly based on the integration of the measured voltage signal $E$ from the potential transformer as in 120a (see the simplified equation (2) below).

$$\phi_r = \left( \frac{\text{constant}}{N} \times \left[ \left( \int_{t_{a-b}}^{t_{a-b}} E \times dt \right) - \left( \int_{0}^{t_{a-b}} E \times dt \right) \right] \right) \quad (2)$$
[0057] The first integration operation in equation (2) is performed on a sufficient (to provide a real image of the transformer's remanent flux) number (b) of full cycles before the circuit breaker opening time (O), which is the reference angle for the beginning of a full cycle, and a sufficient (to provide a real image of the transformer's remanent flux) number (a) of full cycles after the circuit breaker opening time (O). An intermediate result is then obtained, from which a mean value of the integral (represented by the second integration operation in equation (2)), is removed. The result is then multiplied by a calibration constant (referred to as "constant" in equation (2) and whose value may depend on the computation method(s) and component(s) used to determine the remanent flux value) and divided by the number (N) of winding turns to obtain the value of the remanent flux $\phi_r$.

[0058] Using the remanent flux, the controlled switching module 118 may then compute, for each phase (e.g. for one (1) phase for a single phase power transformer or for all three (3) phases for a three-phase power transformer), the circuit breaker closing angle that is optimal for preventing inrush currents and temporary overvoltage. In order to achieve a reliable closing moment, it is desirable for the value of the remanent flux $\phi_r$ to be precisely obtained. In one embodiment, it is desirable for the value of the remanent flux $\phi_r$ to be obtained for each phase. For this purpose, and as will be discussed further below, the controlled switching module 118 (and more particularly the remanent flux determination unit 120) illustratively performs a second step in computation of the remanent flux $\phi_r$ of the tap changer power transformer as in 102 with tap changer 112, namely taking into account a gap or divergence $\Delta N_o$ between the tap changer's status or position (i.e. the number of turns of the transformer's high voltage winding 104b) at circuit breaker opening and the nominal number N of turns. It is illustratively desirable for the tap changer's status to be determined at the time of switching, before the tap changer 112 changes the transformer's tap positions. Since the tap changer's status does not change once the circuit breaker opening operation has occurred and because it typically takes some time (e.g. a few seconds) for the tap changer
112 to start operating after opening of the circuit breaker 108a, the tap changer’s status (i.e. the number of turns) at circuit breaker opening, and accordingly the value of ΔNo, may be obtained a few instants (or milliseconds) after the circuit breaker opening operation, illustratively immediately following the circuit breaker opening operation or at any time thereafter before occurrence of a tap change. In one embodiment, the tap changer’s status and the value of ΔNo are obtained less than ten (10) cycles after the circuit breaker opening operation. Other time intervals may apply.

[0059] Depending on the method used to compute the remanent flux φr (as will be discussed further below with reference to Figure 2b), the simplified equation (3) below may be used by one of the tap changer control unit 114, the remanent flux determination unit 120 of the controlled switching module 118, and sensing devices (not shown), which measure the voltage at the terminals of the tap changer power transformer 102.

\[
\varphi_r = \left( \frac{\text{constant}}{N \pm \Delta N_0} \right) \times \left[ \left( \int_{\alpha}^{\beta} E \times dt \right) - \left( \int_{\beta}^{\gamma} E \times dt \right) \right]
\]

[0060] It should be understood that the parameter ΔNo may relate to an increase or a decrease in the number N of turns. In one embodiment, ΔNo may be comprised in the range between ±10-20%. Other ranges may apply, depending on characteristics of the tap changer 112. Also, although the parameter ΔNo is discussed herein with reference to the high voltage winding 104b, it should be understood that, depending on the transformer winding 104a or 104b whose number of turns the tap changer 112 adjusts, the remanent flux φr may alternatively be computed taking into account a value of the number of turns in the transformer’s low voltage winding 104a.

[0061] As will be discussed further below, the controlled switching module 118 (and more particularly the dynamic flux determination unit 122) may then (e.g. upon receiving from the operator a command to close the circuit breaker 108a)
determine a latest or most recent status (i.e. the number of turns of the transformer's high voltage winding 104b) just before circuit breaker closing and accordingly determine a deviation ANc between the recent number of turns just before circuit breaker closing and the nominal number N of turns of the transformer's high voltage winding 104b. The controlled switching module 118 may accordingly determine a value of the dynamic magnetic flux generated by the generated by the tap changer power transformer 102 at energization thereof. The controlled switching module 118 (and more particularly the switching arrangement closing unit 120) then takes parameters AN0 and ANc into account for computing the optimal circuit breaker closing angle.

[0062] Referring now to Figure 2a in addition to Figure 1a, the controlled switching module 118 illustratively implements a method 200 for controlled switching of the circuit breaker 108a, and accordingly for controlling energization of the tap changer power transformer 102. The method 200 illustratively comprises obtaining (e.g. at the remanent flux determination unit 120 of Figure 1b) at step 202 a measurement of the remanent flux φ1 taking into account the variation AN0 in the number of turns of the high voltage winding 104b of the tap changer power transformer 102. The next step 204 is then to adjust (e.g. at the dynamic flux determination unit 122 and the switching arrangement closing unit 124 of Figure 1b) the closing angles of the circuit breaker 108a in accordance with the "real" (e.g. obtained at step 202) remanent flux and the dynamic flux that takes into account the new number of turns of the tap changer power transformer at closing of the circuit breaker 108a, and more particularly the gap ANc from the nominal number N of turns of the transformer's high voltage winding 104b. As known to those skilled in the art, the tap changer's status may still vary until the circuit breaker closing operation is performed. In one embodiment, the tap changer's latest status is the last available status of the tap changer 112 obtained just (e.g. a few instants or milliseconds) before the circuit breaker closing operation, before occurrence of a tap change. In one embodiment, this latest status corresponds to the tap changer's status as determined by the controlled switching module 118 less than ten (10) cycles before
the circuit breaker closing operation is performed. Other time intervals may apply. Then, the next step 206 is to effect phase-by-phase closing of the circuit breaker 108a by applying any relevant controlled switching strategy known to those skilled in the art.

[0063] With the tap changer 112 in use, the number N of turns varies. Thus, the controlled switching module 118 illustratively takes the value of the number of turns into account when applying equation (1) above. In one embodiment, the controlled switching module 118 takes parameters ΔN₀ and ΔNₛ into account for respectively calculating the remanent flux ϕᵣ and computing the optimal closing angle, as discussed in equations (5) (discussed further below) and (3).

[0064] Referring to Figure 2b, the remanent flux measurement may be obtained (e.g. by the remanent flux determination unit 120 of Figure 1b) at step 202, taking into account parameter ΔN₀, by applying one or more techniques. For this purpose, depending on the configuration of the control system 100, one or more remanent flux calculation methods are used where at least one of steps 302, 304, 306, 308, 310, and 312 may apply. The remanent flux value may then be obtained at step 314 as a combination (e.g. an average value) of the outputs of steps 302, 304, 306, 308, 310, and/or 312. It should be understood that the remanent flux value may also be obtained at step 314 by taking the most suitable (e.g. accurate) result from the results output at steps 302, 304, 306, 308, 310, 312. In particular, one or more of steps 302, 304, 306, 308, 310, 312 may be performed with the result of each step being used to validate the result(s) of the other step(s). Also, when certain equipment provided in system 100 of Figure 1a is not available, suitable one(s) of the remanent flux calculation methods of steps 302, 304, 306, 308, 310, and 312 are selected accordingly for implementation at step 202.

[0065] At step 302, the remanent flux measurement is obtained or calculated directly using the tap changer control unit (reference 114 in Figure 1a), which may be configured to measure the power transformer's remanent flux ϕᵣ. The measurement can be obtained at step 302 from the tap changer control unit 114,
as a numerical or analog signal. The measurement may also be obtained or calculated by the controlled switching module 118 communicating with the tap changer control unit 114 using any suitable communication means.

[0066] At step 304, the remanent flux measurement to be used by the controlled switching module 118 is illustratively obtained or calculated from readings received from sensing device(s) or system(s) (not shown) connected to the power transformer core (reference 103 in Figure 1a) or to the potential transformer 116 or 120a. In one embodiment and as discussed above, the sensing device(s) measure the voltage at the terminals of the tap changer power transformer (reference 102 in Figure 1a), calculate, and provide the value of the remanent flux \( \Phi_r \). In this embodiment, the remanent flux value may be measured and directly provided by the sensing device(s), without computing \( \Delta N_0 \) or applying equation (3) above.

[0067] At step 306, the remanent flux measurement may be obtained or calculated by the controlled switching module 118 using the voltage measured at the potential transformer 120a (e.g. the voltage from the winding 104b controlled by the tap changer 112) and a voltage transform function performed by a simulation model. In one embodiment, the simulation model emulates operation of the tap changer control unit 114 and of the tap changer 112 and allows to obtain the \( \Delta N_0 \) value according to simulation results. The simulation model may be implemented at the controlled switching module 118.

[0068] At step 308, the value of the remanent flux \( \Phi_r \) is obtained or calculated from the measurement of the transformer's voltage at the potential transformer 116 at the low voltage winding 104a, e.g. the winding not controlled by the tap changer 112. In particular, it is possible to obtain the remanent flux \( \Phi_r \) from such a measurement because, at the low voltage winding 104a, the number \( N \) of turns is fixed and the dynamic flux is the same as at the high voltage winding 104b.

[0069] Step 310 may be used instead of step 306, where a more complex simulation strategy is used. At step 310, the remanent flux measurement may be
obtained or calculated by the controlled switching module 118 using voltage from the winding 104b controlled by the tap changer 112 and a coefficient proportional to the measured voltage. In particular, the dynamic flux measurement may be computed using the voltage measured at the potential transformer 120a and a two-column table (or other suitable means), which may be stored in memory and makes a direct correspondence between each one of a plurality of voltage values and a value for $\Delta N_0$, assuming proper and instantaneous operation of the tap changer 112. By querying the memory with the measured voltage, it is possible to determine from the table the expected $\Delta N_0$ corresponding to the measured voltage. The remanent flux value may then be computed accordingly (e.g. using equation (3)).

[0070] Step 312 may be used to calculate the remanent flux value using a voltage ratio between the windings (e.g. the low voltage winding 104a and the high voltage winding 104b) on both sides of the tap changer power transformer, i.e. the ratio between the voltage at the potential transformer 116 and the voltage at either one of the potential transformer 120a and the potential transformer 120b.

[0071] Referring back to Figure 2a, once the remanent flux $\phi_r$ has been computed at step 202 taking into account the change $\Delta N_0$ (deviation or difference between the number of turns at circuit breaker opening and the nominal number of turns) in the number of turns of the power transformer's winding 104b measured at circuit breaker opening, the controlled switching module 118 adjusts the closing angle of the circuit breaker 108a at step 204 taking into account the change $\Delta N_c$ at circuit breaker closing. In particular, step 204 comprises closing the circuit breaker (reference 108a in Figure 1a), thereby energizing the tap changer power transformer (reference 102 in Figure 1a), when the integral of the source voltage $E$ (see equation (1) above), also referred to as dynamic flux $\Phi$ generated by the tap changer power transformer 102 at energization thereof, is substantially equal to the remanent flux $\phi_r$ computed at step 202.
As can be seen from equation (4) below, the prospective dynamic magnetic flux $\Phi$ before the circuit breaker closing operation depends on the alternating source voltage $E$, the value of the remanent flux $\phi$, taken at the time the circuit breaker opening operation is performed, and the number $N$ of turns of the transformer’s winding 104b.

$$\phi = \left( \frac{1}{N} \times \int E \times \partial t \right) + \phi_r$$

(4)

When the dynamic magnetic flux $\Phi$ is below the saturation level (also referred to as flux saturation knee) of the transformer’s core (reference 103 in Figure 1a), the current remains relatively low and increases proportionally to the applied voltage $E$. The range of magnetic flux $\Phi$ below the saturation knee is referred to as the normal operating range of the tap changer power transformer 102. When the flux $\Phi$ is beyond the saturation knee, the current significantly increases. In order to ensure that the dynamic flux $\Phi$ does not increase beyond the core saturation level, the controlled switching module (reference 118 in Figure 1a) implements method 200, and more particularly step 204 thereof, to ensure that circuit breaker 108a is closed and the tap changer power transformer 102 energized at the optimal time. In this manner, the integral of the source voltage $E$ compensates for the initial remanent flux $\phi_r$ and inrush currents and transient overvoltages can be reduced.

The optimal time at which the tap changer power transformer 102 should be energized is determined taking into account the change $\Delta N_c$ (deviation between the number of turns at circuit breaker closing and the nominal number of turns) in the number of turns of the transformer’s winding 104b measured before energization. For this purpose, equation (4) above can be rewritten as:

$$\phi = \left( \frac{\text{constant}}{N \pm \Delta N_c} \times \int E \times \partial t \right) + \phi_r$$

(5)
[0075] It should be understood that the parameter ANc may relate to an increase or a decrease in the number N of turns. In one embodiment, ANc may be comprised in the range between ±10-20%. Other ranges may apply, depending on characteristics of the tap changer 112. Also, although the parameter ANc is discussed herein with reference to the high voltage winding 104b, it should be understood that, depending on the transformer winding 104a or 104b whose number of turns the tap changer 112 adjusts, the dynamic flux Φ may be computed taking into account a value of the number of turns in the transformer’s low voltage winding 104a.

[0076] In order to suitably adjust the closing angle of the circuit breaker 108a at step 204, the dynamic magnetic flux Φ may be computed using some techniques similar to those used for measuring the remanent flux φ, at step 202.

[0077] Referring now to Figure 2c in addition to Figure 2a, the dynamic flux measurement (e.g. dynamic flux curves) may be obtained (e.g. at the dynamic flux determination unit 122 of Figure 1b) at step 204, taking into account parameter ANc, by applying one or more techniques. For this purpose, depending on the configuration of the control system 100, one or more dynamic flux calculation method(s) are used taking into account ANc. For this purpose, at least one of steps 316, 318, and 320 may apply. At step 316, the dynamic flux measurement is obtained or calculated directly using the tap changer control unit (reference 114 in Figure 1a), which may be configured to measure the transformer’s dynamic flux φ, using a signal from the potential transformer 120b (with the connection between the tap changer control unit 114 and the potential transformer 120b not shown in Figure 1a for sake of clarity). The measurement can be obtained at step 316 from the tap changer control unit 114 as a numerical or analog signal. The measurement may also be obtained by the controlled switching module 118 communicating with the tap changer control unit 114 using any suitable communication means.
[0078] At step 318, the dynamic flux measurement may be calculated by the
controlled switching module 118 (e.g. by the dynamic flux determination unit 122)
using the voltage measured at the potential transformer 120a and a voltage
transform function performed by a simulation model. This simulation model
illustratively emulates operation of the tap changer control unit 114 and of the tap
changer 112 and enables to obtain the value of $\Delta N_C$ according to simulation
results.

[0079] Step 320 may be used rather than step 318, where a more complex
simulation model is used. At step 320, the dynamic flux measurement may be
calculated by the controlled switching module 118 using voltage from the winding
104b controlled by the tap changer 112 and a coefficient proportional to the
measured voltage. In particular, the dynamic flux measurement may be computed
using the voltage measured at the potential transformer 120a and a two-column
table that makes a direct correspondence between the measured voltage and the
expected $\Delta N_C$ assuming proper and instantaneous operation of the tap changer
112.

[0080] After at least one of steps 316, 318, and 320, the dynamic flux curves are
then obtained at step 322 as a combination (e.g. an average value) of the outputs
of steps 316, 318, and/or 320. It should be understood that the dynamic flux curves
may also be obtained at step 322 by taking the most suitable (e.g. accurate) result
from the results output at steps 316, 318, 320. In particular, one or more of steps
316, 318, 320 may be performed with the result of each step being used to validate
the result(s) of the other step(s). Also, when certain equipment provided in system
100 of Figure 1a is not available, suitable one(s) of the dynamic flux measurement
methods of steps 316, 318, 320 are selected accordingly for implementation at
step 204.

[0081] Once the prospective dynamic flux curves taking into account the change
$\Delta N_C$ in the number of turns of the transformer’s winding 104b are known, the
optimal closing angle for each phase can be calculated at step 324 (e.g. by the
switching arrangement closing unit 124). As known to those skilled in the art, one embodiment of step 324 is to find the angles on the dynamic curves where the amplitude of the dynamic flux is equal to the remanent flux of each phase obtained or calculated (at step 202 of Figure 2a) at the circuit breaker opening operation. It should be understood that other embodiments may apply.

[0082] Although not illustrated for the sake of clarity, it should also be understood that additional functions, such as setting, self-diagnosis, and alarm functions, other than the functions described herein with reference to Figure 2a, Figure 2b, and Figure 2c, may also be provided by the controlled switching module 118.

[0083] Referring back to Figure 2a, once the remanent flux has been measured at step 202 and the closing angles adjusted at step 204, a circuit breaker controlled closing strategy known to those skilled in the art may be applied at step 206 by the controlled switching module (reference 118 in Figure 1a), and more particularly by the switching arrangement closing unit (reference 124 in Figure 1b). In one embodiment, phase-by-phase closing of the circuit breaker 108a may be performed by selecting at step 206 the first phase of the tap changer power transformer 102 with the highest remanent flux \( \phi_I \) to be energized first. A control signal may then be generated to energize the selected phase and close the circuit breaker 108a at the optimal moment. The remaining (e.g. two (2)) phases are subsequently energized a predetermined number \( n \) of half-cycles after the voltage signal of the first phase to close crosses zero. The number \( n \) of half-cycles may depend on equipment characteristics, on exploitation constraints, and on the selected closing strategy. For example, \( n \) may be equal to \( \frac{1}{2}, 1, 1 \frac{1}{2}, 2, 2 \frac{1}{2}, ... \) In some embodiments (e.g. for a three-phase transformer), energization of one of the remaining two phases may be delayed relative to energization of the other phases. For example, the second phase may be energized \( n \) half-cycles after the voltage signal of the first phase to close crosses zero while the third phase is delayed and energized a few milliseconds later.
Referring now to Figure 3 in addition to Figure 1a, when the controlled switching module 118 is not in use, the tap changer 112 may implement its normal voltage regulation function. The tap changer 112 may indeed operate so that the tap changer power transformer 102 generates a magnetic flux 402 having a peak-to-peak amplitude 404, which remains substantially the same regardless of variations in the peak-to-peak value 406 of the source voltage supplied by the source 106. For instance, different source voltages, namely a rated voltage 408a, a minimal voltage 408b, or a maximal voltage 408c, may be supplied to the system 100. Still, the tap changer 112 may ensure that the magnetic flux 402 remains at the same peak-to-peak value 404, which is substantially equal to the peak-to-peak value (not shown) of the rated voltage 408a. This in turn ensures that the voltage supplied to the load 110 has the amplitude of the rated voltage.

Referring now to Figure 4, without taking into account the tap changer 112 influence on the deviations $\Delta N_0$ or $\Delta N_C$ from the nominal number $N$ of turns of the transformer’s high voltage winding 104b, different magnetic fluxes 410a, 410b, 410c may be calculated by the controlled switching module 118 depending on the source voltage 408a, 408b, or 408c supplied by the source 106. In particular, when the rated voltage 408a is supplied, the controlled switching module 118 may calculate a rated magnetic flux 410a. When the minimal voltage 408b is supplied, the controlled switching module 118 may calculate a minimal erroneous magnetic flux 410b that differs from the rated magnetic flux 410a by an error 412a (when measured at the peak value). When the maximal voltage 408c is supplied, a maximal erroneous magnetic flux 410c may be calculated, the flux 410c differing from the rated magnetic flux 410a by an error 412b (when measured at the peak value). Although not illustrated, it should be understood that the source voltage applied by the source 106 may have any value between the minimal and maximal voltages 408b, 408c. Thus, the calculated magnetic flux may have any value between the minimal and maximal erroneous magnetic fluxes 410b, 410c.
[0086] Figure 5 illustrates an absolute error between the rated magnetic flux (reference 410a in Figure 4) and the magnetic flux for a tap changer (reference 112 in Figure 1a) at ±12.5% for the illustrated example, which depends on the tap changer range limits. It can be seen that, using the controlled switching module 118 to implement controlled switching of the circuit breaker (reference 108a of Figure 1a) with the change (ΔNo or ΔNc) in the transformer winding's number of turns taken into account, the error in the remanent flux calculation and the error related to the dynamic flux calculation can be minimized, e.g. brought to substantially zero (0). In particular, the error is illustratively null at ninety (90) and 270 degrees. The error is then maximal (e.g. 0.125PU in the illustrated example) when the source voltage approaches the limits specified by the tap changer 112, e.g. at zero (0), 180, and 360 degrees. The error illustratively depends on the voltage amplitude compared to nominal and on the flux angle at the closing moment of the first phase. By implementing a closing strategy where circuit breaker closing is performed at closing angles of substantially ninety (90) or 270 degrees, it is therefore possible to achieve a substantially null error. In particular, this closing strategy may be used independently without computing the remanent flux, e.g. when the methods discussed above with reference to Figure 2a, Figure 2b, and Figure 2c cannot be used or provide inconsistent results, such that a remanent flux calculation cannot be obtained.

[0087] It should be understood that, although the change (ΔNo or ΔNc) in the transformer winding’s number of turns is presented and illustrated herein as symmetrical, the change in the number of turns implemented by the tap changer may also be asymmetrical.

[0088] It should be noted that the present invention can be carried out as a method, can be embodied in a system, and/or on a computer readable medium. The embodiments of the invention described above are intended to be exemplary only. The scope of the invention is therefore intended to be limited solely by the scope of the appended claims.
CLAIMS:

1. A method for controlling energization of a tap changer power transformer, the tap changer power transformer having a first winding and a second winding and a tap changer connected to a given one of the first and the second winding, the tap changer configured to adjust positions of a plurality of taps of the given winding for modifying a number of turns of the given winding, the given winding connected to a voltage source through a switching arrangement moveable between a closed position for connecting the tap changer power transformer to the source, thereby energizing the tap changer power transformer, and an open position for disconnecting the tap changer power transformer from the source, thereby de-energizing the tap changer power transformer, the method comprising:

   determining a first status of the tap changer, and accordingly a value of a remanent flux remaining in the tap changer power transformer, after the switching arrangement is placed in the open position;

   determining a second status of the tap changer, and accordingly a value of a dynamic magnetic flux generated by the tap changer power transformer, before the switching arrangement is moved from the open position to the closed position;

   determining from the remanent flux value and the dynamic magnetic flux value a closing angle at which to place the switching arrangement to the closed position, the remanent flux value substantially equal to the dynamic magnetic flux value at the closing angle; and

   outputting a control signal for causing the switching arrangement to be moved from the open position to the closed position at the closing angle, thereby energizing the tap changer power transformer.

2. The method of claim 1, wherein determining the first status of the tap changer comprises determining a first difference between a nominal value of the number of turns of the given winding and a first value of the number of turns, the first value determined after the switching arrangement is placed in the open position and before the tap changer adjusts the positions of the plurality of taps in
response to the switching arrangement being placed in the open position, the remanent flux value determined on the basis of the first difference.

3. The method of claim 2, wherein determining the second status of the tap changer comprises obtaining a most recent status of the tap changer before the switching arrangement is moved from the open position to the closed position, the most recent status obtained by determining a second difference between the nominal value and a second value of the number of turns of the given winding, the second value determined a predetermined time period before the switching arrangement is moved from the open position to the closed position, the dynamic magnetic flux value determined on the basis of the second difference.

4. The method of claim 3, wherein the remanent flux value is determined as:

$$\phi_r = \left( \frac{\text{constant}}{N \pm \Delta N_0} \right) \times \left( \left[ \int_{0}^{a} E \times \frac{\partial t}{\partial t} \right] - \left[ \int_{b}^{0} E \times \frac{\partial t}{\partial t} \right] \right)$$

where $\phi_r$ is the remanent flux value, $E$ is an alternating voltage originating from the voltage source, $0$ is an opening time at which the switching arrangement is placed in the open position, $a$ is a first predetermined number of full cycles after the opening time, $b$ is a second predetermined number of full cycles before the opening time, $N$ is the nominal value of the number of turns of the given winding, $\Delta N_0$ is the first difference, and constant is calibration constant.

5. The method of claim 4, wherein the dynamic magnetic flux value is determined as:

$$\phi = \left( \frac{\text{constant}}{N \pm \Delta N_C} \right) \times \left( \int E \times \frac{\partial t}{\partial t} \right) + \phi_r$$

where $\Phi$ is the dynamic magnetic flux value and $\Delta N_C$ is the second difference.

6. The method of claim 1, wherein the remanent flux value is determined on the basis of data received from at least one sensing device connected to one of the
tap changer power transformer and a potential transformer connected to one of the first and the second winding, the at least one sensing device configured to measure a voltage at terminals of the tap changer power transformer and compute therefrom the remanent flux value.

7. The method of claim 1, wherein the remanent flux value is determined on the basis of a voltage measured at a potential transformer connected to another one of the first and the second winding, a number of turns of the other winding not controlled by the tap changer.

8. The method of claim 1, wherein the remanent flux value is determined on the basis of a ratio between a first voltage measured at a first potential transformer connected to the first winding and a second voltage measured at a second potential transformer connected to the second winding.

9. The method of claim 1, wherein:

   * the remanent flux value is determined from a first measurement received from a tap changer control unit, the tap changer control unit connected to the tap changer for controlling operation thereof and configured to measure the remanent flux value; and/or
   * the dynamic magnetic flux value is determined from a second measurement received from the tap changer control unit, the tap changer control unit configured to measure the dynamic magnetic flux value.

10. The method of claim 5, wherein:

   * the remanent flux value is determined on the basis of a first voltage measured at a potential transformer connected to the given winding and the first difference obtained from a result of a simulation model performed to emulate operation of the tap changer; and/or
   * the dynamic magnetic flux value is determined on the basis of a second voltage measured at the potential transformer and the second difference obtained from the result of the simulation model.
11. The method of claim 5, wherein:
   the remanent flux value is determined by
   querying a memory with a voltage measured at a potential
   transformer connected to the given winding, the memory having stored
   therein a plurality of voltage values, a plurality of values for the first
   difference, and a first correspondence between each one of the plurality of
   voltage values and each one of the plurality of values for the first difference,
   determining a selected one of the plurality of values for the first
   difference corresponding to the measured voltage, and
   computing the remanent flux accordingly; and/or
   the dynamic magnetic flux value is determined by
   querying the memory with the voltage, the memory having stored
   therein a plurality of values for the second difference and a second
   correspondence between each one of the plurality of voltage values and
   each one of the plurality of values for the second difference,
   determining a selected one of the plurality of values for the second
   difference corresponding to the measured voltage, and
   computing the dynamic magnetic flux accordingly.

12. The method of any one of claims 1 to 11, wherein the closing angle is
determined for each one of at least one phase of the tap changer power
transformer and the control signal is output for causing the switching arrangement
to be moved to the closed position at the closing angle for each one of the at least
one phase.

13. The method of claim 12, further comprising selecting a first phase of the tap
changer power transformer having a highest remanent flux value, generating the
control signal for energizing the first phase, and, a predetermined number of half-
cycles after a voltage signal of the first phase crosses zero, generating the control
signal for energizing at least one remaining phase of the tap changer power
transformer.
14. A system for controlling energization of a tap changer power transformer, the tap changer power transformer having a first winding and a second winding and a tap changer connected to a given one of the first and the second winding, the tap changer configured to adjust positions of a plurality of taps of the given winding for modifying a number of turns of the given winding, the given winding connected to a voltage source through a switching arrangement moveable between a closed position for connecting the tap changer power transformer to the source, thereby energizing the tap changer power transformer, and an open position for disconnecting the tap changer power transformer from the source, thereby de-energizing the tap changer power transformer, the system comprising:

   a remanent flux determination unit configured to determine a first status of the tap changer, and accordingly a value of a remanent flux remaining in the tap changer power transformer, after the switching arrangement is placed in the open position;

   a dynamic flux determination unit configured to determine a second status of the tap changer, and accordingly a value of a dynamic magnetic flux generated by the tap changer power transformer, before the switching arrangement is moved from the open position to the closed position; and

   a switching arrangement closing unit configured to determine from the remanent flux value and the dynamic magnetic flux value a closing angle at which to place the switching arrangement to the closed position, the remanent flux value substantially equal to the dynamic magnetic flux value at the closing angle, and output a control signal for causing the switching arrangement to be moved from the open position to the closed position at the closing angle, thereby energizing the tap changer power transformer.

15. The system of claim 14, wherein the remanent flux determination unit is configured to determine a first difference between a nominal value of the number of turns of the given winding and a first value of the number of turns, the first value determined after the switching arrangement is placed in the open position and before the tap changer adjusts the positions of the plurality of taps in response to
the switching arrangement being placed in the open position, and determine the remanent flux value on the basis of the first difference.

16. The system of claim 15, wherein the dynamic flux determination unit is configured to determine a second difference between the nominal value and a second value of the number of turns of the given winding, the second value determined a predetermined time period before the switching arrangement is moved from the open position to the closed position, and determine the dynamic magnetic flux value on the basis of the second difference.

17. The system of claim 16, wherein the remanent flux determination unit is configured to determine the remanent flux value as:

\[ \varphi_r = \left( \text{constant} \times \frac{1}{N \pm \Delta N_c} \left[ \left( \int_{\partial_{-b}}^{\partial_{+a}} E \times \vartheta \right) \left( \int_{\partial_{-b}}^{\partial_{+a}} E \times \vartheta \right) \right] \right) \]

where \( \varphi_r \) is the remanent flux value, \( E \) is an alternating voltage originating from the voltage source, \( O \) is an opening time at which the switching arrangement is placed in the open position, \( a \) is a first predetermined number of full cycles after the opening time, \( b \) is a second predetermined number of full cycles before the opening time, \( N \) is the nominal value of the number of turns of the given winding, \( \Delta N_0 \) is the first difference, and constant is calibration constant.

18. The system of claim 17, wherein the dynamic flux determination unit is configured to determine the dynamic magnetic flux value as:

\[ \Phi = \left( \text{constant} \times \frac{1}{N \pm \Delta N_c} \right) \left( \int E \times \vartheta \right) + \varphi_r \]

where \( \Phi \) is the dynamic magnetic flux value and \( \Delta N_c \) is the second difference.

19. The system of claim 14, wherein the remanent flux determination unit is configured to determine the remanent flux value on the basis of data received from at least one sensing device connected to one of the tap changer power transformer and a potential transformer connected to one of the first and the second winding,
the at least one sensing device configured to measure a voltage at terminals of the tap changer power transformer and compute therefrom the remanent flux value.

20. The system of claim 14, wherein the remanent flux determination unit is configured to determine the remanent flux value on the basis of a voltage measured at a potential transformer connected to another one of the first and the second winding, a number of turns of the other winding not controlled by the tap changer.

21. The system of claim 14, wherein the remanent flux determination unit is configured to determine the remanent flux value on the basis of a ratio between a first voltage measured at a first potential transformer connected to the first winding and a second voltage measured at a second potential transformer connected to the second winding.

22. The system of claim 14, wherein:

the remanent flux determination unit is connected to a tap changer control unit, the tap changer control unit connected to the tap changer for controlling operation thereof and configured to measure the remanent flux value, the remanent flux determination unit configured to determine the remanent flux value from a first measurement received from the tap changer control unit; and/or

the dynamic flux determination unit is connected to the tap changer control unit and configured to determine the dynamic magnetic flux value from a second measurement received from the tap changer control unit, the tap changer control unit configured to measure the dynamic magnetic flux value.

23. The system of claim 18, wherein:

the remanent flux determination unit is configured to determine the remanent flux value on the basis of a first voltage measured at a potential transformer connected to the given winding and the first difference obtained from a result of a simulation model performed to emulate operation of the tap changer; and/or
the dynamic flux determination unit is configured to determine the dynamic magnetic flux value on the basis of a second voltage measured at the potential transformer and the second difference obtained from the result of the simulation model.

24. The system of claim 18, wherein:

the remanent flux determination unit is configured to determine the remanent flux value by querying a memory with a voltage measured at a potential transformer connected to the given winding, the memory having stored therein a plurality of voltage values, a plurality of values for the first difference, and a first correspondence between each one of the plurality of voltage values and each one of the plurality of values for the first difference, determining a selected one of the plurality of values for the first difference corresponding to the measured voltage, and computing the remanent flux accordingly; and/or

the dynamic flux determination unit is configured to determine dynamic magnetic flux value by querying the memory with the voltage, the memory having stored therein a plurality of values for the second difference and a second correspondence between each one of the plurality of voltage values and each one of the plurality of values for the second difference, determining a selected one of the plurality of values for the second difference corresponding to the measured voltage, and computing the dynamic magnetic flux accordingly.

25. The system of any one of claims 14 to 24, wherein the switching arrangement closing unit is configured to determine the closing angle for each one of at least one phase of the tap changer power transformer and to output the control signal for causing the switching arrangement to be moved to the closed position at the closing angle for each one of the at least one phase.

26. The system of claim 25, wherein the switching arrangement closing unit is configured to select a first phase of the tap changer power transformer having a highest remanent flux value, generate the control signal for energizing the first phase, and, a predetermined number of half-cycles after a voltage signal of the first
phase crosses zero, generate the control signal for energizing at least one remaining phase of the tap changer power transformer.

27. A tap changer power transformer comprising:

- a power transformer comprising a first winding and a second winding, a given one of the first and the second winding having a plurality of taps, each one of the plurality taps providing a tap voltage;
- a tap changer connected to the given winding, the tap changer configured to adjust positions of the plurality of taps for modifying a number of turns of the given winding;
- a voltage source;
- a switching arrangement connecting the tap changer to the voltage source, the switching arrangement moveable between a closed position for connecting the tap changer power transformer to the source, thereby energizing the tap changer power transformer, and an open position for disconnecting the tap changer power transformer from the source, thereby de-energizing the tap changer power transformer; and
- a control unit configured to:

  determine a first status of the tap changer, and accordingly a value of a remanent flux remaining in the tap changer power transformer, after the switching arrangement is placed in the open position;

  determine a second status of the tap changer, and accordingly a value of a dynamic magnetic flux generated by the tap changer power transformer, before the switching arrangement is moved from the open position to the closed position;

  determine from the remanent flux value and the dynamic magnetic flux value a closing angle at which to place the switching arrangement to the closed position, the remanent flux value substantially equal to the dynamic magnetic flux value at the closing angle; and
output a control signal for causing the switching arrangement to be moved from the open position to the closed position at the closing angle, thereby energizing the tap changer power transformer.
START

202

OBTAIN REMANENT FLUX MEASUREMENT TAKING INTO ACCOUNT VARIATION IN NUMBER OF TURNS OF TAP CHANGER POWER TRANSFORMER AT CIRCUIT BREAKER OPENING

204

ADJUST CLOSING ANGLES IN ACCORDANCE WITH REAL REMANENT FLUX AND DYNAMIC FLUX THAT TAKES INTO ACCOUNT NEW NUMBER OF TURNS OF TAP CHANGER POWER TRANSFORMER AT CIRCUIT BREAKER CLOSING

206

APPLY CIRCUIT BREAKER CONTROLLED CLOSING STRATEGY

END

FIGURE 2a
FIGURE 2b

1. Obtain or calculate remanent flux value using tap changer control unit.
2. Obtain or calculate remanent flux value using sensing device(s).
3. Obtain or calculate remanent flux value using simulation model and voltage from winding controlled by tap changer.
4. Obtain or calculate remanent flux value from winding not controlled by tap changer.
5. Obtain or calculate remanent flux value using voltage from winding controlled by the tap changer and coefficient proportional to measured voltage.
6. Calculate remanent flux value using voltage ratio between windings on both sides of tap changer power transformer.
7. Obtain remanent flux value.
316

OBTAIN OR CALCULATE DYNAMIC FLUX CURVES USING TAP CHANGER CONTROL UNIT

318

CALCULATE DYNAMIC FLUX CURVES USING SIMULATION MODEL AND VOLTAGE FROM THE WINDING CONTROLLED BY THE TAP CHANGER

320

CALCULATE DYNAMIC FLUX CURVES USING VOLTAGE FROM THE WINDING CONTROLLED BY THE TAP CHANGER AND A COEFFICIENT PROPORTIONAL TO THE MEASURED VOLTAGE

322

OBTAIN PROSPECTIVE DYNAMIC FLUX CURVES

324

CALCULATE EACH PHASE CLOSING ANGLE

FIGURE 2c
FIGURE 3

Time in degrees (1 cycle in steady state)

Rated voltage
Minimal voltage
Maximal voltage
Magnetic flux

Amplitude in pu

0.5
1
1.5
-0.5
-1
-1.5
30 60 90 120 150 180 210 240 270 300 330 359
### A. CLASSIFICATION OF SUBJECT MATTER

**IPC:**
- H02P 13/06 (2006.01)
- H01F 27/42 (2006.01)

According to International Patent Classification (IPC) or to both national classification and IPC.

### B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

**IPC:** H02P; H01F (2006.01)

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched.

Electronic database(s) consulted during the international search (name of database(s) and, where practicable, search terms used)

Questel-Orbit (FAMPAT); Keywords: "transformer, inrush, tap changer, remanent flux; residual flux"

### C. DOCUMENTS CONSIDERED TO BE RELEVANT

<table>
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* Further documents are listed in the continuation of Box C.  

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