A Unified Approach to Controlled Switching of Power Equipment

Gabriel Benmouyal, Normann Fischer, Douglas Taylor,
Mark Talbott-Williams, and Ritwik Chowdhury
Schweitzer Engineering Laboratories, Inc.

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***Abstract*—The aim of controlled switching of power equipment is to reduce, if not eliminate, the voltage and current transients that result from energizing or de-energizing the equipment by way of a circuit breaker operation. This paper reviews what can be achieved with a modern controlled switching device in terms of improving power quality, protecting both the power equipment and the circuit breaker, and improving protective relay reliability.**

I. Introduction

Switching operations are a major source of power system transients. For instance, capacitor bank switching can create current surges and overvoltages. Energization of power inductors can create a significant dc offset that can in turn saturate power transformers. Shunt reactor de-energization can cause circuit breaker reignitions that can result in equipment failure. Transformer energization typically creates significant inrush currents that create harmonics in the voltage and current signals, cause harmonic overvoltages, and can lead transmission line protection relays to misoperate. Energization of transmission lines with trapped charges during fast reclosing can lead to line overvoltages that cause relay misoperation.

One method to reduce switching transients when energizing or de-energizing electrical equipment is to use pre- and post-insertion resistors. However, this approach is costly because it requires circuit breakers that include these resistors. Additionally, the protection schemes need to account for situations such as the failure of the pre- and post-insertion resistors and be able to bypass such failures in a timely manner. The other method that is gaining favor in the last few years is what is known as "controlled switching." The aim of power apparatus controlled switching is to reduce and possibly eliminate these transients and therefore contribute to protecting the power equipment, improving the power quality, and making the protective devices more reliable.

The combination of circuit breakers with stable closing and opening characteristics and present-day digital technology has allowed devising intelligent controlled switching devices (CSDs) that can be applied to any equipment type. Controlled switching is best implemented with breakers with independent pole operation. Less efficient strategies can still be devised with gang-operated circuit breakers. The purpose of this paper is to review the controlled switching principles of different equipment types and to demonstrate how intelligent CSDs can be applied to achieve transient-free circuit breaker operations.

II. Controlled Closing Fundamental Principles

The controlled closing of a power apparatus consists of triggering the electrical make of a circuit breaker pole contact at a desired voltage point-on-wave angle. This operation reduces or eliminates voltage or current transients that can result from closing in a random fashion. The nature of the voltage or current transients depends on the equipment type being energized.

A. Circuit Breaker Pole Average Closing Time

The average circuit breaker pole closing time, or TClose in this paper, is the average time interval between the instant when the voltage step is applied on the circuit breaker pole closing coil and the instant when the two sides of the pole contacts touch (i.e., the mechanical make).

In order to avoid any arcing influence, the circuit breaker pole closing time is measured with the circuit breaker disconnected from the network. Typically, the mechanical make instant is determined when the measured contact resistance is zero.

It has been established that a circuit breaker pole closing time remains fairly constant over time. This paramount property has informed the development of a technique for controlled closing on power equipment.

B. Factors Impacting the Closing Time

In normal operation, the circuit breaker experiences slight departures from the ideal nominal closing time, $TClose_{NOM}$. Impacts to the nominal closing times may be broadly characterized as coming from two sources: installation environmental conditions and the operational history of the circuit breaker.

1) Environmental Factors

The following environmental factors influence the closing time of the circuit breaker and represent the effect that the immediate installation environment has on circuit breaker closing time:

- Ambient temperature.
- Closing coil supply voltage.
- Energy stored by the circuit breaker actuating mechanism, expressed as a pressure measurement.

The compensated closing time can be expressed mathematically as the sum of $TClose_{NOM}$ plus the compensations for all three sources of deviation:

$$TClose = TClose_{NOM} + \Delta TC_{TEMP} + \Delta TC_{SV} + \Delta TC_{PRES} \quad (1)$$

The three compensating variations are calculated from measured ambient temperature, closing coil supply voltage, and pressure. When all three measurements are at their nominal values, all three compensating variations are equal to zero. Each of the three compensating curves can be stored in the CSD in the form of tables or curves approximated by linear segments. Before a closing operation, TClose is determined by adjusting $TClose_{NOM}$ by each of the three compensating variables as necessary.

2) Operational History Factors

Historical factors represent the effect over time that the operational history of the circuit breaker has on the nominal close time. Operational history factors that lead to deviation from $TClose_{NOM}$ are:

- Drift in the nominal closing time following subsequent closing operations.
- Change in the nominal closing time, depending upon the idle time between two closing operations.

The compensation based on the previous operations of the circuit breaker can be expressed mathematically as [1] [2]:

$$\Delta TC_{PREV} = \sum_{n=1}^{N} w(n) \bullet \left[TClose_{meas}(n) - TClose(n) \right] \quad (2)$$

In (2), for a total of *N* closing operations, the difference between the measured closing time and the calculated closing time is performed for each operation. This difference is multiplied by a weighting factor w(n) for each operation, where the sum of all *N* weighting factors w(n) is equal to 1. The outcome of the sum in (2) provides the trend in the drift of the nominal closing time. It should be borne in mind that implementation of the compensation provided by (2) requires the accurate measurement of the closing time in real time.

Idle time compensation can be expressed mathematically as:

$$\Delta TC_{IDLE} = f\left(T_{IDLE}\right) \quad (3)$$

In (3), T_{IDLE} is the elapsed time between the previous operation and the next closing operation. Equation (3) expresses that the idle time compensation is simply a function of the elapsed time.

After the five compensating deviations have been evaluated, the final closing time will be equal to:

$$\begin{aligned} TClose = TClose_{NOM} + \Delta TC_{TEMP} + \Delta TC_{SV} + \Delta TC_{PRES} + \ldots \\ \Delta TC_{PREV} + \Delta TC_{IDLE} \end{aligned} \quad (4)$$

C. Impact of Prestrike or Pre-Arcing

For a circuit breaker pole during a close operation, the electrical make, or pre-arcing, occurs when the voltage across the pole contact exceeds the dielectric withstand capability of the contact gap. The common measure of the circuit breaker pole dielectric strength is the rate of decay of dielectric strength (RDDS) expressed in kV/ms. The RDDS is assumed to be infinite for an ideal circuit breaker as long as the two sides of the pole contact do not touch mechanically. Fig. 1 represents the prestrike characteristic at a voltage peak (represented in per unit [pu]). From Fig. 1 and for an RDDS of the slope S_0, the electrical make time, or t_{elec}, can be determined by solving (5) for *t* [1] [2]:

$$\left|V_{bkr}(t)\right| = S_0 \bullet \left(t - t_{mech}\right) \quad (5)$$

where:

$V_{brk}(t)$ is the voltage across the circuit breaker.

t_{mech} is the instant when the pole contacts touch.

Equation (5) expresses simply that t_{elec} is found at the intersection of the voltage curve and the line of the S_0 slope and passes by the point t_{mech} on the abscissa.

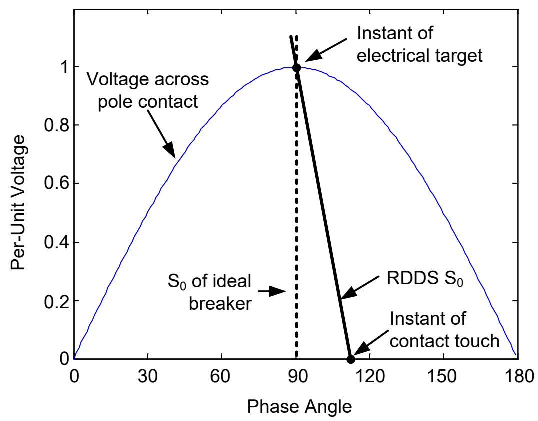

Fig. 1. Prestrike characteristic at a voltage peak

From the preceding, we can see that the higher the RDDS slope, the closer t_{elec} and t_{mech} are. For an ideal circuit breaker, the two quantities are equal.

For applications where closing is performed at a fixed voltage point-on-wave angle, the setting TCarc is introduced. It allows correction compensation for the difference between the electrical and mechanical makes.

D. Single-Phase Controlled Closing

Taking into account the circuit breaker pole closing time, controlled closing consists of applying the voltage step on the closing coil so that the pole electrical make occurs at a set angle of the reference voltage. In this paper, this set angle is called TCpow.

By reviewing Fig. 2, we can determine that the integer number of reference voltage cycles to implement a closing operation can be calculated as follows:

$$\text{NCyc} = \text{ceil}\left[\text{TClose} - \left(\text{TCpow} + \text{TCarc}\right) + 1\right] \tag{6}$$

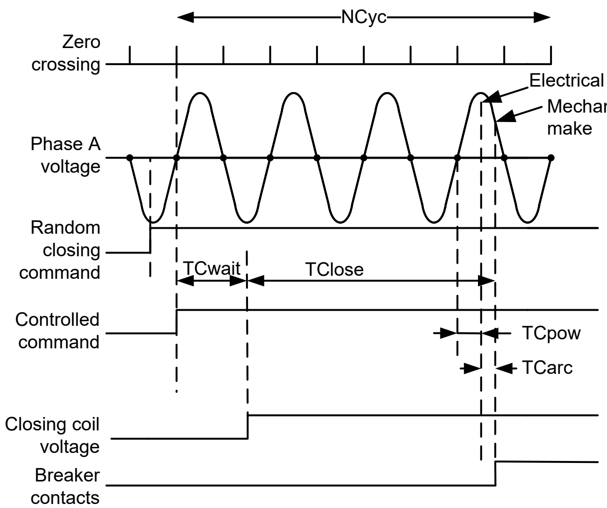

Fig. 2. Single-phase controlled closing timing principles

In (6), ceil is the operation that rounds to the nearest greater integer. TClose, TCpow, and TCarc are three introduced settings.

Once NCyc has been determined, and assuming the closing operation starts at a positive zero crossing of the reference voltage, we must wait an interval of time (TCwait) before the voltage step is applied to the closing coil. In many applications, some of which are defined later in the paper, it is necessary to apply an additional delay (TCdel) to the circuit breaker pole closing. In view of this additional delay, the final waiting time can be calculated as follows:

$$\begin{aligned}\text{TCwait} &= \text{NCcyc} - \text{TClose} - 1 \\ &\quad + \left(\text{TCpow} + \text{TCarc}\right) + \text{TCdel}\end{aligned} \tag{7}$$

E. Three-Phase Controlled Closing

In the previous example of single-phase controlled closing, the timing reference was selected as the positive-going zero crossing of the reference voltage. The same principles applied for single-phase closing can be easily extended to three-phase closing by selecting a single timing reference that is applied to all three phases. We define TCwait.a/A as the waiting time for Phase A with the time reference being fixed with respect to Phase A itself. We define TCwait.a/B as the waiting time for Phase A with the timing reference belonging to Phase B. Note that the timing reference does not have to necessarily be a zero crossing. Assuming that the timing reference belongs to Phase A, and assuming an ABC phase rotation, three-phase controlled closing can be implemented by computing the three waiting times as follows:

$$\begin{aligned}&\text{TCwait.a / A} \\ &\text{TCwait.b / A} = \text{TCwait.b / B} + 1/3 \\ &\text{TCwait.c / A} = \text{TCwait.c / C} + 2/3\end{aligned} \tag{8}$$

In (8), all parameters are in cycles, ensuring that the waiting times remain independent from frequency. Equation (7) allows computing TCwait.a/A, TCwait.b/B, and TCwait.c/C because each of the three phases is considered as independent. Fig. 3 shows the phase relation for all three phases, A, B, and C, with an ABC phase rotation.

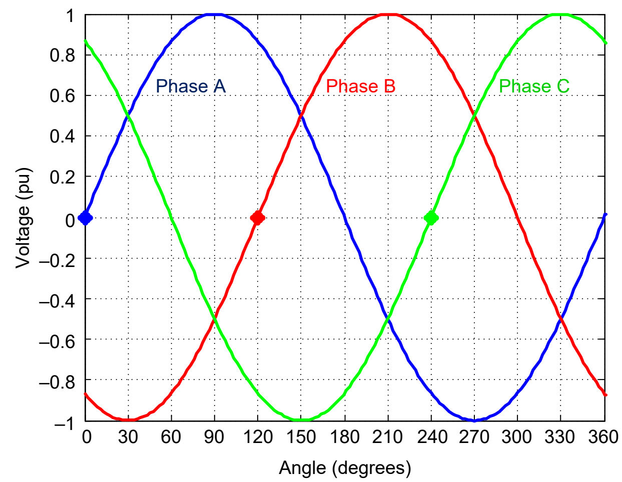

Fig. 3. Phase relation between three-phase unit voltage with ABC rotation

Three-phase controlled closing is implemented by applying (7) to calculate the three waiting times and an equivalent to (8), depending on the selection of a timing reference point. Equation (8) is directly applicable if the common reference point is the Phase A voltage positive-going zero crossing.

F. Controlled Closing Settings Summary

For each phase, two circuit breaker-related settings have been defined: TClose and TCarc. For each phase, two application-related settings have also been introduced, namely TCpow and TCdel. This paper demonstrates that with a total of 12 settings, or 4 settings for each phase, the controlled closing of any power equipment can be performed. Table I provides the units of all 4 settings.

TABLE I
CLOSING SETTING UNITS

Setting	Definition	Units
TClose	Compensated circuit breaker pole closing time	Milliseconds
TCarc	Difference between electrical arcing and mechanical contact	Degrees
TCpow	Voltage point-on-wave closing angle	Degrees
TCdel	Additional closing delay	Cycles

In Table I, TCpow and TCarc are degrees and can readily be converted into cycles. TClose is the only setting with units in milliseconds. TClose can be converted to cycles by using a measurement of the network frequency (FREQ) at the instant that controlled closing is performed:

$$\text{TClose}_{\text{cycles}} = \frac{\text{TClose}_{\text{ms}} \bullet \text{FREQ}}{1{,}000} \tag{9}$$

Fig. 4 shows the simulation of a three-phase closing example at a peak of the respective unit phase voltage with the following applied settings:

$$\begin{array}{lll} \text{TClose.a} = 22 \text{ ms} & \text{TClose.b} = 21 \text{ ms} & \text{TClose.c} = 23 \text{ ms} \\ \text{TCpow.a} = 90^\circ & \text{TCpow.b} = 90^\circ & \text{TCpow.c} = 270^\circ \\ \text{TCarc.a} = 10^\circ & \text{TCarc.b} = 10^\circ & \text{TCarc.c} = 10^\circ \\ \text{TCdel.a} = 0 \text{ cyc.} & \text{TCdel.b} = 0 \text{ cyc.} & \text{TCdel.c} = 0 \text{ cyc.} \end{array} \tag{10}$$

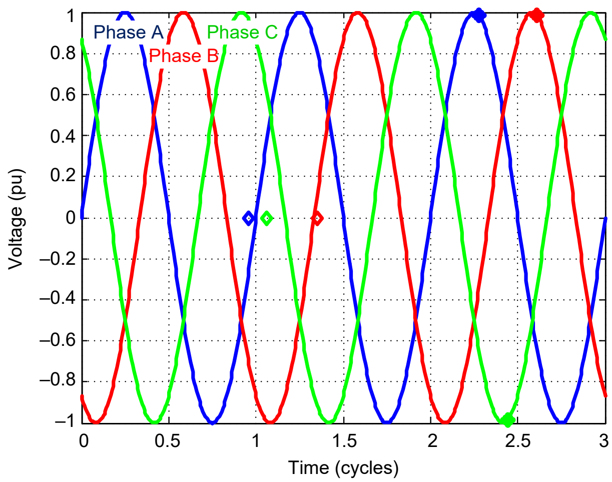

Fig. 4. Example of three-phase circuit breaker closing

In (10), all the settings are referenced with respect to each phase and are considered independent.

In Fig. 4, the timing reference is the Phase A positive-going zero crossing. The diamonds on the horizontal axis represent the waiting times for each of the three poles with respect to the timing reference. The stars on the voltage waveforms represent the instant when the circuit breaker poles close mechanically. Note that these instants appear slightly after the waveform peaks because of the introduced setting TCarc of 10 degrees for all three phases.

III. Requirements for Controlled Closing of Power Equipment

A. Controlled Closing on Capacitor Banks

Capacitor banks are the most switched devices in the power system because they enable voltage control by supplying reactive power support. The current through a capacitor is proportional to the rate of change of voltage across the capacitor, hence the controlled switching objective is to minimize the rate of change of voltage across the capacitor.

$$i_C = C\frac{dV_C}{dt} \tag{11}$$

Prior to energization, the voltage across a capacitor is typically close to zero. After disconnecting from the power system, the discharge times for capacitor banks via discharge resistors are in the order of 5 minutes [3]. It is hence safe to assume that the controlled closing of capacitors will be initiated when the voltage across the capacitor is small.

When a single de-energized capacitor bank is closed in an uncontrolled manner, e.g., at a voltage peak, a significant current surge flows through the capacitor and the bus voltage collapses to zero (the initial voltage across the capacitor). There is a subsequent transient recovery voltage that overshoots the system nominal voltage and can cause an overvoltage in the order of 50 percent, as seen from field measurements of uncontrolled capacitor bank energization [4]. This significant overvoltage imposes dielectric stress on any equipment connected to the local bus. The surge travels through the line and can cause remote effects, such as overvoltages on lines terminated on a transformer.

Because of the prevalence of capacitors in the modern power system, it is not uncommon to have multiple capacitor banks at a given bus. If a capacitor bank is energized back-to-back with another bank connected and energized on the same bus, the transient surge current can be significantly higher with circulating currents from one bank to the other.

B. Controlled Closing on Power Reactors

Shunt reactors are engaged to limit overvoltages on lightly loaded lines, especially long lines that have significant shunt susceptance [5]. The current through a reactor is the area under the voltage curve, as shown in (12), which incurs a dc offset when closed at a voltage zero with a possibility of reactor saturation and inrush. The objective of controlled switching is to close at a voltage peak, which corresponds to a current zero through the inductor (the initial current before closing).

$$i_L = \frac{1}{L}\left(\int v_L dt + \lambda_{init}\right) \tag{12}$$

We do not consider the initial flux linkage (λ_{init}) term for reactors because they have gapped- or air-core designs and hence store negligible or no residual flux, respectively.

When a reactor bank is energized in an uncontrolled manner, e.g., at a voltage zero, the dc offset in the current can cause gapped-core designs to draw significant inrush currents. This inrush current has a dc component that typically decays slowly (taking more than a second) because the reactor losses are typically low. The slow decaying dc offset may cause relay misoperations because of local power transformer saturation in addition to reducing power quality via the injection of harmonics into the system [4].

C. Controlled Closing on Unloaded Power Transformers

The primary objective of the controlled closing of power transformers is to reduce or even eliminate the inrush currents that can accompany a closing operation performed in a random fashion [6] [7]. For a single-phase system, the basic principle for controlled closing for unloaded transformers is that the instantaneous flux (also called the prospective flux) developed by the voltage at the instant of closing should be equal to the residual flux in the magnetic core. This requirement creates the main difficulty associated with controlled closing on transformers: the necessity of measuring the residual flux following the circuit breaker opening.

Controlled closing on transformers becomes particularly attractive from an economical point of view when inrush currents are the cause of potentially destructive overvoltages; controlled closing is in competition with solutions like inserting closing resistors, which is more expensive [8]. Furthermore, eliminating the transformer inrush currents reduces the demand for reactive power that accompanies these currents, and that could be detrimental in some instances to the network voltage regulation or stability.

D. *Controlled Closing on Unloaded Transmission Lines*

The primary objective of controlled closing applied to unloaded transmission lines is to reduce or eliminate the traveling-wave overvoltages that can be induced on the line with random closing. Different controlled closing strategies can be defined, depending on if the transmission line, at the moment of closing, contains trapped charge or not and if the transmission line is compensated or not [1] [2]. The basic principle is to close the circuit breaker at the instant that the point-on-wave angle of the source voltage is equal to the point-on-wave angle of the voltage on the transmission line. This prevents the development of a voltage step that, in turn, initiates traveling waves on the line.

The most trivial case is controlled closing on a transmission line with no trapped charge and no compensation; it suffices to close at a voltage point-on-wave angle equal to zero.

Controlled closing on a transmission line with trapped charge becomes particularly critical when high-speed reclosing schemes are employed [9]. Controlled closing consists then in closing at a voltage corresponding to the polarity of the trapped charge. In order to implement this scheme, the CSD has to memorize the trapped charge polarity at the instant of the circuit breaker poles opening.

Controlled closing on transmission lines with shunt reactor compensation is the most difficult to implement; the combination of the line equivalent capacitance and the reactor creates a resonant circuit. Upon the circuit breaker poles opening, a voltage is created on the line at the frequency of the resonant circuit. In order to implement proper controlled closing, it is necessary that at the instant of the circuit breaker pole closing, the voltage on the bus or source side be equal to the voltage of the resonant circuit on the line side. The difficulty lies in the prediction of the latter.

IV. Controlled Closing Strategy of a Single-Phase Transformer

A. *Optimal Closing Time for a Single-Phase Transformer*

We consider the single-phase transformer of Fig. 5 and assume that the voltage at nominal frequency, F_{nom}, across the primary winding, is provided as:

$$v(t) = V_{max} \bullet \sin\left(2\pi \bullet F_{nom} \bullet t\right) \tag{13}$$

The steady-state flux in the core, also called the prospective flux, is provided by the integral of the voltage or:

$$\phi(t) = \frac{-V_{max}}{2\pi F_{nom}} \bullet \cos\left(2\pi \bullet F_{nom} \bullet t\right) \tag{14}$$

Fig. 6 shows the phase relation between the unit voltage corresponding to (13) and the unit flux corresponding to (14).

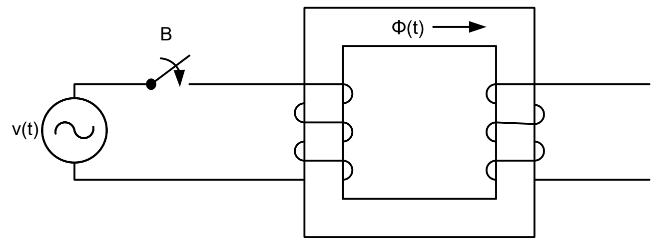

Fig. 5. Single-phase transformer

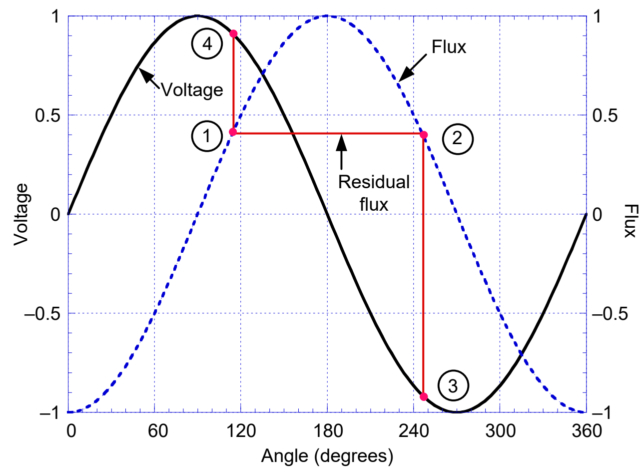

Fig. 6. Phase relation between unit voltage and unit prospective flux

We assume there exists a residual flux in the core that could be Point 1 or 2 in Fig. 6. We want to determine the voltage point-on-wave angle closing instant so that the flux induced at the optimal closing moment, t_{opt}, corresponds to the residual flux. From (14), the residual flux is provided by:

$$\phi_{residual} = \frac{-V_{max}}{2\pi F_{nom}} \bullet \cos\left(2\pi \bullet F_{nom} \bullet t_{opt}\right) \tag{15}$$

From (15), we get:

$$\frac{\phi_{residual} \bullet 2\pi F_{nom}}{-V_{max}} = \cos\left(2\pi \bullet F_{nom} \bullet t_{opt}\right) \tag{16}$$

The closing instant is provided then by:

$$t_{opt} = \frac{\arccos\left(\dfrac{\phi_{residual} \bullet 2\pi \bullet F_{nom}}{-V_{max}}\right)}{2\pi F_{nom}} \tag{17}$$

Because we have:

$$\phi_{max} = \frac{V_{max}}{2\pi \bullet F_{nom}} \tag{18}$$

We finally get:

$$t_{opt} = \frac{\arccos\left(\dfrac{\phi_{residual}}{-\phi_{max}}\right)}{2\pi \bullet F_{nom}} \tag{19}$$

In (19), the angle in the numerator must be expressed in radians so that the optimum time is expressed in milliseconds in the interval 0 to 16.666 ms at a nominal frequency of 60 Hz. If we now express the inverse cosine in units of degrees, the point-on-wave closing angle, TCpow, is in the same units:

$$\mathrm{TCpow} = \arccos\left(\frac{\phi_{\mathrm{residual}}}{-\phi_{\max}}\right) \tag{20}$$

With the residual flux shown in Fig. 6, the solution of (20) allows the determination of the voltage point-on-wave angles corresponding to Points 3 and 4 from Fig. 6. The historical engineering practice dictates selecting the smaller angle corresponding to Point 4.

B. Example of Closing on a Single-Phase Transformer

The single-phase transformer represented in Fig. 7 was modeled in electromagnetic transients program (EMTP) software [10]. The hysteresis characteristic of the nonlinear magnetizing inductance is represented in Fig. 8. The circuit breaker is modeled as an ideal switch.

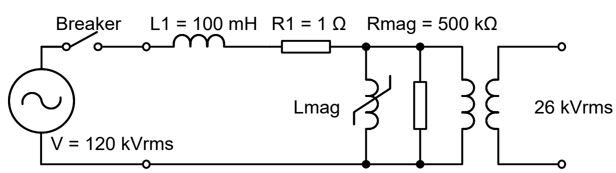

Fig. 7. Single-phase transformer model

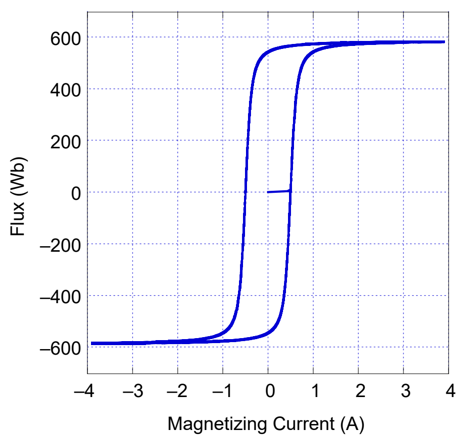

Fig. 8. Transformer hysteresis characteristic

The circuit breaker in Fig. 7 was opened at time 68 ms. The transformer residual flux is shown in Fig. 9b to be 211.7 Wb. The maximum flux is measured as 447.48 Wb. From (20), the optimum point-on-wave voltage closing angle is calculated to be:

$$\mathrm{TCpow} = \arccos\left(\frac{\phi_{\mathrm{residual}}}{-\phi_{\max}}\right) = \arccos\left(\frac{211.7}{-447.88}\right) = 118.21° \tag{21}$$

Fig. 9 shows the voltage, flux, and magnetizing current with controlled closing corresponding to TCpow in (21). Obviously, the magnetizing current remains small and there is no inrush current. Fig. 10 shows the same quantities with random closing using the TCpow setting at 0°. The magnetizing current now jumps to more than 2,000 A.

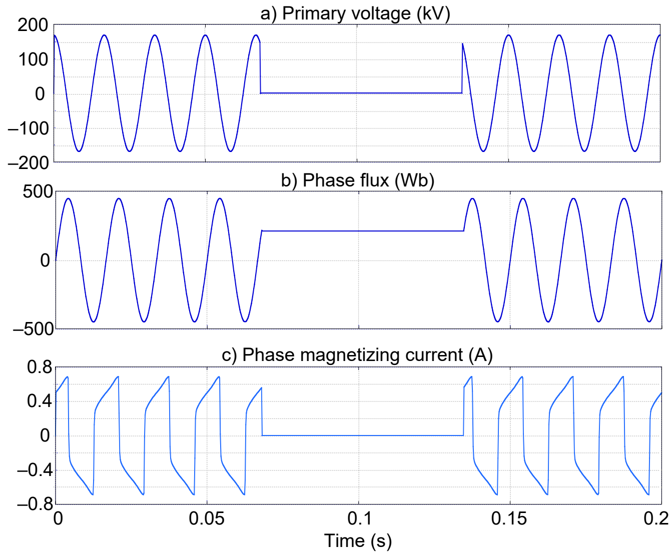

Fig. 9. Single-phase transformer controlled switching

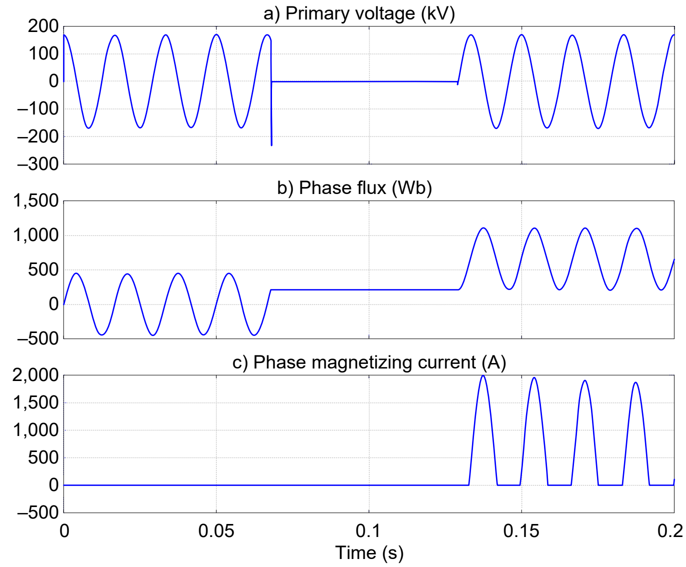

Fig. 10. Single-phase transformer random switching

C. Determining the Residual Flux

To be able to use (19) or (20), it is necessary to have a prior measurement of the residual flux. This can be accomplished by integrating the voltage across the phase winding, starting one or two cycles before the circuit breaker opening, as shown in Fig. 11. By starting the integration at exactly a voltage maximum (or minimum), we eliminate any constant bias in the integral value. Integration can be stopped when the voltage goes to zero.

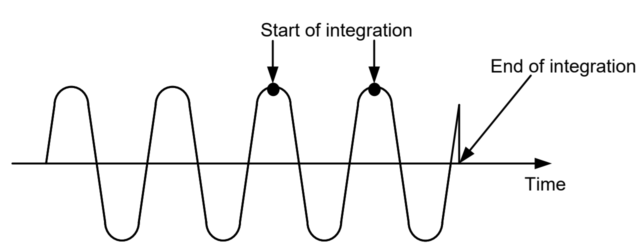

Fig. 11. Start of integration on voltage waveform

Continuous integration can be expressed as:

$$\phi_{residual} = \int_{t=0}^{t=t_0} v(t) \bullet dt \tag{22}$$

In (22), $t = 0$ corresponds to a voltage maximum or minimum at least one cycle before the pole opening, and $t = t_0$ corresponds to the time when the voltage has gone to zero following the circuit breaker opening.

Assuming numerical integration is performed with a sampling frequency (Fsamp) for the voltage instantaneous values, the trapezoidal rule of integration can be applied as shown in (23):

$$\phi_{residual} = \sum_{n=1}^{n=N-1} \left(\frac{v_n + v_{n+1}}{2} \right) \bullet \frac{1}{Fsamp} \tag{23}$$

The same principles apply to the numerical integration; n = 1 must correspond to a voltage maximum or minimum one cycle at least before the pole opening, and n = N–1 corresponds to a few samples after the voltage has gone to zero. An accurate voltage measurement may be obtained from a magnetic voltage transformer.

D. *Grading Capacitor Issues*

1) *Grading Capacitor Network Impact*

Grading capacitors can be installed across the circuit breaker pole interruption chambers for the purpose of evenly distributing the voltage across these chambers. This is represented in Fig. 12, where C1 is the resulting grading capacitor of more than one capacitor in series.

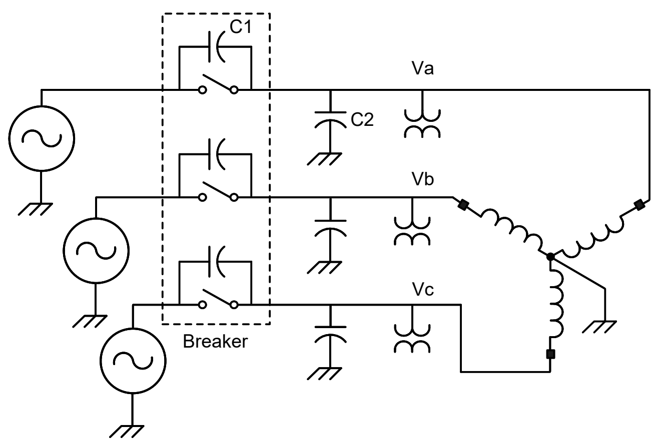

Fig. 12. Grading equivalent capacitor C1 location

Because a stray capacitance exists between the transformer primary circuit and the ground, represented by C2 in Fig. 12, a voltage divider is created by capacitors C1 and C2 in parallel with the transformer input impedance Z(s). The outcome of this voltage divider is that a residual voltage will exist across C2 when the circuit breaker pole is open and voltages at nominal frequency (F_{nom}) will be impressed on the transformer primary windings. If no grading capacitors are present across the circuit breaker, the integration of the voltage can be stopped practically after the circuit breaker opens and the voltage goes to zero. If grading capacitors are present, integration of the voltage must continue after the circuit breaker has opened until the flux reaches a final average steady-state value. Furthermore, when the circuit breaker poles are opened, the voltage divider circuit will create a voltage transient that will change the transformer core residual flux trajectory after the voltage has been integrated.

2) *Example With Single-Phase Transformer*

A grading capacitor is added to the single-phase network of Fig. 7. As shown in Fig. 13, let Z(s) be the transformer input impedance and V(s) be the source voltage; when the circuit breaker is opened, the voltage VT(s) at the transformer primary will undergo a transient that is determined by the transfer function defined in (24). The transient voltage VT(s) must now be integrated to obtain the flux.

$$VT(s) = \frac{C1}{C1 + C2 + \frac{1}{sZ(s)}} V(s) \tag{24}$$

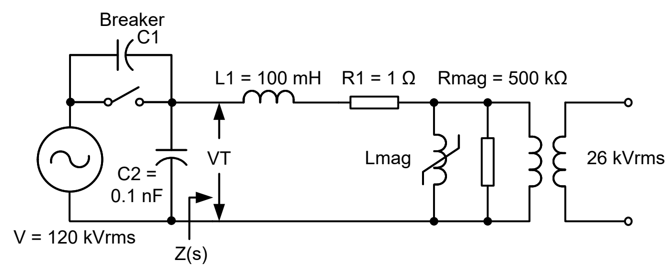

Fig. 13. Circuit breaker pole with grading equivalent capacitor

In order to gain an understanding of the effect of grading capacitors on the flux trajectory, the circuit breaker was opened at time 66.5 ms and the voltage integrated to get the flux, with values of C1 as 0, 4, 6, and 8 nF and a constant value of C2 of 0.1 nF. The flux trajectories are shown in Fig. 14. Obviously, as the value of the grading capacitor is increased, the flux undergoes a reduction of its final value. Before the final average value is reached, the flux trajectory appears as a decaying exponential with a time constant that is reduced as C1 increases. For larger C1 values, the final flux exhibits a constant "micro-oscillation."

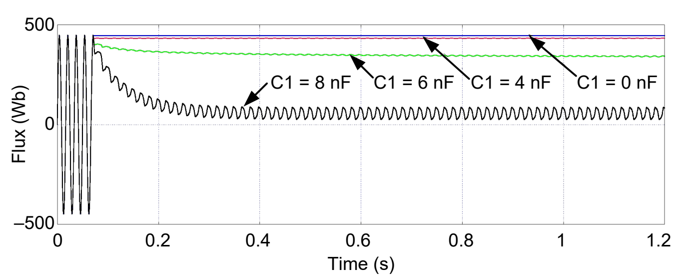

Fig. 14. Flux trajectories with C1 varying from 0 to 8 nF

With the grading capacitor set to 8 nF, an attempt was made to implement a controlled closing operation around 0.6 s where the average flux settled to its final value. The average of the micro-oscillation was calculated to be 56.45 Wb, and the maximum flux was calculated to be 448.2 Wb. Equation (20) was used to calculate the optimum point-on-wave closing angle:

$$\text{TCpow} = \arccos\left(\frac{56.45}{-448.2}\right) = 97.24^\circ \tag{25}$$

Controlled closing was performed with this angle value obtained from (25), and the result is shown in Fig. 15. Examining Fig. 15, we can see that the inrush current has been eliminated. For the sake of completeness, a random closing operation was performed with a value of TCpow equal to 6.52°. Substantial inrush current was created, as shown in Fig. 16.

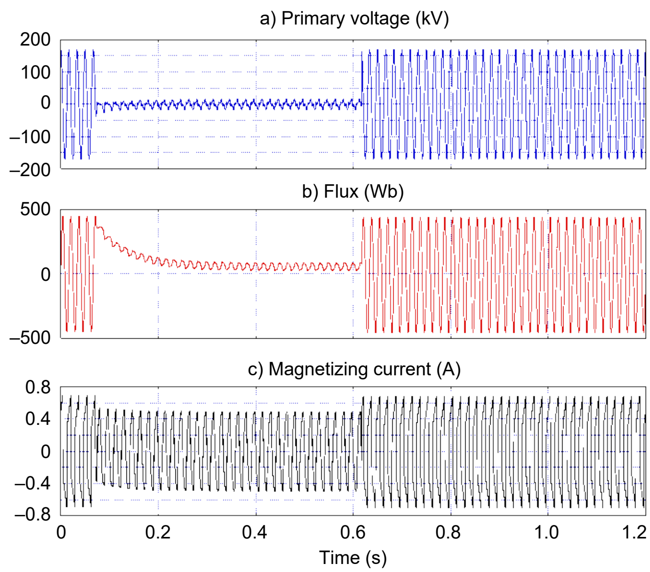

Fig. 15. Primary voltage, flux, and magnetizing current with controlled closing

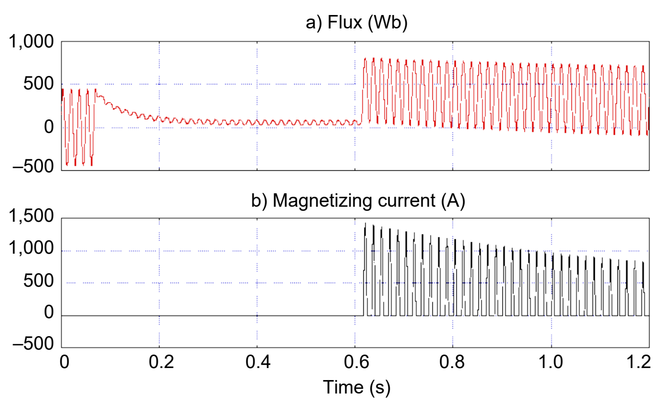

Fig. 16. Primary flux and magnetizing current with random closing

This example demonstrates that the controlled switching of a transformer can be accomplished even with the presence of grading capacitors that entail micro-oscillations, provided that the voltage integration has been prolonged enough after the circuit breaker opening to get to the final average value of the residual flux. The difficulties here lie in the characterization of the flux decay time constant and the level of residual micro-oscillations. The results presented in this section are very much in line with the latest research [11] [12] [13], and the issues of grading capacitors were still being investigated at the time this paper was written.

3) Grading Capacitor Impact Summary

Grading capacitors installed across the transformer circuit breaker interruption chambers add complexities to the issue of transformers switching. They affect the transient response of the voltage at the transformer primary and, consequently, the trajectory of the flux after the circuit breaker opens. The time constant of the flux decay together with the magnitude of the remaining micro-oscillation cannot be predicted in advance and must be measured on site in real time. Consequently, the duration of the voltage integral after the circuit breaker has been opened must be determined experimentally. Each transformer-circuit breaker configuration must be analyzed separately by experimental measurements.

It is interesting to note that at least one U.S. utility assumes that the grading capacitors installed on its circuit breakers will lead to a condition of zero residual flux in the transformer's core after the circuit breaker has been opened [4]. It appears that this particular situation cannot be generalized.

V. Three-Phase Transformer Configurations and Controlled Closing Strategies

A. *Independent-Core Three-Phase Transformers*

The magnetic paths related to the three phase windings in a three-phase transformer are magnetically independent when the flux in one of the three paths does not depend on either of the two other fluxes. The only situation where three-phase transformers have magnetically independent cores is when three single-phase transformers are separately energized by three voltage sources, as shown in Fig. 17.

B. *Dependent-Core Three-Phase Transformers*

The magnetic paths related to the three phase windings in a three-phase transformer are magnetically dependent when the flux in one of the three paths depends on the voltages across the other two phase windings.

Various situations will create dependent-core three-phase transformers. Fig. 18 shows three single-phase transformers where an additional delta-connected tertiary winding has been added. By virtue of the delta-connected windings, the sum of the three fluxes in all three cores is automatically equal to zero. The presence of one voltage phase will create equal fluxes in the two other cores such that their sum is equal and opposite to the flux in the core supplied with the single voltage. Fig. 19 shows a three-legged core transformer automatically creating magnetically dependent cores; the presence of any of the phase voltage will create fluxes in the two other legs. Note that the sum of the three fluxes in magnetically dependent three-phase transformers is always zero in either steady or transient states [6] [7] [14]. In the same perspective, and irrespective of the magnetic core structure, a three-phase transformer with any set of delta-connected windings will fall in the class of dependent-core transformers.

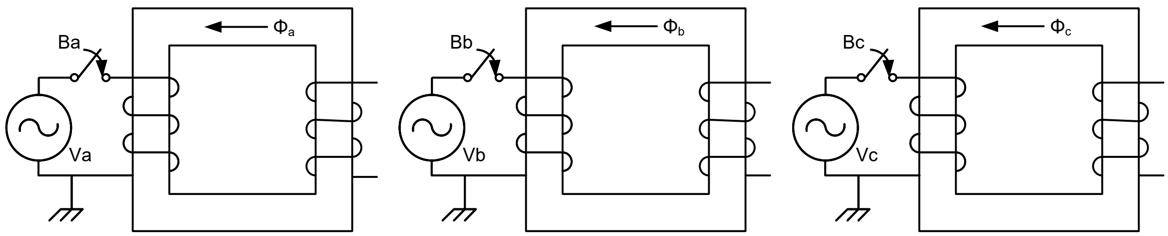

Fig. 17. Three-phase transformers with magnetically independent cores

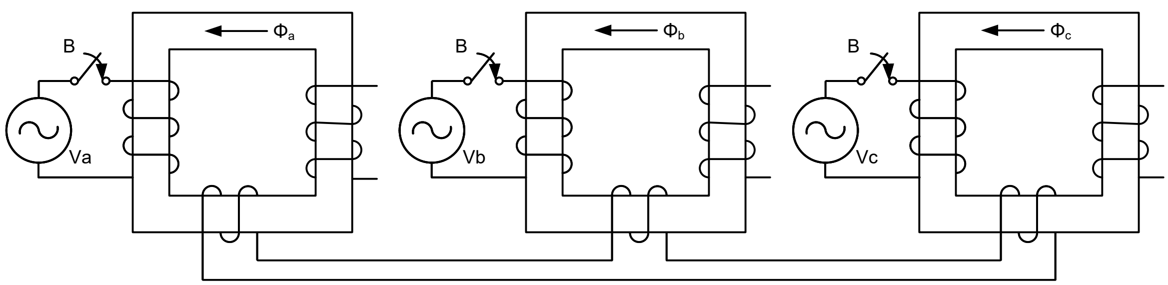

Fig. 18. Single-phase transformers with delta-connected tertiary windings

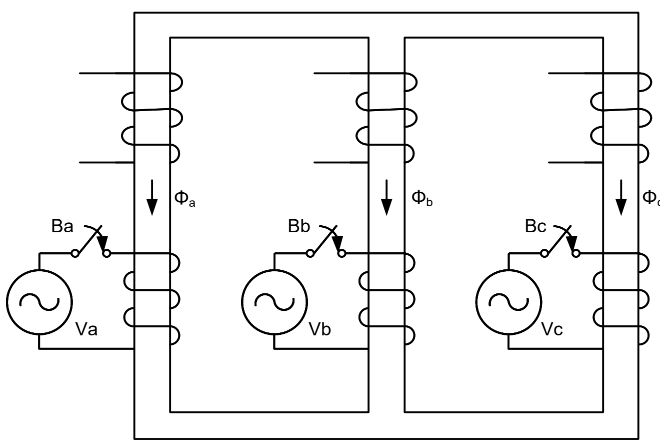

Fig. 19. Three-phase, three-legged core transformer

C. *Case of Three-Phase Transformers With Magnetically Independent Cores*

The strategy for controlled closing on three-phase transformers with magnetically independent cores is straightforward because each phase is a single-phase transformer. The strategy consists of the following steps:

- Calculate the residual flux in each magnetic core on a per-phase basis following the opening.
- Calculate TCpow for each phase, following (20).
- Close each phase circuit breaker pole independently, following the calculated TCpow measurements. Assume TCdel for each phase is equal to zero.

This strategy is shown in Table II. Practically, there is only one transformer configuration that leads to magnetically independent cores: single-phase transformers with wye-grounded connection at both the primary and the secondary winding.

D. *Case of Three-Phase Transformers With Magnetically Dependent Cores*

Two situations must be addressed with magnetically dependent cores:

- Three-phase transformers with wye-grounded connected primary windings.
- Three-phase transformers with wye-floating or delta-connected primary windings.

In both situations, the delayed closing strategy has been commonly applied. It is described in the next subsection.

E. *Delayed Closing Strategy for Energizing Three-Phase Transformers*

The delayed strategy to energize three-phase transformers with magnetically dependent cores has been defined by Dr. John H. Brunke in [6]. This strategy has been practically universally applied since it was defined [8] [11] [13]. It consists of the following steps:

- Close the phase with the maximum residual flux at the optimal calculated point-on-wave angle following (20). After a delay of *N* half-cycles, the residual fluxes in the two other phases will disappear and a steady state corresponding to the prospective fluxes is reached.
- The optimal time for closing the two remaining phases corresponds to the instant when their fluxes are equal. This leads to the optimal closing time when the voltage of the first closed phase is zero. Note that at this instant, the sum of the fluxes in the two remaining phases is equal and opposite to the flux of the phase that has been closed first.

Theoretically, any phase, irrespective of its residual flux, could be closed first. The advantage of closing on the phase with the highest residual flux is to reduce the dielectric stress because the circuit breaker pole is closed at a lower voltage.

1) Application to Three-Phase Transformers With Wye-Grounded Primary Windings

When closing on three-phase transformers with wye-grounded primary windings, delayed closing can be applied. Delayed closing involves the following steps:

- Calculate the residual flux in each phase magnetic core following the opening operation.
- Select the phase with the maximum residual flux and pick out the three TCpow and three TCdel measurements as indicated in Table III.

In Table III, we assume Phase A has the maximum calculated residual flux. We start by closing the Phase A pole with the calculated TCpow.a with no delay so that TCdel.a is shown to be zero. Phases B and C must then be closed simultaneously with a delay when their respective fluxes will be equal. With an ABC phase rotation, the instant when the two fluxes will be equal in Phases B and C corresponds to the instant when the voltage point-on-wave angles are respectively 60° and 300°. These are the two numbers shown in Table III. Because the two Phase B and C poles must be closed with a delay, TCdel.b and TCdel.c are shown to be a multiple *N* of half-cycles. *N* is supposed to be selected so that after the delay, the transient fluxes in the magnetic cores will have faded away and steady state has been reached.

The rationale for closing Phase B or C first in Table III is the same as the one for closing Phase A first.

2) Application to Three-Phase Transformers With Wye-Floating or Delta-Connected Primary Windings

The strategy for closing on transformers with wye-floating or delta-connected (see Fig. 20) primary windings is summarized in Table IV and is also an application of the delayed closing principle. Here, we cannot start by closing a single phase because no current will circulate and no flux will be created. We must start by closing two phases simultaneously. The corresponding residual flux must be calculated for the corresponding phase-to-phase voltages. As an example, the residual flux with respect to Phases A and B must be calculated as:

$$\varphi_{residual.ab} = \int_{t=0}^{t=t_0} \left[v_a(t) - v_b(t) \right] \bullet dt \tag{26}$$

Applying (20), we get the point-on-wave switching angle with respect to the differential Phase A-B:

$$\text{TCpow.ab} = \arccos\left(\frac{\phi_{residual.ab}}{-\phi_{max.ab}} \right) \tag{27}$$

Reviewing Fig. 21, we can see that an angle of –30° has to be added to TCpow.ab in order to get the switching angle with respect to Phase A:

$$\text{TCpow.a} = \text{TCpow.ab} - 30° \tag{28}$$

TABLE II
OPTIMUM TCPOW CLOSING INSTANTS FOR TRANSFORMERS WITH INDEPENDENT CORES

Configuration	TCpow.a	TCpow.b	TCpow.c	TCdel.a	TCdel.b	TCdel.c
Yg-Yg (independent)	$\arccos\left(\frac{\phi_{residual.a}}{-\phi_{max.a}}\right)$	$\arccos\left(\frac{\phi_{residual.b}}{-\phi_{max.b}}\right)$	$\arccos\left(\frac{\phi_{residual.c}}{-\phi_{max.c}}\right)$	0	0	0

TABLE III
OPTIMAL TCPOW CLOSING ANGLE WHEN CLOSING OF WYE-GROUNDED TRANSFORMERS

	Maximum Flux	TCpow.a	TCpow.b	TCpow.c	TCdel.a	TCdel.b	TCdel.c
1	A	$\arccos\left(\frac{\phi_{residual.a}}{-\phi_{max.a}}\right)$	60°	300°	0	0.5 • N	0.5 • N
2	B	300°	$\arccos\left(\frac{\phi_{residual.b}}{-\phi_{max.b}}\right)$	60°	0.5 • N	0	0.5 • N
3	C	240°	120°	$\arccos\left(\frac{\phi_{residual.c}}{-\phi_{max.c}}\right)$	0.5 • N	0.5 • N	0

TABLE IV
OPTIMAL CLOSING TCPOW WHEN CLOSING ON WYE-FLOATING OR DELTA-CONNECTED TRANSFORMERS

	Maximum Flux	TCpow.a	TCpow.b	TCpow.c	TCdel.a	TCdel.b	TCdel.c
1	A-B	$\arccos\left(\frac{\phi_{residual.ab}}{-\phi_{max.ab}}\right) + \text{DCCA}$	TCpow.a – 120°	270° (TCpow.a ≤ 150°) 90° (TCpow.a > 150°)	0	0	0.5 • N
2	B-C	270°	$\arccos\left(\frac{\phi_{residual.bc}}{-\phi_{max.bc}}\right) + \text{DCCA}$	TCpow.b – 120°	0.5 • N	0	0
3	C-A	TCpow.c + 240°	270°	$\arccos\left(\frac{\phi_{residual.ca}}{-\phi_{max.ca}}\right) + \text{DCCA}$	0	0.5 • N	0

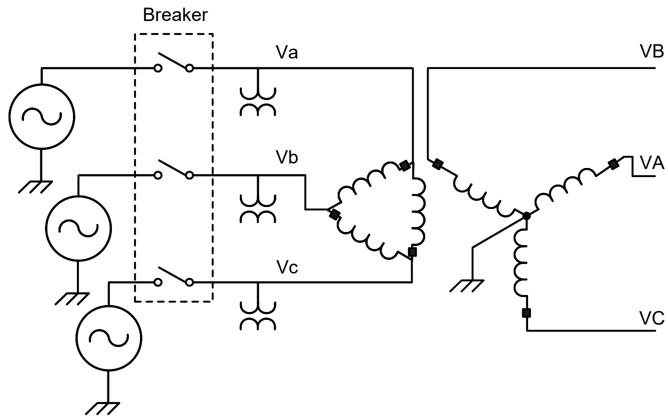

Fig. 20. Delta-connected windings in the primary with wye-grounded-connected windings in the secondary

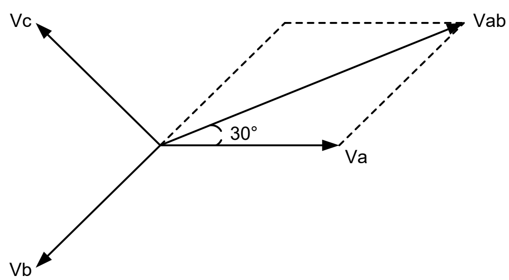

Fig. 21. Angle correction between delta and wye connection

Following the nomenclature shown in Table IV, we define a delta connection compensating angle (DCCA) so that in this case DCCA is equal to –30°:

$$TCpow.a = TCpow.ab + DCCA \quad (29)$$

As for Table III, after the three differential residual fluxes have been calculated, we must select the one with maximum value.

F. *Case of Three-Phase Transformers With No Residual Flux*

Irrespective of whether the cores are magnetically independent or not, and irrespective of the primary connection windings, the optimum closing angle when closing on a three-phase transformer with zero residual flux can be derived from Table II, Table III, and Table IV by systematically setting the calculated optimum closing angle TCpow to 90 or 270° when required because the residual flux is zero. The results are shown in Table V. As an example, Line 1 of Table V corresponds to the magnetically independent cores of Table II where TCpow.a and TCpow.b are set to 90° and TCpow.c is set to 270°. In another example, Line 2 of Table V corresponds to Table III where Phase A arbitrarily has the maximum flux and therefore TCpow.a is set to 90°. All the other settings in Table III, i.e., TCpow.b, TCpow.c, TCdel.a, TCdel.b, and TCdel.c, have not been changed.

VI. Controlled Closing Strategies for Capacitor Banks and Shunt Reactors

Controlled closing strategies for shunt capacitors and reactors have been addressed in [4] and are summarized in Table VI.

For wye-grounded shunt capacitors, TCpow is 0° or 180°, as indicated in Table VI. For a wye-floating or delta arrangement, closing must first be done on two phases simultaneously so that the voltage across the selected phases is zero at the closing instant. In Table VI, closing is done first on Phases A and C when the voltage across the two phases is zero, corresponding to TCpow.a = 30° and TCpow.c = 150°. Once Phases A and C are closed, the voltage on the capacitor bank side of the Phase B circuit breaker floats at a value of 0.5 • (VA + VC). This voltage has the opposite polarity of VB, and the circuit breaker can hence be closed when VB is at a zero crossing. Phase B is then closed at TCpow.b = 0°.

Controlled closing of shunt reactors is similar to controlled closing on transformers. Assuming that the phase reactor magnetic circuits are independent, assuming zero residual flux and a wye-grounded arrangement, the strategy is provided on the third line of Table VI. TCpow for all phases is 90° or 270°. The strategy is identical to Line 1 of Table V for a transformer with zero residual flux. If shunt reactors are wye-grounded, the magnetic circuits are dependent, and assuming again zero residual flux, the strategy is the same as for transformers and provided by Line 2 of Table V.

Table V
Optimum TCpow Closing Instants For Transformers With Zero Residual Flux

	Configuration	TCpow.a	TCpow.b	TCpow.c	TCdel.a	TCdel.b	TCdel.c
1	Yg-Yg (independent)	90°	90°	270°	0	0	0
2	Yg* (dependent)	90°	60°	300°	0	0.5 • N	0.5 • N
3	Y*, D*	60°	300°	270°	0	0	0.5 • N

* Primary arrangement, irrespective of the secondary or tertiary configuration.

Table VI
Optimum TCpow Closing Instants for Capacitors and Reactors

	Equipment	Configuration	TCpow.a	TCpow.b	TCpow.c	TCdel.a	TCdel.b	TCdel.c
1	Shunt capacitors	Yg	0°	0°	180°	0	0	0
2	Shunt capacitors	Y, D	30°	0°	150°	0	0	0
3	Reactors (independent)	Yg	90°	90°	270°	0	0	0
4	Reactors	Y, D	60°	300°	270°	0	0	0.5 • N

For shunt reactors with a wye-floating or delta arrangement and still zero residual flux, the strategy consists of applying the delayed closing strategy for transformers because the magnetic circuits are no longer independent. As shown on Line 4 of Table VI, Phases A and B must be closed at the instants when the Phase A-B voltage is at its maximum. Phase C is then closed with a delay. This strategy is identical to Line 3 of Table V and applicable to transformers with zero flux.

In the preceding cases, zero residual flux has been assumed. If, exceptionally, shunt reactors with residual flux do exist, the same strategies defined in Table II, Table III, and Table IV are applicable, depending on the configuration.

VII. Example of Transformer Delayed Closing Strategy Simulation in EMTP Software

The single-phase transformer in Fig. 7 was used to build a three-phase transformer with wye-grounded connected windings in the primary and delta-connected windings in the secondary, as shown in Fig. 22.

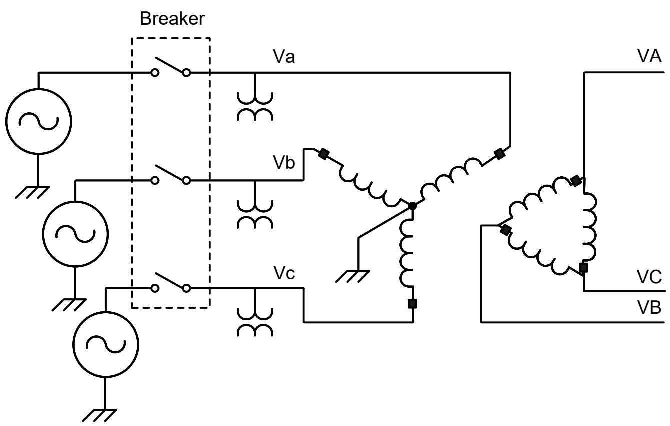

Fig. 22. Wye-grounded windings in the primary with delta-connected windings in the secondary

In order to implement controlled closing, the strategy of Table III was applied. The circuit breaker was opened at 42 ms. Following the circuit breaker opening, the phase with the highest flux must be determined. Fig. 23 shows the primary phase fluxes. Obviously, Phase B has the highest residual flux. The optimum closing angle for Phase B is calculated as:

$$\text{TCpow.b} = \arccos\left(\frac{\phi_{\text{residual.b}}}{-\phi_{\text{max.b}}}\right) = \arccos\left(\frac{410.7}{-448.35}\right) = 156.35° \quad (30)$$

Following the indications of Table III, controlled closing will be accomplished with the following settings:

$$\begin{array}{lll} \text{TClose.a} = 0 \text{ ms} & \text{TClose.b} = 0 \text{ ms} & \text{TClose.c} = 0 \text{ ms} \\ \text{TCpow.a} = 300° & \text{TCpow.b} = 156.35° & \text{TCpow.c} = 60° \\ \text{TCarc.a} = 0° & \text{TCarc.b} = 0° & \text{TCarc.c} = 0° \\ \text{TCdel.a} = 3 \text{ cyc.} & \text{TCdel.b} = 0 \text{ cyc.} & \text{TCdel.c} = 3 \text{ cyc.} \end{array} \quad (31)$$

In (31), all closing times are set to 0 ms because we are using an ideal EMTP switch in the simulation, and all three TCarc settings have been set to 0 cycles. TCdel.a and TCdel.c have been set to 3 cycles.

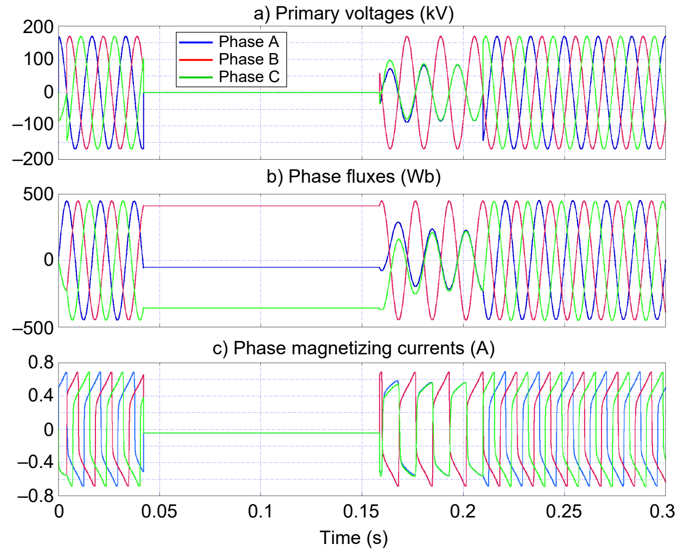

Fig. 23. Phase primary voltages, fluxes, and magnetizing currents during controlled closing

Following the controlled closing, the phase fluxes and magnetizing currents are shown in Fig. 23b and Fig. 23c, respectively. Examining Fig. 23b and Fig. 23c, we can see that inrush currents have been eliminated.

Fig. 24b and Fig. 24c show the phase fluxes and magnetizing currents, respectively, following a random closing operation. Inrush currents are now in the order of a few thousand amperes for Phase B in particular.

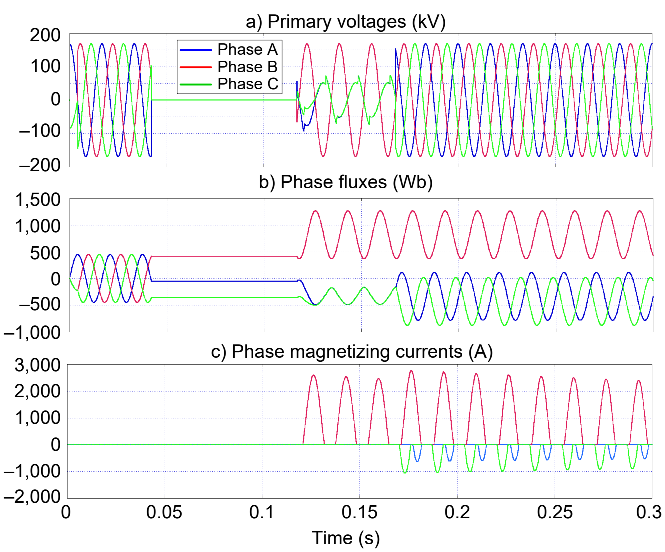

Fig. 24. Phase primary voltages, fluxes, and magnetizing currents during random closing

VIII. Controlled Closing Strategies for Transmission Lines

As discussed in Section III, Subsection D, the goal of controlled closing on unloaded transmission lines is to minimize the voltage impressed across the circuit breaker contacts immediately before the closing instant. The circuit breaker voltage difference just prior to the energizing instant serves as the source of the voltage traveling wave that propagates down the transmission line via the distributed inductance and capacitance of the line. When this voltage traveling wave reaches the open circuit at the remote end of the line, the voltage wave is fully reflected, resulting in a voltage doubling effect. The worst-case closing instant occurs when trapped charge on the transmission line leads to a dc line voltage magnitude of 1 pu and the circuit breaker is closed at the instant the voltage magnitude of the source behind the circuit breaker is 1 pu with the opposite polarity of the line voltage. These conditions can result in a voltage traveling wave of 2 pu, and the remote line end could theoretically experience an overvoltage of 4 pu. Clearly, severe overvoltages can result in damage to equipment subjected to this abnormal condition.

We illustrate the difference between controlled and uncontrolled switching using the simulation of an unloaded transmission line with trapped charge during a single-phase high-speed reclosing event. The system is represented in Fig. 25. The Phase A pole is opened at a negative voltage minimum. In order to implement high-speed reclosing while also reducing the transient overvoltage, the Phase A pole should be closed when the source voltage is at a negative minimum.

Therefore, the simulated controlled closing should have the following settings:

$$\begin{aligned} \text{TClose.a} &= 0 \text{ ms} \\ \text{TCpow.a} &= 270° \\ \text{TCarc.a} &= 0° \\ \text{TCdel.a} &= 0 \text{ cyc.} \end{aligned} \tag{32}$$

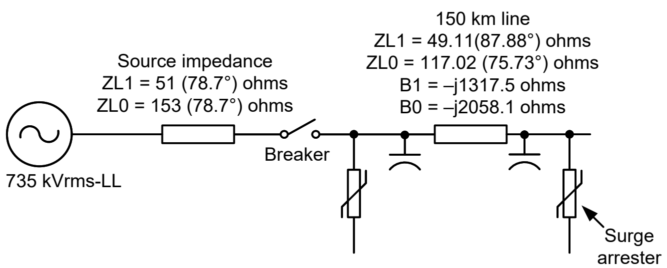

Fig. 25. 735 kV transmission line

Fig. 26 represents the controlled closing simulation results. The source end (left-side) Phase A line voltage plot is shown in Fig. 26a. The open-circuited remote end (right-side) Phase A line voltage plot is shown in Fig. 26b. The 60 Hz voltage oscillations on Phase A, present at both line terminals during the pole-open period, are due to the Phase B and C coupling. Currents through the left- and right-side line surge arresters are shown in Fig. 26c and Fig. 26d, respectively. From these plots, we can infer that traveling-wave line overvoltages are well controlled and at a minimum. The surge arrester conducts a minor amount of current due to the slight overvoltage experienced by Phase A during the pole-open period caused by the coupling of Phases B and C.

Fig. 27 represents the random closing simulation results with the closing at a worst-case scenario corresponding to a source voltage positive peak. The resulting plots in Fig. 27 are in the same order as in Fig. 26. From Fig. 27a and Fig. 27b, we can infer that line traveling-wave overvoltages at both line terminals are significant and force the surge arresters into full conduction, as shown in Fig. 27c and Fig. 27d. Comparing the left and right surge arrester conduction levels, we can see that the right-hand line terminal (open circuit) has more than double the conduction level than the left-hand line terminal, indicating the more severe overvoltage, as expected.

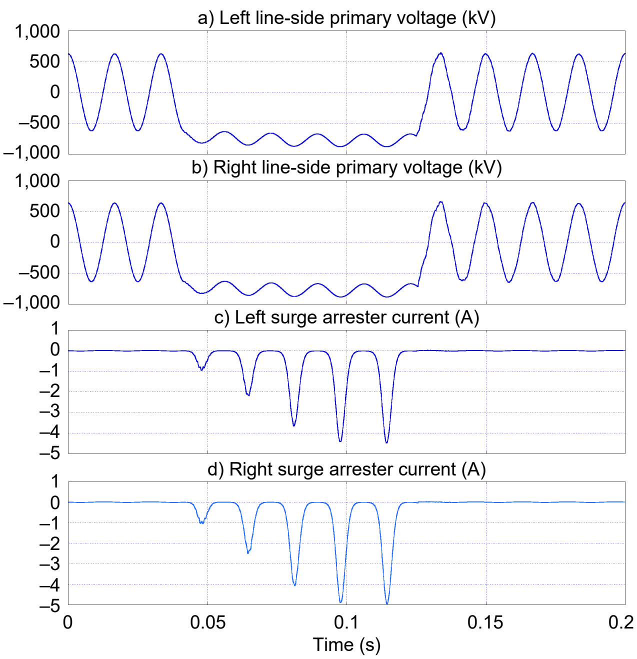

Fig. 26. Controlled closing on transmission line with trapped charge

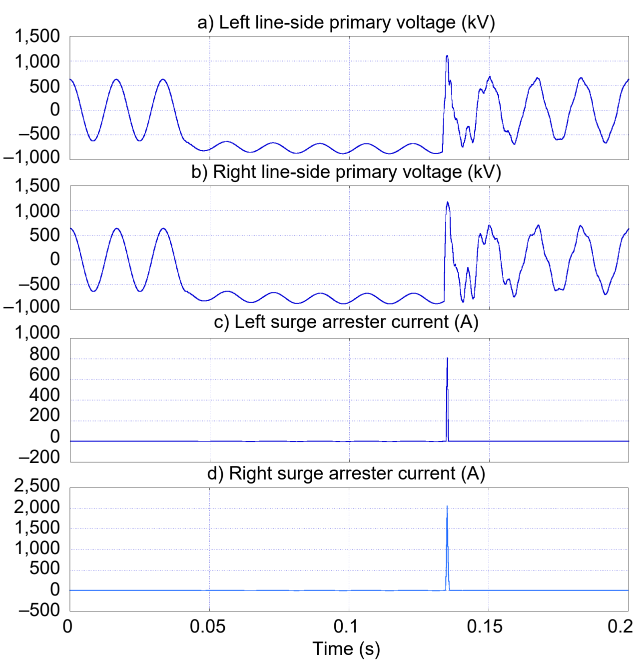

Fig. 27. Random closing on transmission line with trapped charge

A real-life situation bearing some resemblance to the example is provided in [9]; high-speed reclosing was performed on a 345 kV transmission line connected at one extremity to a busbar with a surge arrester connected. Following the overvoltage at the line terminal caused by the random switching during the reclosing operation, the surge arrester was forced into conduction. The current-based differential relay protecting the busbar saw the current flowing into the surge arrester as an internal fault and misoperated.

The difficulty of precise controlled closing of transmission lines lies in correctly predicting the dc voltage of the line just prior to the instant of line energization. In cases of trapped charge, the trapped charge can decay over time and the rate is dependent on several factors [15]. With shunt reactors, the line voltage will experience a natural resonance once the circuit breaker poles open and will be very difficult to predict correctly. Because of these challenges, one utility's approach to controlled line energization assumes each phase has zero trapped charge and energizes the phases at consecutive voltage zero crossings [4]. Without knowledge of the trapped charge on the line, this strategy provides for optimal line energization performance by limiting the voltage difference across the circuit breaker when considering all possible values of the dc line voltage.

IX. Controlled Opening Fundamental Principles

During an opening operation, following the pole contact mechanical separation, an arc will be present across the two contact sides until it extinguishes itself when the current flowing through the pole reaches zero.

The main purpose of circuit breaker controlled opening is to avoid reignition that could be damaging to both the circuit breaker and the equipment because of the overvoltages associated with this condition [1] [2]. This is particularly true when de-energizing shunt reactors. Because the voltage is leading the current by close to 90°, if the two sides of the pole contact were to depart when the current is close to zero, a voltage maximum will be impressed on the pole contact when the distance is at a minimum. It is desirable therefore, to avoid this situation, that the contact separation occurs before the current reaches zero. As shown in Fig. 28, a minimum arcing time, Tamin, must be allowed before the arc extinction at current zero so that reignition will be avoided for most circuit breakers. This dictates that the pole opening must occur inside the zone defined as a reignition-free window in the figure. By taking the current through the equipment as the reference signal, controlled opening allows imposing the contact separation at a predefined current point-on-wave angle.

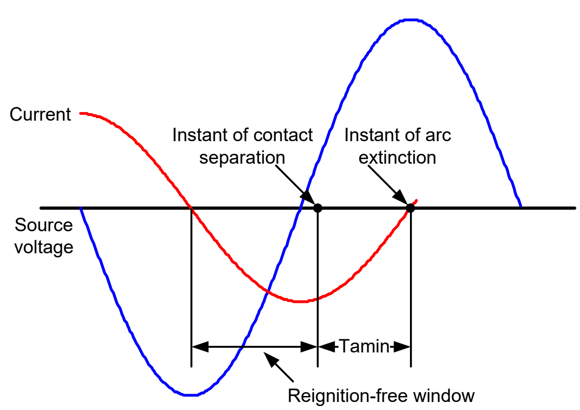

Fig. 28. Principle of minimum arcing time

A. *Circuit Breaker Pole Average Opening Time*

The average circuit breaker pole opening time, or TOpen in this paper, is the time interval between the instant when the voltage step is applied on the pole opening coil and the instant when the two sides of the pole contact mechanically depart.

As for the circuit breaker pole closing time and in order to avoid any arcing influence, the circuit breaker pole opening time is measured with the circuit breaker disconnected from the network. Typically, the opening time is measured between the instant the voltage step is applied to the opening coil and the contact resistance goes to infinity.

B. *Factors Impacting the Opening Time*

In operation, the actual opening time, TOpen, is expected to deviate from the ideal nominal operating time $TOpen_{NOM}$. The same five factors that impact the value of the nominal closing time, $TClose_{NOM}$, will impact the nominal opening time, $TOpen_{NOM}$.

1) *Environmental Factor Impacts*

As done with (1) for the closing time, the compensated opening time adjusts for the impact of the ambient temperature, the opening coil supply voltage, and any circuit breaker pole actuating principle pressure measurement. Compensated opening time can be expressed as:

$$TOpen = TOpen_{NOM} + \Delta TO_{TEMP} + \Delta TO_{SV} + \Delta TO_{PRES} \quad (33)$$

The same techniques used for storing the compensating curves described for the closing time can be equally used for opening time.

2) *Historical Factor Impacts*

Using the same principle of calculating operational drift as the one expressed in (2), compensation based on the previous opening operations can be implemented as the weighted deviation between expected and actual opening times using (34):

$$\Delta TO_{PREV} = \sum_{n=1}^{N} w(n) \cdot \left[TOpen_{meas}(n) - TOpen(n)\right] \quad (34)$$

As in (3) used for closing, the idle time compensation for the opening operations can be implemented as a function of the time spent idle using (35):

$$\Delta TO_{IDLE} = f(T_{IDLE}) \quad (35)$$

After the five compensations have been evaluated, the final opening time will be equal to the nominal opening time adjusted by the compensations:

$$TOpen = TOpen_{NOM} + \Delta TO_{TEMP} + \Delta TO_{SV} + \Delta TO_{PRES} + \ldots \quad \Delta TO_{PREV} + \Delta TO_{IDLE} \quad (36)$$

C. *Single-Phase Controlled Opening*

Controlled opening consists of triggering the pole contact separation at a desired reference current point-on-wave angle. If this angle is sufficiently far from the next zero crossing, the contact dielectric strength will be high enough when the arc extinguishes that the possibility of restrike or reignition will be minimal.

Taking into account the circuit breaker pole opening time, controlled opening consists of applying the voltage step on the opening coil so that the pole mechanical break will occur at a set angle of the reference current. In this paper, this set angle is called TOarc. Following the mechanical break, the ensuing arc will extinguish itself at the next reference current zero crossing.

Looking at Fig. 29, the integral number of reference current cycles to implement the opening operation is computed as:

$$\mathrm{NOcyc} = \mathrm{ceil}(\mathrm{TOpen} + \mathrm{TOarc}) \tag{37}$$

In (37), TOpen and TOarc are two introduced settings.

Once NOcyc has been determined, and assuming the opening operation starts at a positive zero crossing of the reference current, we must wait an interval of time (TOwait) before the voltage step is applied to the opening coil. TOwait is computed as:

$$\mathrm{TOwait} = \mathrm{NOcyc} - \mathrm{TOpen} - \mathrm{TOarc} \tag{38}$$

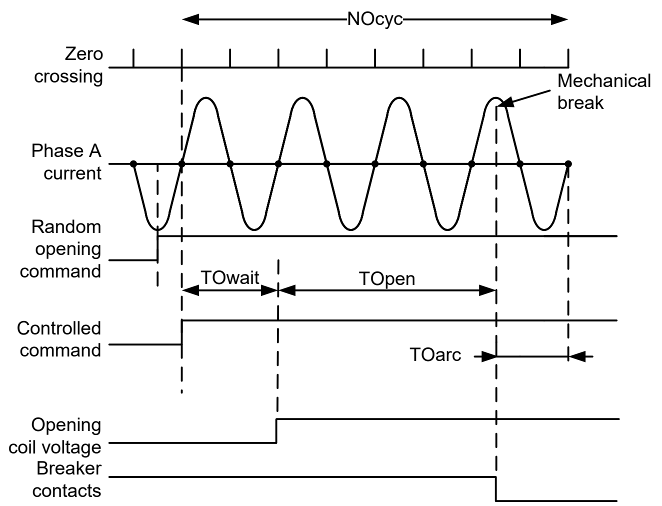

Fig. 29. Single-phase controlled opening timing principles

D. *Three-Phase Controlled Opening*

As has been done for three-phase controlled closing, the principles for single-phase opening introduced in the previous paragraph can be extended to three-phase opening by applying the same procedure: selecting a single timing reference that will be applied to all three phases. We define TOwait.a/A as the waiting time for Phase A with the time reference being fixed with respect to Phase A itself. We define TOwait.b/A as the waiting time for Phase B with the timing reference belonging to Phase A. Note that the timing reference does not necessarily have to be a zero crossing. Assuming the timing reference belongs to Phase A, and assuming an ABC phase rotation, three-phase controlled closing can be implemented by computing the next three waiting times as follows:

$$\begin{aligned}&\mathrm{TOwait.a/A}\\&\mathrm{TOwait.b/A} = \mathrm{TOwait.b/B} + 1/3\\&\mathrm{TOwait.c/A} = \mathrm{TOwait.c/C} + 2/3\end{aligned} \tag{39}$$

Equation (38) allows computing TOwait.a/A, TOwait.b/B, and TOwait.c/C because each of the three phases is considered independent. Three-phase controlled opening is implemented by applying (38) to calculate the three self-referenced waiting times and an equivalent to (39), depending on the selection of a common timing reference point. Equation (39) is directly applicable if the common reference point is the Phase A current positive zero crossing.

E. *Controlled Opening Strategies*

Table VII presents a set of TOarc settings for different power equipment applied by a major North American utility [4].

Looking at Fig. 29, note that the convention in this paper is that the origin for the measurement of TOarc is the second positive zero crossing of the reference current last cycle and the measurement is positive going to the left direction.

TABLE VII
OPTIMUM TOARC OPENING ANGLE

Equipment	**Configuration**	**TOarc.a**	**TOarc.b**	**TOarc.c**
Shunt capacitors	Yg	270°	270°	90°
Shunt capacitors	Y, D	270°	300°	60°
Reactors	Yg	270°	270°	90°
Reactors	Y, D	270°	300°	60°
Transformers	Yg-Yg	270°	270°	90°
Transformers	Yg	270°	270°	90°
Transformers	Y, D	270°	300°	60°

X. CONCLUSION

The stability of circuit breaker characteristics over time allows implementation of controlled switching of power equipment. Controlled switching of power equipment is best implemented with independent pole operation circuit breakers.

The variation of circuit breaker closing and opening times with environmental parameters (ambient temperature, coil supply voltage, and pressure of actuating device) can be compensated for the use of stored tables or mathematical functions of these variations. Similar corrections exist for compensation based on previous operations and idle time compensation.

The controlled closing of power equipment can eliminate or reduce undesirable voltage or current transients otherwise present during a random closing operation. It improves power quality, helps in protecting the equipment, and improves protective relay reliability.

The controlled opening of power equipment allows the elimination of destructive circuit breaker restrike or reignition.

Controlled closing on transformers can be made systematic for any transformer configuration using four closing settings for each of the three phases. It necessitates the determination of the residual flux in each of the three phases following an opening operation. Grading capacitors are adding a complication to this calculation because the integration of the phase voltages could have to be extended in time following the circuit breaker poles opening.

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XII. Biographies

Gabriel Benmouyal, P.E., received his BASc in electrical engineering and his MASc in control engineering from Ecole Polytechnique, Université de Montréal, Canada. In 1978, he joined IREQ, where his main fields of activity were the application of microprocessors and digital techniques for substations and generating station control and protection systems. In 1997, he joined Schweitzer Engineering Laboratories, Inc. as a principal research engineer. Gabriel is a registered professional engineer in the Province of Québec and an IEEE senior member and has served on the Power System Relaying Committee since May 1989. He holds more than six patents and is the author or coauthor of several papers in the fields of signal processing and power network protection and control.

Normann Fischer received a Higher Diploma in Technology, with honors, from Technikon Witwatersrand, Johannesburg, South Africa, in 1988; a BSEE, with honors, from the University of Cape Town in 1993; a MSEE from the University of Idaho in 2005; and a PhD from the University of Idaho in 2014. He joined Eskom as a protection technician in 1984 and was a senior design engineer in the Eskom protection design department for three years. He then joined IST Energy as a senior design engineer in 1996. In 1999, Normann joined Schweitzer Engineering Laboratories, Inc., where he is currently a fellow engineer in the research and development division. He was a registered professional engineer in South Africa and a member of the South African Institute of Electrical Engineers. He is currently a senior member of IEEE and a member of the American Society for Engineering Education (ASEE).

Douglas Taylor received his BSEE and MSEE degrees from the University of Idaho in 2007 and 2009, respectively. Since 2009, he has worked at Schweitzer Engineering Laboratories, Inc. and currently is a lead research engineer in the research and development division. Mr. Taylor is a registered professional engineer in the state of Washington and is a member of IEEE. His main interests are power system protection and power system analysis. He is the author of several technical papers and holds one patent.

Mark Talbott-Williams received his BSEE from Washington State University in 2014. He joined Schweitzer Engineering Laboratories, Inc. in 2014 and holds the position of power engineer in the research and development division. He is a member of IEEE.

Ritwik Chowdhury received his bachelor of engineering degree from the University of British Columbia and his master of engineering degree from the University of Toronto. He joined Schweitzer Engineering Laboratories, Inc. in 2012, where he has served as an application engineer and presently works as a research engineer. He has authored several technical papers on power system protection and control. His interests include the analysis and control of generators and their systems, controlled switching, and generator and line protection. He is a member of IEEE.

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