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Experiences and Actual Research in Controlled Unloaded Transformer Switching

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Abstract: Electricity market liberalization, electricity industry deregulation, new/distributed energy sources and emerging technologies as a "Smart Grid" will increase the amount of switching situations. A random, unloaded transformer energization leads to high inrush currents and voltage disturbances, which can cause unnecessary operations of protection relays and impose mechanical stresses to the transformer windings. Situations have been reported, whereby intensive and repetitive inrush currents even caused a thermal explosion of a power transformer. A conventional solution for these issues it to apply a pre-insertion resistor. However, the application of a pre-insertion resistor and especially its maintenance are cost intensive and therefore, investigations on controlled transformer switching have been done taking into account the residual flux that remains within the transformer core after an unloaded transformer de-energization. First field experiences could be obtained in the year 2004/2005. This paper shows state of the art techniques of actual controller systems and proposes new research items.

Keywords: Unloaded transformer, Controlled switching, CSS, Residual flux, Grading capacitor, Inrush currents, Switching strategies

1. Introduction

Global changes resulting from factors such as electricity market liberalization, electricity industry deregulation, new/distributed energy sources and emerging technologies as a "Smart Grid" will increase the amount of switching situations. Considering that life-cycle cost reduction of transmission and distribution systems is becoming increasingly important, phenomena as inrush currents and overvoltages based on random switching cases have to be prevented.

Controlled switching has become an economical substitute for a closing resistor[1] and is commonly applied to reduce switching surges. Main applications are shunt reactor switching, shunt capacitor switching, unloaded line energizations and unloaded transformer energizations – Compare **Fig. 1**. Currently, controlled switching is often specified for shunt capacitor and shunt reactor banks. It can provide several economical benefits such as the elimination of closing resistors and its extensive maintenance costs, [1]. In addition, it also provides various technical advantages such as an improved power quality and suppression of system transients in transmission and distribution systems. A controlled unloaded line energization reduces overvoltages by closing at the instant of the voltage minimum across the circuit breaker. Controlled switching of unloaded transformer system considers the residual flux remaining after a transformer de-energization in order to determine the optimal re-energization instant.

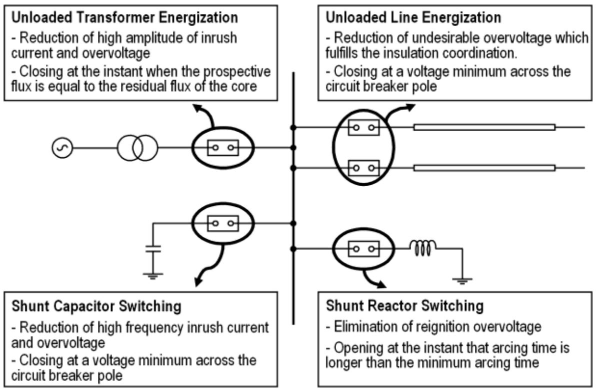

Fig. 1 Main applications for controlled switching systems (CSS).

2. Installation Records

According to the CIGRE surveys from the year 1989 to 2001 (**Fig. 2**), approximately 2,400 controlled switching systems (CSS) were supplied and installed around the world at the end of 2001. Considering a quadratic interpolation of these values, more than 6700 units are estimated to be in service in 2009. Before 1995, the number of installations was limited because of the technological immaturity. Since the late 1990's installations have rapidly increased, because effective

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compensation algorithms became available using advanced sensors and reliable digital relay technologies. In the year 2007, about 67% of the installations worldwide are applied to capacitor banks.

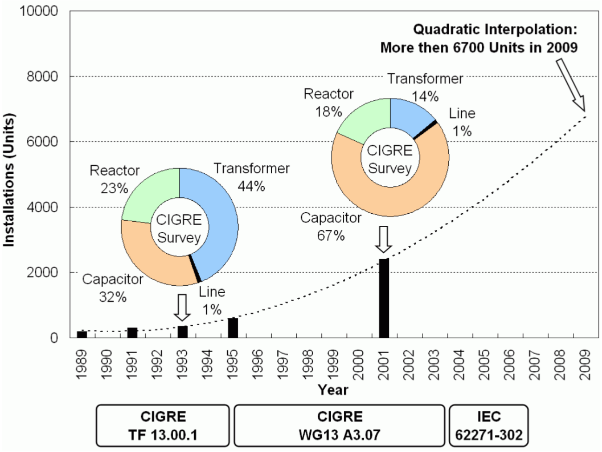


Fig. 2 Interpolation of CIGRE surveys on installation records of controlled switching in worldwide service.

Controlled switching has been less often applied on unloaded transformer systems, due to the unknown residual flux after a transformer de-energization, [2]. In 1999, the CIGRE working group 13.07 published an Electra article describing switching strategies for various transformers configurations, [3]. However the practical implementation of these strategies remained unexplained, because of the unknown residual flux approximation. An additional difficulty was the coupling between phases due to a transformer delta connection or a common magnetic core.

Subsequent studies found that the residual flux can be approximated by integrating the voltage at the transformer terminals, [4),5]. Furthermore, switching strategies for circuit breakers with independent pole operations (IPO) have been presented in [6),7]. In the same publications it was also noted that in most three-phase transformers, the sum of the residual flux values is almost zero. This is true for transformers with a three-legged core or a delta connection - Most power transformers contain at least one delta connection for the measurement of the applied voltage. In 2004, the CIGRE WG A3.07 summarized these research results and published an Electra article[8]. Since then, controller systems taking into the residual flux are being installed and the research is ongoing focusing on more specific items such as switching strategies for more special configurations of transformer/circuit breaker systems, on the residual flux approximation without a voltage measurement at the transformer terminal or on simulations of inrush currents and voltage disturbances.

3. Principle of a CSS

A CSS is typically composed of an independent pole operated circuit breaker and a controller with sensors that measure the system voltage, the current through the circuit breaker, the ambient temperature and the operating pressure of the drives.

The term CSS refers to the technique of controlling the timing of pre-strike (In case of a closing operation) or controlling the contact separation instant (For an opening operation) of each circuit breaker pole with respect to the phase angle of the system voltage or the system current.

A schematic timing sequence of a circuit breaker closing operation at a pre-determined phase angle is illustrated in **Fig.3**. The randomly issued closing command is delayed by an appropriate amount of time taking into account the calculated closing time for the next operation and the pre-arcing time in order to initiate the current at the targeted phase angle. The rate of decline of dielectric strength (RDDS) determines the making instant and depends on the circuit breaker performance. Temperature, control voltage and operating pressure determine the closing time.

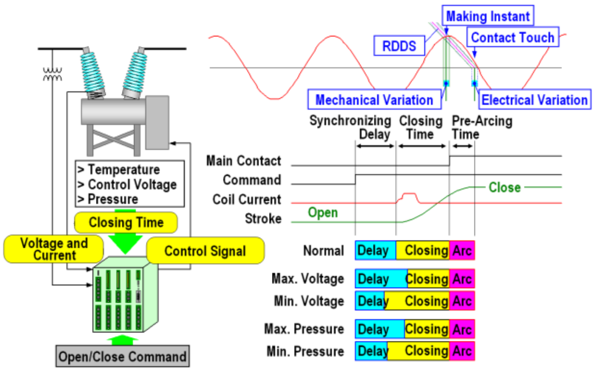


Fig. 3 A CSS controls the timing of pre-strike considering the switching circuit breaker's varied closing time.

4. Controlled Transformer Switching

The magnetic circuit of a power transformer can be described by a saturable core inductance. For reasons of economy, transformers are designed with an operational peak flux close to this saturation level, [3]. Considering that during an unloaded transformer energization the residual flux superimpose with the prospective flux

(Integral of the source voltage), the resulting "total" flux might go into the saturation region, which causes inrushes currents as it is shown schematically in the upper illustration of **Fig. 4**., [6),7)]. The magnitude of the appearing inrush currents depend on the saturation inductance, the "locked in" [8)] residual flux and the energization instant. The optimal energization instant is when the superimposition of the residual flux and the prospective flux remains within the unsaturated region of the transformer core inductance, which is the case when the energization instant is targeted at the crossing of the residual flux and the prospective flux - Compare the waveforms below in **Fig. 4**.

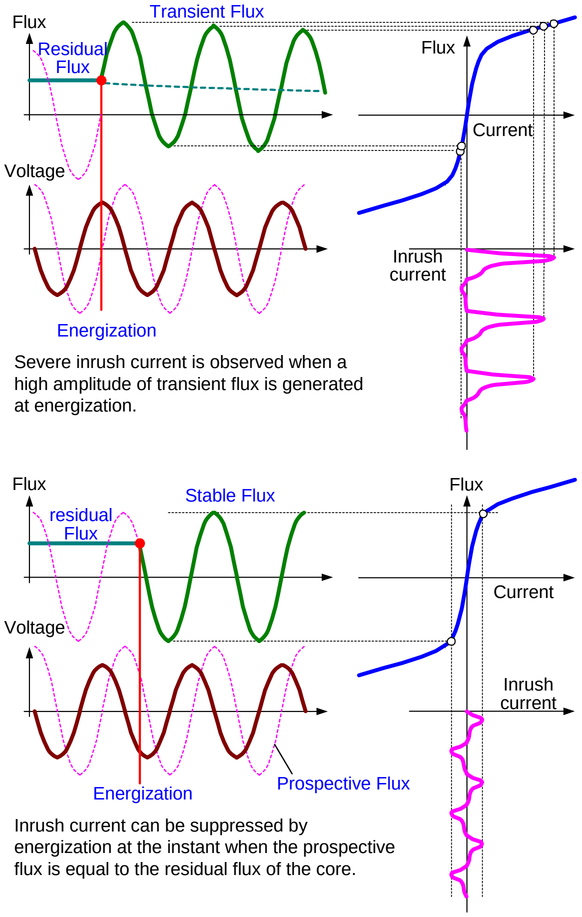


Fig. 4 The superimposition of the residual flux and the prospective flux can go in the saturated region of the transformer core inductance, causing inrush currents.

The described inrush currents can become several times larger then the rated transformer current, which mechanically stresses the transformer windings. Further, a voltage drop will be observable based on the asymmetric inrush currents. The voltage drop affects the operation of utility devices or results in unnecessary tripping of protection relays. Recently, load equipment such as power electronics and electronic equipment, which is sensitive to system voltage drops, has rapidly increased and therefore it is important to suppress these voltage drops in order to maintain and improve the system stability and power quality. An uncontrolled, random transformer energization can exceed a voltage drop of 10% based on inrush currents of several thousand amperes.

4.1 RDDS and Scattering

If the switching circuit breaker energizes an unloaded transformer system at the optimal energization target (Crossing of the residual flux and the prospective flux), no transient flux phenomenon occurs and no inrush current flows. However in an actual field situation, the ratio of decay of dielectric strength (RDDS) as well as the mechanical and electrical scattering have to be taken into account.

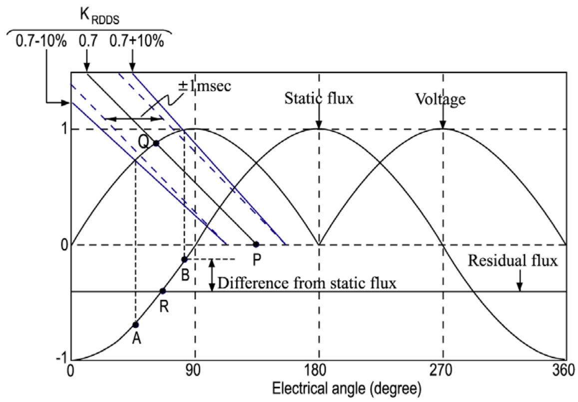


Fig. 5 In field, a circuit breaker's RDDS, mechanical and voltage scattering have to be taken into account.

Figure 5 shows how a circuit breaker's RDDS and scattering can be considered for evaluating the practical energization target based on the optimal target. A residual flux level of -0.4[p.u.] of the static flux peak is assumed and the optimal target lays at the instant R, which corresponds to the point Q within the voltage waveform across the circuit breaker (Pre-strike). From the point Q the RDDS line can be drawn crossing the voltage zero at the point P, which corresponds to mechanical contact closing instant. A mechanical scattering of ±1ms is illustrated (Dotted lines) and the electrical scattering of ±10% is shown. The scattering range describes how accurately an optimal target can be controlled. The maximal scattering corresponds to the points A and B in the static flux waveform. The difference of the residual flux from the static flux will determine the magnitude of inrush currents caused by scattering and therefore inrush currents can be more effectively suppressed by setting as a practical closing target the point when the maximally possible difference between static flux and residual flux becomes minimal within the scattering range. **Figure 6** is based on the waveforms in **Fig. 5** and shows the result of calculating the maximal difference between the static flux and the residual flux at every electric angle. The practical contact separation point P in **Fig. 6** is slightly shifted from the optimal contact separation point P in **Fig. 5**. This shift increases, the lower the RDDS value is and the larger the mechanical and electrical scattering becomes.

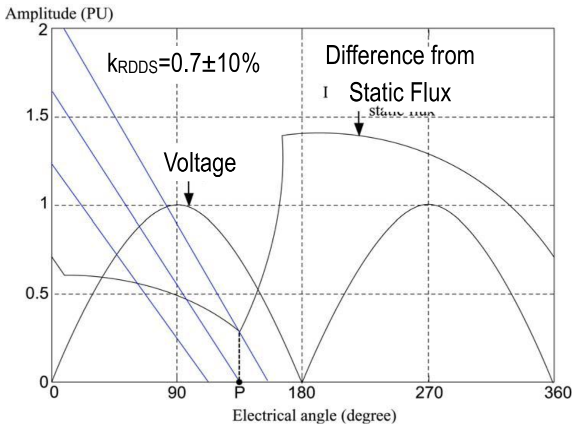


Fig. 6 The maximal difference of the residual flux from the static flux within the scattering range is illustrated based on the waveforms in **Fig. 5**.

4.2 Delayed IPO Switching Strategy

Most switching situations have a star-delta interconnected power transformer with ground connection at the transformer's star point. The delta connection influences the dynamic residual flux behavior after the energization of one phase and is typically applied, because most transformer systems contain at least one delta connection for measuring the transformer terminal voltage. The delayed IPO switching strategy[2),6),7),8)] considers the dynamic flux behavior of a star-delta interconnected transformer system applying the two energization targets as described below:

(1) The phase at which the residual flux is maximal (Phase U in **Fig. 7**) is first energized at the phase angle, when the residual flux meets the static flux.

(2) Because of the delta connection or a common core structure the remaining two phases V and W relax together, simultaneously crossing the static flux at the voltage zero crossing of the U phase, which is the second energization target.

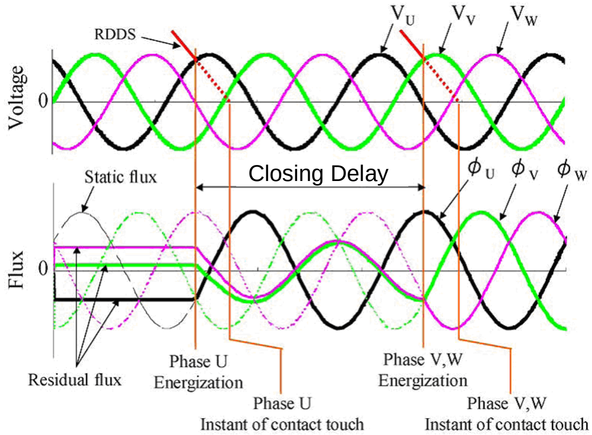


Fig. 7 The delayed IPO switching strategy is applied on star-delta interconnected transformer systems with ground connection. The strategy applies two targets.

4.3 Actual Field Application

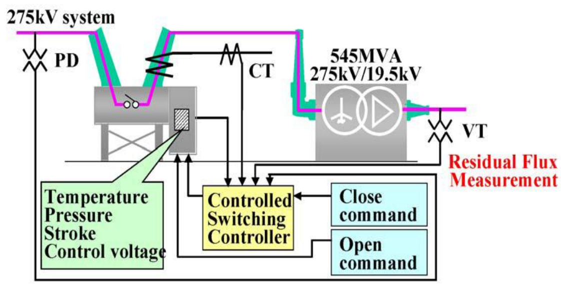


Fig. 8 Configuration of a CSS for an unloaded transformer/circuit breaker system (545MVA transformer, 275kV circuit breaker system), [9)].

Figure 8 shows the configuration diagram of a CSS applied to an extra high voltage power transformer taking into account the residual flux, [9)]. In this configuration, the transformer terminal voltage is measured with an inductive voltage transformer (VT) during the transformer de-energization for obtaining the residual flux based on the voltage integral - A maximal residual flux of approximately 40% was generated. As shown in **Fig. 9**, a random energization of the unloaded transformer system can lead to inrush currents of several thousand Amperes, which causes a voltage drop of 11.2%. Applying the switching strategy described in section 4.2, inrush currents and voltage disturbances can strongly be reduced (**Fig. 10**).

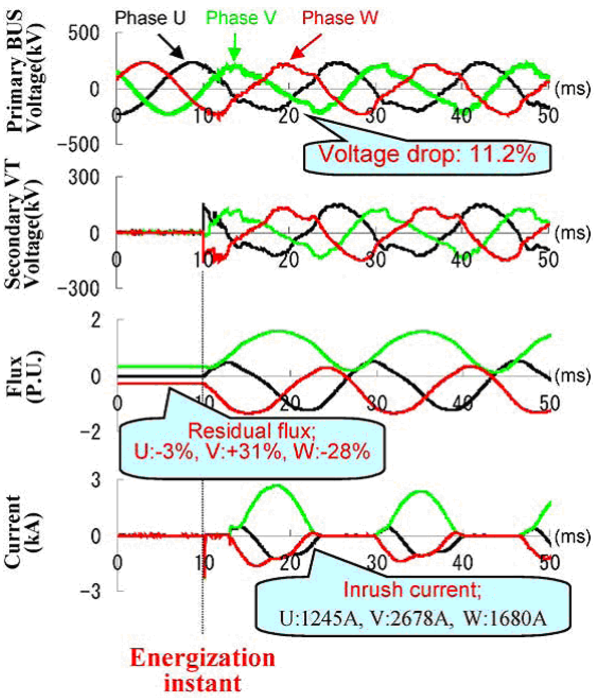


Fig. 9 Random energization of the unloaded 545MVA transformer in **Fig. 8**, [9].

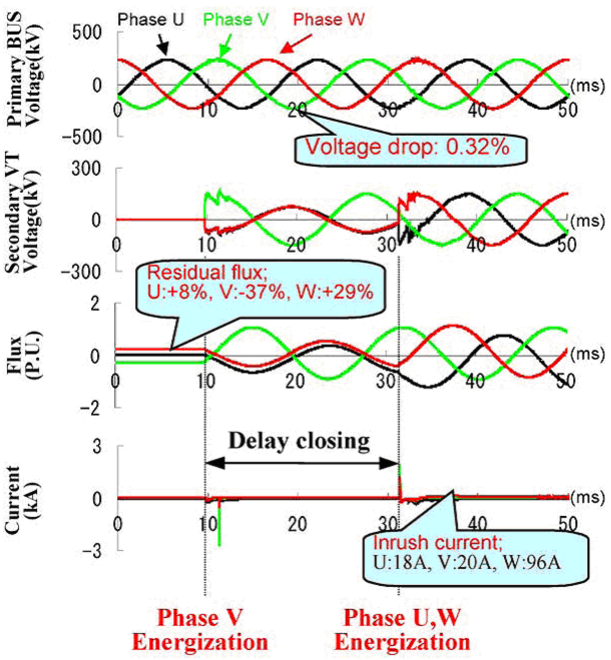


Fig. 10 Controlled energization (Delayed IPO strategy) of the unloaded 545MVA transformer in **Fig. 8**, [9].

The system has been operated in the field for half a year in order to evaluate its practical reliability: Voltage and current waveforms, circuit breaker operating conditions and the residual flux before each re-energization have been recorded and analyzed. **Figure 11** shows the resulting RMS voltage drops within an idle time of up to 278 [hrs]. The results from the commissioning tests could be reproduced in field and the requirement of a voltage drop of less then 2% is fulfilled.

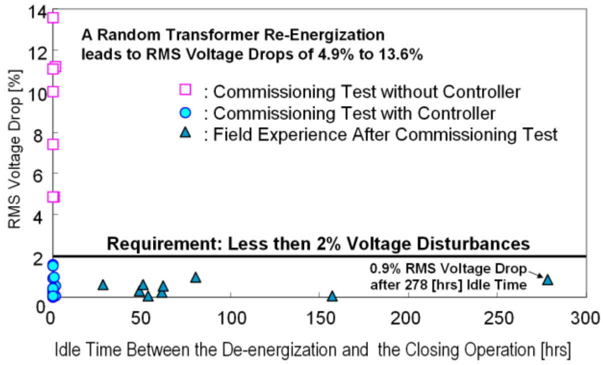


Fig. 11 RMS voltage drops during a transformer re-energization with and without SSC. The idle time did not influence the switching result.

5. Actual Research Items

Chapter 4 explained techniques of state of the art controller systems for unloaded power transformers, pointing out its practical relevance. Research about controlled unloaded transformer switching is ongoing with focus on more specific items such as the residual flux behavior, switching strategies for systems with limited specifications and on pre-simulations of a switching situation in order to evaluate the influence of a switching strategy.

5.1 Residual Flux Behavior

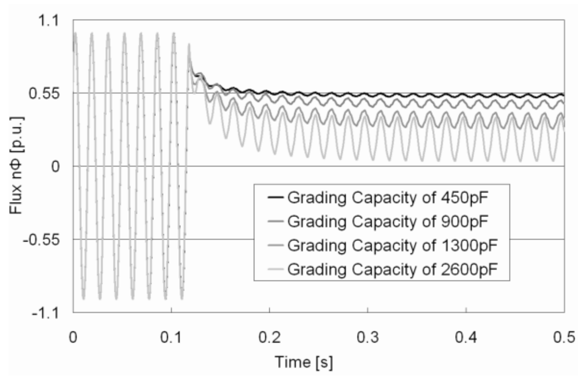


Fig. 12 Residual flux of a single-phase, 50kVA transformer (6.6kV:210V). Voltage measurements have been taken for the same de-energization angle but with varied grading capacitance, [10].

As it was previously explained, a state of the art transformer CSS determines the optimal making targets based on the residual flux constellation. The residual flux is typically assumed as a "locked in" level after a transformer de-energization. The measurements in 10) (**Fig. 12**) however showed that if the switching circuit breaker is equipped with grading capacitors, micro oscillations appear around the residual flux level due to the current passing through the grading capacitors. It was analytically shown that for a larger grading capacitance, the residual flux level decreases and the appearing micro oscillation amplitude increases. A CSS can take this behavior into account by considering the median line of the micro oscillations or by a continuous, online evaluation of the residual flux.

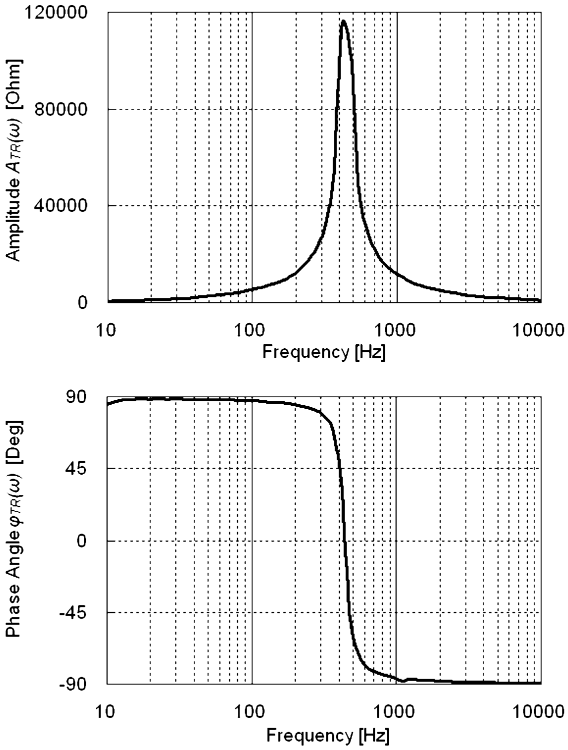


Fig. 13 Amplitude $A_{TR}(\omega)$ and Phase Angle $\varphi_{TR}(\omega)$ of an unloaded, 60MVA single-phase transformer measured with a commercially available frequency response analyzer (NF FRA5087).

If a circuit breaker is equipped with grading capacitors, also system transients can influence the residual flux. Is this the case, the actual flux level not necessarily correspond to the voltage integral while the system transients appear, because the transients can contain frequencies of 0.1Hz up to 50MHz, which will also influence the impedance of an unloaded transformer system. **Figure 13** shows the magnitude $A_{TR}(\omega)$ and phase angle $\varphi_{TR}(\omega)$ of an unloaded, 60MVA single-phase transformer. Amplitude and phase angle have been measured with a commercially available frequency response analyzer (NF FRA5087) - ω is equal to 2π · *f*. Based on these measurements the corresponding reel and imaginary transformer impedance can be calculated. The reel impedance is maximal and the imaginary impedance is minimal if the phase angle becomes zero, which is at 418Hz in case of the unloaded 60MVA transformer. System transients mainly containing this frequency (Temporary overvoltages TOV or slow front overvoltages SFO) will therefore not fully affect the residual flux, because of the comparably large resistive losses. It is possible to approximate a transformer impedance as the one illustrated in **Fig. 13** by a linear resistance *R*, linear inductance *L* and linear capacitance *C*, which are in parallel. The resistance *R* can be parameterized by the amplitude value of the phase angles zero crossing. For the evaluation of *L* and *C* the characteristic angular frequency f_0 in **Eq. 1** and any point of the amplitude $A_{TR}(\omega)$ in the frequency domain can be considered – Compare **Eq. 2**.

$$\omega_0 = 2\pi \cdot f_0 = \frac{1}{\sqrt{L \cdot C}} \qquad (1)$$

$$\left| A_{TR}(\omega) \right| = \frac{1}{\sqrt{\left(\frac{1}{R}\right)^2 + \left(\omega C - \frac{1}{\omega L}\right)^2}} \qquad (2)$$

Based on **Eq. 1** and **Eq. 2**, the analytical expression of *C* and *L* in **Eq. 3** and **Eq. 4** are calculated. These analyses can be used for the development of a filter that is applicable on the voltage measurement while system transients appear in order to evaluate the actual residual flux level.

$$C = \frac{1}{\omega - \frac{\omega_0^2}{\omega}} \cdot \sqrt{\frac{1}{\left| A_{TR}(\omega) \right|^2} - \frac{1}{R^2}} \qquad (3)$$

$$L = \frac{1}{\omega_0^2 \cdot C} \qquad (4)$$

A further research item considers that the voltage measurement at the transformer terminal is not always available and that the residual flux can not be approximated by the corresponding voltage integral. In such a case, the residual flux characteristic of a specified transformer/circuit breaker system over a full de-energization cycle (360[Deg]) could be obtained and stored as look up table into a CSS - An exemplary characteristic is illustrated in 11). The advantage of such a procedure is that a switching strategy, as explained in section 4.2, can be directly applied. As disadvantage it has to be mentioned that every transformer/circuit breaker system has an individual residual flux characteristic and in field only a limited amount of measurements might be available. A neural network is proposed in 11), which approximates the residual flux characteristic based on a very limited amount of measurements (in example 4 measurements). This can be a practical solution for this approach.

Efforts have also been done for a direct simulation of the residual flux behavior. In example 12), applied a Preisach model and came up with a good approximation result. However, very specific information about a transformer/circuit breaker system (Current chopping level, frequency dependent transformer impedance etc.) are necessary, because during the transient de-energization process the measurable transformer terminal voltage contains frequencies of up to 800Hz. Such specific information is typically not available and can not be deduced from nameplate information.

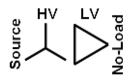
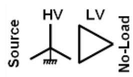
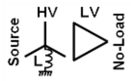
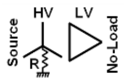
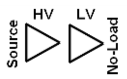
If the residual flux level can not be approximated, probably the most practical solution is to apply a fixed de- and re-energization target. Depending on the switching strategy an optimal de-energization target can be specified. The corresponding optimal re-energization target is obtainable based on a few measurements even if the actual residual flux remains unknown during the evaluation process.

5.2 Simulation of Inrush Currents

Before a CSS is applied in field, its effect on inrush currents and the voltage drop of the system can be simulated based on existing low- and mid-frequency transformer models. These transformer models are typically grouped into 3 types: Mathematical models, topological models and saturable transformer models. Out of practical reasons the saturable transformer model type is often applied, even if they have certain limitations regarding the topology of the equivalent circuit, [13]. Corresponding model parameters are obtainable based on transformer nameplate information except its hysteresis loop and saturation characteristic. These parameters might be provided by the manufacturer of the regarded transformer system. If they are not available, the recently published algorithm in 14) can evaluate the parameters based on two standard measurements.

5.3 Switching Strategies

Table 1 The 3GO switching strategy from 15) applied on various transformer interconnections.

Transformer Interconnection	Energization at the Worst Target	Energization at the Optimal Target[15]
	Maximal Inrush Current Peak: 2.22kA	Maximal Inrush Current Peak: 0.39kA
	Maximal Inrush Current Peak: 2.59kA	Maximal Inrush Current Peak: 0.57kA
 L=23.45H	Maximal Inrush Current Peak: 2.22kA	Maximal Inrush Current Peak: 0.39kA
 R=363Ω	Maximal Inrush Current Peak: 2.23kA	Maximal Inrush Current Peak: 0.41kA
	Maximal Inrush Current Peak: 3.34kA	Maximal Inrush Current Peak: 0.54kA

Not only the residual flux approximation improves, also new switching strategies are being developed. In example, if the circuit breaker only provides a three gang operation (3GO), the switching strategy as explained in section 4.2 can not be controlled. A 3GO switching strategy is proposed in 15). This switching strategy determines the phase angle with the minimal difference between the residual flux and the prospective flux of all three phases together as optimal re-energization target. In the following this switching strategy is applied on a saturable 400kV:18kV, 250MVA transformer model[13] with varied transformer interconnections: Winding resistances are 0.8 Ω and 0.003 Ω; Winding inductances are 100mH and 0.9mH for the primary respectively secondary transformer side. Eddy currents are considered with a 1.0E5 Ω resistance in parallel to the saturable transformer inductance, which is 646H in the unsaturated area and 472mH in the saturated area. The saturated area starts from 1040WbT. The overall transformer inductance is considered with a pole to ground capacitance of 2800pF at the primary transformer side and with 1000pF at the secondary transformer side. As residual flux constellation before the transformer re-energization the following pattern is defined: A-phase 60%, B-Phase -15% and C-Phase -45%. As shown in **Table 1**, the same switching strategy can be applied on each transformer interconnection resulting with a strong reduction of the inrush currents. Same result can be achieved for different residual flux constellations except the case, if each phase shows an almost zero residual flux level. Then the difference between the prospective flux and residual flux of all three phases is constantly large.

Different to 3GO switching strategies, IPO strategies depend on the transformer interconnection and therefore switching strategies are being developed. A new idea is to measure the dynamic residual flux after the first re-energization rather then only switching at a fixed voltage angles as it is applied for the second target of the delayed IPO switching strategy (Section 4.2). This idea shall be explained for a star-delta interconnected transformer system with a Petersen coil at the transformer' s star-point. **Figure 14** shows the simulation result of the delayed switching strategy applied on the above described transformer model. The Petersen coil was similar to the one in **Table 1**, L=23.45H: A low inrush current of 0.21kA results, because of the voltage drop across the Petersen coil. This can be seen at the second energization target, where the prospective flux is not exactly equal to the residual flux. Considering that the dynamic flux right after the first re-energization target (A-Phase) and applying independent switching instants for the B- and C-Phase a complete elimination of inrush currents will result, because each phase can be switched at the exact instant, when the residual flux meets the prospective flux (**Fig. 15**). The same idea can be applied on further transformer interconnections.

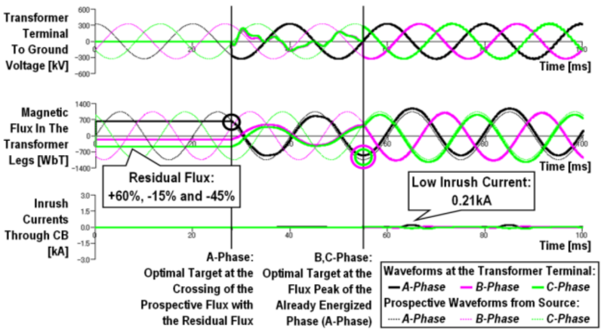


Fig. 14 Simulation result of the same 250MVA transformer model as in **Table 1**: The delayed IPO switching strategy leads to a low inrush current peak of 0.21kA.

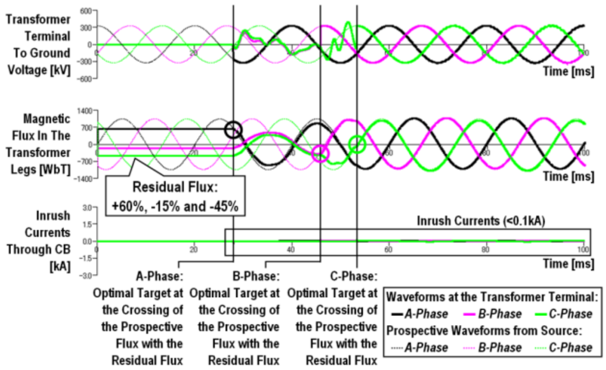


Fig. 15 Simulation result of the same 250MVA transformer model as in **Table 1**: IPO switching strategy considering the dynamic residual flux after the energization of the A-phase. Inrush currents are lower then 0.1kA.

6. Conclusions

In the year 1999 first research results on controlled unloaded transformer switching taking into account the residual flux within a transformer have been published. 5 years later, first field applications could be realized because of the development of the residual flux approximation. This paper presents actual techniques of state of the art CSS for unloaded transformer systems and summarizes/proposes actual research items: Research on the residual flux behavior, development of new switching strategies and research on the simulation of inrush currents.

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