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Point on Wave Energization Strategy and Sequential Phase Shifting for Sympathetic Inrush Current Mitigation in Three-Phase Transformer - Measurement

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Abstract: Inrush currents generated when an electrical transformer is energized can achieve great values and cause abnormal difficulties in the power grid. The sympathetic inrush current phenomenon is resulted in the power system when a transformer is energized with the existence of other transformer already energized. The main objective of this article is the attenuation of sympathetic inrush current in a three-phase transformer. The control technique is carried out by the consideration of the residual flux value when de-energizing the transformer as well as respecting the three-phase shifting. Moreover, an experimental setup to measure the inrush current will be presented. Furthermore, a technique for controlling the circuit breaker to energize a 2 kVA three-phase transformer which allows the sympathetic inrush current to be attenuated was also applied and tested in the experimental. The contribution of this paper is that this technique is applied in measurements with an in-depth estimation of the residual flux. The proposed technique made it possible to completely eliminate the sympathetic inrush current.

Keywords: Three-phase transformer, Sympathetic inrush current, Acquisition, Measurements, Control switching.

Introduction

The sympathetic inrush current is a transient phenomenon, in a power system, resulting from the interaction between transformers, i.e. this current appears when a transformer is energized in an electrical system, the latter containing one or more transformers, but are not put into transient mode (already powered). Figure 1 shows the relationship between flux and inrush current, also how an inrush current is generated in a transformer, therefore, the existence of a residual flux in a transformer core at the time of energizing the latter results in a considerable magnetizing current, which can in some cases reach a value ten times higher than the rated transformer current. from results said that the amplitude of this transient current, called inrush current, can reach the transformer short-circuit current (Steurer & Frohlich, 2002), a good analysis of this phenomenon in several circumstances is mandatory and necessary to make a good design and planning of the protection system. Following this necessity, several analytical and numerical methods have been developed in the literature (Bertagnolli, 1996; Specht, 1951; Holcomb, 1961).

Furthermore, to reduce and mitigate the inrush currents produced when energizing transformers, several methods are developed and proposed. Like that proposed by Cano-González et al. in (Cano-González et al., 2017) where they made a detailed comparison between four strategies, the authors here identified that these strategies are a result of a combination between the possibility of taking into consideration the residual flux in the core of the transformer and the possibility of using circuit breakers with independent poles. It found also Brunke et al. in (Brunke et al., 2001, 2001b), they suggested a strategy to mitigate the inrush current of three-phase and single-phase transformers, they are considered among the first in this field. Therefore, the proposed technique is validated theoretically and by measurement. In addition, this strategy is based on three techniques: Delayed, Rapid and that of taking into consideration the residual flux for a simultaneous closing. To increase the transient inductance and subsequently reduce the inrush current, Cheng et al. (2004) based on the technique of modifying the distribution of the coils of the winding. This technique is considered new in this field. There is also a simple technique based on the integration of a resistance in the neutral of the three-phase transformer, this technique is proposed in (Arand, 2013; Abdulsalam et al., 2017; Abdelsalam et al., 2015; Cui et al. , 2005). This is not enough but the authors exploit the phase shift of the three phases to create a sequential excitation. A method proposed by the authors in (Xu et al., 2005) which uses a photovoltaic source for the elimination of the inrush current; the authors applied an opposing magnetic flux, taking into account the moment of the maneuver. In (Cano-González et al., 2015), the authors used a controllable circuit breaker to isolate the neutral of the transformer, here the residual flow and the sequential one are taken into account. In (Cano-González et al., 2015), a method for isolating the neutral of the three-phase transformer by controlled switching is presented, taking into account the sequential and residual flow of the phases.

There are different paths to limit the interaction of daily transformer energization with load protection and relays. This is what the authors address in (Schramm et al., 2011), They also demonstrated the technique of using resistors connected in parallel with the circuit breakers during transformer energization. First, the circuit breaker is opened so that current inevitably passes through the resistance, and after a short time, the circuit breaker is closed, eliminating the resistance effect. In the article (Rudez et al., 2016), in order to extract the equivalent circuit, the authors used state equations resulting from the resolution of differential equations. This method is modal and is based on a systematic study of the derivation of vectors and eigenvalues. In addition, the authors studied the consequences and impacts of the transient regime on transformers already energized by a transformer energized at full load. In the article we also find a comparison of the measurements results taken using the Wide Area Monitoring System (WAMS) with the simulation results. The authors in (Pontt et al., 2007) have used the technique of reducing the transient current by increasing the impedance of the coil. The technique was implemented to reduce the inrush current and its effects, relying on the tap changer of the connected transformer.

In this study, for measuring the sympathetic inrush current using a dSPACE data acquisition system, an experimental setup with a three-phase transformer will be presented. Then, the residual flux is extracted while the circuit breaker is opened through a strategic technique to estimate the flux waveform. This extracted value is used to erase the instantaneous flux value in the next energization to reduce the sympathetic inrush current in three-phase transformer. Using Faraday's laws, the flux wave is estimated from the voltage wave, and through it the residual flux is induced when the circuit breaker is opened. To reduce the values of the currents resulting from the influence of a transformer under the transient regime on already energized transformers, or the so-called sympathetic inrush current, the method that was proposed by the authors in (Yahiou et al., 2019) was exploited in this work. It is sufficient to calculate the value of the residual flux for only one phase U, and use it as a value to calculate the optimal time to close the circuit breaker without the appearance of the sympathetic calling current, without calculating the optimal time for the other phases V and W. Therefore, by exploiting the time of the phase U, the time of the V and W phases is calculated by adding the value of the phase shift $2*\pi/3$ and $2*\pi/3$ respectively. The technique proposed here is applied to real-time measurements.

Relationship between Inrush Current and Magnetic Flux

When energizing of any unloaded transformer, it will result in the presence of an unloaded current in the steady state and the inrush current in the transient regime. This current has a direct relationship with the magnetic flux waveform of the transformer core, and this is what Figure 1 shows. As shown in the figure, one of the most important reasons that leads to the appearance of an inrush current at the instant of transformer energization is the presence of residual flux in the core (it can reach values that exceed ten times the nominal current of the transformer). In the normal case (no residual flux), there is only the magnetizing current to the transformer at the operating moment.

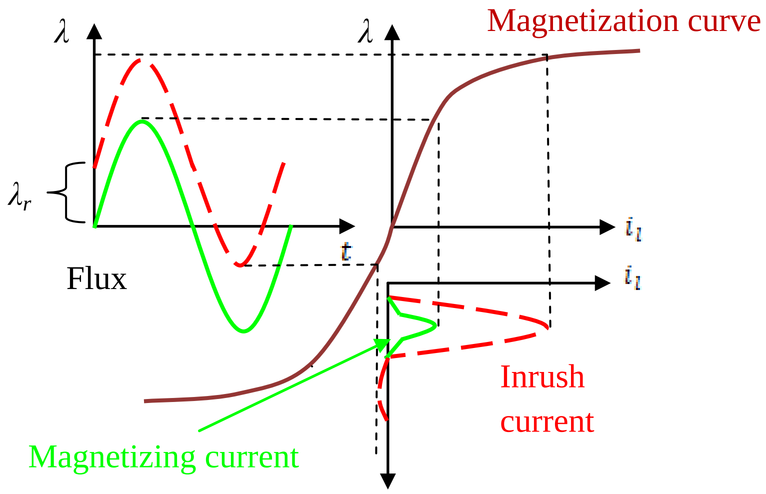

Figure 1. Relationship between inrush current and magnetic flux

Test Proceedings and Measurement Setup

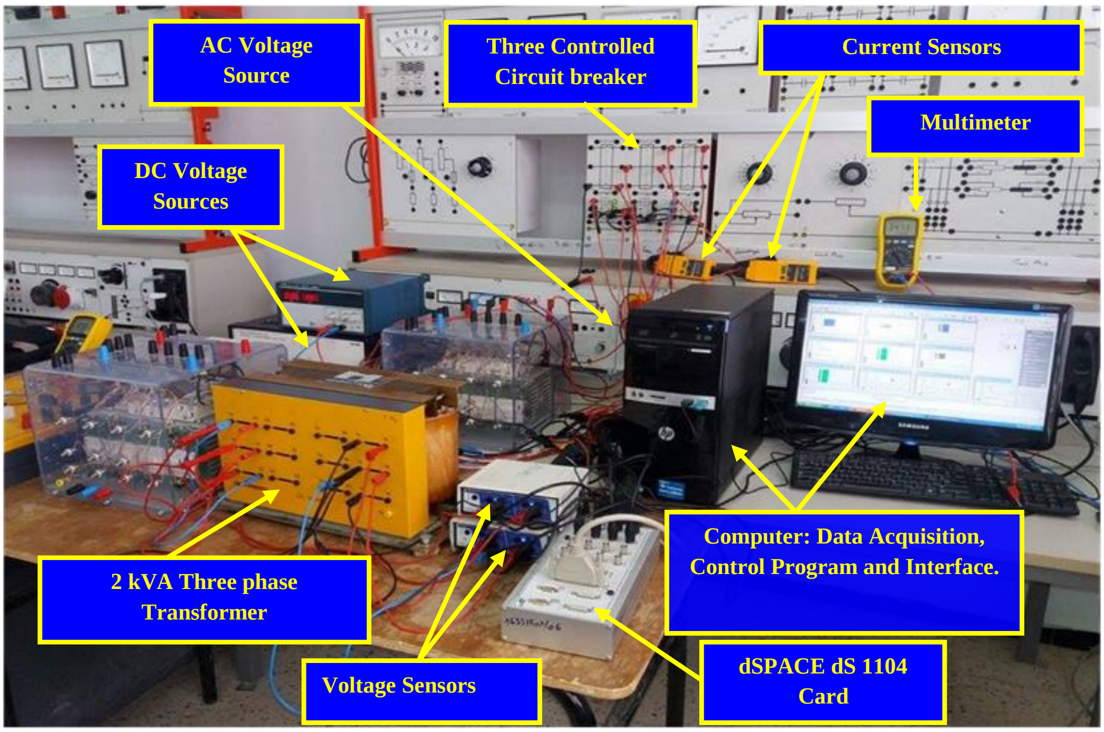

Figure 2. Laboratory setup for inrush current measurement.

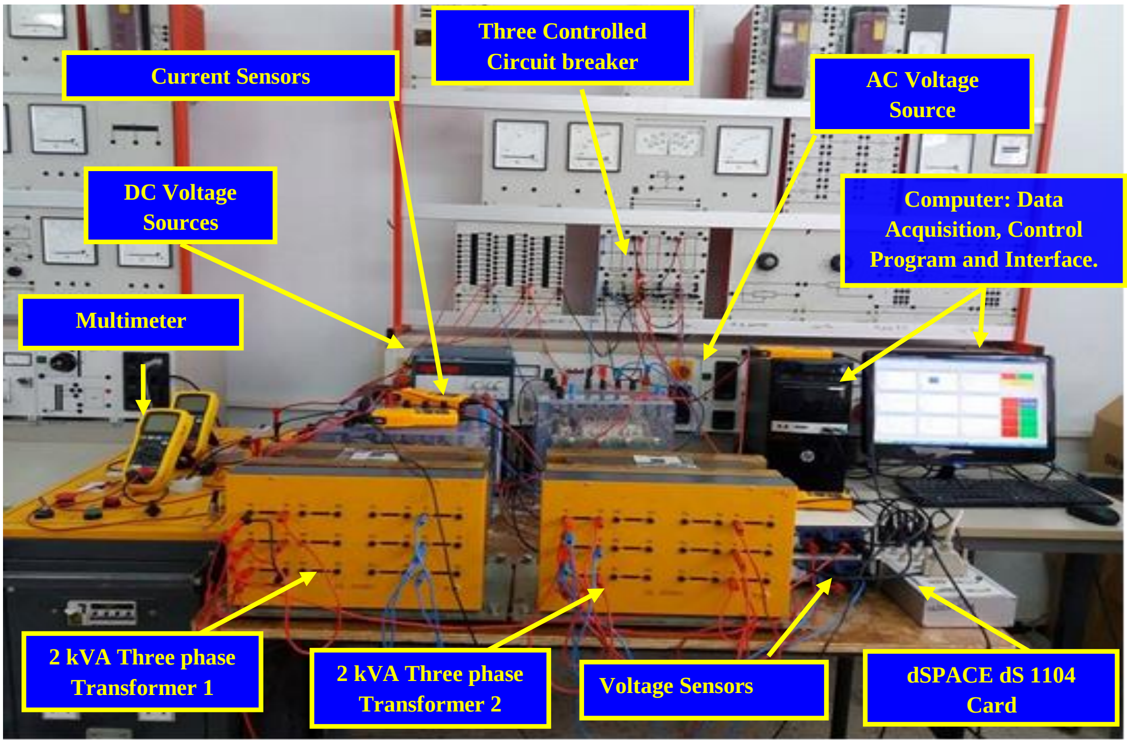

Figure 3. Sympathetic inrush current measurement setup.

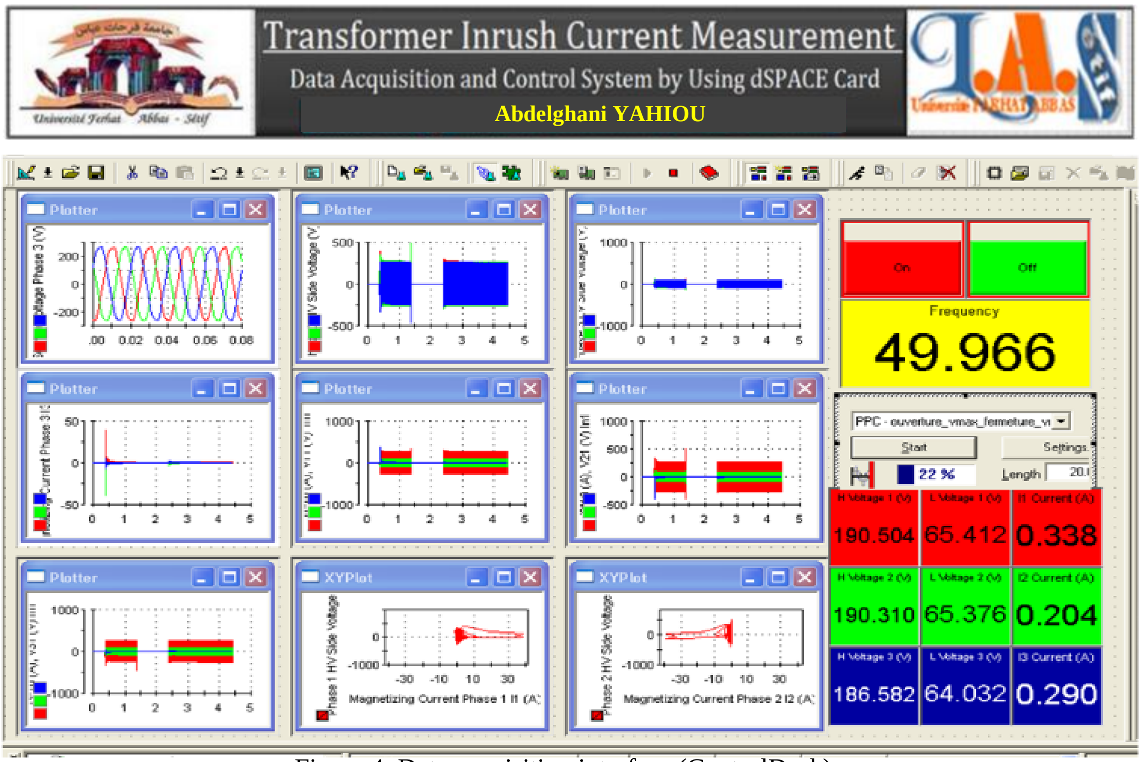

Figure 4. Data acquisition interface (ControlDesk).

Figures 2 and 3 respectively show a setup picture of the inrush current measurement and a setup picture of the sympathetic inrush current measuring for a three-phase transformer, with the label of each part used. The 2kVA transformer is supplied by three-phase power source through a voltage of 220 volts. The applied voltage and magnetizing current are measured using a voltage probe and a current sensor respectively. Using the ControlDesk program installed in the computer with the data acquisition system (dSPACE 1104 card), we can obtain waveforms for various quantities (voltage and current). We obtain the same waves using a digital oscilloscope to confirm those of computer. Figure 4 is the ControlDesk interface, through which all data are obtained and stored in the MATLAB program

Random sympathetic Inrush current

For the random energization, Figure 5 represents the measurement waveforms of the sympathetic inrush current in the second transformer T2 (already energinzed) resulted by the interaction with transformer T1 (under inrush current).

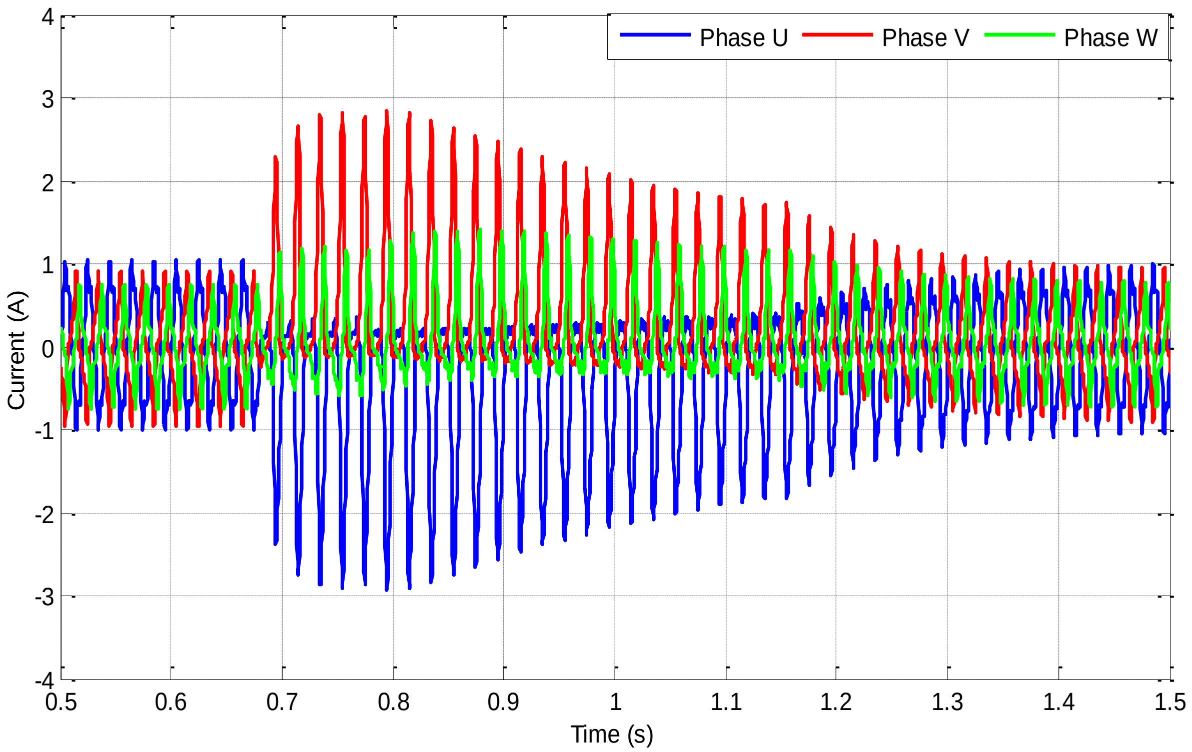

Figure 5. Sympathetic inrush current of transformer T2.

Sympathetic Inrush Current Mitigation

This part of the article is devoted to presenting the proposed sympathetic current reduction technique. MATLAB was used as program with dSPACE to apply the proposed technique on three-phase transformer, and the laboratory measurement results showed the extent of its effectiveness in mitigation of this transient current. Calculating the optimal closing moment is the basis of the technique applied to the transformer T1 under the inrush current. This calculation is done by taking into account the point on the voltage wave and the appropriate value of the residual flux, of course for phase U only, and also acquiring the value of the residual flux for the next process. Regarding the two phases (V and W), the optimal timing is calculated by adding the phase shifting with the U phase

Control Process

Here in this part, the method of closing and opening the circuit breaker is presented, whether using the proposed control technique or the random state. The first energization of transformer T1 is random. After a short closing period, there is also a random opening of the circuit breaker. Then there is a second energization of the same transformer with the application of the proposed technique. Here, the information stored when the breaker is opened is taken and matched to the appropriate point on the voltage wave, and used as data to calculate the ideal time to close the breaker for turn U without appearance of the sympathetic current. Transformer 2 is already supplied and is not concerned with any opening or closing of the breaker. In order to ensure the effectiveness of this technique, its similar and good results in the field of sympathetic current mitigation, the previous operations are repeated five times before the results can be judged (Figure 6).

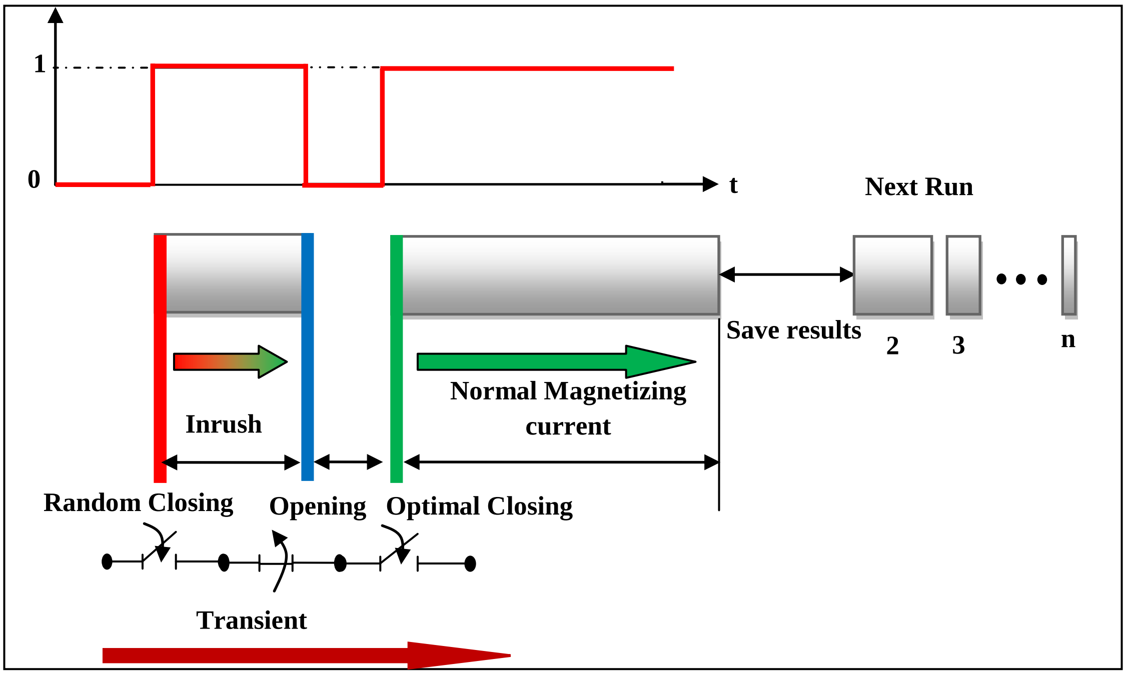

Figure 6. Process of opening and closing the circuit breaker

Principle of Controlled Switching

As is the case with magnetic circuits (here, the case of a coiled transformer core), considering that the electric voltage wave is completely sinusoidal, applying the laws of magnetization there is a proportionality and relationship between the electrical voltage *v* applied to the coil and the magnetic flux in the core. The method for calculating the optimal closing time, for phase U, of the circuit breaker is the same as that used in the article (Yahiou et al., 2019)

Figure 7 is a graphical illustration of the various stages of opening and closing the breaker using the control technique, it illustrate the relationship between the two waveforms of the applied voltage *v* and the magnetic flux λ. In addition, in order to avoid a decrease or change in the value of the residual flux, the time between opening and closing is not large. The various stages in the proposed technique are explained in the flow chart of Figure 8.

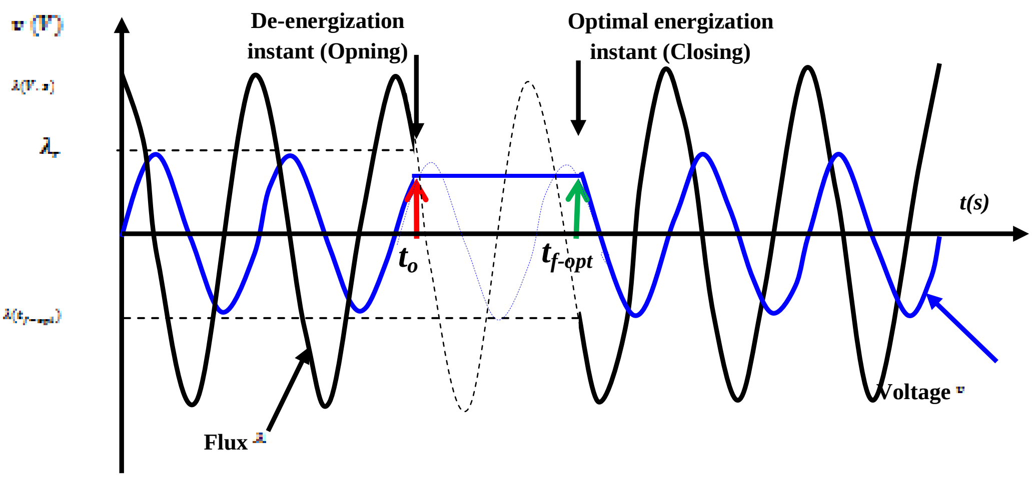

Figure 7. Optimal switching time and relationship between flux and votage.

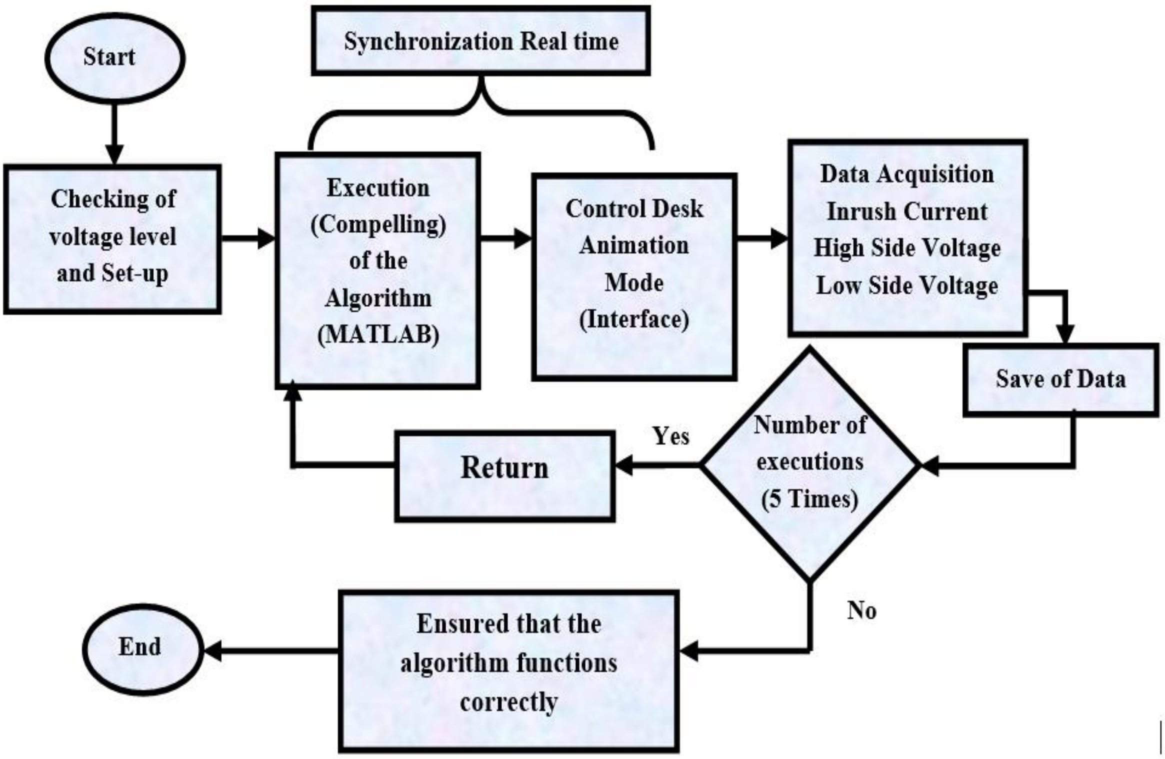

Figure 8. Flow chart of the proposed technique stages.

Control Technology and its Application in Real Time

The technique for calculating the flux values to be used to control the breaker is shown in Figure 6. The following stages explain the steps of this technique and the measurement in real time:7

1- The identical three-phase transformers T1 and T2 are connected in parallel, and the high-voltage side is supplied by source with a voltage value of 220 volts, which is the nominal value. Measurement signals are obtained through measuring instruments.
2- To be able to achieve synchronization between the sinusoidal signal of the simulation program (MATLAB) and the pressure signal used in the measurement, a Phase-Locked Loop (PLL) was used. The goal of this synchronization is to detect the crossing point of the voltage signal through the zero point. Here an order is given to the three breakers to close, regardless of the value of the residual flux.
3- The magnetic flux signal of the same phase is estimated by integrating the voltage signal U.
4- Estimate the residual flux value at the opening instant of the circuit breaker via ControlDesk interface.
5- After calculating the optimal time for closing the circuit breaker on phase U, the ControlDesk interface is used in synchronous with executing the MATLAB program.
6- For the two phases U and W, the circuit breaker is closed after the phase U with a small time difference estimated as the phase shifting.
7- In all previous steps, the three-phase transformer T2 is always supplied.

Figure 9 and Figure 10 display respectively a flow chart of the steps for estimating the optimal time for closing the breakers, as well as an illustrative diagram of the alternation of the three phases when the breakers are closed.

The advantage of the technique proposed in this article is that the optimal time for closing the breaker is calculated for only one phase U. This calculation is used to estimate the optimal time for closing the breaker for the two other phases V and W, by adding the phase shifting, respectively, of 2*π/3 and 4*π. /3.

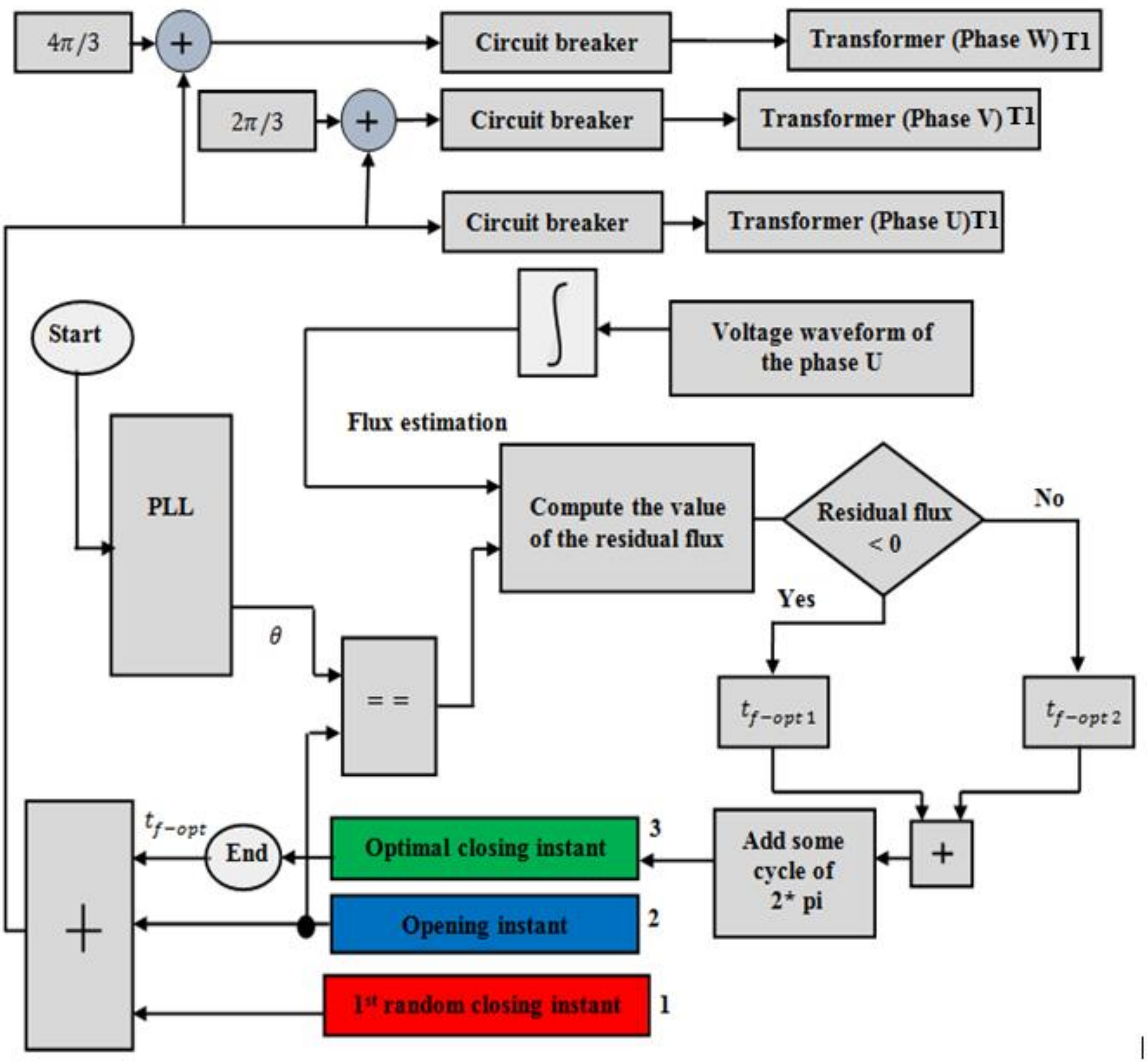

Figure 9. Diagram of the time and flux estimation steps

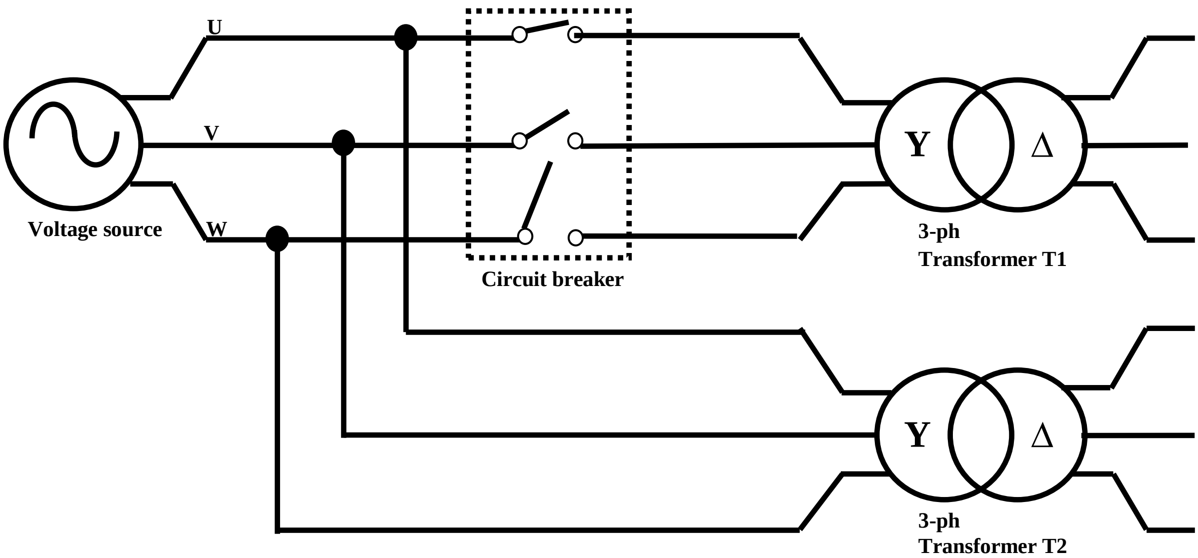

Figure 10. Illustrative diagram of the phase shifting energization

Results

Figures 11 and 12 are the obtained results for applying the proposed technique for sympathetic inrush current reduction in real-time measurements. When the circuit breaker is opened, the value of the residual magnetic flux in the core is estimated. This quantity is taken into account in calculating the optimal time to close the circuit in a controlled and not random manner. So we do not find any presence of the sympathetic inrush current for transformer T2.

As can be observed from Figure 11 and Figure 12, it is clear that from the experimental results there is reduction of the sympathetic inrush current in three-phase transformer T2. The sympathetic inrush is decrease to the no-load current value regardless of the residual flux pattern. A significant attenuation of sympathetic current has been reached since the de-excitation and excitation are controlled, the open and close of the circuit-breaker is made at the same point on voltage wave. The effectiveness of the proposed controlled switching was confirmed and has a direct influence on the re-energization of the transformer.

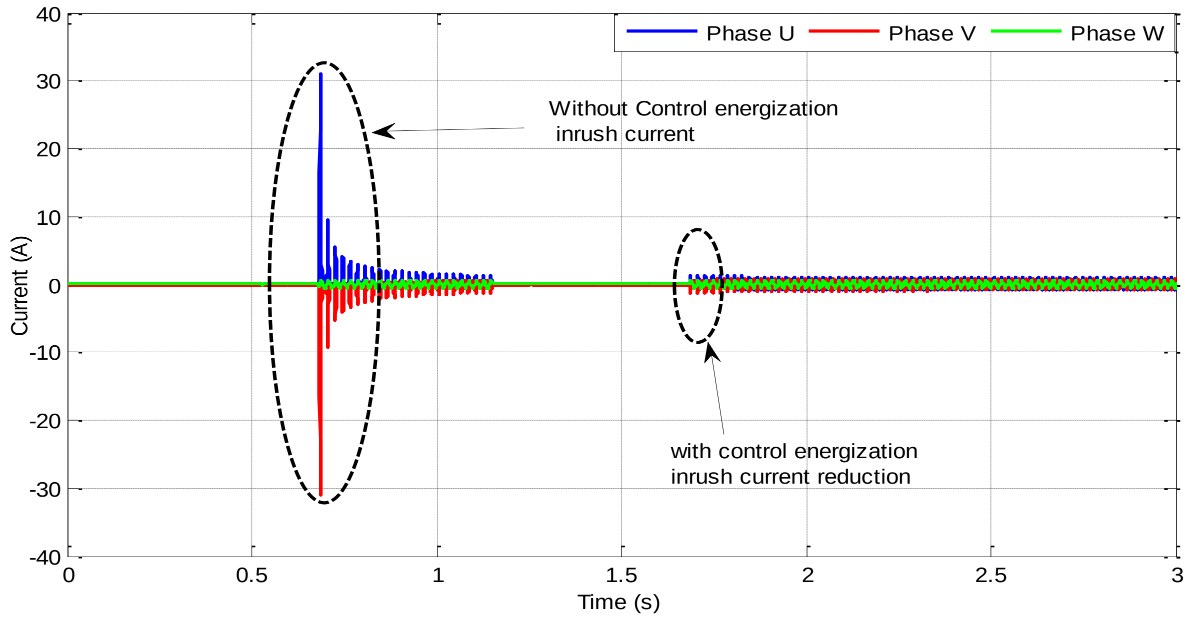

Figure 11. Inrush current mitigation by controlled switching of transformer T1.

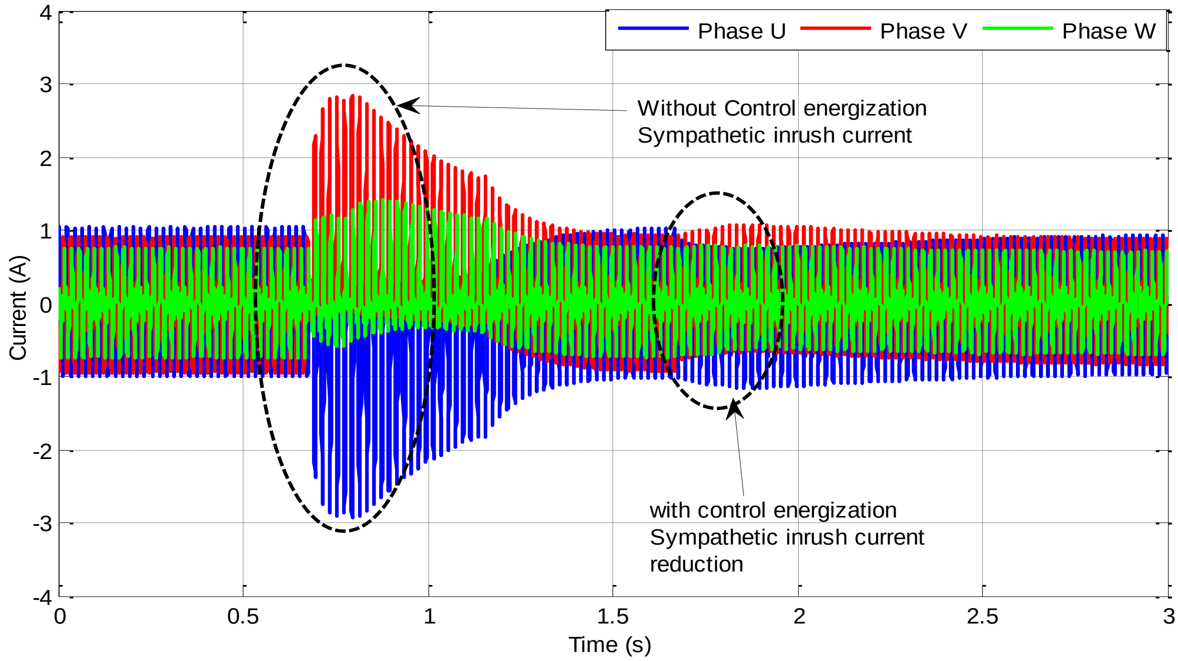

Figure 12. Sympathetic inrush current mitigation by controlled switching of transformer T2.

Conclusion

The work proposed in this article summarizes a set of software experiments carried out with the aim of measuring the inrush current and the sympathetic current resulting from the influence of a transformer situated under the transient regime on a transformer connected to the electrical network and already energized. The main goal of this completed work is to propose a technique that enables us to reduce, or rather eliminate, this sympathetic current in three-phase transformers. The proposed technique depends mainly on finding a point on wave of the electric voltage, and thus the magnetic flux is proportional to the value of the residual flux in the core of the first transformer, from which the sum of the two values equals zero. The proposed technique was demonstrated practically through experiments in the laboratory using the data acquisition system (dSPACE card).

The results obtained proved the accuracy of the technique in eliminating the sympathetic current. The advantage of the technique proposed in this article is that the optimal time for closing the breaker is calculated for only one phase U. This calculation is used to estimate the optimal time for closing the breaker for the two other phases V and W, by adding the phase shifting. The proposed technique resulted in complete attenuation of sympathetic outflow. The technique applied here is in the experiment with a good study of the residual flux. Deletion of the inrush current in the first transformer inevitably leads to the deletion of the sympathetic inrush current in the second transformer

Scientific Ethics Declaration

The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Acknowledgements or Notes

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