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Inrush Current Reduction by a Point-on-wave Energization Strategy and Sequential Phase Shifting in Three-Phase Transformer

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ABSTRACT

The main goal of this work is the mitigation of inrush current in a three-phase transformer. This inrush current appears when energizing a no-load or lightly loaded transformer. It can reach very high values and can cause failures in the electrical system. The control strategy is achieved by considering the value of the residual flux when the transformer is de-energized as well as by respecting the phase shifting between the three phases. To measure the inrush current, an experimental configuration with a data acquisition system using dSPACE 1104 card was developed and is presented in this paper. A technique to control the circuit breaker for energizing a 2 kVA three-phase transformer without the appearance of inrush current was also tested and applied in the experimental setup. The specific contribution of this work is that this technique is applied in the measurements with a thorough investigation of the residual flux. The proposed technique achieved complete elimination of the inrush current.

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NOMENCLATURE			
ϕ	Iron core flux	v	Applied voltage
λ	Linkage flux.	λr	Residual linkage flux.
i_l	Reactive magnetizing current.	t_{close}:	Closing time
λ_{max}	Maximum linkage flux	V_{max}	Maximum voltage.
ω	Angular pulsation.	n1 :n2	Transformation ratio
it	Total magnetizing current	ir	Active magnetizing current

1. INTRODUCTION[1]

Inrush current is a phenomenon that appears during the energization of an unloaded transformer in a power system. Due to the high value of the first peak of this inrush current, which sometimes reaches the value of the short circuit current [1]. It is necessary to conduct an investigation and analysis under several constraints and conditions in order to predict the protection system intended for the transformer. For this purpose, several analytical and numerical methods have been developed, as reported in literature [2- 4]. To mitigate and eliminate these transient currents in single or three-phase transformers, many techniques have been proposed in the literature. Cano-González et al. [5] conducted a comparative analysis of four of these strategies that depend on whether the residual flux can be measured and whether independent-pole-operated or three-pole-operated circuit-breakers are used. The work carried out by Brunke et al. [6, 7] have considered to be one of the first studies presented in the field of inrush current reduction in single or three-phase transformers, both in simulation and measurement. The technique is based on three strategies: a rapid, delayed, and simultaneous closing strategy taking into account the residual flux. To increase the value of the transient inductance, as well as to reduce the inrush current. Cheng et al. [8] presented a new approach where they modified the transformer coil

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distribution. Arand et al. [9], Abdulsalam, and Xu [10], Abdelsalam and Abdelaziz [11] and Cui et al. [12] suggested a simple technique by the insertion of a resistance between the neutral of the transformer and the ground, taking into account the sequential energization of the three phases. Using an existing photovoltaic generator. Xu et al. [13] investigated the mitigation of the transient inrush current; the technique was based on applying the opposite flux with taking the switching instant into consideration. A method for isolating the neutral of a three-phase transformer using controlled switching was presented by Cano-González et al. [14]. The method takes the residual flux into consideration and respects the phase shifting between the three phases. To be able to protect the load for daily switching and reduce the interaction with other relays in transformers, several methods were proposed by Schramm et al. [15]. In addition, a strategy based on placing resistances before energization with the transformer was presented. The resistances are inserted in parallel with the circuit breakers. The effect of the resistance is controlled by opening and closing the circuit breaker: if the circuit breaker is open, the current passes through the resistances, while if it is closed, the resistances have no effect. Based on the state space equation to represent the equivalent circuit, Rudez et al. [16] have chosen a format to solve the differential equations. Moreover, they presented a consistent study for deriving the eigenvectors and self-values. They also investigated the effect of energizing a fully loaded transformer (application of transient regime), with the presence of transformers under constant operation (i.e. with no transient regime) and compared the measurement results obtained using WAMS (Wide Area Monitoring System) with those obtained through simulations. To reduce the inrush current levels in the transformer and its effects on the electrical system, Pontt et al. [17] used a technique based on the transformer tap changer to increase the impedance value of the transformer winding.

Gamji et al. [18] presented a method to reduce the inrush current using the modified transient current limiter (MTCL), which overcomes the drawbacks of the conventional transient current limiter (TCL) during normal operating mode. The proposed MTCL gives lower current/voltage THD and power losses. This approach minimizes the cost by operating one limiting reactor instead of two. The performance of the method was tested experimentally and also by PSCAD/EMTDC simulation. The efficacy of the method was confirmed by comparing the results obtained with MTCL with those obtained with TCL. Ebadi et al. [19] simulated 510 different cases of inrush current in order to study the REF relay maloperation under inrush current conditions.

To measure the inrush current in a three-phase transformer, a laboratory experimental setup with an acquisition system (dSPACE card) is detailed and presented in this article. The technique presented and proposed by Yahiou et al. [20, 21] has exploited to reduce the three-phase transformer transient current. This technique is based on Faraday's law to estimate the magnetic flux waveform via the voltage waveform, then the value of residual flux at the de-energizing moment (the circuit breaker is open) is estimated. The main contribution of the present work is the exploitation of the method previously proposed by Yahiou et al. [20, 22], using a single phase transformer, to reduce the inrush current in three-phase transformers, where the residual flux value and the optimal time to close the circuit breaker for only the first phase (U) are calculated. For the other phases (V and W), the previous calculations are used. Thus, the optimal time to close the circuit breaker for the phases V and W is also calculated by adding the phase shifting (2*π/3), without calculating each one separately. The technique was applied to real-time measurements.

2. FLUX AND INRUSH CURRENT RELATIONSHIP

Fig. 1 depicts the appearance of unloaded current when energizing a transformer, either in the steady state or in the transient state and its relation with the magnetic flux waveform. It is clear that the existence of a residual flux value at the instant of energization of the transformer leads to an inrush current peak (with values that can be ten times greater than the nominal current). In the steady state, i.e. when the transformer is energized without the appearance of this transient current, there is only the magnetizing current.

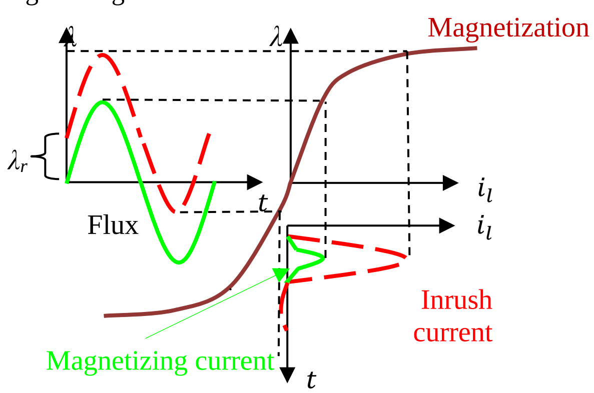

Figure 1. Flux Vs Magnetizing current of the unloaded transformer (transient and steady state)

3. MATERIALS AND METHOD

3.1. Laboratory configuration and measurement proceedings

Construction of References The measurement setup is shown in Fig. 2. A three-phase voltage source with 220 V AC supplies the 2 kVA three-phase transformer. The current sensor and voltage probe are used to measure the magnetizing current waveforms and the applied voltage, respectively. The waveforms are acquired using the data acquisition system (dSPACE 1104 card connected to the computer with the Control Desk software) and by a digital oscilloscope simultaneously. The storage, data acquisition, control, and analysis were performed under the MATLAB environment and using the dSPACE experimental software, as shown in Fig. 3, which shows the Control Desk interface developed.

These measurement experiments complement the work conducted in the same research field and reported in literature [22].

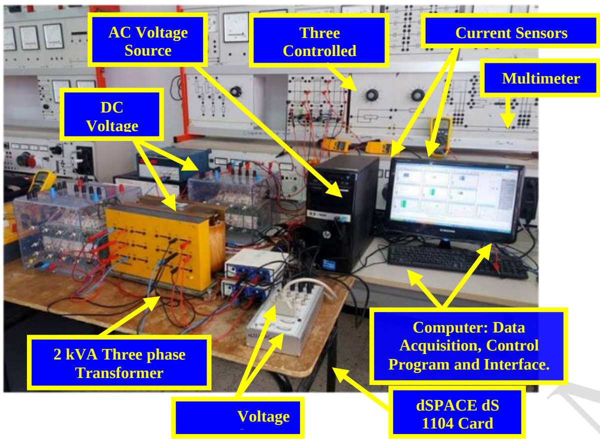

Figure 2. Measurement setup

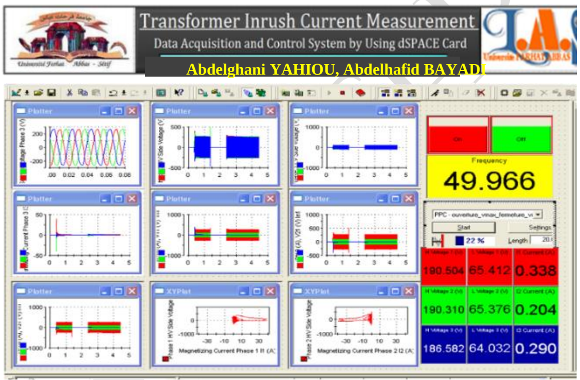

Figure 3. Data acquisition interface (Control Desk)

In the steady state, the voltage value is gradually increased from zero until the nominal voltage value for the transformer primary side, which is rated at 220 volts, while the secondary side remains in an open circuit. Fig. 4 portrays the steady state current waveform for the 2 kVA transformer. For the transient case, three breakers are used to energize the three-phase transformer. The voltage value is fixed at 220 Volts. The current waveforms are recorded via the acquisition system, after giving a random impulse to the breaker to close at the desired moment.

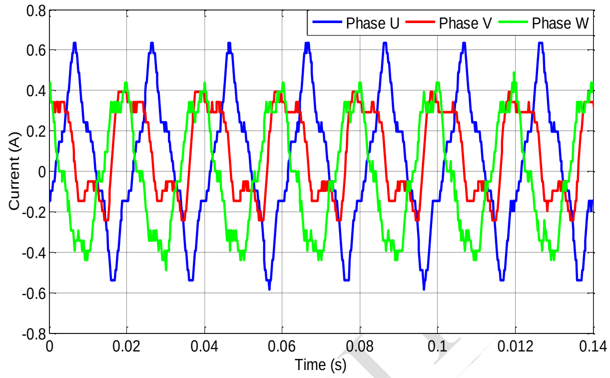

Figure 4. Magnetizing current (steady state)

The measured inrush current waveform of the three-phase transformer is shown in Fig. 5.

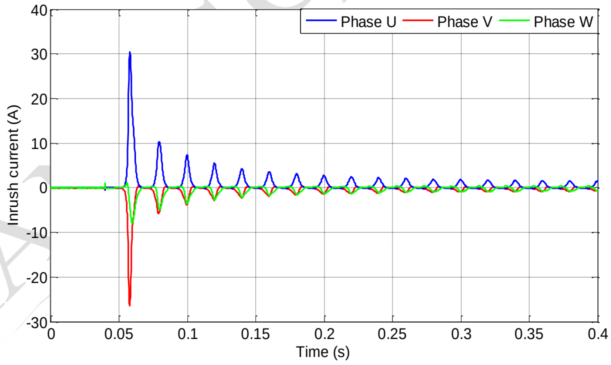

Figure 5. Magnetizing inrush current (transient)

As shown in Fig. 5, the magnetizing current value in the transient state is much higher than the current value in the steady state, especially in the first peak where it can reach the value of the short-circuit current, and then there is a gradual decrease of this current until it reaches the value of the steady state value after a few seconds.

As the inrush current can create failures in the transformer (protection relays) as well as affect the quality of the service in the power system (voltage), ongoing research in the field seeks to reduce this inrush current. The method proposed here to achieve this is detailed in the following section.

3.2. Controlled energization to mitigate inrush current The technique proposed in this article to reduce three-phase transformer inrush current is presented in this section. The technique, modeled with MATLAB, was applied in the laboratory measurement setup, and the results demonstrated its effectiveness. The mitigation technique is mainly based on computing the optimal closing instant and considering the point-on-wave voltage waveform just for the first phase U. It is sufficient to calculate the residual flux for the phase U, and for the other phases (V and W), it is sufficient to add only the phase shifting between them and the phase U.

3.2.1. Principle of the control procedure The main goal of this section is to detail the procedure for opening and closing the circuit breaker. The first energization of the three-phase transformer is done randomly (the circuit breaker is closed). This closing lasts for a well-defined period, then the three-phase transformer is de-energized randomly (circuit breaker open). Finally, the circuit breaker is closed a second time (transformer re-energization), this time not randomly, but applying the control technique that takes into consideration the magnetic flux data for the latest opening of the breaker, i.e. point-on-wave of the primary voltage of phase U.

This procedure is repeated several times (5 times) to ensure that the technique gives similar results for the same conditions on the voltage wave point, i.e., good elimination of the inrush current for the three phases whatever the operating conditions of the transformer (Fig. 6).

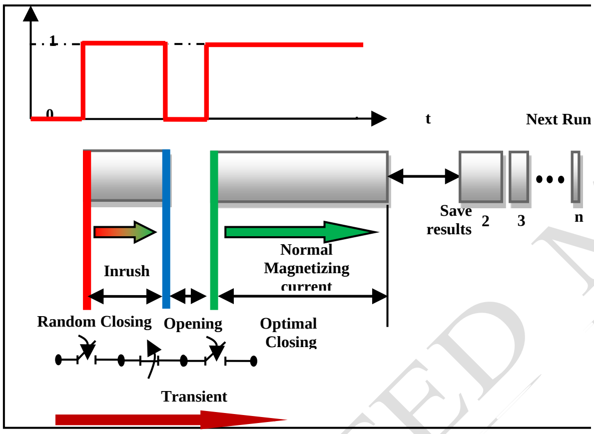

Figure 6. Explanation of the circuit breaker closing and opening procedure

3.2.2. Control technique in equation In a magnetic circuit wound by a coil and as in a transformer, there is proportionality between the iron core flux ϕ and the voltage v applied to the winding. Therefore, considering that the voltage is sinusoidal, and by considering Faraday's law, it is possible to write:

$$v(t) = V_{max}\, sin(\omega t) = n_1 \frac{d\emptyset}{dt} = \frac{d\lambda}{dt} \quad (1)$$

where:

V_{max} is the maximum value of the voltage and λ is the flux. The integration of equation (1) gives:

$$\lambda(t) = \int V_{\max} \sin(\omega t) dt = -\frac{V_{\max}}{\omega} \cos(\omega t) + K \quad (2)$$

At the closing moment of the breaker, the flux value is the residual flux λ_R. Therefore, it is possible to write equation (2) as follows:

$$\lambda_R = -\frac{V_{\max}}{\omega} \cos\left(\omega t_{cl-opt}\right) + K \quad (3)$$

Considering that, at two instants $t_{cl\text{-}opt}$ and top, the value of λ_R has a constant and equal value, the constant K becomes equal to:

$$K = \lambda_R + \frac{V_{\max}}{\omega} \cos\left(\omega t_{cl-opt}\right) \quad (4)$$

Equation (2) becomes:

$$\lambda(t) = -\frac{V_{\max}}{\omega} \cos(\omega t) + \frac{V_{\max}}{\omega} \cos\left(\omega t_{cl-opt}\right) + \lambda_R \quad (5)$$

To eliminate the transient current, it is necessary to compensate the residual flux value by the flux value at the closing moment, i.e., the total flux becomes the flux of the steady state (the flux waveform does not move as was the case of what is shown in red color in Fig. 1)

$$\lambda(t) = -\frac{V_{\max}}{\omega} \cos(\omega t) \quad (6)$$

This means that:

$$\lambda_R + \frac{V_{\max}}{\omega} \cos\left(\omega t_{cl-opt}\right) = 0 \quad (7)$$

The optimal instant of energization can be calculated as follows:

If $\lambda_R < 0$:

$$t_{f-opt\,1} = -\frac{1}{\omega} \arccos\left(\frac{\lambda_R}{\lambda_{max}}\right) \quad (8)$$

Else:

$$t_{f-opt\,2} = \frac{1}{\omega}\left[\arccos\left(\frac{\lambda_R}{\lambda_{max}}\right) + 1\right] \quad (9)$$

The relationship between the flux λ and the applied voltage v at the commanded closing instant and the opening moment of the breaker is well explained graphically in Fig. 7. It is as summed that the time between opening and closing is not very large so that there is no change in the residual flux value in the two moments.

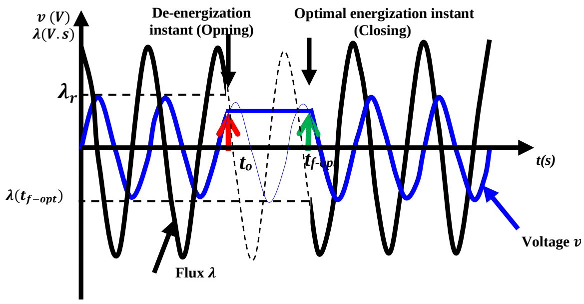

Figure 7. Voltage-flux relationship for optimal switching on

The flowchart of the different steps in the control technique is given in Fig. 8. Equation (7) is the essential basis of this inrush current mitigation technique.

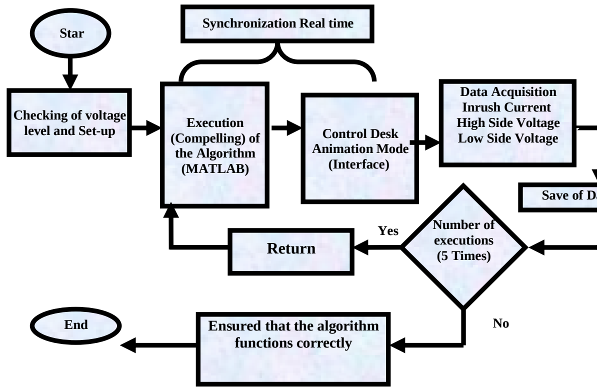

Figure 8. Data acquisition system and control strategy steps

3.2.3. Measurement steps and real-time application of the control technique To estimate the flux waveform and to control the circuit breaker, a control and measurement plan was carried out as explained in Fig. 9. A detailed clarification of the strategy is given in the following steps:

1) Fixing the voltage source to a value of 220 V, which represents the nominal voltage value for the primary side of the three-phase transformer, the current and voltage waveforms are captured and recorded via the acquisition system.
2) The Phase-Locked Loop (PLL) is used to synchronize the signal of the measurement voltage and the sinusoidal signal of the simulation under MATLAB. The PLL helps us to know the zero crossing moment for the voltage signal. The three breakers receive a pulse to close at this time (zero crossing), without considering the flux value at this closing moment.
3) Using the integration tool of such a signal, it is possible to obtain the flux waveform of the phase U through the voltage signal for the same phase.
4) The flux value when the circuit breaker opens is taken as a residual flux value for phase U.
5) The circuit breakers of phases V and W open later than the circuit breaker of phase U.
6) Execution of the MATLAB program on the Control Desk interface at the same time, i.e., synchronization (estimation of the optimal instant to close the circuit breaker of phase U).
7) The circuit breakers of phases V and W close optimally later than the circuit breaker of phase U.
8) The steps are repeated to confirm the validity of the technique and that whatever the point on the voltage wave it gives the same results. In addition, it is necessary to sweep the entire voltage wave, from 0 at 2π with a pitch of 1/6.

Figs. 9, 10, and 11 display the procedure of the residual flux estimation, the method for calculating the optimal closing moment, and the explanatory scheme of the sequential closing of the three circuit breakers.

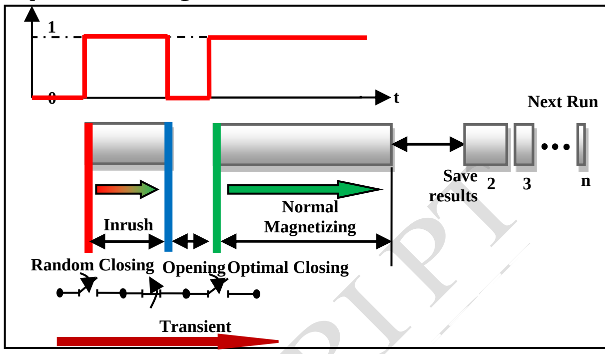

Figure 9. Flux measurement and Control strategy

In this study, the residual flux was calculated for only one column (the column of phase U), and from that the optimal time to close the circuit breaker for phase U was calculated. To this point, we added the phase shifting of 2*π/3 and 4*π/3 for an optimal closing of the circuit breakers for phases V and W respectively. Hence, the residual flux for other columns was not calculated.

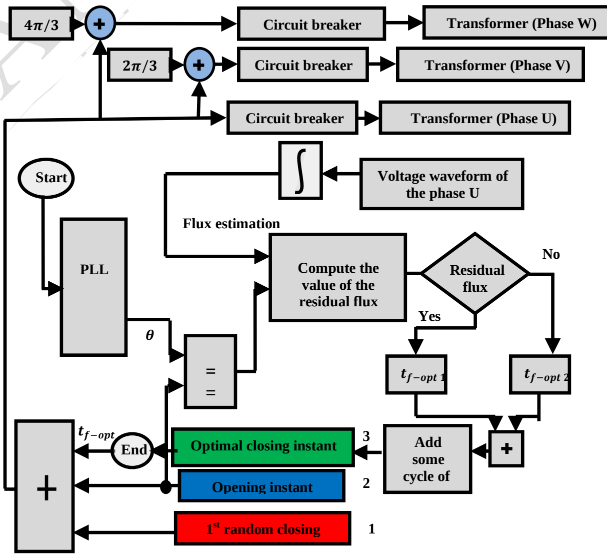

Figure 10. Flow chart of the control strategy and flux estimation

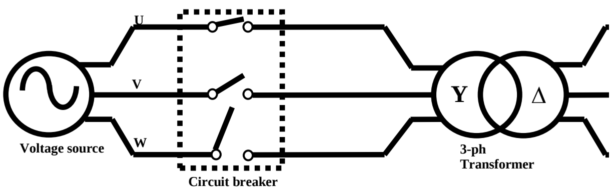

Figure 11. Explanatory scheme of the sequential phase energization

4. RESULTS

Figs. 12 and 13 display the experimental results with the application in real time of the proposed strategy. Initially, the three-phase transformer is switched on. After the three-phase transformer is de-energized, at the opening moment of the breaker, the value of the residual flux is computed. Lastly, the transformer is switched on again by closing the breaker, but not in a random way, since here, the program interferes to calculate the optimal time to close the breaker in such a way that the inrush current does not occur. This concerns phase U. As for the opening and closing instants of the breakers for phases V and W, they are equal to the opening and closing instants of the breaker for phase U plus the values $\frac{2\pi}{3}$ and $\frac{4\pi}{3}$respectively, without calculating the instants in terms of residual flux for both phases U and W.

As explained earlier, the angle value α is changed on the voltage wave with a step of $\frac{\pi}{6}$, starting from the value 0 to the target of 2π and the results are shown in Figs. 12 and 13 are for the values of the angle $\alpha = \frac{\pi}{2}$ and $\alpha = 0$, respectively

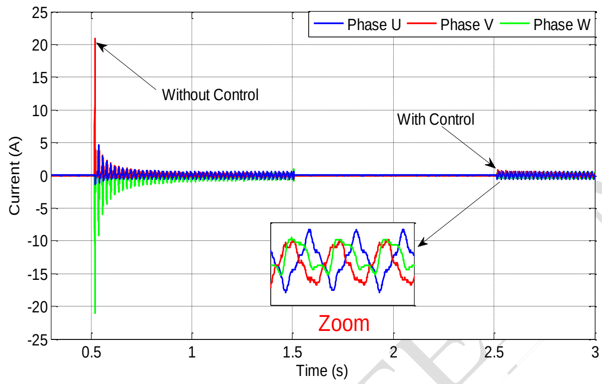

Figure 12. Inrush current mitigation with a point on voltage waveform angle$\alpha = \frac{\pi}{2}$.

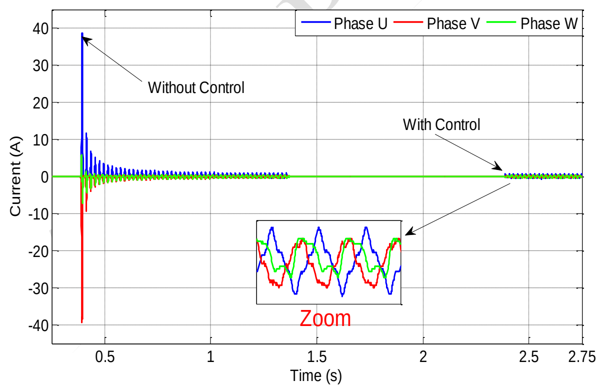

Figure 13. Inrush current mitigation with a point on voltage waveform angle $\alpha = 0$

5. DISCUSSION

The experimental results, presented in Figs. 12 and 13, show that there is a complete fade-out of the three-phase transformer inrush current upon application of the technique proposed in this article. As anticipated, when the three-phase transformer is first switched on, high values of the inrush current occur, due to the random impulse given to the breaker to close at any time without calculating the appropriate and optimal instant, and whatever the angle (α) value.

On the other hand, when the three-phase transformer is switched on the second time using the proposed technique, which calculates the optimal moment for closing the breaker, it is noticeable that there is no occurrence of the inrush current (only of the magnetizing current), because the circuit breaker is closed at the same point of the voltage wave as where it was opened. This proves the efficacy of the proposed technique to control and mitigate the inrush current for three-phase transformers.

CONCLUSION

In the work summarized in this article, a control technique was proposed to reduce and eliminate the transient regime when a three-phase transformer is switched on. The proposed algorithm is based mainly on a strategy of compensating the residual flux value of the first phase U in the three-phase transformer core by the instantaneous value of the flux at the closing instant of the breaker.

This technique was tested in the laboratory measurement configuration in real-time using the data acquisition system (dSPACE card). The results obtained demonstrate the reliability of the control technique. Moreover, it also enables the optimal closing moment of the breaker to be obtained more rapidly without complicating the calculations. It is also sufficient to calculate the instant just for one phase U and then to calculate the instant for the phases V and W with respect to U.

The proposed technique resulted in a complete mitigation of the inrush current. The technique was applied herein the experiment with a good investigation of the residual flux.

In future work, we intend to apply the proposed technique to reduce and eliminate the transient current resulting from the interaction between three-phase transformers, one of them exposed to the transient regime (energization) while the others are already energized (Sympathetic phenomenon).

LIST OF ABBREVIATIONS

dSPACE: Digital Signal Processing and Control Engineering
ControlDesk : dSPACE experiment software for seamless ECU development.
WAMS: Wide Area Monitoring System
AC: Alternative Current

DC: DirectCurrent

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هدف اصلی این کار کاهش جریان هجومی در ترانسفورماتور سه فاز است. این جریان هجومی هنگام روشن کردن یک ترانسفورماتور بدون بار یا با بار کم ظاهر می شود. می تواند به مقادیر بسیار بالایی برسد و باعث خرابی در سیستم الکتریکی شود. استراتژی کنترل با در نظر گرفتن مقدار شار باقیمانده هنگامی که ترانسفورماتور قطع می شود و همچنین با رعایت تغییر فاز بین سه فاز به دست می آید. برای اندازه گیری جریان هجومی، یک پیکربندی

آزمایشی با یک سیستم اکتساب داده با استفاده از کارت dSPACE 1104 توسعه داده شد و در این مقاله ارائه شده است. تکنیکی برای کنترل قطع کننده مدار برای انرژی دادن به یک ترانسفورماتور سه فاز ۲ کیلوولت آمپر بدون جریان هجومی نیز آزمایش و در تنظیمات آزمایشی اعمال شد. سهم ویژه این کار این است که این تکنیک در اندازه‌گیری‌ها با بررسی کامل شار باقیمانده به کار می‌رود. تکنیک پیشنهادی به حذف کامل جریان هجومی دست یافت.