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## REMANENT FLUX MEASUREMENT AND OPTIMAL ENERGIZATION INSTANT DETERMINATION OF POWER TRANSFORMER

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**Abstract** – The inrush currents generated during a energization of power transformer can reach very high values and may cause many problems in power system. In this paper method for controlled energization of power transformer based on measuring of remanent flux of magnetic core is presented. The remanent flux is measured and memorized at the last de-energization of transformer and then applied at next energization. Experimental results of inrush currents at controlled energization of transformer are presented.

Keywords: inrush current, remanent flux, transformer.

### 1. INTRODUCTION

The energization of a power transformer can generate high amplitude of inrush currents, which stress the windings and can cause maloperation of protection relays and fuses and prolonged temporary harmonic voltages, which in turn lead to a degradation in the quality of electricity supply [1,2].

The flux in a transformer energized by a steady-state alternating voltage varies from a peak negative value to an equivalent positive value during one half-cycle of the voltage wave. At a de-energization of transformer a remanent flux can remain in transformer magnetic core. If this remanent flux is of the same polarity as the prospective flux at the energization of transformer then the inrush current can reach very high values [1,3].

To reduce the magnitude of inrush currents a controlled switching may be applied for energization of power transformers [4 -6]. Instant of circuit breaker closing need to be synchronized with supply voltage taking into account the remanent flux of magnetic core. To achieve a controlled energization the remanent flux have to be measured.

The practical problem is measurement of remanent flux because an implementation of ordinary magnetic field sensors. In this paper a method for remanent flux determination and on its base controlled energization of power transformer is presented. The remanent flux is measured at the last de-energization of transformer and memorized. This memorized value is then used for an optimal instant determination at the next energization of transformer. It is shown by experiments that magnetic core

hold on the remanent flux during the time in wich transformer is disconnected from power supply.

The proposed method was implemented on a laboratory prototype for optimal energization of power transformers. The validity of this method was confirmed experimentally on laboratory prototype. It was verified that the inrush current transients are eliminated using this method for energization of power transformers.

### 2. TRANSFORMER INRUSH CURRENT PHENOMENA

Because of economic reasons power transformers are designed to operate close to saturation point. When the power frequency voltage  $u$  is applied on primary winding of a transformer a flux  $\phi$  is established in the core. Ignoring losses, relationship between the applied voltage and core flux is

$$u = N \frac{d\phi}{dt} \quad (1)$$

where  $N$  is number of turns of the primary winding. Applied voltage is

$$u = U_m \sin(\omega t + \alpha) \quad (2)$$

where  $U_m$  is applied voltage peak and  $\alpha$  is phase angle. Substituting (2) in (1) and integrating yields

$$\phi = -\frac{U_m}{\omega N} [\cos(\omega t + \alpha)] + k \quad (3)$$

Taking that normal flux peak  $\phi_m = (U_m/\omega N)$  the constant  $k$  of integration at the phase angle of energization  $\alpha$  is

$$k = \phi_r + \phi_m \cos \alpha \quad (4)$$

where  $\phi_r$  is remanent flux of core.

And finally flux as a function of time can be expressed as

$$\phi = \phi_r + \phi_m [\cos \alpha - \cos(\omega t + \alpha)]. \quad (5)$$

From (5) it can be seen that peak flux in the core is dependent upon the closing phase angle and the remanent flux. The peak value of flux can reach two times normal maximum with no residual flux in the core. With flux

superimposed upon the remanent flux the total flux can be higher than twice normal maximum. Fig. 1. illustrates influence of flux on inrush current. The peak transient flux (marked with a in Fig. 1.) exceeds the normal peak steady flux (marked with d in Fig. 1.) and produces magnetizing or inrush current (marked with c in Fig. 1.). This current is the transient inrush current of the transformer and its peak value can be few times higher then the nominal transformer current.

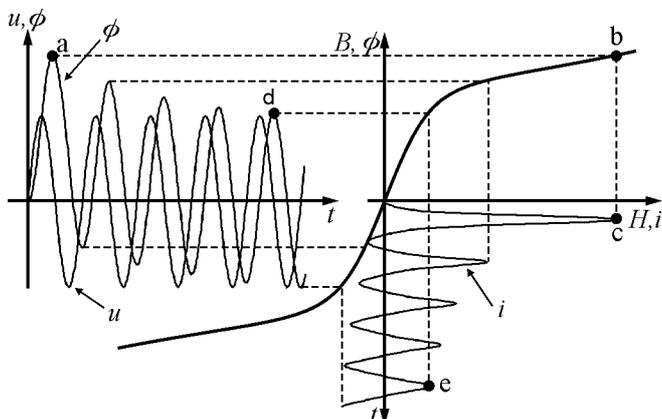


Fig 1. Relationship between the core flux and inrush current of the transformer

### 3. PRINCIPLE OF REMANENT FLUX MEASUREMENT

The method for remanent flux measured is based on Faraday’s low of induction. The remanent flux is measured at the last de-energization of transformer. Measuring system is shown in Fig. 2. At a same time when the transformer is switched-off the switch S is closed. When the secondary winding of transformer is no loaded the secondary voltage  $u$  is measured during the transformer switching off.

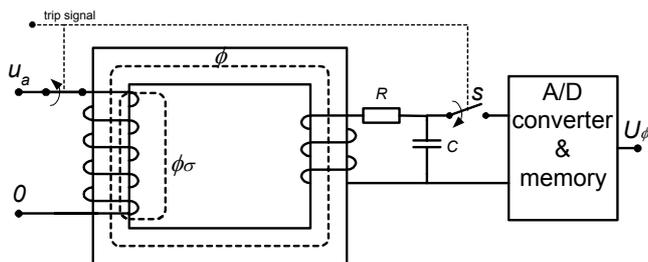


Fig. 2. Remanent flux measuring system

From the Faraday’s low induced voltage in the secondary winding is

$$u = -N \frac{d\phi}{dt} \tag{6}$$

Integrating the measured voltage the flux  $\phi$  in a moment of switching-off is obtained

$$\phi = -\frac{1}{N} \int u dt \tag{7}$$

For an integrator we used a serial connection of high ohmic resistor and a low capacitance capacitor, Fig. 2. The voltage on the capacitor is proportional to the remanent flux of the transformer. This voltage is memorized and used as an information for optimal instant determination at the transformer energization.

As it can be seen this method is relatively simple and its main disadvantage is that the remanent flux is determined at the instant of last de-energization not as it can be expected at an instant before energization of transformer. However the experiments show that remanent flux of transformer when the transformer is disconnected does not change significantly [7]. Because of that the remanent flux measured in such way can be used for determination of optimal instant for the power transformer energization.

### 4. OPTIMAL ENERGIZATION INSTANT

The flux in a transformer energized by a steady-state alternating voltage varies from a peak negative value to an equivalent positive value during one half-cycle of the voltage wave. At a de-energization of transformer a remanent flux can remain in transformer magnetic core. If this remanent flux is of the same polarity as the prospective flux at the energization of transformer then the total flux can be higher than twice normal maximum, Fig 3.

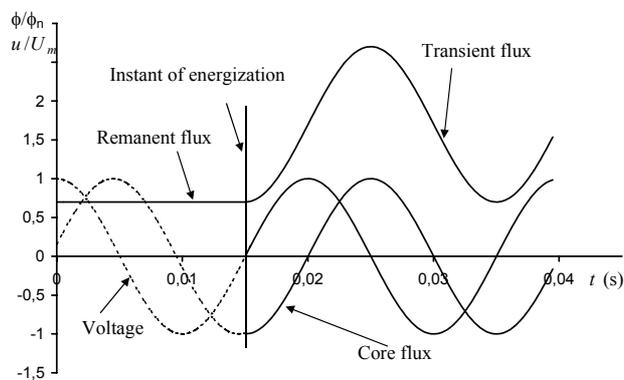


Fig. 3. Transient flux appearance

The optimal instant for transformer energization is point where remanent and prospective flux are equal, Fig. 4. If the transformer is energized at optimal instant then the inrush currents transients are eliminated.

There are two optimal energization instants per cycle of power frequency for a single phase transformer. In these instants a prospective (virtual) flux is the same as the remanent flux and both instants have same priority.

For transformers that have delta windings or three legged cores the situation is more complex. Here the core fluxes are not independent. For the three phase transformers, looking only one phase, there is also two optimal instants. But because of remanent fluxes in other two phases it is shown that the only one instant is optimal [7].

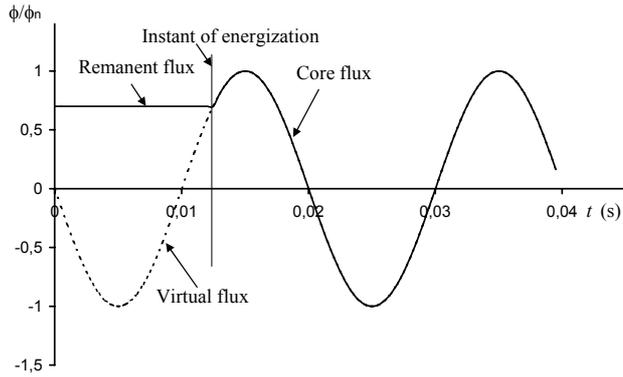


Fig. 4. Optimal instant of transformer energization

5. EXPERIMENTAL RESULTS

The experimental system for optimal energization of a three phase power transformer has been set up and tested, Fig. 5. Since the core fluxes in three phase power transformers are not independent the remanent fluxes  $\phi_{ra}$  and  $\phi_{rb}$  in phase  $a$  and  $b$  are measured. On the base of this fluxes and synchronization voltage  $u_{sync}$  logic circuit determine the optimal instant for energization.

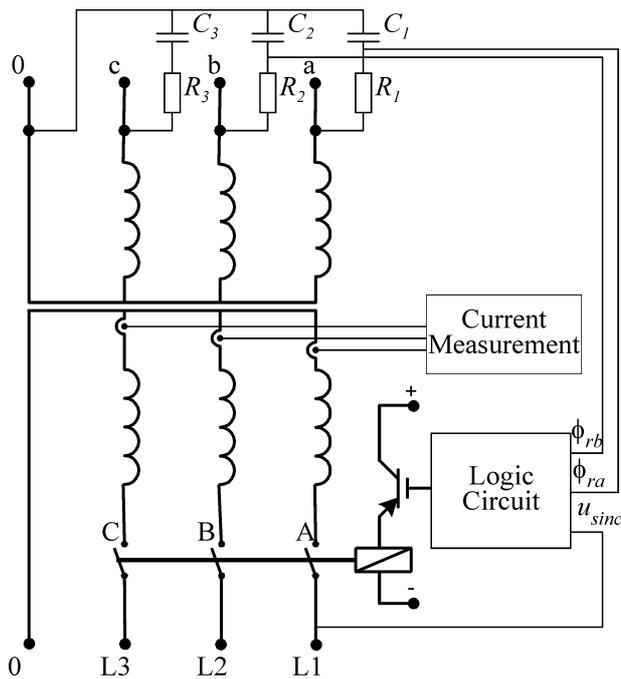


Fig. 5. System for transformer controlled energization

For verification of proposed method the inrush currents of the transformer are measured. Fig. 6. shows measured inrush current waveforms and Fig. 7. shows time propagation of harmonic components of inrush current in phase  $a$  for non controlled energization. As it can be seen from Fig. 6. and 7. the peak value of inrush currents are few times higher than the transformer nominal current and there are significant amount of harmonics.

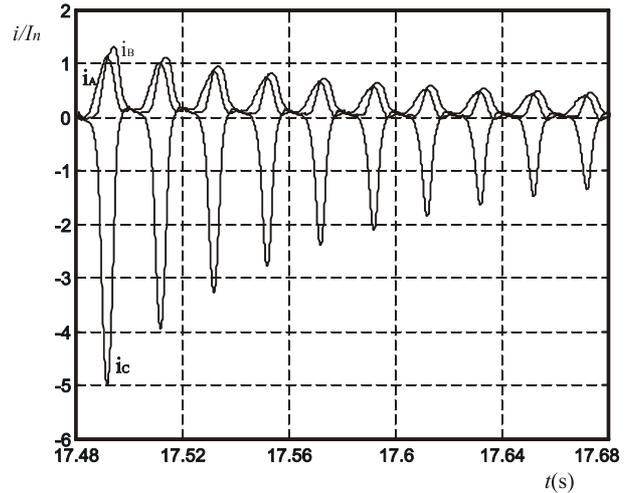


Fig. 6. Inrush current waveforms for non controlled energization of three phase transformer.

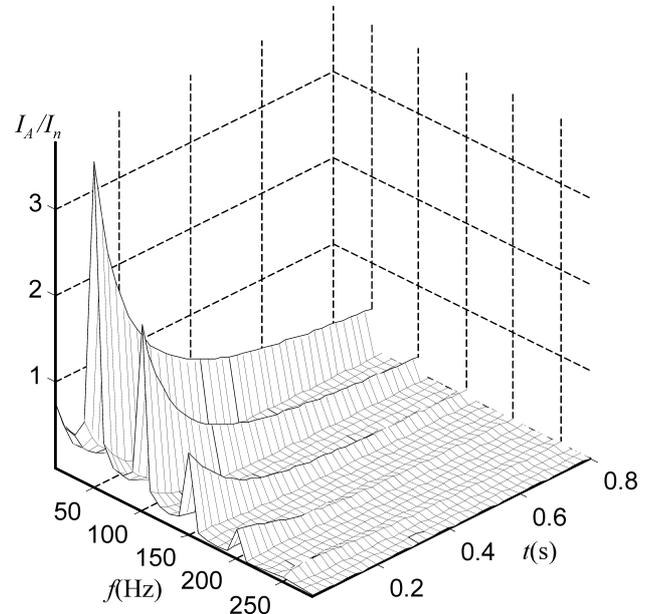


Fig. 7. Time propagation of inrush current harmonic components in phase  $a$  for non controlled energization

Fig. 8. shows measured current waveforms and Fig. 9. shows time propagation of current harmonic components in phase  $a$  with transformer energization at optimal instant. From the Fig. 8. and 9. it is obvious that the inrush current transients with controlled transformer energization are eliminated.

Finally, the inrush currents of the transformer are measured during the sequentially transformer energization and de-energization. Fig. 10. shows current in phase  $a$  for sequentially transformer energization and de-energization. Because of simplicity the current envelopes (maximum and minimum value in each period) are shown. It is shown that proposed method is good solution for controlled transformer energization.

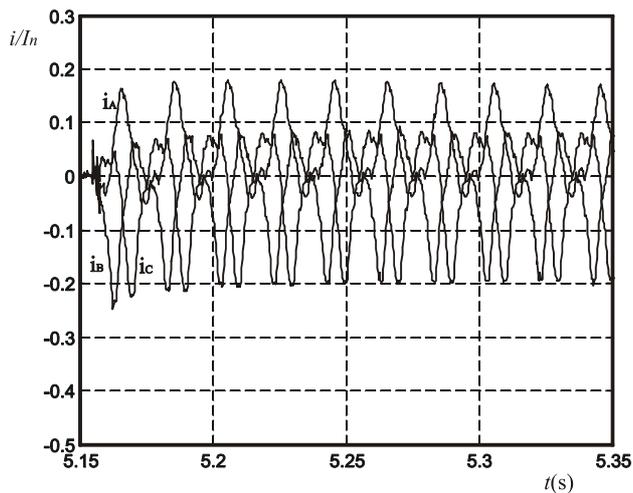


Fig. 8. Inrush current waveforms for controlled energization of three phase transformer

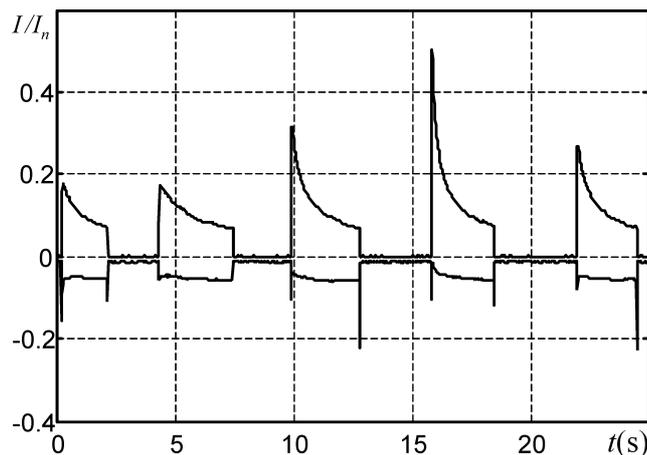


Fig. 10. Current envelopes for sequentially transformer energization and de-energization

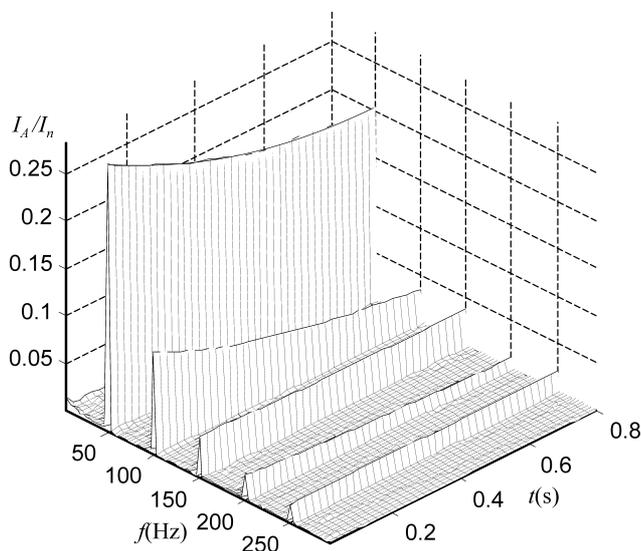


Fig. 9. Time propagation of inrush current harmonic components in phase a for controlled energization

### 6. CONCLUSIONS

In this paper the method for remanent flux measurement of unloaded transformer is presented. The algorithm for optimal energization instant of transformer using measured remanent flux is developed. The experimental system for optimal energization of a three phase power transformer has been set up and tested. The verification of algorithm for optimal energization was carried out by a comparison of the inrush currents. Inrush currents are measured for non controlled energization and for controlled energization of transformer. Experimental results show that the inrush currents transients are eliminated using this method for energization of three phase power transformer.

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