A NEW TECHNIQUE FOR MITIGATION OF TRANSFORMER INRUSH CURRENT

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ABSTRACT

Transformer inrush currents are high-magnitude, harmonic-rich currents generated when transformer cores are driven into saturation at the time of switching-on. These have an adverse effect on the security and stability of the power system. In this paper, a new simple and efficient technique for inrush current reduction is proposed. It is based on core flux reduction prior to primary circuit energization. Flux reduction can be achieved by applying a voltage to the core with the help of a tertiary winding. The effectiveness of the proposed technique is established through both computer simulation using PSCAD and laboratory experiments. The investigations indicate that the method reduces the magnetization inrush currents significantly.

INTRODUCTION

Transformers belong to a class of vital and expensive components in electric power systems. The costs associated with repairing a damaged transformer is very high. Also, outages of transformers can interrupt the power supply for considerable durations. Inrush currents are instantaneous currents flowing in the transformer primary circuit when it is energized. They are normally of short duration, usually of the order of milliseconds. Inrush currents are found to have very high magnitude, high harmonic content and a DC component. In the case of three phase transformers, these currents are highly unbalanced [1]. Some of the problems caused by inrush currents are unwanted tripping of protective relays and fuses, mechanical stress on transformer windings, oscillatory torque in motors and resonance in the system [5]. Even though unwanted tripping of relays can be avoided by differential protection, the momentary stress imparted to the windings can reduce the life of transformer windings.

Inrush currents are caused by core saturation [1]. Transformers are designed to operate below the knee of the saturation curve. However, when those are switched-on on no-load, flux builds upto a high value, thereby falls in the saturation region and this causes the current to increase. When a transformer is switched off, the excitation current follows the hysterisis curve to zero. The flux density value will change to a non-zero value B_r, depending on the material of the core. If the transformer is switched on again at the zero crossing instant of voltage, the flux should be at its negative peak as flux lags behind applied voltage by 90°. As per the constant flux linkage theorem, the flux instead of starting from negative maximum value, starts from Φ_r, the residual flux. Flux eventually reaches the positive peak value of $2\Phi_m + \Phi_r$ in the half cycle. This drives the core into saturation thereby resulting in high currents.

Some of the inrush current reduction techniques currently in use are based on eliminating the asymmetry in core flux at the time of switching on. It has been shown that the optimum instant for switching on a transformer is at the peak value of voltage wave [2]. Using a pre-insertion resistor also helps in reducing the inrush current considerably [3]. Changing the core material for reducing the residual flux, or auxiliary windings on the core that act as an auxiliary air gap also helps in reducing inrush currents [4]. However, it is observed that, most of the present techniques for the mitigation of transformer inrush currents are found to be dependent on the switching instant of the breaker.

PROPOSED TECHNIQUE

In this work, a simple and efficient technique is proposed for the reduction of transformer inrush currents by reducing the residual flux in the core, which utilizes an approach similar to the synchronous closing of capacitors. During synchronous closing, the voltage is applied at an instant when its value is equal to the value of voltage due to stored charge in the capacitor. In the case of transformers the problem arises when the value of flux present in the transformer core is not equal to the induced flux. This can be corrected in two ways, either by switching on the voltage at an appropriate instant or by adjusting the flux in the core. In the former method, the switching instant of the breaker is to be controlled, which is not recommended for transformers of high ratings. For adjusting the flux in the transformer, a voltage which is in phase with the primary voltage is to be applied using a tertiary winding. This will produce a flux in the core which will oscillate at 50Hz and then when the primary voltage is applied the flux present in the core will be the same as the flux induced by the voltage. Thus there will not be any asymmetry. The investigations were carried out using PSCAD software. It was found that inrush currents could be reduced considerably using this technique. The simulated results were tested by conducting actual experiments. The experimental results are found to tally with that of the simulations. It was found that even if the AC voltage to tertiary winding is withdrawn after a few seconds, the method was still found to be effective. Hence, the effect of applying a transient voltage was tested.

SIMULATION RESULTS

Transformer with no mitigation technique

The effectiveness of the proposed technique is investigated on a single phase 230V/230V, 1kVA through simulating using PSCAD 4.2. The maximum possible inrush currents are first found out by simulating the transformer circuits. The effect of residual flux is then incorporated in the circuit by connecting a current source in parallel with the primary winding as sown in Fig.1. The residual flux is directly proportional to the current applied. The output of the current source is adjusted such that the residual flux at the time of turn on is equal to 0.8 p.u.

Simulations are carried out for two types of secondary circuits. In the first case, the secondary winding of the transformer is left open. In the second case, a highly inductive R-L series circuit is connected in the secondary circuit. This is based on the assumption that distribution line is a short distance line that can be represented by an RL circuit. Also, transformer at no load condition behaves as a highly reactive RL circuit. The value of resistance is taken as 100Ω and inductor is taken as 0.5H.

The inrush current measured in the primary circuit without incorporating the residual flux is found to be 25A. The addition of residual flux increased the inrush current by about 20A. This is in accordance with the existing theory as proposed in [1].

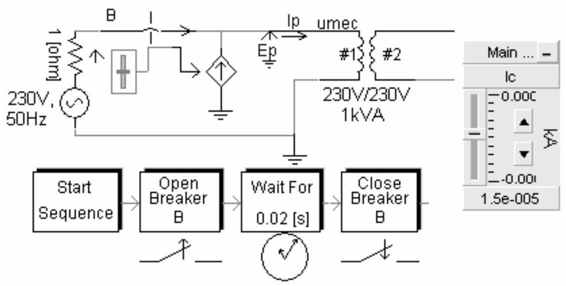

Fig. 1: Circuit used to simulate the unmitigated inrush currents

Thus, reducing the residual flux at the time of switching-on the transformer helps in reducing the inrush currents. The waveforms for an unmitigated transformer are shown in Fig. 2. The inrush currents obtained at various switching instants in both cases are given in Table I.

It can be observed from the waveforms that the inrush currents are unsymmetrical. This is due to flux saturation. In this particular case, the flux rises to a value as high as 2.8 p.u when the primary supply is turned on. Thus in the positive half cycle it will cause a current several times that of rated current to flow. But in the negative half cycle the flux has very low value, hence causes a very low value of current in this half cycle. This phenomenon exists till the flux reduces to its normal value of 1 p.u. The inrush current also reduces as the flux reduces.

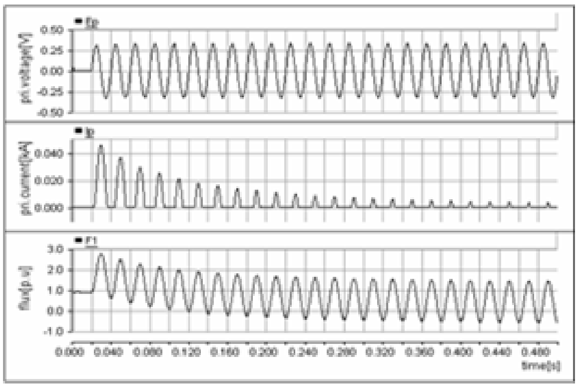

Fig. 2: Unmitigated inrush current and core flux waveforms of a single phase transformer with residual flux in the core

Table I

Peak inrush currents obtained when switched on at various instants for various loads in secondary

Switching Instant (rad)	Secondary open		Secondary with R-L circuit	
	Inrush current (A)	Settling time (s)	Inrush current (A)	Settling time (s)
0	47.47	1.5	49.37	1.3
π/2	21.7	1.3	23.41	1.0
π	-0.27	0.02	2.987	0.02
3π/2	21.7	1.3	24.86	1.0

Transformer with mitigation technique applied

The proposed mitigation technique is simulated by incorporating a tertiary winding rated for 230V. A 230V AC voltage of 50Hz is applied to the tertiary winding initially keeping the primary circuit open. The primary supply is switched-on after a few cycles. The tertiary circuit is opened immediately after the energization of primary winding. Application of voltage with a tertiary winding helps in wiping out the residual flux and reducing the asymmetry in core flux at the time of switching-on. For this it is essential that the primary supply and tertiary supply be in phase.

The applied tertiary voltage, primary voltage and primary current waveforms are shown in Fig 3. The primary voltage is applied 0.1s after the application of tertiary voltage. However there will be a voltage induced across the primary winding due to the voltage across the tertiary winding.

The simulation results given in Table 2, show that this method is equally efficient at all switching instants of the primary supply, unlike most of the existing techniques that are based on controlled switching. The time taken by the current to settle to its steady state value is also reduced. The tertiary winding can be used for some other purpose, if required, as there is no need to retain the tertiary voltage once the primary voltage is switched on. Incorporating a tertiary winding of the same voltage rating as that of the primary winding becomes a costly affair for large power transformers. Hence, reducing the rating of the tertiary winding is tested. It is observed that the tertiary winding rating can be reduced to a value as low as 75V, and still appreciable inrush reduction could be achieved.

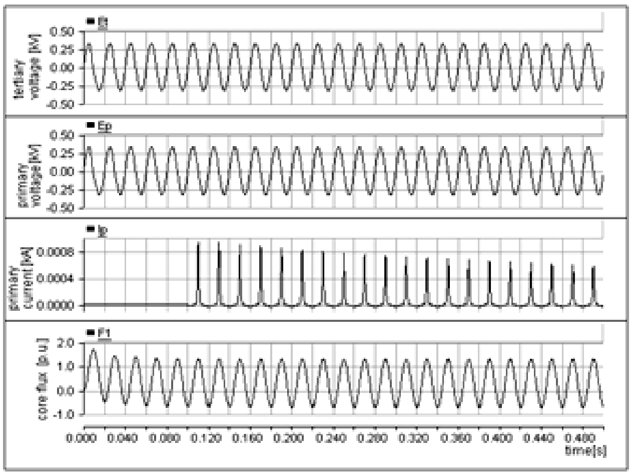

Fig. 3: Mitigated inrush current and core flux waveforms

Table 2
Peak inrush currents obtained at various switching instants when the proposed reduction technique is applied

Switching Instant (rad)	Secondary open		Secondary with R-L circuit	
	Inrush current (A)	Settling time (s)	Inrush current (A)	Settling time (s)
0	1.25	1.0	4.88	0.5
π/2	1.31	0.8	5.33	0.5
π	1.16	0.8	3.98	0.1
3π/2	0.98	1.0	3.37	0.1

From the simulations it is observed that the tertiary winding voltage can be withdrawn within cycles of its application. Hence, the effect of applying a transient voltage to the tertiary winding is tested. In order to apply a transient voltage to the tertiary winding a capacitor is made use of. The circuit used for this purpose is shown in Fig 4. By measuring the values of resistance and inductance of the transformer winding, the value of the required capacitor can be designed.
The capacitor is initially charged from a DC voltage source. At this time it is isolated from the transformer circuit. After charging, the voltage source is disconnected and the capacitor is connected to the tertiary winding of the transformer. The capacitor discharges through the tertiary winding thereby applying a transient voltage across the winding. The value of capacitor and DC source is selected as 10μF and 12V respectively.

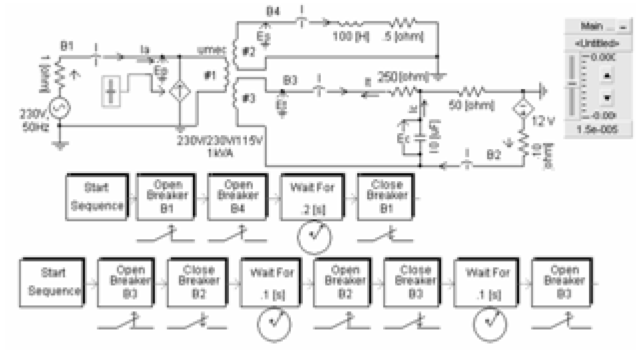

Fig. 4: Circuit used for simulating a transformer with transient voltage applied to the tertiary winding.

In the circuit the breaker B4 is left open throughout to simulate a situation with secondary of the transformer open. Initially, the breaker B1 is kept open, the breaker B2 is closed and the breaker B3 is open. Closing B2 charges the capacitor to the value of the DC source connected to it. After 0.1s, B2 is opened and B3 is closed. Thus the capacitor is disconnected from the source and is connected to the tertiary winding. The capacitor discharges through the winding. Thus a transient voltage is applied to the transformer. This voltage causes the flux in the transformer core to reduce from its initial value to zero. The primary circuit breaker B1 is closed at 0.1s after the application of the voltage to the primary.
The switching instant of the primary voltage is varied from 0° to 360°, the inrush currents obtained are tabulated in Table 3.

Table 3
Inrush currents for various loads in secondary when tertiary winding rating is reduced (switching instant 0°)

Switching instant (rad)	Inrush current	
	Secondary open (A)	Secondary with R-L circuit (A)
0	16.5	13.5
π/2	0.62	0.61
π	-20.63	-22.9
3π/2	-0.11	-0.25

It is observed that on application of the capacitor discharge voltage the initial flux reduces from a value of 0.8 p.u. to 0. Thus the residual flux is wiped out. The waveforms obtained are similar to the case when the residual flux is absent. The waveforms shown in Fig. 5 are for a switching instant of 0°. It can be seen that at 0.1s, that is when the capacitor is connected to the tertiary winding the flux starts to decrease to 0 p.u. from its initial 0.8p.u. Thus flux build up is limited to a value of 2 p.u. Otherwise it would have raised to 2.8p.u.

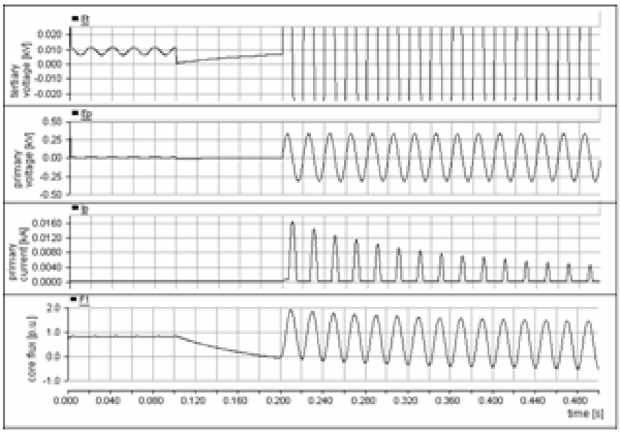

Fig. 5: Tertiary voltage, primary voltage, mitigated inrush current and core flux waveforms of a transformer when transient voltage is applied to tertiary winding

The investigations reveal that the proposed method is capable of reducing the residual flux significantly. However, if the residual flux in the core is far below the value for which it is designed, then there are chances that the results may deteriorate for certain switching instants.

EXPERIMENTAL RESULTS

The experiments are conducted on a 1-Φ 230V/230V transformer with a tertiary winding rated for 115V. The waveforms are acquired with the Yokogawa DL750 Scopecorder and analyzed by using the dedicated software Waveform viewer. Initially inrush currents of the order of 58A are measured when no mitigation technique is applied. Tertiary winding is rated for 115 V. The same voltage is applied to the winding initially and the primary is turned on after some time. This was carried out with the secondary left open. The switching instant was changed by switching on the primary supply at random. It was found that the inrush current reduced considerably.

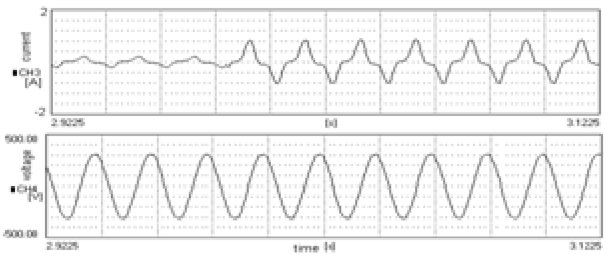

Fig. 6: Measured voltage and current in the primary circuit when 230V is applied to the 230V tertiary winding

CONCLUSION

In this paper, an effective method for suppressing inrush current in single-phase transformers has been proposed. The proposed scheme aims at reducing the flux in the core by applying a voltage across it prior to the energization of the primary winding. The voltage is applied with the help of a tertiary winding. The simulation investigations performed reveal that the proposed approach suppresses the inrush current for single phase transformers at any primary voltage switching instants.

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