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Improved bridge type inrush current limiter for primary grounded transformers

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ABSTRACT

This paper presents a new method for suppression of the transformer inrush current of primary grounded transformers. A newly designed diode-bridge in a neutral winding transformer controls the inrush current using simple power circuit topology without any control or gate drive circuits or measurement tools. Since the number of diodes in this design has been minimized, the ripple and electrical losses decrease while operational reliability increases. The proposed method has been evaluated in laboratory tests and computer simulations. The good agreement of experimental and simulation results verifies the effectiveness of this method.

1. Introduction

When a transformer is energized, a large transient current may flow. The features of this transient or inrush current depend on various parameters [1] such as the amplitude of the applied primary voltage, the instant of the switching, the primary inductance and resistance values and the residual flux in the transformer.

Since this inrush current is a temporary event, it should be distinguished from a short-circuit current, which can damage system components if it is not interrupted by a circuit breaker. In addition, the magnetic stresses of such high currents may weaken the insulation of transformer and result in turn-to-turn faults in the winding of the transformer. Hence, some mitigation methods have been proposed to limit the transformer inrush current.

One of such methods is based on the insertion of resistance in series with the transformer windings or use of an optimally sized grounded point resistance at the neutral side [2,3]. By energizing each phase of the circuit breaker sequentially, the limiting resistance acts as an inrush current limiter (ICL). It was found that the optimal value of a grounded resistor is 8.5% of the unsaturated magnetizing reactance of the transformer [4], and extensive investigation showed that this resulted in an 80% reduction of the inrush current.

Another proposed method is based on controlling the instant of switching [5]. Each switch is closed at the peak voltage by employing phase detector devices, resulting in a considerable decrease in the amplitude of the inrush current. Although these methods have some advantages, they also have disadvantages: they can be costly or need advanced and complicated controlling devices that are able to close switches individually with a time delay equal to a phase difference of 120° [6].

A transformer using an asymmetric winding configuration has been proposed based on a three-layered s–p–s and four-layered s–p–s–p configuration for the cross-sectional part of the primary winding, where s and p are the secondary and primary windings [7], respectively. The main drawback of this structure is its complex design.

Recently, a method using a diode bridge in series with a single-phase transformer was presented in [8]. The structure of the proposed system is simple, and requires no control device, gate driving system or measurement circuit. Hence, the use of these types of bridges to limit the inrush current could be considered the onset of a new generation of ICLs. Although this solution has many advantages, some distortions [8] were seen in the load voltage in the steady-state operation mode, caused by diode voltage drop or the effects of superconductor resistance.

The current study marks the start of a new era for inrush current mitigation using a simple diode-bridge structure connected to a low-resistance coil. The advantages of this solution include the use of fewer diodes, lower harmonic distortion and reduced power losses of diodes in the steady state. Also, other advantages of the proposed method also involves a simple structure and low cost.

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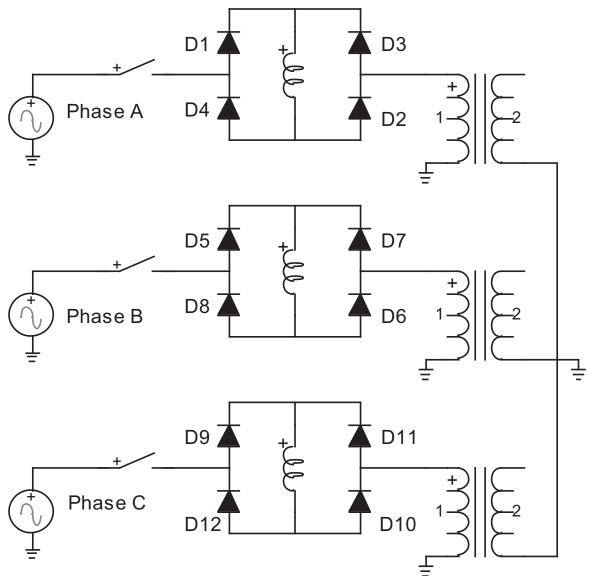

Fig. 1. Diode-bridge, a new generation of inrush current limiter.

2. Three diode-bridges in three phases

As shown in Fig. 1, one of the most recent inrush current mitigation methods is a system, where three diode-bridges are arranged in series with a transformer and a source. Thus, no external control equipment is needed. Furthermore, its simple and low cost structure are other advantages of this ICL system [9,10].

The principle of operation of this ICL consists of two modes; the first mode is the charging mode and the second one is the discharging mode [8].

At first, when the transformer is energized, a pair of diodes from each phase is the forward biased so the DC current reactors are included in the loops. In this case, because of considerable variations in the line current, a large voltage drop ($L_{ICL(di/dt)}$) will occur in the circuit; therefore, the inrush current amplitude will go down considerably. Following this, the charging mode will continue until the ICL's current reaches its first peak value, where the discharging mode starts. In this case, all the diodes are forward biased, so the DC reactor acts like a free wheel in the loops. This procedure will continue for several cycles until the DC reactor current reaches the same level as the line current. After a few cycles, this current will have a smooth DC waveform with constant amplitude. Thus, after the charging mode, the diode-bridges do not have any effect on the circuit operation and act as short circuits [11–13].

In Fig. 2, the phase currents of the transformer are shown. In this case, the inrush current limiter has not been connected to the transformer. Fig. 3 shows the same currents in the case of application of the conventional ICL (shown in Fig. 1). The current reduction is clearly visible.

The use of series diodes seriously limits the applications of the method of Tarafdar Hagh and Abapour [8] to very small transformers having low efficiency. Under those conditions, the inefficiencies of the diodes are not significant. However, for high power applications with highly efficient transformers (more than 99%) doubling or tripling the steady state losses is not an option, this is where the proposed method stands on the other conventional solutions.

3. Power circuit topology of proposed ICL

The use of the diode-bridge based system for inrush current mitigation offers greater benefits than many other methods. This is too colloquial, this method is not flawless. Its drawbacks include harmonic distortion in the load voltage, a higher probability of diode failure, diode voltage drop and increase in resistor value in the DC reactor after a few years. To overcome these problems, this paper proposes a new structure based on a diode-bridge (Fig. 4).

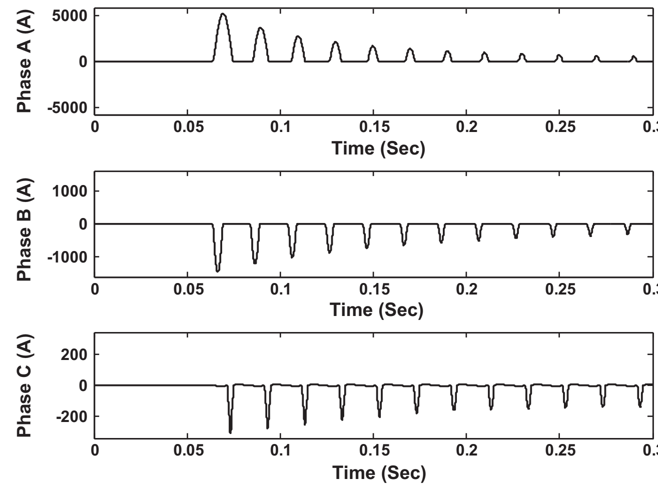

Fig. 2. Test results for phases A–C with no inrush current mitigation (initial flux = 0.8, 0.4, 0.4 and switching time is 60 ms).

As can be seen in Fig. 4, the number of diodes is reduced from 12 (in the conventional methods) to 8. Moreover, it will be shown that the maximum inrush current using this method is approximately half that of the maximum current in the conventional diode-based method. The reduced number of diodes and lower inductance result in lower cost, increased reliability of the ICL, better load voltage quality on the secondary side of the transformer, reduced current ripple and lower losses in the bridge diodes.

3.1. Theoretical analysis

The operation of the ICL can be divided in two modes: charging mode and discharging mode.

3.1.1. Charging mode

When the circuit breaker is switched on, it will go on until the ICL's current reaches its first peak value. Assuming that the circuit breaker A closes at zero degree, D1 and D7 would be forward biased; therefore, according to Fig. 5, i_a, the current in phase A, passes through the ICL inductance and flows to the ground. On the

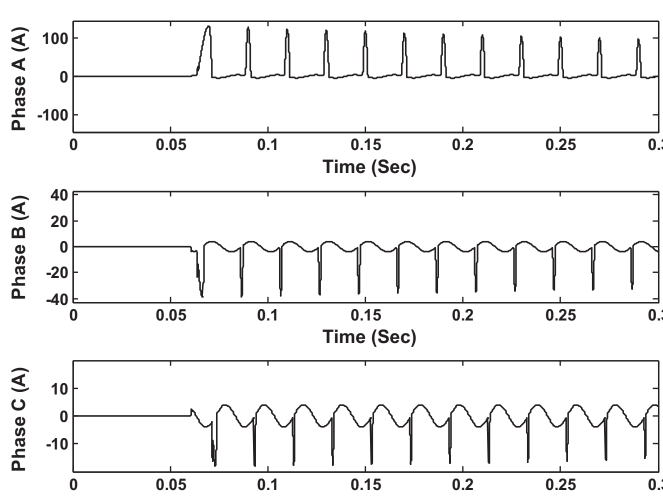

Fig. 3. Test results for phases A–C using conventional inrush mitigation technique.