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Diode Bridge T-type LC Reactor as Transformer Inrush Current Limiter

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Abstract. An improvement inrush current limiter (ICL) is presented to form a highly effective inrush filter which further reduce the inrush current peaks and ripple voltage. The proposed ICL is constructed using a diode bridge and T-type LC reactor consisting of two inductors and one capacitor. The proposed ICL is connected at each phase of the primary winding of three phase transformer. The line current is rectified by the diode bridge and the increase in inrush current is limited by the T-type LC reactor. The proposed ICL is effective in reducing the peak inrush current by 80% more compared to single inductor type reactor. The potential of resonance take place in T-type reactor is completely avoided since the LC filter resonant frequency is very low while the lowest frequency the LC filter will ever see is well above is resonant point. The proposed ICL is numerically tested using simulation package PSCAD.

Keywords: Diode-bridge reactor, inrush current limiter, recovery inrush, transformer protection mal-operation.

1 Introduction

Severe transients are frequently present on the power transmission lines in the form of voltage spikes or voltage excursions, either temporary or in permanent basis. Voltage spikes leads to different adverse effects. Due to transformer core flux cannot change instantaneously, any abrupt change of magnetizing voltage may results in magnetizing inrush currents. If the voltage spike is large enough, it can cause failure of electrical components. In other circumstances, severe transients can cause nuisance tripping in the protective system employed; reducing the reliability of the equipments. Reactors have been employed in electrical transmission systems to depress voltages from lightning strikes and to limit switching currents and fault currents [1]. In 2007, inrush current limiter (ICL) made of diode bridge reactor have been proposed by M. Tarafdar Hagh and M. Abopour [2]. They proposed that a diode bridge is connected at the primary winding of transformer as inrush current limiter such that the line current is rectified by the diode bridge and the increase in inrush current is limited by a single inductor. It needs no controller, no gate driving system and the power circuit topology is simple. This type of inrush current limiter has been applied to solve the problem of transformer saturation in dynamic voltage restoration (DVR) by P. Arboleya etc. in 2009 [3].

In practical, a capacitor or an inductor alone is not used as a filter. This is because the use of series inductance has the disadvantages of decreasing the voltage and current output of the rectifier. When single capacitor is used, the peak and effective values of the rectifier current tend to increase with the capacitor size. On top of that, the ripple factor of inductor filter is directly proportional to the load resistance while the ripple factor of capacitor filter is inversely proportional to the load resistance. These problems can be solved by combining inductor and capacitor to form a LC filter which is independent of the load resistance. Although diode bridge reactor proposed by [1] is effective in alleviating high frequency effects of long cables, reducing rate of voltage (dv/dt) and stress due to uneven voltage distribution, and inrush peaks. However, inductor used alone is only partially effective in reducing the peak voltage appearing at the end of long lines. The capacitive effects of long cables can produce charging current in the order of 10 - 20A which can cause spurious protective trips. A better solution is by combining reactors with capacitors to form a highly effective inrush filter which can further reduce dv/dt and the voltage peaks as well as overcoming capacitive effects of long cables. An improvement of previous diode bridge reactor is proposed by replacing the single inductor with T-type LC reactor as shown in Fig. 1. The incremental cost of adding the filter component to the reactor is minimal.

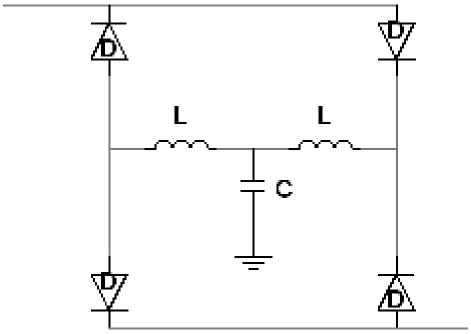


Fig. 1. Diode bridge T-type LC reactor.

2 Diode Bridge T-type LC Reactor Topology

Figure 1 shows the single phase power circuit topology of the proposed inrush current limiter. Three sets of similar circuit are connected to each phase of primary winding of three phase transformer. By selecting a suitable value of L and C, the impact of transformer transient will not affect the output voltage. Indeed, the reactor has no effect on the normal operation of the whole power system. Despite the unintended resonance, T-type LC reactors are frequently used in AC/DC power supply to separate DC voltage from a small amount of high frequency AC voltage. The inductor and capacitor used in T-type LC filter are typically quite large where inductor in several Henry while capacitor in few thousand microfarad; resulting in very low resonant frequency. For example, combination of 5H inductor and 1000μF capacitor will produce a resonant frequency of as low as 2.25Hz. For 50Hz power supplies, the lowest frequency the filter will ever see is 100Hz, which is well above its resonant point. Therefore, the potential of resonance take place in T-type LC reactor is completely avoided. Thus, resonant combinations of capacitance and inductance can be employed to create very effective inrush current limiter [4]. Another side effects of T-type LC reactor that can be neglected is the voltage drop due to reactor resistance. The reactor resistance compared to the system resistance is considered negligible. The only side effect of the reactor will be forward voltage drop across the rectifier diode which resulting in reactor discharge gradually and producing a current ripple through it [2]. The proposed ICL has two modes of operation, charging mode and discharging mode which will be discussed in the following section.

2.1 Charging Mode

The single phase equivalent circuit of charging mode is shown in Fig. 2. In the charging mode, only two diodes are turn on. A.C. current gets dropped across the first inductor and is not allowed to reach the output. The remaining part of the a.c. component which passes through first inductor is by passed through the shunt capacitor. In practice, a small amount of ripple still remains in the output voltage. The second inductor will filter the remaining ripples. Thus, the voltage across reactor limits an increase in inrush current soon after any fault with negligible ripple factor.

Mathematical model developed by [2] will be employed to analysis the circuit in Fig.2. The only difference is the circuit has two groundings, one is source grounding while is other is capacitance grounding. Both cannot be short together in the circuit analysis. By separating capacitor, C, from the circuit, the following equation is obtained.

$$V\sin(\omega t) = ri(t) + Ldi(t)/dt + 2V_{DF} \tag{1}$$

Where $Z_s = r_s + L_s$, $Z_e = r_e + L_e$, $Z_d = r_d + L_d$, $r = r_s + r_e + 2r_d$, $L = L_s + L_e + 2L_d$.

Z_s stands for source impedance, Z_e stands for load impedance and Z_d stands for inductor impedance. By setting initial condition $i(t_o) = 0$, the current equation can be obtained from (1).

$$i(t) = e^{-(r/L)(t-t_o)}\{-\frac{V}{z}\sin(\omega t_o - \theta) + \frac{2V_{DF}}{r}\} + \frac{V}{z}\sin(\omega t - \theta) - \frac{2V_{DF}}{r} \qquad (2)$$

where $z = \sqrt{(r^2 + (\omega L)^2)}$, $\theta = \tan^{-1}(\omega L/r)$. Based on equation (2), z for T-type LC reactor is two times larger than single inductor ICL proposed by [2]. This will results in lower inrush current.

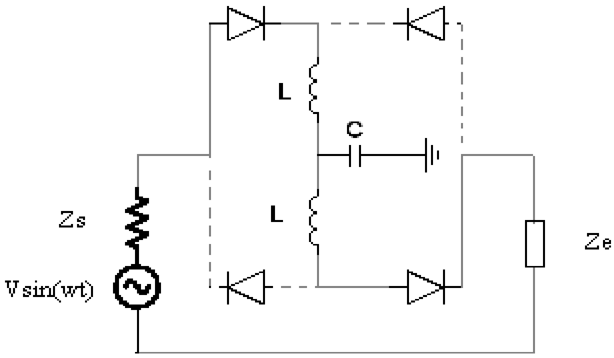


Fig. 2. Charging mode.

2.2 Discharging Mode

Discharging mode starts when the inrush current reaches its maximum value. In discharging mode, all diodes are conducting due to charged current in the T-type LC reactor. Figure 3 illustrates the single phase equivalent circuit for discharging mode. Based on Fig. 3, the following voltage equation can be obtained.

$$V\sin(\omega t) = ri(t) + Ldi(t)/dt \qquad (3)$$

By letting peak inrush current time as t_2, the inrush current during discharging mode is

$$i(t) = e^{-(r/L)(t-t_2)}\{i(t_2) - \frac{V}{z}\sin(\omega t_2 - \theta)\} + \frac{V}{z}\sin(\omega t - \theta) \qquad (4)$$

Where $r = r_s + r_e$, $L = L_s + L_e$, $z = \sqrt{(r^2 + (\omega L)^2)}$, $\theta = \tan^{-1}(\omega L/r)$. The reactor carries only DC current after a few cycles and has no more effect on the circuit operation.

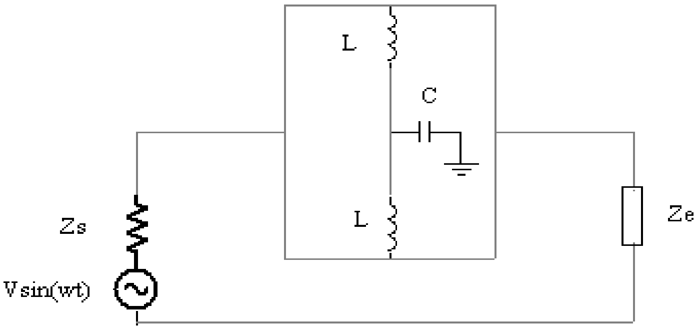


Fig. 3. Discharging mode.

3 Case Study

The proposed diode bridge T-type LC reactor is applied to solved the problem of transformer nuisance tripping due to recovery inrush cause by removal of external fault. The single line diagram of the case study is illustrated in Fig. 4. The paper would analyze the existence of inrush current upon occurrence of an external fault and recovery inrush after clearing an external fault. False tripping due to external fault may occur in two conditions. One condition is when external fault current combined with ratio mismatch would generate a false differential signal. Another condition is when the current transformers saturated during external fault would produce an extra differential signal. Recovery inrush due to clearance of external fault resemble to energizing a transformer. When a near external fault is cleared, the transformer recovers to its normal level. The return of voltage may force a d.c. offset on the transformer flux linkages, resulting in recovery inrush. However, recovery inrush is much lower than energizing inrush and less likely to cause severe saturation of the transformer core. Recovery inrush is similar to energizing inrush if and only if a three phase solid fault occur at the interconnected bus bar and the fault is cleared [5].

The transmission system consists of two power sources each connected to a pair of parallel transformers. Fault was occurred on a transmission line connecting both pair of parallel transformers. However, the circuit breakers connected on each side of the parallel transformers were undesirably tripped because after removal of external fault, there was high recovery inrush flowing through the circuit for a short period of time. The diode bridge T-type LC reactor is applied to solve the problem of nuisance tripping. It is assumed that the fault of three lines to ground occurs at the transmission line at t = 0.3 seconds and this fault is removed after 2 seconds. Fig. 5 shows the comparison between transformer primary side current with and without T-type LC reactor. The important information derived from Fig. 5 is the peak inrush current without T-type LC reactor is as high as 200A, but the peak inrush current is reduced to 2A after T-type LC reactor is connected to the primary side of transformer.

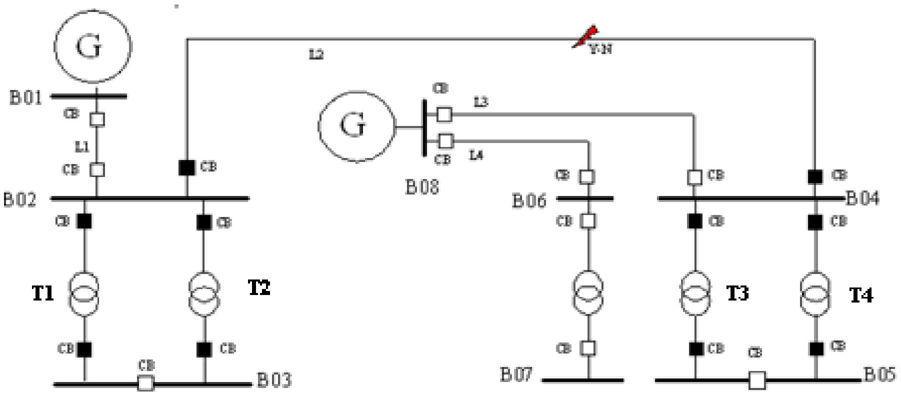
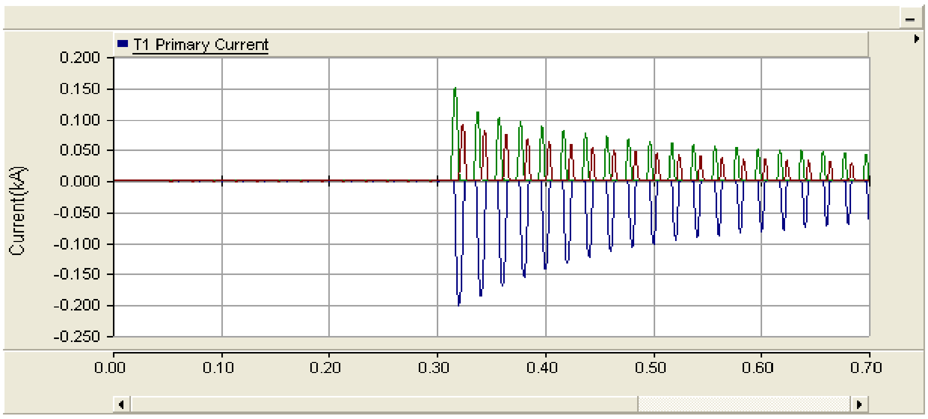
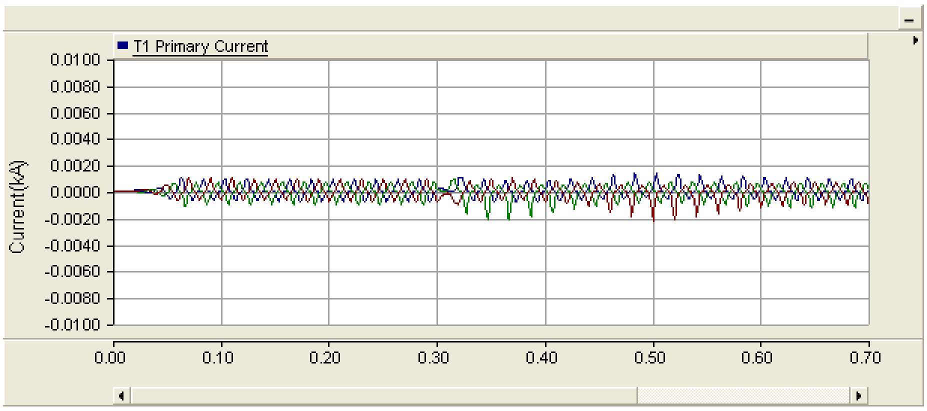


Fig. 4. Single line diagram of the case study.



(a) Without T-type LC reactor.



(b) With T-type LC reactor.

Fig. 5. Comparison of inrush current measured at the transformer primary side.

Fig. 6 shows the comparison of two types of reactors used in diode bridge reactor and their respective peak inrush current measured as in Table 1 and Table 2 for various types of faults. The important information derived from Table 1 is T-type reactor is much more effective than single inductor reactor by further reduced the inrush peak by at least 80%. The T-type reactor works in the way that the inductors should block out any high frequencies, while the capacitor should short out any high frequencies as well; both working together to allow only low frequency signals pass to the load. However, noted that combination of capacitors and inductors would cause resonance in the circuit. The problem is that an LC filter has input impedance and output impedance which must be matched in order to avoid the resonance scenario. The problem can be solved by matching the source impedance with the filter input impedance and matching the filter output impedance with the load impedance to produce a flat response.

Fig. 7 shows the comparison of voltage measured at the primary side of transformer for each type of reactor. In both cases, 0.025 seconds of voltage are affected by the external fault. But the ripple voltage and rate of voltage change for T-type LC reactor is better than single inductor reactor. The calculation shows that T-type LC reactor has 12% ripple voltage lower that single inductor reactor. From these results, it is confirmed that T-type LC reactor is a better inrush current limiter with lower inrush peak and ripple voltage.

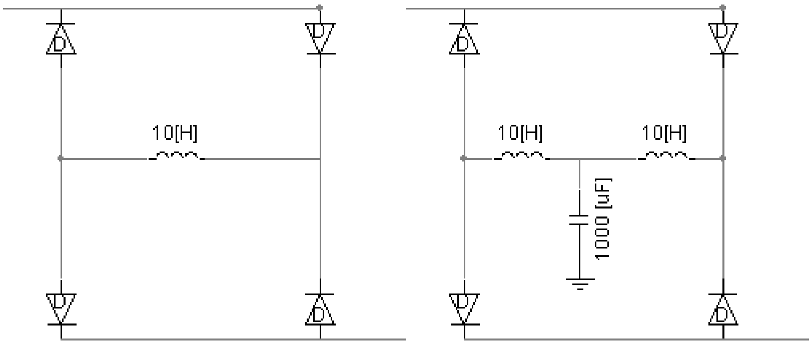


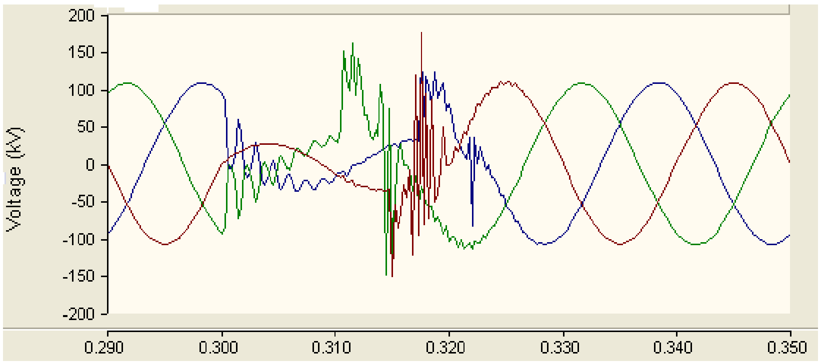
Fig. 6. Left: Single inductor (L reactor), Right: T-type LC reactor.

Table 1. Peak inrush measured based on power circuit in Figure 4 for 10H inductance.

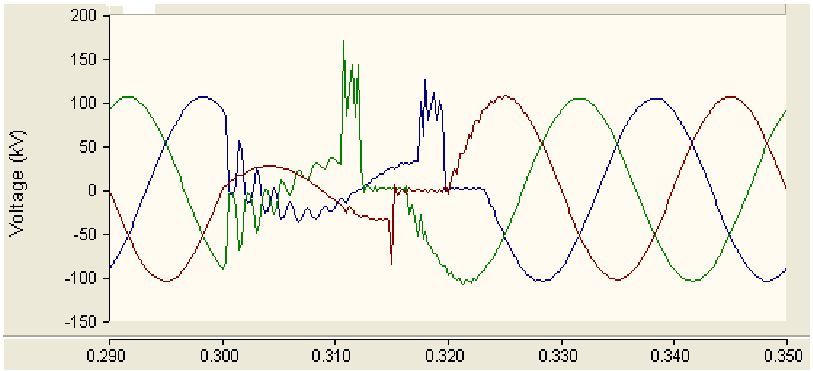
	T-Type LC Reactor			**L Reactor**
Fault Type	1000μF	5000μF	9500μF	10H
AG	1. 5A	3A	5A	18A
ABG	3.5A	4A	6A	20A
BCG	1.3A	2A	2.5A	13A
ABCG	2.5A	8A	10A	20A
AB	1.5A	3A	5A	18A

Table 2. Peak inrush measured based on power circuit in Figure 4 for 5H inductance.

	T-Type LC Reactor			**L Reactor**
Fault Type	1000μF	5000μF	9500μF	10H
AG	2A	2.5A	4.2A	30A
ABG	4A	3A	6A	40A
BCG	1.3A	1.8A	2.5A	22A
ABCG	2.5A	6A	10A	43A
AB	2A	3A	5A	32A



(a) Single inductor reactor.



(b) T-type LC reactor.

Fig. 7. Transformer primary winding voltage upon occurrence of fault at 0.3 seconds.

4 Conclusion

This paper analyzed the use of T-type LC reactor with diode bridge as an inrush current limiter. The paper shows the improvement of new proposed reactor compared to single inductor reactor in terms of peak inrush reduction and ripple voltage reduction. The case study proved that T-type LC reactor is effective in restraining transformer from false tripping due to recover inrush. Further works are the experimental verification and consideration of other application of the proposed inrush current limiter to transmission systems.

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