SELECTION OF EFFECTIVE MITIGATION METHOD FOR INRUSH CURRENT IN POWER TRANSFORMER

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ABSTRACT

Power Transformers are energized depending on load requirement by closing of circuit breakers which generate asymmetrical flux and result into saturation of transformer core. Due to which huge transient magnetizing inrush current is generated. Inrush current can be as high as ten to fifteen times its rated current. The magnitude of inrush current depends upon residual flux, angle of voltage during energization of transformer, source strength, and leakage impedance. This inrush current will further increase if a feeder containing multiple transformers is energized. DC-component of inrush transient currents of the incoming transformer generates additional saturation in the already connected transformers.

The inrush current in transformer could cause many problems from mechanical stress on transformer windings to harmonics injection, and system protection malfunction. Tripping of electrical protective devices may be caused by the asymmetrical voltages and prolonged transient harmonic overvoltage, affecting the stability and reliability of the whole electrical systems. Different methods to reduce this inrush current have been discussed and implementation of Dynamic Voltage Restorer (DVR) to control inrush current is highlighted in this paper.

Keywords: *Dynamic voltage restorer, Inrush current, Mitigation, Saturation, Transformer*

I. INTRODUCTION

The excitation characteristic of the transformer core is a nonlinear relationship between the flux and magnetizing current. The operating range of magnetic field for transformers is in linear region. In the steady state, transformers are designed to operate below the knee point of their saturation curve. However, when transformers are energized, flux can rise to a high value in the saturation region and magnetizing current increases drastically. When a transformer is first energized, a transient current up to 10 to 15 times larger than the rated transformer current can flow for several cycles. Worst case inrush happens when the primary winding is connected at an instant around the zero-crossing of the primary voltage, (for a pure inductance would be the current maximum in the AC cycle). This inrush current will further increase if a feeder containing multiple transformers is energized.

DC-component present in inrush transient currents of the incoming transformer generates additional saturation in the already connected transformers. In fig. 1 two heavy industrial loads are connected to a common feeder. In heavy duty industrial loads, parallel auxiliary transformers are used to

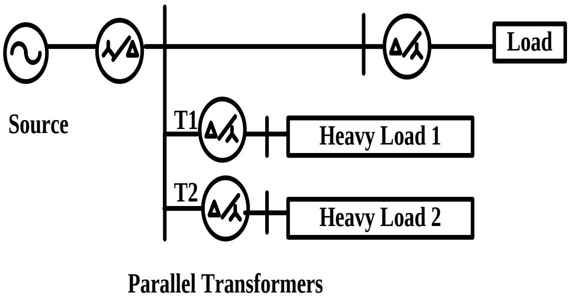

Figure 1 : Generalised power system with power transformer

increase the system performance. When the heavy load 1 is fed by first transformer and load two is switched off due to no power requirement. Load requirement is dynamic and is dependent on the process under consideration. When an additional load is switched on, there is sudden paralleling of transformers. It leads to large inrush current. Long duration transients will result into saturation in the existing transformer core. This affects power quality of feeder and if load power requirement is huge, it has adverse impact on power transmission.

For large transformers with low winding resistance and high inductance, these inrush currents can last for several seconds until the transient has died away and the regular AC equilibrium is established. Saturation of transformer affects performance and increases insulation stress. To avoid magnetic inrush, the inductive load needs to be synchronously connected near a supply voltage peak, in contrast with the zero voltage switching which is desirable to minimize sharp edged current transients with resistive loads such as high power heaters. [1, 2]

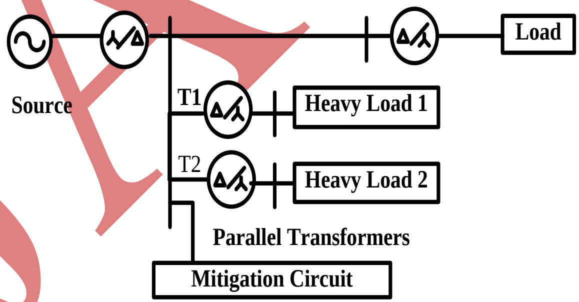

Figure 2: Power System with power transformer inrush current mitigation circuit

Fig. 2 shows in general the connection of mitigation circuit to improve power quality at feeder. Here mitigation circuit has a sensing input and it responds to variation in input signals. As the sensed parameters crosses limit, mitigation circuit is energised which takes corrective action and reduces magnetic inrush current. Reliability and fast response are desired features of mitigation. Inrush current recurrence depends on its own swiching and adjcent transformer switching. If number of transient switching are more, then to maintain consistent performance different methods are analysed.

II. DIFFERENT METHODS

There are many possible mitigation methods which are discussed below are different circuits which are effective in certain operating conditions.

A. NTC Power Thermistor

One of the most common methods used to suppress inrush current is to connect NTC (Negative Temperature Coefficient) power thermistors in series to the line. The resistance of a thermistor varies inversely with temperature and offers variable resistance. One of the main problems with this method is that the thermistor requires a cool down-time to increase its resistance before it can take the next impulse of inrush current. If the system were turned OFF and ON repeatedly in a short amount of time, the thermistors would not have sufficient time to recover in order to limit the current again [1]. Fig. 3 shows effectiveness of NTC to reduce heavy inrush current.

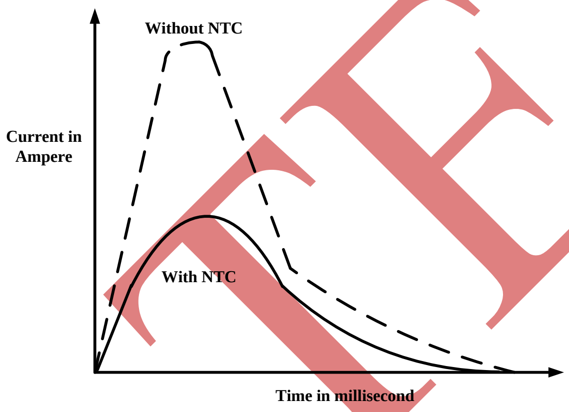

Figure 3 : Effect of NTC on inrush current

B. Current limiting impedance

Current limiting impedance can also be used to limit inrush current of transformer. In fig. 4 current limiting impedance is shown that would be bypassed by a short circuit after some time has passed in order to limit the current at the start, but still conserve power in steady state. This impedance could be a resistor, an inductance, or a series combination of both. The drawback of current limiting impedance is power losses that result from steady state current flowing through them. However, these impedances are commonly bypassed by short-circuiting them to suppress such losses [2].

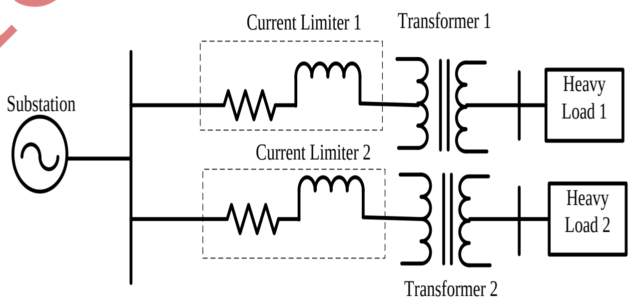

Figure 4: Current limiting impedance on power transformer

The response time of current limiter is decided by its time constant. There has to be optimied value for such circuits which cannot be generalised. When heavy inrush current start flowing through operating transformer, limiter damps its magnitude. It has coulped in such a way which demagnetises to avoid saturation current.

C. Synchronous Closing

Each winding of the transformer should be switched at the maximum of the voltage so that inrush current can be reduced to avoid saturation. Also by triggering the system at a phase angle that is different from the supply voltage source inrush current can be minimized. The concept behind this technique is to trigger the circuit at the specific phase at which the transient response of the circuit would be minimized. In order to trigger the system at a specific phase-angle compared to the voltage source, a delay can be implemented in the switching mechanism that depends on the phase-angle which depends upon the impedance of the system. Such delays are usually achieved by a separate clock, synchronized with the voltage source [3].

If we choose to switch transformers at voltage zero-crossing instant, the calculated inrush currents will be approximately 10% higher. It is observed that the total inrush currents for four, eight, and sixteen transformers are 23%, 26%, and 27% larger than for a single transformer, respectively.

D. Tap changer utilization

To reduce the inrush current, a higher impedance of the winding is required so, connecting the transformer using the maximum number of turns (lowest tap) in the windings to increase the impedance and reducing the inrush current and their effects. This possibility was accepted due to their reduced cost and easy application. Thyristor tap changers may be configured to provide continuous or discrete level control. Continuous control is based on delay angle control, Delay angle control generates harmonics. To achieve little or no harmonic generation, tap changer must provide discrete level control [4].

E. Active Series Compensators

An active inrush current compensator is capable of reducing the inrush current effectively during startup. The proposed compensator is based on an inverter-based series compensator which is comprised of a single-phase inverter and series transformer. Voltage sags are very frequent events with energization of transformer or starting of large motors although their duration is very short. Hence, during voltage stabilizer mode, the existing series compensator is controlled by a voltage stabilizer controller and superimposes a compensating voltage on the inverter output whenever the load voltage deviate from the nominal value. This strategy is easier to implement because it requires no information of the transformer parameters [6]. Each power transformer should have dedicated series compensator. Active series compensator has to be critically designed to avoid losses in the form of heat. The magnetic coupling is again in anti-phase if the amount of current passing through compensator is exceeding set value. Switching in the compensator is fast to have proper demagnetizing effect during transients.

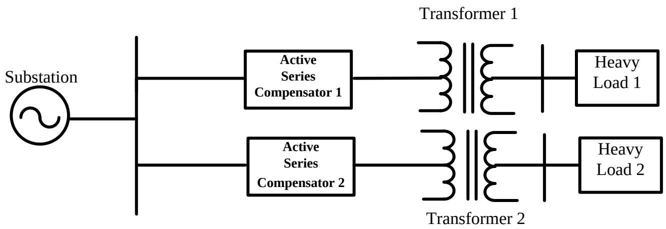

Figure 5: Mitigation by active series compensator

Fig. 5 shows two active series conpensators which are connected in series with respective transformers. They have independent switch mode controller circuits with energy storage elements. Depending on inrush current, active series compensator acts to limit current of transformer.

F. Controlling BH curve of transformer

Magnetising and demagnetizing pattern can be controlled to limit large inrush current . It is achieved by resonanting transformer with LC circuit. It is more optimized for medium loading condition [7].

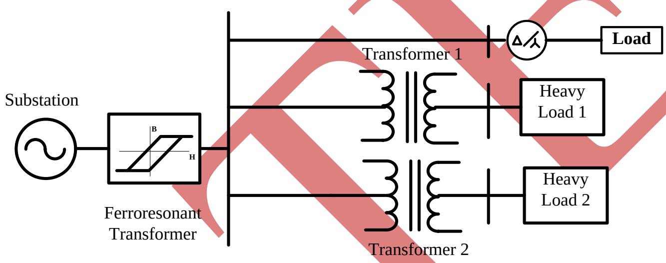

Figure 6: Controlling BH curve for inrush current

Fig. 6 shows ferroresonant transformer connected in series with substation. This transformer is designed in such a way that B-H curve limits individual inrush current.

G. Dynamic Voltage Restorer

Dynamic voltage restorer (DVR) has very fast dynamic response. It is featured for current limiting. Thus impact of overvoltage is less. Along with compensation, the harmonics are minimized to improve power quality. Voltage restoration helps in minimizing the fault impact as well as increase stability [7-8].

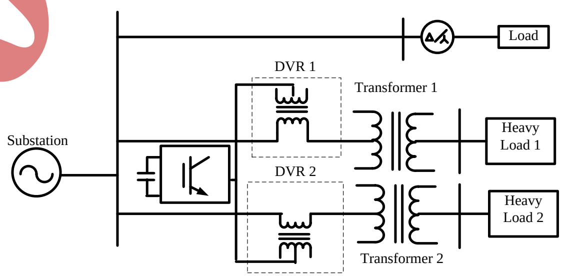

Figure 7: Dynamic voltage restorer as mitigation circuit

In fig. 7 two dynamic voltage restorer are connected in to reduce voltage dip. This is achieved by common controller. It consist of a series transformer, an inverter and a storage device. These components are designed depending in inrush current damping.It has fast recovery compared to power frequency.

H. Ultra fast capacitor

An ultra-fast capacitor (UF capacitor) charging and discharging reduces transients. Ultra capacitor is source of energy. It acts as a dynamic voltage source. Two control switches are connected in parallel and this combination is connected in series. One switch controls charging while another is present in discharging. Controller signals are controlling switches. The closed loop operation can be achieved based in the value of overvoltage [9].

I. Inrush current limiting reactors

This method employs reactors in series with the capacitor bank. The reactor increases the magnitude of the surge impedance, effectively reducing the peak value of the inrush current. Also, since the current through the reactor cannot change instantly, the higher frequency components of the transient are limited and the severity of the current inrush transient is reduced. Sometimes reactors are built intentionally with higher resistances to increase damping of the transient [10].

J. Energized by a less capable source

If energized by a less capable source, such as a generator set, the current inrush would be somewhat less than when energized by a utility line, but still very large because of the large short circuit current capability of a synchronous generator. In either case, the severe power transient induced by switching on transformers can be very disruptive to the electrical system, particularly when it is being powered up.

If the utility line is live, switching on transformers would not induce a significant inrush current if the transformers were to be energized in a stagger mode allowing sufficient time for the inrush current on each transfer to decay sufficiently (typically 2 to 3 seconds) before switching on the next transformer [11].

However, typically due to cost constraints, in most cases the connection between the transformer and the utility line would be made using a fuse protected switch which would not allow for staggering transformer switch-on, and therefore, all transformers would be energized simultaneously. Energizing multiple transformers at once would then induce a much stronger inrush current onto the utility line, but with a reasonable stiff power source it would be well within the utility source capabilities.

III. SIMULATION RESULTS

All methods discussed in the above section are considered based on capacity of transformer. Among all types of mitigation , the DVR technique is found to be more prominent

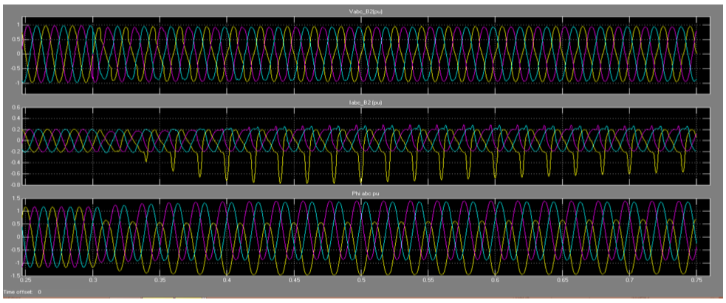

Figure 8: Transient response while paralleling of transformer

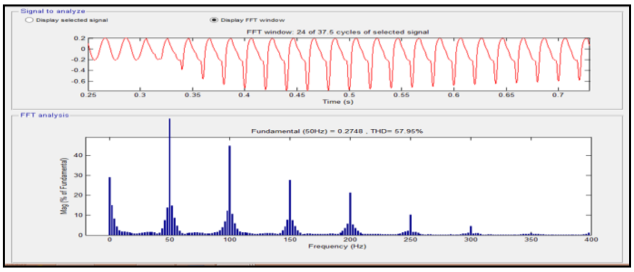

Figure 9: Transient response while paralleling of transformer without Dynamic voltage Restorer

method irrespective of capacity of transformer. Simulation is done to observe parallel performance of transformers. Paralleling of transformers during switching operation is shown in fig. 8. It shows variation in transformer voltages, currents and fluxes. The transients present are high which leads to saturation in magnetic core. Figure 9 shows Fourier analysis of current. It shows large amount of DC and second harmonic component. Large amount of zero and second harmonic of component creates imbalance in fluxes. This has impact on not only core but also insulation strength of both windings .Effect of mitigation on transient operation is observed in fig. 10.This shows less variation in transformer voltages, currents and fluxes. It has less total harmonic distortion

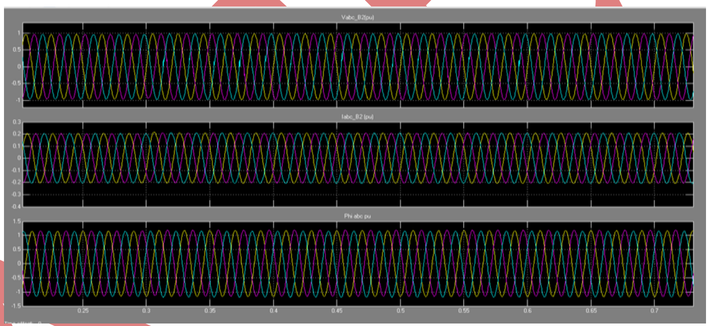

Figure 10: Transients of paralleling of transformer using DVR

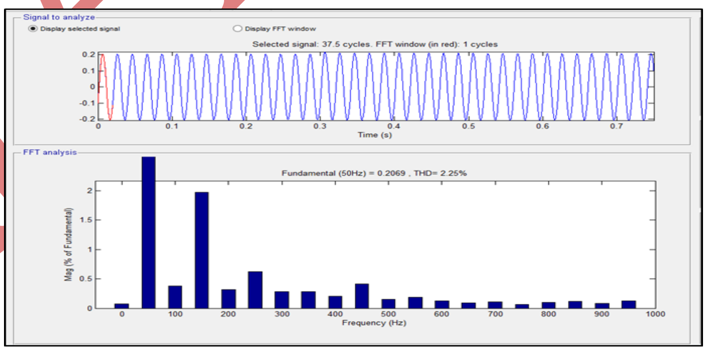

Figure 11: Harmonic analysis transient response while parellilng of transformer using Dynamic voltage Restorer

Fig. 10 and 11 show mitigation using DVR and harmonic analysis. Harmonic spectrum shows large reduction in dc and second harmonic component.

IV. CONCLUSION

In the paper the effects of transformer inrush current on power system and several techniques have been mentioned which can mitigate inrush current due to energization of transformer. Depending upon the system requirement and costing, method can be chosen. NTC is most common and widely used device for inrush current mitigation where the frequency of operation is limited. DVR systems have the advantage that they are highly efficient and have very fast response. Tap changer method is one of the cheapest techniques. This method has variable and accurate control. Synchronous closing is the most efficient and can reduce the inrush current to great extent. Ultra-capacitor is more attractive futuristic mitigation method. This paper highlights on DVR mitigation technique by using proper simulation and analysis of with and without mitigation. Simulation results shows large reduction in harmonics and thus in total harmonic distortion of power transformers.

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