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Ferroresonance: Causes, Effects and Remedies

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ABSTRACT

Electricity power distribution networks are sometimes disturbed by a phenomenon known as ferroresonance. Causes, effects and remedies of ferroresonance are discussed in this paper. It is a nonlinear resonance in transformers which occurs during switching operations and lightning on networks containing inductors, capacitors and iron core materials that easily saturates. Over voltages, over currents and distortions results, causing overheating, damage to equipment, transformers and sometimes explodes. Difficult to predict, hence, in solving its problems, no mathematical solution is applicable yet. However, theoretical principles, simulations and measurements are commonly adopted. Secondary sources were used and the paper undoubtedly shall guide designers, manufacturers of transformers and operating personnel to ensure equipment longevity and safe operations for effective service delivery.

Introduction

Ferroresonance occurs when inductance, capacitor and iron core that saturates easily are connected in a circuit, particularly potential transformers used for stepping down voltages. Power transformers also suffer from this phenomenon during switching operations and lightning. According to Mork (2006, Vaughn, 2012), ferroresonance in transformers was first reported in 1907 and Boucherot in 1920 used the term ''ferroresonance'' to describe a complex resonance oscillation consisting of series resistance, inductance and capacitance (RLC) circuits. It's resonating occurrence does not follow any particular pattern, thus, termed nonlinear.

The phenonmenon was identified in 1930s when series capacitors were used to improve voltage regulation in distribution systems (Mork, 2006), shown in figure 1

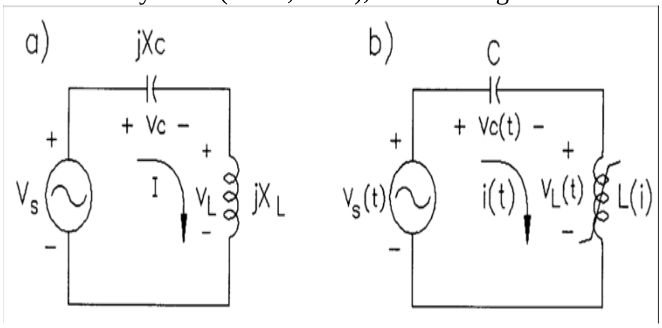

Figure 1. (a) A linear L-C circuit, and b) a nonlinear L-C circuit. Source; Mork (2006).

Following the destructive nature of ferroresonance, researchers developed interest in power systems consisting of capacitors, core materials that easily saturates. Transformers become the prime equipment in studying ferroresonance in electrical transmission and distribution systems due to its saturable core. The capacitive reaction arises from circuit components such as circuit breakers, grading capacitance and in transmission voltage transformers (Vaughn, 2012).

Systems with low resistance are prone to ferroresonance, mostly in voltage transformers supplying measuring devices that easily resonates. Ferroresonance conditions commonly manifests after circuit disturbances from transient, lightning or switching operations, producing sustained overvoltages and overcurrents leading to current and voltage waveform distortion, destroying transformers and other equipment connected to it.

Simulation on three-phase, 100kva, 33/0.415kv power transformer considering Ferrranti rise, results into 24.0kv and 46.7kv loaded and unloaded lines respectively, revealing ferroresonance induced stress on line insulations (Ezechukwu , 2009).

Factors influencing ferroresonance

(a) Initial conditions of the system. These include initial charge on capacitors. When the transformer is not saturated, current flow is near zero with the capacitor not charging or discharging. But, as transformer getting saturated, the transformer voltage falls to almost zero.

(b) The nature of transformer iron core saturation. Saturation depends on material's ability to saturate easily. An inductive iron core in series with a capacitor supplied from alternating current source produces the following results;

i. Nonlinear oscillation from an unloaded transformer due to inductance.

ii. Grading capacitance involving circuit breaker causes inductance in electromagnetic voltage transformers.

iii. During OFF and ON operations of an unloaded transformer, electrostatic coupling produces capacitance.

(c) Residual fluxes in the transformer core. In Abdulsalam el al, (2006), during energization, the initial fluxes will be the same as residual fluxes of the transformer windings. As energization increases, flux also increases, reaches maximum causing saturation and reduces thereafter.

(d) Type of transformer winding connection. According to Abdulsalam (2006) the delta winding current depends only on the rate of change of flux 'induced voltages at the secondary. And in testguy.net (2018), a three-phase, four wire primary star-delta connected transformers rated between 25kva and 35kva, on energizing or de-energizing may cause ferroresonance when single-pole switch is used in the primary side. Baitch(2000), unloaded delta/star connected transformer and long power cable switched on at the same time using single-phase switchgear can result into ferrorresonance.

(e) Capacitance of the circuit. When a coupling capacitance is used with a nonlinear magnetizing inductance of a transformer, the capacitor voltage can cause varying oscillations leading to ferroresonance (Kumar and Ertem, 2018)

(f) Point-of-wave switching operation. Energizing transformer at different points on the voltage wave induces varying ferroresonance oscillations (Chakravarthy and Nayar,2018)

Due to nonlinearity and complex nature of the above factors predicting ferroresonance becomes extremely uncertain, or the use of mathematical calculations in providing its solution is not possible (Mork, 2006). Theoretical approach is adopted in this paper using secondary sources.

Ferroresonance

Application of magnetizing force to a ferrous (iron) material produces flux density, results in saturation due to nonlinearity of such materials. At saturation, no additional contribution to flux can be provided by the material. Saturation is therefore a function of the magnetic materials involve and it's working flux density. Ferroresonance is a situation where the nonlinear magnetic properties of iron in transformer iron core interact with capacitance existing in electrical network producing a nonlinear tuned circuit with an unexpected resonance frequency (Abdallah, 2005). During ferroresonance, voltage or current jumps from one stable condition to another.

Using aged underground systems increases incidence of ferroresonance, leading to dangerous conditions for equipment, systems, operating personnel and customers (Vaughn, 2012). However, in Csanyi (2015), field measurements and experiments were conducted and the voltages measured. Ferroresonance may be identified by noting associated overvoltages, overcurrent, sustained levels of distortion, loud noise (magnetostriction), malfunctioning of protective devices, flickering of electric lights, overheating, electrical equipment damage and insulation breakdown (Valverde et al, nd)

In Askari (nd), field measurements and simulations using nonlinear dynamic method with 400kv/110v, 100VA voltage transformer, star grounded 5-leg core transformers result into transformer failure, cable failure, appliance failure, failed arresters, fluctuating voltages, bubble or charred (burned and blackened from fire) paint on the transformer tank. Similar experiment was reported in Abdallah (2005) using 3kva transformer, 380v/220v, and core-type air-cooling star-star connected. The result as shown below:

(a) Ferroresonance causes hazardous overvoltages and overcurrents in the three-phase core- type transformers

(b) At no-load, the overvoltage and overcurrent increases due to ferroresonace.

(c) Overvoltages and overcurrents during switching from unsymmetrical systems are higher than those obtained from balanced transformers phases.

Ferroresonance occurrence is illustrated in figure 2. Unloaded three-phase transformer with delta connected primary, effectively grounded uses single-pole switches and shielded cables, having capacitance to ground (C). When the switch in phase A is closed, the remaining two phases energizes through the cable capacitances from B-G and C-G. Inrush current flows via the windings of legs A-B and A-C.

On closing the switch (A), the applied voltage could saturate transformer iron core producing abrupt current through the transformer windings and capacitances of phases B and C. Transformer remaining in saturation in and out, line-to-line and line-to-ground overvoltages shall occur, and failure of arresters and insulation in the transformer or system. On the other hand, closing the three-phases at the same time prevent ferroresonance occurrence.

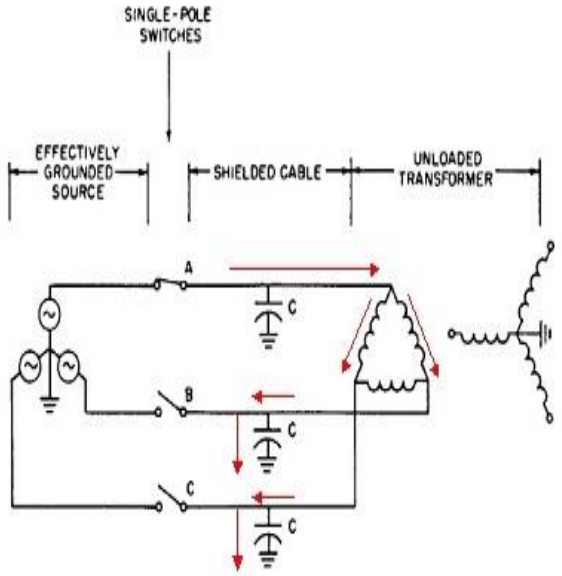

Figure 2. Switching delta connected transformer. Source Yepyep (2012).

Causes

- Unloaded 3-phase system consisting of inductive and capacitive components is interrupted by single phase means (Wikipedia10 Oct.2014, Vaughn, 2012, Veepee, 2012)
- Inadequate knowledge about ferroresonance conditions by operating personnel can cause explosions (Belanger, 2016)
- In Valverde et al (nd), ferroresonance results from saturable (nonlinear) inductance connected in series with a capacitor.
- According to Csanyi (2015), when line capacitance resonates with the magnetizing reactance of an iron core while it goes in and out of saturation.
- During either energization or deenergization, closing a three-phase with one phase open.
- The existence of a series resonance causes very large voltages across the inductive and capacitive (L-C) components.
- A single-pole Voltage Transformer with improper earthing cable, the impedance of the transformer and the earthing constitutes oscillating circuit (Stejkel,2013)
- Blowing of one or more fuses in a distribution system (Yepyep,2012)

Effects

- Overvoltages and overcurrents occur in an electrical power system, may reach twelve times line to ground voltage which is risky to transmission and distribution equipment and operational personnel (Wikipedia10 October 2014)
- Damages to network instruments like surge arresters and series capacitances, lightning arresters, transformers, buried cables and switching devices, breakdown of insulation (Abbasi and Fathi, 2017, Vaughn 2012).
- Output frequency, $F = F_f + F_h$ where F_f = fundamental frequency (50Hz) f_h= harmonic frequency and terminal voltage rises to $E+V_h$, and the current I, rises to I_t+I_h where E=supply voltage, V_h = harmonic voltage, I_t = normal current, I_h= harmonic current. Note: $I_f + I_h$ produces magnetic inrush current (Ezechukwu, 2013).

- In Veepee (2012) unloaded transformer overvoltage during ferroresonance may rise to say 10 times its original value which causes oil filled transformers to ignite and explode like bomb resulting from heated oil.
- Ferroresonance conditions may lead to violent voltage failure and nuisance tripping of protective devices.
- Vaughn (2012 where ferroresonance occur in transformers, oil heats to temperature extremes within minutes, blowing out of vents and bubbling paint on top of the transformer. Surge arrestors destroyed.
- Sizes of iron core materials used for electromagnets and transformers are limited based on saturation.
- The first indication of the condition is usually a very loud rattle of the transformer magnetostriction in the laminated core (Vaughn, 2012).
- In Mork (2006), a three-phase bank of unloaded or lightly loaded single-phase transformers can experience ferroresonance when one or two of the three source phases are disconnected due to switching or fuse clearing
- There could be low-level ferroresonance capable of boiling the life out of a transformer with a whimper (small or weak noise).

Remedy

Appropriate measures need be applied to prevent ferroresonance at all cost and in Milicevic and Rutnik (2008), "the phenomenon is very much unwanted in electrical power systems". Methods required to achieve remedy include the following:

❖ Loading of the secondary above 20 percent is sufficient to prevent resonance or by using a 3-phase interrupting device (Wikipedia10 October 2014)

❖In Veepee (2012) loading depends on cable length and transformer design. However, a 10% load for an open phase may reduce the effects of ferroresonance. When two phases are involved and a long cable length above 1km, the transformer loading should not be less than 25%. Reducing cable lengths decreases capacitive and inductive reactions associated with resonance, but, for delta connected primary, the cable length should not be more than 100 feet (30m). For a star connected primary may be longer.

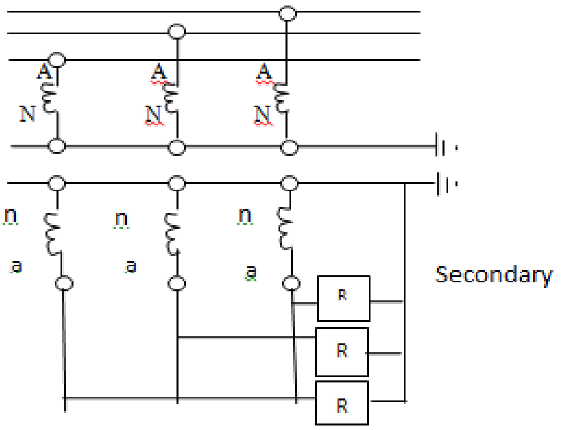

Figure 3. Protection of VT with one secondary against ferroresonance Source; Ferracci, (1998).

❖Veepee (2012), resistance grounding, star connected primary can prevent ferroresonance. The resistance value must be sufficient to avoid the bank from acting as a low-impedance current source, but, low enough to eliminate ferroresonance. Similarly, star connected transformers with both neutrals grounded and linked to the system neutral.

❖In designing voltage transformers, it is important to use magnetic core materials that may not saturate within line voltage range.

❖Introducing losses by connecting loads prevents ferroresonance (Ferracci, 1998, Ezechukwu,O.A , 2009) such as VT with star connected one load each secondary or delta connected two loads one resistor, illustrated in figures 3 and 4 respectively.

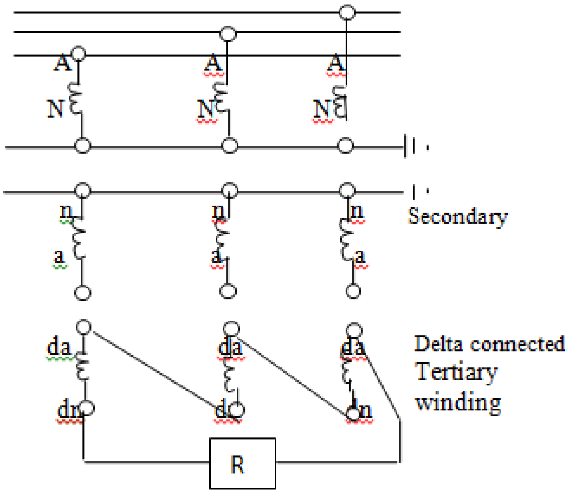

Figure 4. Protection of VT with two secondaries against ferroresonance. Adapted from (Ferracci.1998).

❖Decreasing the capacitance to well below that necessary to sustain triple frequency.

❖Proper training of field personnel (Veepee,2012)

❖For unearthed primary connections, surge arresters can reduce overvoltage associated with ferroresonsnnce.

❖In Ezechukwu (2009), designing of transformers should accommodate 25% overload and 16% increase in insulation and conductor sizes.

❖According to Gajjar (2008), damping of oscillation is very important.

Conclusion and Recommendation

The causes, effects and remedies of ferroresonance are presented in this paper. The study reveal that during switching or lightning or similar transients, iron core materials saturates, leading to abrupt and abnormal rise in voltage, current and frequencies as the systems jump from one stable state to another.

Ferroresonance is complex, difficult to predict and defy mathematical solutions. In ferroresonance or nonlinear resonance, the inductive reactance depends on both frequency and the magnetic flux density of an iron core. Saturation of the iron core materials in distribution transformers after circuit disturbances is dangerous to both equipment and operating personnel. Field measurements, simulations and experimental activities confirm that ferroresonace is hazardous and complex, require proper understanding by field workers.

The paper will be valuable to designers, manufacturers, operators of transformers, transmission lines and distribution systems in order to secure equipment longevity, operational safety and service continuity for customer's satisfaction, particularly, when causes are timely identified and preventive (remedies) measures correctly applied.

Recommendations

➢Designers should ensure better iron core materials capable of reducing ferroresonance

➢Field personnel to be more safety conscious when operating transformers, transmission lines and distribution networks

➢Proper training of operators to understand ferroresonance conditions.

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