The study of ferroresonance effects in electric power equipment

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Abstract

Ferroresonance causes overvoltages and overcurrents which may jeopardize the safety of power system equipment. In this paper, a comprehensive study of the phenomenon was made using a 3 phase, core type, 100kva, 33/0.415kv Dy11 power transformer and Matlab simulations. Atani injection substation, in Onitsha, was taken as a model and parameters were taken from there for the studies. The results show that ferroresonance can cause dangerous over voltages and overcurrents in core type transformers.

Methods of mitigating ferroresonance effects in power system equipment are also suggested.

Keywords: Ferroresonance; over-voltage; transformer; power system

1. Introduction

Ferroresonance can cause dangerous over-voltages and over-currents in electrical power equipment, more especially in transformers, inductors and cables (Kirlicek and Taylor,1959). It’s nuisance phenomenon is responsible for the switch-in inrush current in power transformers and other iron core equipment.

2. Ferroresonance calculation in power cables

Ferranti effect (rise)

Figure 1 is an equivalent circuit of a single phase supply cable. The phenomenon is studied along side the Ferranti effect which usually affects the cable insulation in a switch yard and consequently leading to ferroresonance.

The line is represented by a “T” model of Fig 2.1. There will be a rise in voltage at C after load is lost. \( V_{\text{source}} \) is ideal and its voltage remains a power frequency sinusoid with no voltage ‘regulation’

The distributed parameters of the transmission line has the following expressions:

\[
Z_0 \approx \sqrt{\frac{L}{C}}
\]

\[
\mu \approx \frac{Z_0}{\sqrt{L_c}}
\]

\[
C \approx \frac{1}{\mu Z_0}
\]

\[
\omega \left[ L_{\text{source}} + L \frac{1}{2} \right] \approx K \frac{1}{w C l}
\]

Where:

- \( L_{\text{source}} \) = Generator + Transformer inductances
- \( L \) = Inductance per meter of line
- \( C \) = Capacitance per meter of line
- \( l \) = Length of line.

Where

- \( K \) is arbitrary constant.

When \( K = 1 \), there is a true resonance with very high no-load current.
K < 1, a ferroresonance situation with intermediate load, K = \( \frac{1}{2} \), a Ferranti rise effect.
Ferrantic rise is quite a problem with cables and so values which are consistent with cables in Atani injection substation in Onitsha, were selected for this study.

Viz; \( \mu \approx 1.22 \times 10^{-7} \text{ m/s} \)
\( Z_o \approx 50 \Omega \)

\( V_{source} \approx 33KV \sin wt \)
\( w \approx 2\pi \times 50 = 314.2 \text{ rad/sec} \)
\( L_{source} \approx 0.25mH \)
\( R_{LOAD} \approx 45\Omega \)

Solving the above equations;

1. \( L \approx \frac{Z_0}{\mu} \)
\( = \frac{50}{1.22 \times 10^{-7}} \approx 4.098 \times 10^{-6} \text{ H/m} \)
\( \approx 4.098 \mu \text{ H/m} \)

2. \( C = \frac{1}{\mu_0} \cdot \frac{1}{2\pi \times 50} = 1.639 \times 10^9 \text{ F/m} \)
\( \approx 1.64nF/\text{m} \)

3. \( w[L_{source}+L\left(\frac{1}{2}\right)] = \frac{1}{2wCi} \)

So,
\( 2wwCl[L_{source}+L\left(\frac{1}{2}\right)] = 1 \)

Substituting the values in the above equation, i.e \( 2 \times 314^{2} \times 1.639 \times 10^{-9} \times \left[0.25 \times 10^{-8} + 4.098 \times \left(\frac{1}{2}\right)\right] = 1 \)
\( 3.236 \times 10^{-9} \times [0.25 \times 10^{-8} + 2.049 \times 10^{-10}] = 1 \)
\( 8.09 \times 10^{-8} \times l + 6.36 \times 10^{-9} \times l = 1 \)
\( 6.63 \times 10^{-9} \times l + 8.09 \times 10^{-8} \times l - 1 = 0 \)

So finding the length of the line,
\( a \approx 6.63 \times 10^{-10} \)
\( b \approx 8.09 \times 10^{-8} \)
\( c \approx -1 \)
\( x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a} \)
\( x = 387776 \text{ or } x = -388962 \)

But length of a line cannot be – ve.

Hence \( x = l = 387776 = 38.8 \text{KM} \)

4. \( L_{source} \approx 0.25 \mu \text{H} \)
\( \frac{L}{2} \approx \frac{4.098 \times 10^{-4} \times 387776}{2} = 79.5 \mu \text{H} \)

5. \( C_l \approx 1.639 \times 10^{-9} - 9 \times 387776 = 63.6 \text{ uF} \)

Simplifying the T and \( \pi \) Network at Load and no-load conditions;
Before removing the load, the circuit was as shown in Fig2.:

![Fig. 2.0. Ferranti rise in cable under load condition.](image)

Attached MATLAB solution (FERRANTI.M) table1, shows that the Voltage at the end of the circuit, with load in the system is

\( V_{\text{end}} = 24 \text{ Kv Rms} \text{ L-59.1} \)

When there is loss in Load. Fig 2.1 shows the no-load condition

![Fig. 2.1. Ferranti rise on no-load.](image)

\( V_{\text{end}} = 46.7 \angle 0^\circ \text{ Kv rms} \)

Table. 1.Matlab solution output for Ferranti rise of Fig 2.0 and Fig. 2.1

<table>
<thead>
<tr>
<th>OUTPUT OF FERRANTI.M</th>
</tr>
</thead>
<tbody>
<tr>
<td>( v_{\text{end, wl}} = )</td>
</tr>
<tr>
<td>ans = 2.4007e+004</td>
</tr>
<tr>
<td>ans = -59.0923</td>
</tr>
<tr>
<td>( v_{\text{end, nl}} = )</td>
</tr>
<tr>
<td>ans = 4.6737e+004</td>
</tr>
<tr>
<td>ans = 0</td>
</tr>
</tbody>
</table>

The analysis and simplification of the two networks under load and no-load conditions shown above was done with matlab7.5. The solution is described and shown in table 1.0;
Due to the Ferranti Rise, insulation at the end of the line will be exposed to about 24.0kV rms under loaded conditions but 46.7kV rms on no-load. This shows the consequence of ferroresonance. The high voltage at the end of the line reduces the insulation of our power equipment cables and therefore exposing them to risk of damage which may lead to power system failure.

3. Simulation and analysis on a three phase iron core dy11 transformer

The simulation and experimental data are taken at the Control Panel of the Atani injection substation in Onitsha. The study was carried out on a 100KVA 33/0.415KV auxiliary transformer with DY11 vector group and ONAN type. The aim of this simulation is to investigate and measure the sudden increase (jump-up resonance) in voltages and current as a result of the ferroresonance effect. This experiment was carried out in three stages:

a. Measurement of ferroresonance when the transformer is on no-load.

b. Measurement of ferroresonance at unsymmetrical switching of the three phase transformer at no-load.

c. Measurement of ferroresonance when the transformer is on load.

The ferroresonant circuit diagram for this experiment is shown in the figure 3.

![Ferroresonant experiment circuit for 3 Ø DY11 transformer](image)

Fig. 3. Ferroresonant experiment circuit for 3 Ø DY11 transformer.

From the Fig. 3., a series capacitor of C = 4.0μF was used with all primary phases connected to supply (4.0μFis assumed the effective capacitance of the primary phase bushings of the transformer). The rated voltage is about 50KV). The switches, connected to each phase of supply, are in closed position while those at the secondary side of the transformer are in open position, thereby, disconnecting the load. Then, the supply voltage was increased in steps of 2kV from 0 to 34kV and then reduced in same steps also from 34kV to zero using the three phase variable voltage source. In each step in the forward direction as well as in the backward direction, the reading of the supply voltage, V1, the Primary terminal voltages, V2, at phases VAB, VBC, VCA, and the primary current at no-load, I3L, were recorded and plotted in Figs.4,5,6,7, 8 and 9.

![Graph of primary terminal voltage against supply voltage at no-load](image)

Fig. 4. Graph of primary terminal voltage against supply voltage at no-load.

From graphs figures4 and 5, ‘jump’ (rapid increase) due to ferroresonance when the transformer was energized on no-load was observed. This phenomenon of overshoot in voltages and current occurs at

V1 = 20kV causing

i. A jump-up in the primary induced voltage that reached as high as ∆VAB = 23kV
ii. A jump-up in the primary current that reached as high as ∆I = 2.79A

B. Measurement of Ferroresonance during Unsymmetrical switching of Three-Phase Transformer at No - Load

In the circuit of figure 3., the series capacitor of C = 4.0μF was used in series with only two primary phases (B and C) connected to supply. That is, Switch1 is in open position while switch2 and Switch3 are in closed position. Then, the supply voltage was again increased in steps as described in (a) above with other parameters remaining constant parameters remaining.
voltage at no-load during unsymmetrical switching of
the transformer.

From Figures 6 and 7, a ‘jump’ (rapid increase) due
to ferroresonance during the unsymmetrical switching
of the transformer on no-load was also observed. This
phenomenon of overshooting in voltages and currents
occur at \( V_1 = 26 \text{kv} \) causing
i. A jump-up in the primary terminal voltage that
reached as high as \( \Delta V_{AB} = 31 \text{kv} \)
ii. A jump-up in the primary current that reached as
high as \( \Delta I = 3.25 \text{A} \). (Compare with values of the
Primary current of the transformer by calculation,
1.75A, and that by experiment in figure 5 and figure 7).
The jump-up ferroresonance caused by unsymmetrical
switching is greater than that when all the primary
phases are connected to supply.

C. Measurement of Ferroresonance when the
transformer is on load

From the circuit in figure 3.0, a three -phase
constant load impedance, \( Z_L \), was connected across the
transformer secondary windings. This was done by
closing the secondary switch, thereby, connecting the
load impedance to the transformer. The series capacitor
of \( C = 4.0 \mu \text{F} \) was used again with all the primary phases
connected to supply. Then, again, the supply voltage
was increased in steps as described in (a) above and the
graph is displayed in Fig.8. Note the primary induced
voltage recorded in the forward step is the same as that
of the backward step. Also the primary induced
voltages \( V_2 \) is the same in all phases (i.e. \( V_{AB} = V_{BC} =
V_{CA} = V_2 \)).

From figures 8 and 9, it could be seen that under the
load impedance, \( Z_L \), condition, there is no jump-up
voltage or jump-up current (ferroresonance) in primary
terminal voltages and currents. This means that loading
a transformer will reduce or prevent the jump-up
resonance phenomenon.

Figure 10 displays both the normal primary current
and the transient current due to ferroresonance at the
instant the transformer was switched on. It will be
observed that the effect of the transient is to distort the
normal waveform as shown in Fig.11.
Joltage is may be an expensive in Jits, a single (Jacobian 72, the following assertions are ne to ferroresonance. 

6. Alternatives of results of ferroresonance on distortion of primary waveform due to 

3. 4. one in each secondary circuit. It is, current[AMPS] 

0.5 
0.5 
1.5 

-1.5 

time [micro secs] 

primary waveform under ferroresonance condition 

Fig.11. Distortion of primary waveform due to ferroresonance. 

5. Conclusion and recommendations 

4. Prevention of ferroresonance 

Ferroresonance can be prevented by eliminating one of the pre-conditions. Several alternatives of various practicalities include: 

• Preventing the system from becoming ungrounded under any conditions. (This may not be entirely possible. 

• Purchasing a Transformer designed to operate at much lower inductance values, so that the saturation point is at least twice the system voltage (Berrostegueta, J, 2001 ) [This may be an expensive alternative. 

• Introducing losses by means of load resistances. (This is the alternative chosen.) 

In wye-wye connected Transformers, three resistors can be connected, one in each secondary circuit. It is important to pick resistor values carefully, as the resistors connected this way will continuously absorb power and can affect the accuracy of connected metering (Horak J, 2004). 

Where an open corner delta secondary exists, a single resistor across the open delta is advisable(Jacobian D.A,2003,Gallagher et al,1983). This has the advantage that it does not affect the measurement accuracy of the transformer or introduce losses during normal operating conditions. Only during an unbalanced condition (such as may initiate ferroresonance in the first place) does the resistor provide damping. 

The appropriate value of resistance is given (Karlicek and Taylor,1959) as 

\[ 100 \times \omega L_a N^2 \] 

where \( L_a \) is the transformer primary inductance in millihenries and \( N^2 \) is the transformer turns ratio. 

Considering the situations analyzed above, the preventive measures that can be taken to avoid the appearance of the ferroresonance are based in three main points. 

- Avoid the configurations prone to ferroresonance (Greenwood,1971,Mork B. A. et al,1994): Not only during the design process but also during the system normal operation (i.e. selecting the correct combination 

between the transformer connections and the core construction type, three-phase switching, etc.). 

• The system components should be kept out of the dangerous ferroresonance zone (i.e. minimizing the capacitance by switching very close to the transformer terminal, using larger transformers and shorter cables, etc.). 

• Make sure the energy provided by the source is not enough to maintain the phenomenon (Bohmann et al,1993), introducing losses to reduce its effects (i.e. switching transformers with some load, grounding the primary windings through a resistance, etc.) 

References 


