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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 ferroresonce can cause dangerous over voltages and overcurrents in core type transformers. Methods of mitigating ` ferroresonance effects in power system equipment are also suggested

Keywords: Ferroresonsce,over-voltage,transformer,power system..

Introduction

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

FERRORESONANCE CALCULATION IN POWER CABLES

FERRANTI EFFECT (RISE)

Figure 1.0 is an equivalent circuit of a single phase supply cable. The phenomenon is studied along side the Feranti effect which usually affects the cable insulation in a switch yard and consequently leading to ferroresonance.

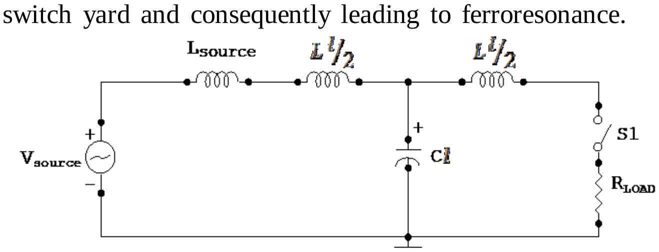

Figure 1.0: equivalent circuit of 1-phase conductor for the calculation of Ferranti rise

Where:

L_{source} = Generator + Transformer inductances

L = Inductance per meter of line

C = Capacitance per meter of line

l = Length of line.

The line is represented by a "T" model of Fig2.l. There will be a rise in voltage at C after load is lost. V_{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.

$$Zo = \sqrt{\frac{L}{C}}$$

$$L = \frac{Zo}{\mu}$$

$$\mu = \frac{1}{\sqrt{LC}}$$

$$c = \frac{1}{\mu Zo}$$

$$\omega\left[Lsource + L\,{}^{l}/_{2}\right] \approx k\frac{1}{\omega Cl}$$

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 = ½ , 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;

$$\mu = 1.22\,X\,10^{7}\ m/s$$

$$Zo = 50\Omega$$

$$V_{SOURCE} = 33kv\ sin\omega t$$

$$\omega = 2\pi f \text{ rad/sec}$$

Where f = 50Hz

$$\omega = 2\,x\,\pi\,x\,50 = 314.2\ rad/sec$$

$$L_{SOURCE} = 0.25mH$$

$$R_{LOAD} = 45\Omega$$

Solving the above equations;

1. $$L = \frac{Zo}{\mu} = \frac{50}{1.22\,x\,10^{7}\ m/s}$$

$$= 4.098\,x\,10^{-6}\ H/m$$

$$= 4.098\mu H/m$$

2. $$c = \frac{1}{\mu Zo} = \frac{1}{1.22\,x\,10^{7}\ x\,50} = 1.639\,x\,10^{-9}\ F/m$$

$$= 1.64\text{n}F/m$$

3. $$\omega\left[Lsource + L\,{}^{l}\!/_{2}\right] = \frac{1}{2\omega Cl}$$

so,

$$2\omega.\omega Cl\left[Lsource + L\,{}^{l}\!/_{2}\right] = 1$$

Substituting the values in the above equation,

i.e. $2 \times 314.2^2 \times 1.639 \times 10^{-9} \times l\ [0.25\times10^{-3} + 4.098 \times 10^{-6} \times l/2] = 1$

$3.236 \times 10^{-4}\ l\ [0.25 \times 10^{-3} + 2.049 \times 10^{-6}\ l] = 1$

$8.09 \times 10^{-8}\ l + 6.63 \times 10^{-10}\ l_2 = 1$

$6.63 \times 10^{-10}\ l_2 + 8.09 \times 10^{-8}\ l - 1 = 0$

So finding the length of the line,

$$ax^2 + bx + c = 0$$

a $\equiv$ 6.63×10^{-10}

b $\equiv$ 8.09×10^{-8}

c $\equiv$ -1

$$x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

=> x = 38,777.6 or x = - 38,899.62

But length of a line cannot be – ve.

Hence $x = l$ = 38,777.6m

= 38.8km

4. $L\,{}^{l}\!/_{2}$ = $4.098 \times 10^{-6} \times 38{,}777.6/2$

= 0.0795H

= 79.5mH

5. Cl = $1.639 \times 10^{-9} \times 38{,}777.6$

= 6.36×10^{-5} F

= 63.6 x 10-6F

= 63.6 μF

Simplifying the T and π Network at Load and no-load conditions;

Before removing the load, the circuit was as shown in Fig2.:

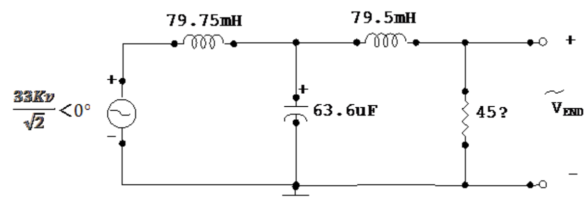

Figure 2: Ferranti rise in cable under load condition

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

V_{END} = 24 Kv Rms $\angle -59.1^{o}$ When there is loss in Load. Fig 2.1 shows the no-load condition

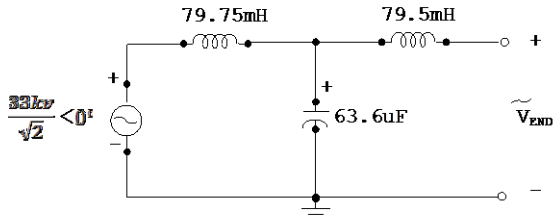

Figure 2.1 Ferranti rise on no- load

V_{END} = 46.7kv rms $\angle 0^{o}$

OUTPUT OF FERRANTI.M

```
v_end_wl =
ans =
  2.4007e+004
ans =
  -59.0923
v_end_nl =
  4.6737e+004
ans =
  4.6737e+004
ans =
    0
```

TABLE 1.0; Matlab solution output for Ferranti rise of Fig 2.0 and Fig. 2.1

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.

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 3.0.

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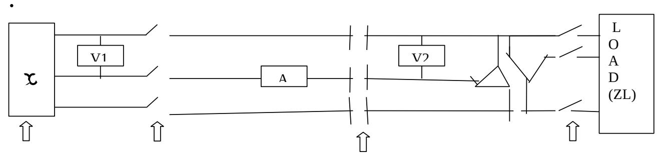


3Ø power Primary Switch Capacitors Secondary Source Switch

Fig. 3.0: Ferroresonant experiment circuit for 3 Ø DY11 transformer

From the figure 3.0, a series capacitor of C = 4.0μF was used with all primary phases connected to supply (4.0μF is assumed the effective capacitance of the primary phase windings for transformers of that type. 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, V_1 , the Primary terminal voltages, V_2, at phases V_{AB}, V_{BC}, V_{CA}, and the primary current at no-load, I_{NL}, were recorded and plotted in Figs.4,5,6,7, 8&9.

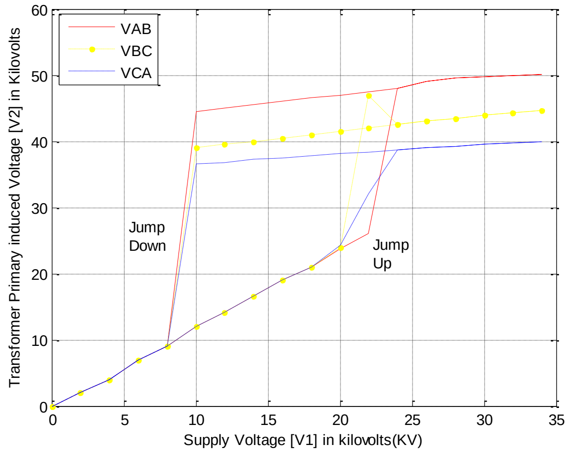


Figure 4.0: Graph of primary terminal voltage against supply voltage at no load

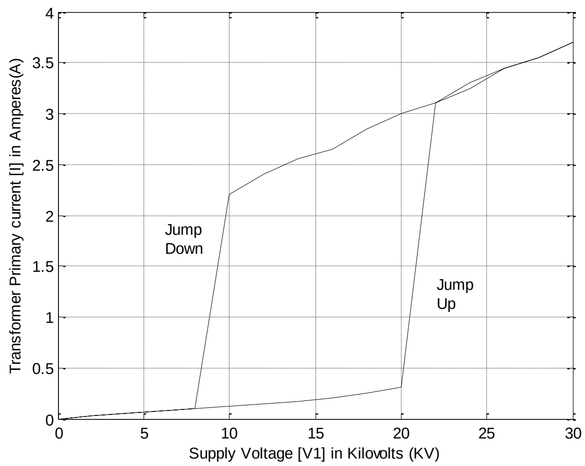


Figure 5.0: Graph of Primary induced current versus supply voltage at no-load.

From graphs of figures4 & 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 V_1 = 20kv causing

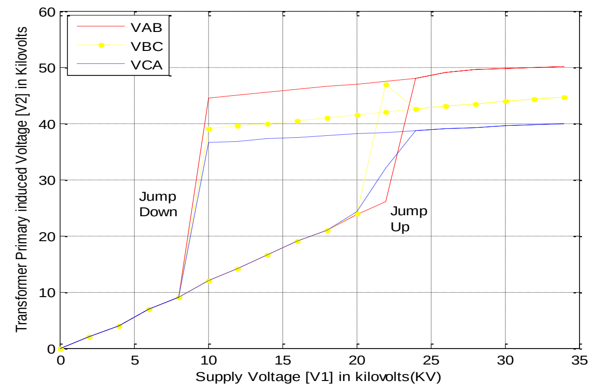
i. A jump-up in the primary induced voltage that reached as high as $\Delta V_{AB} = 23kv$

ii. A jump-up in the primary current that reached as high as $\Delta I = 2.79A$

B. Measurement of Ferroresonance during Unsymmetrical switching of

Three- Phase Transformer at No - Load

In the circuit of figure 3.0, 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



t.

Figure 6: Graph of primary induced voltage against supply voltage at no-load during unsymmetrical switching of the transformer.

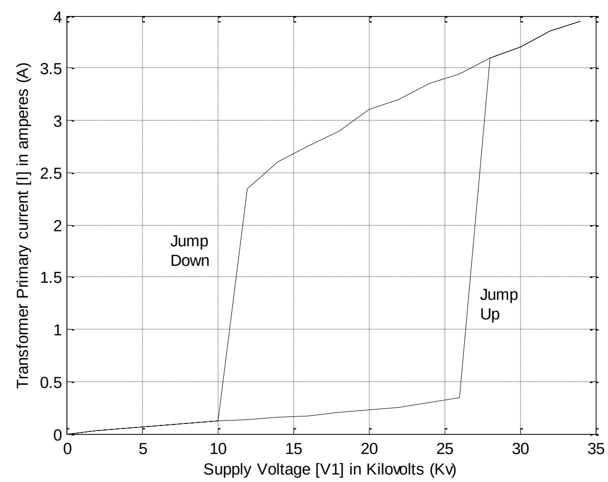


Figure 7 Graph of Primary induced current versus supply voltage at no-load during unsymmetrical switching of the transformer

From Figures 6 & 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 = 26kv causing

i. A jump-up in the primary terminal voltage that reached as high as $\Delta V_{AB} = 31kv$

ii. A jump-up in the primary current that reached as high as $\Delta I = 3.25A$. (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 = 4.0μF 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 Fig8.: 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. $V_{AB} = V_{BC} = V_{CA} = V_2$).

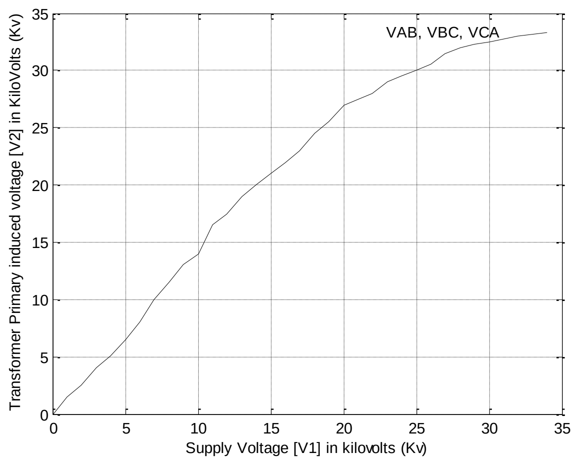


Figure 8: Graph of primary induced voltages against supply voltages when the transformer is on-load

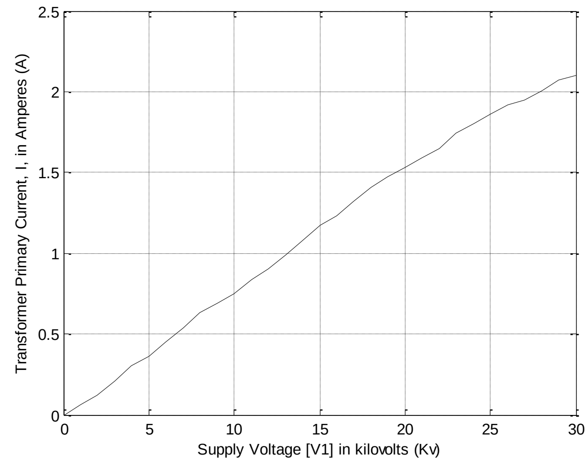


Figure 9: Graph of Primary induced current versus supply voltages when the transformer is on-load.

From figures 8 & 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 Fig11.

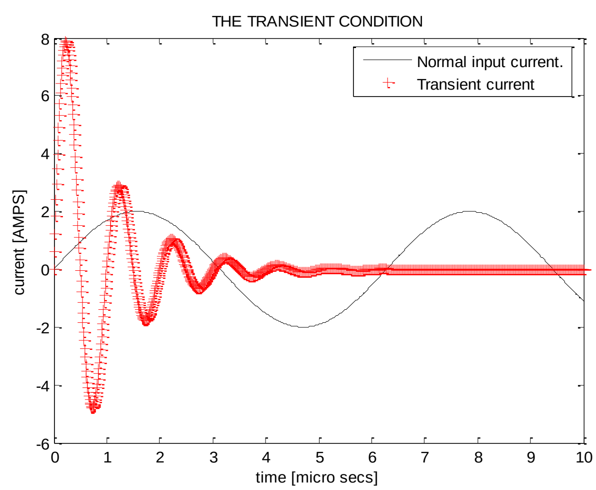


Fig.10: Primary normal current and the switching in-rush current (due to

ferroresonance) of the transformer plotted at the same time base

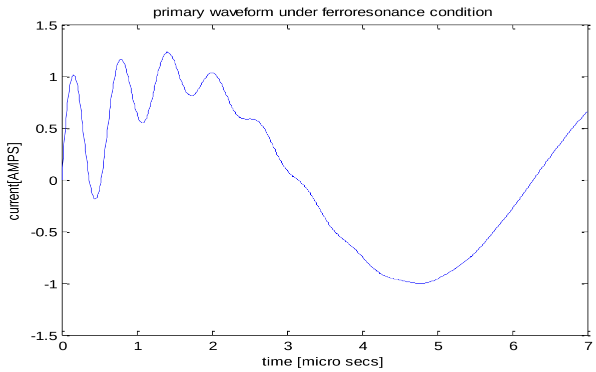


Fig11: distortion of primary waveform due to ferroresonance

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. (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.

Where an open corner delta secondary exists, a single resistor across the open delta is advisable. 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 by Karlicek and Taylor [1] as

$$\mathbf{100 \ x} \ \frac{L_a}{N^2}$$

where L_a is the transformer primary inductance in millihenries and N^2 is the transformer turns ratio. [2]

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, 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, introducing losses to reduce its effects (i.e. switching transformers with some load, grounding the primary windings through a resistance, etc.)

CONCLUSION AND RECOMMENDATIONS

From the simulation and experimental results of ferroresonance effects , the following assertions are made;

- The increased voltage as a result of ferroresonance reduces the insulation strength of our power equipments, cables etc, and therefore exposing them to the risk of damage and consequently resulting in power failure.
- Ferroresonance can cause dangerous overvoltages and overcurrents in three phase transformers.
- The damaging effect of ferroresonance is more prominent when the transformer is on no load or single-phasing
- . It causes high levels of distortions in the current and voltage waveforms.

Based on the findings, it is hereby recommended that transformers should be designed to withstand at least 25% overload and the insulation and conductor size should be stepped up by not less than 16%.in order to withstand comfortably ferroresnance over-voltages and over-currents.

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