FERRORESONANCE
- its Occurrence and Control in Electricity Distribution Networks

by

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SUMMARY:

The phenomenon of ferroresonance in distribution systems was described in a paper by the author presented at the 1974 Annual Conference of the Electricity Supply Engineers Association of New South Wales. The purpose of this paper is to update the information in that paper and to help in understanding the phenomenon.

Ferroresonance is a non-linear resonance that occurs when there is a non-linear inductance, a capacitance, a voltage source and low losses in an electric circuit. The practical realisation of this phenomenon can occur when single phase switching is used on the distribution network such that both delta-connected transformers and cables or long overhead lines are simultaneously switched when the network is lightly loaded. The phenomenon can also occur when voltage transformers interact with the capacitance of elements such as long transmission lines, capacitor banks or circuit breaker capacitance. The occurrence of ferroresonance can result in damage to the electrical equipment. Accordingly action should be taken to avoid its occurrence.

1 INTRODUCTION

Ferroresonance is a phenomenon that has been described in the literature as early as 1914. Further significant research was undertaken in the 1930’s in association with its occurrence on long transmission lines. In the 1960’s transient network analysers were used to carry out research and practical papers dealing with the phenomenon appeared.

The author undertook research work while with Prospect County Council in the early 1970’s to investigate the phenomenon in association with the occurrence of ferroresonance on the 11kV. The interest at the time was as a result of the increasing use of underground cables and the use of single phase operating switchgear in the distribution system. This resulted in a number of papers including a paper presented to the ESEA of NSW at its Annual Conference in 1974 (Ref 1) and at the 1979 CIRED Conference (Ref 2).

The investigations were carried out to determine the nature and extent of the problem and to define practical measures that may be taken in the control of the phenomenon.

The research resulted in the development of the "Baitch Ferroresonance Critical Cable Length Formula" which can be used to determine a maximum cable length that can be safely switched in conjunction with a lightly loaded distribution transformer.

In recent years further work has been undertaken in researching the phenomenon of ferroresonance which has resulted in both a better understanding of the phenomenon and in the ability to undertake analysis of the circuit to predict behavior. A useful reference on this subject can be found at Ref (3).

2 THEORETICAL TREATMENT OF FERRORESONANCE

2.1 Resonance

The ferroresonant circuit is characterised by a series circuit consisting of an iron-cored, and therefore nonlinear, inductance in series with a capacitance excited by an alternating current voltage source as shown in Figure 1.

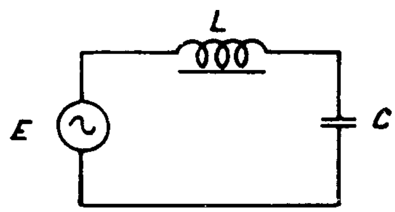


Figure 1 – Typical Ferroresonant Circuit

For a series circuit in sinusoidal conditions the vectorial relationship between the voltages (assuming that the inductance has a resistive component):

$$\underline{E} = \underline{V}_L + \underline{V}_R + \underline{V}_C +$$

In a linear circuit, resonance will occur when the circuit is "tuned", with the reactance of the capacitor being equal to that of the inductance.

$$\omega^2 L C = 1$$

The amplitude of the current I is then equal to:

$$I = \frac{E}{R}$$

The voltage magnitude across the capacitor and across the capacitor is a function of the quality factor (K) for the circuit:

$$K = \frac{L\omega}{R} = \frac{1}{RC\omega}$$

Accordingly, the voltage across the inductance and capacitance for the linear circuit can be many time the applied voltage E.

For a particular value of frequency and capacitance, only one value of inductance will satisfy this equation for the linear circuit. Should the inductance be less than required for resonance, the circuit behaves as a capacitive circuit, but if the inductance is greater, it behaves as an inductive circuit. Vector diagrams for these two conditions (ignoring resistive effects) are shown in

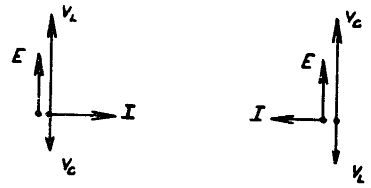


Figure 2 Vector diagram of LC circuit

2.2 Ferroresonance

The differences between a ferroresonant circuit and a linear circuit described above, are that for a given value of frequency (ω):

- Resonance is possible over a wide range of capacitance values (C)
- The frequency of the voltage and current waves may be different to that of the sinusoidal voltage source
- It is possible to have several stable steady state values for a particular set of conditions, depending on the initial conditions of charge and flux on the capacitance and inductance respectively
- Jump phenomena can occur where the circuit moves from one stable state to another as a result of change in the value of parameters.

An explanation for some of these characteristics can be illustrated by utilising a graphical approach to the representation of the vector diagrams for a (lossless) ferroresonant circuit.

Consider the diagram in Figure 3.

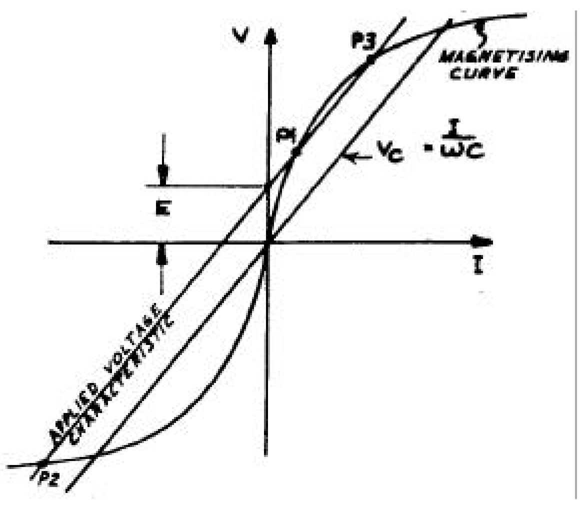


Figure 3 Graphical Construction for Analysis of Circuit

Figure 3 shows the voltage current characteristic for the iron cored inductance (the magnetising curve) and the voltage-current characteristic of the series capacitance. The operating point for the circuit can be determined for the applying an applied voltage curve parallel to the capacitance characteristic. The points where the applied voltage curve cuts the inductance magnetising curve, are points where Kirchhoffs Law for the sum of the voltages around a circuit being equal to zero is satisfied.

It will be noted that in this diagram (where the series capacitance is quite large), when the applied voltage is small the applied voltage curve cuts the magnetising curve at three locations (P1, P2 and P3). In fact only P1 and P2 are stable positions.

It will be noted that if the slope of the capacitive characteristic curve is varied, the applied voltage curve will still cut magnetising curve at 3 points. Only if the capacitive curve is steep and with a slope greater than the magnetising curve does the applied voltage curve only cut the magnetising curve at one point (P1).

If the voltage applied is increased, it will be noted that operating points P2 and P3 no longer exist and the only stable operating point is at P1. Accordingly, if the circuit were operating at P1, an increase in applied voltage would result in the circuit exhibiting a "jump" from P1 to P2.

The vector diagram for the operating points P1 and P2 are shown in Figure 4.

Figure 4 Vector Diagrams

At operating point P1 the largest voltage is that across the inductance and is equal to, for lossless circuits, the arithmetic sum of the applied voltage plus the voltage across the capacitance. At operating point P2 the largest voltage is that across the capacitance and is equal to the sum of the applied voltage and the voltage across the inductance. It is this voltage which presents danger to electrical equipment.

2.3 Ferroresonant States

More recent investigations (Ref 4) have now shown that there are basically four different ferroresonant types as follows:

- Fundamental mode
- subharmonic mode
- quasi-periodic mode
- chaotic mode

In the fundamental mode as illustrated in Figure 4, the voltage and currents are periodic with a period T equal to the system period and can contain a varying rate of harmonics.

In the subharmonic mode as illustrated in Figure 5, the voltage and current are periodic with a period nT that is a multiple of the source frequency. Accordingly, this is referred to as the subharmonic n.

In the quasi-periodic mode as illustrated in Figure 6, the voltage and current is not periodic. The spectrum is discontinuous where the frequencies are expressed as $nf_1 + mf_2$ where n and m are integers and f_1 / f_2 an irrational real number.

In the chaotic mode as illustrated in Figure 8 the spectrum of frequencies is continuous and occupies an area on the voltage, current plane referred to as the "strange attractor".

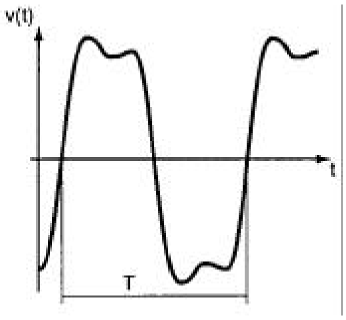


Figure 5 Fundamental mode of ferroresonance

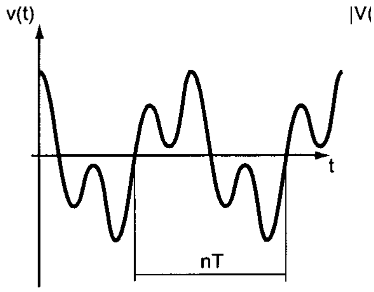


Figure 6 Subharmonic mode of ferroresonance

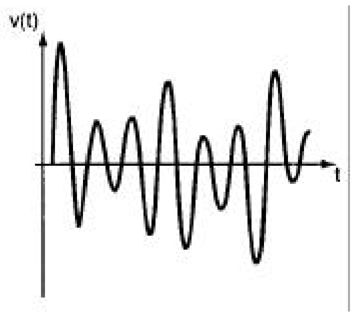


Figure 7 Quasi-periodic mode of ferroresonance

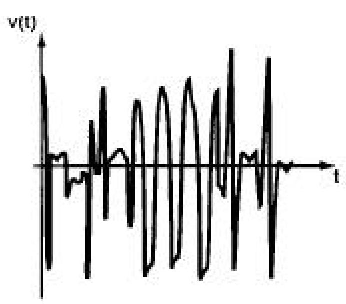


Figure 8 Chaotic mode of ferroresonance

In summary, the phenomenon of ferroresonance is a complex one where there are several steady states for a given circuit, their appearance are highly sensitive to system parameters and sensitive to initial conditions. Small variations can cause sudden jumps between two different states and initiate one of the ferroresonance modes.

2.3 Mathematical modeling

Much effort has been put into researching methods for analysing ferroresonant circuits over the years. However, none of the approaches (apart from the simplified graphical method referred to above) presents a simple methodology.

Both analog simulation and time domain digital simulation in the transient state can be used. However, as ferroresonance is sensitive to parameter values and to initial conditions, such studies do not tend to provide useful results.

Methods have been developed for the establishment of steady-state conditions utilising numerical methods. These are now providing a basis for some better insight into the existence of ferroresonant conditions.

3 OCCURRENCE OF FERRORESONANCE IN DISTRIBUTION SYSTEMS

3.1 Basic arrangement

The requirements for the occurrence of ferroresonance in a distribution system is an unloaded delta/star connected transformer to be switched at the same time as a length of power cable is switched. The transformer and cable are to be switched on and from the network by sequentially operating single phase operating three-phase switchgear such as a drop out fuse, underslung links or single phase operating switchgear such as Holec Magnefix MD4.

It does not matter whether the cable is connected to a tail-ended transformer or simply adjacent to the transformer. If both are simultaneously switched, the equivalent circuit is the same.

An equivalent three-phase circuit for a tail-ended transformer arrangement is shown in Figure 9.

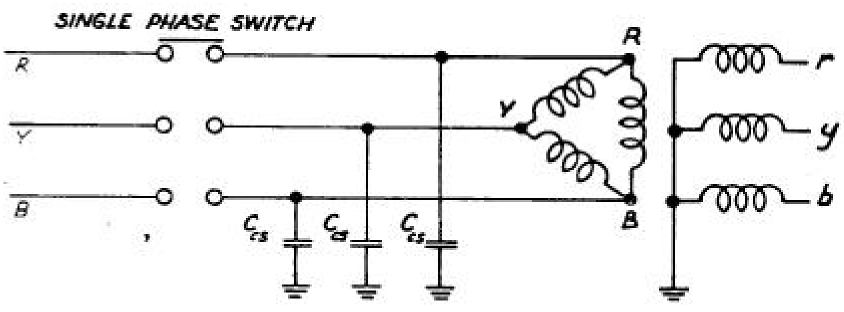


Figure 9 Three-phase equivalent circuit

Due to the presence of the core-to-sheath capacitance of the power cable, despite the fact that only one phase is energised, two parallel series circuits are formed through the magnetising inductance of the delta winding of the transformer in series with the core-to-sheath capacitance of the power cable. This is illustrated in Figure 10.

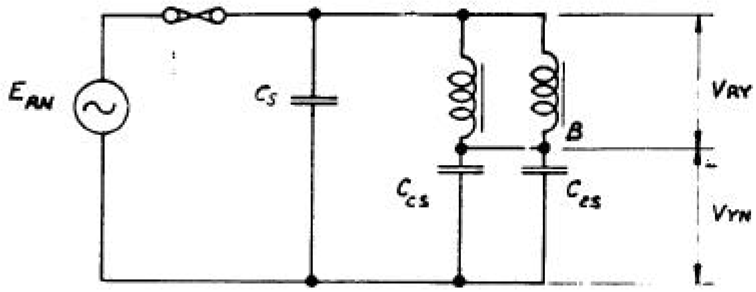


Figure 10 Single phase equivalent circuit

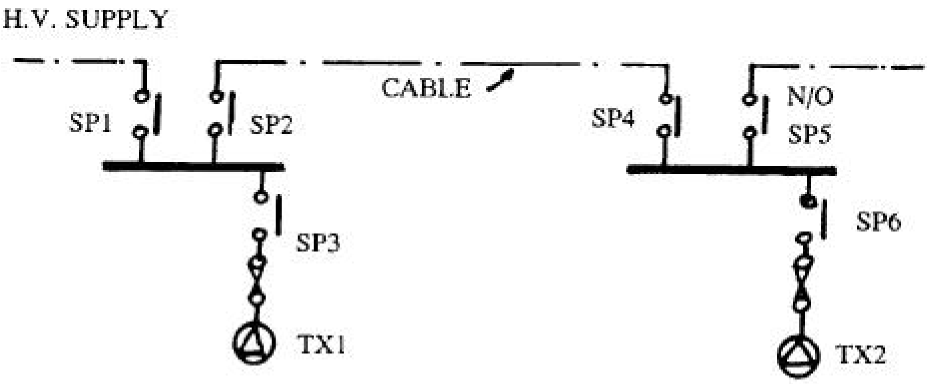
If the cable is a paper-insulated belted cable (and so there is no screen around each core), an additional element of the cable core-core capacitance appears across the magnetising inductance of the delta winding of the transformer. This is typically one-third the core-to-sheath capacitance and has the effect of altering the shape of the magnetising inductance.

For an 11kV system, the system applied voltage is 6.35kV phase to earth. When the ferroresonant state is at P1 as referred to in Section 2.2, the voltage across the core-to-sheath capacitance of the cable is the sum of the applied voltage plus the voltage across the delta winding of the distribution transformer.

In field testing undertaken by the author with Prospect County Council in the early 1970's, the voltages measured across the core-to-sheath capacitance were as high as 21.3kV for an 11kV system. As the basic insulation level for an 11kV cable is 12kV / √3 (=6.93kV), this is more than 3 times the basic insulation level and presents a danger to the installation.

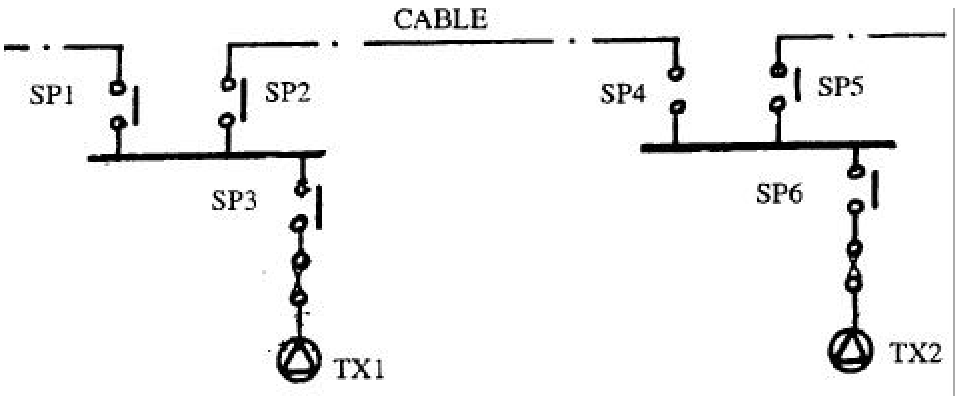
3.2 Other Configurations

Examples where ferroresonance would occur are given in the following diagrams. In these diagrams, an indication is provided for switching conditions where ferroresonance could occur. As ferroresonance is avoided if the transformer is switched separately from the cable, the diagram indicates where switching should take place to avoid ferroresonance occurring.



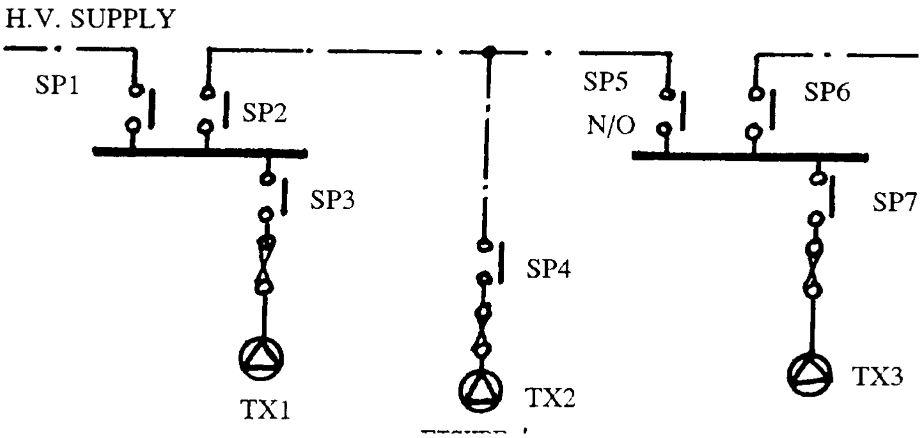
Ferroresonance occurs	Recommended to avoid ferroresonance
Switch TX1 and TX2 at SP1	Switch TX1 at SP3 Switch TX2 at SP6
Switch TX2 at SP2	Switch TX2 at SP6

Figure 11 Single phase switching cable network



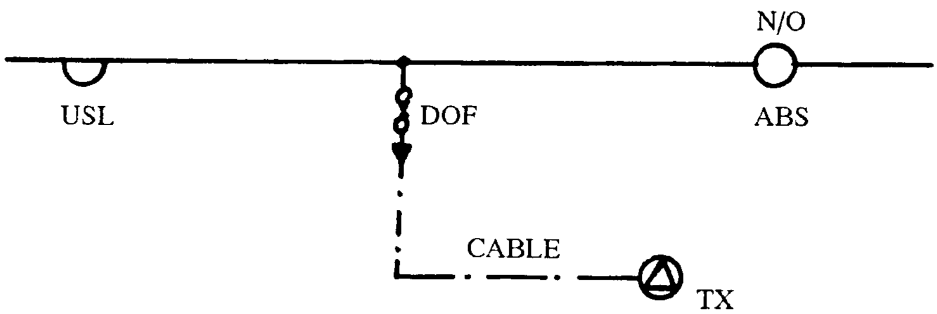
Ferroresonance occurs	Recommended to avoid ferroresonance
Switch TX1 at SP1	Switch TX1 at SP3

Figure 12 Single phase switching cable network



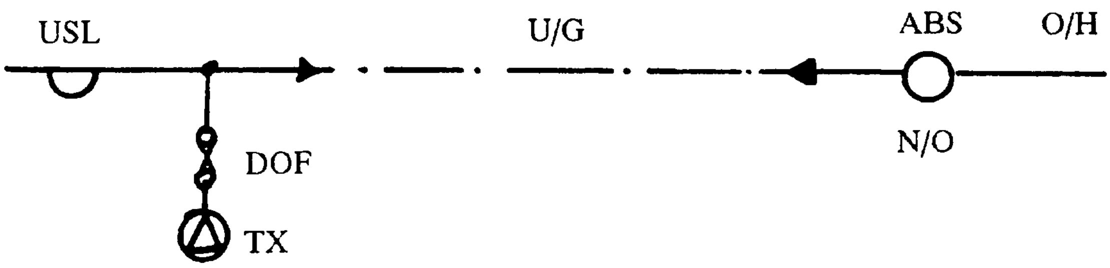
Ferroresonance occurs	Recommended to avoid ferroresonance
Switch TX1 and TX2 at SP1	Switch TX1 at SP3, Switch TX2 at SP4
Switch TX2 at SP2	Switch Tx2 at SP4

Figure 13 Single-phase switching cable network with tee



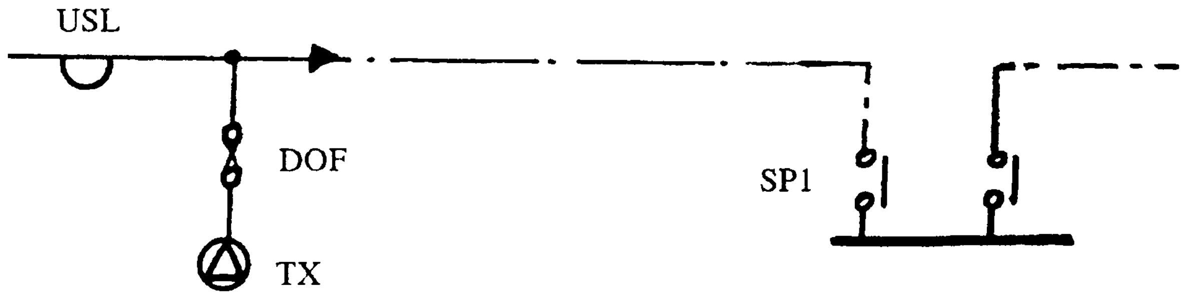
Ferroresonance occurs	Recommended to avoid ferroresonance
Switch TX at single phase underslung links	Switch TX and cable with 3phase air-break switch
Switch TX at drop-out fuse of TX	Switch at USL or DOF if cable length shorter than critical cable length

Figure 14 Switching overhead/Underground network with pole substation



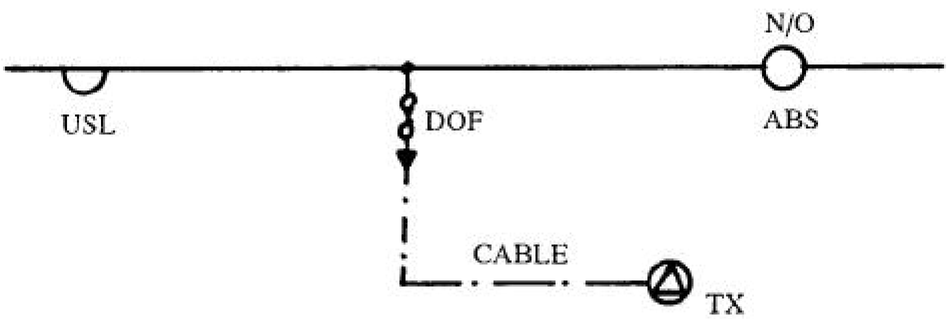
Ferroresonance occurs	Recommended to avoid ferroresonance
Switch TX at single phase underslung links	Switch TX at drop-out fuse of TX
	Switch TX and cable with 3phase air-break switch

Figure 15 Switching overhead/underground network with pole substation



Ferroresonance occurs	Recommended to avoid ferroresonance
Switch TX at single phase underslung links	Switch TX at drop-out fuse of TX
Switch TX at SP1	

Figure 16 Switching overhead/underground network with pole substation



Ferroresonance occurs	Recommended to avoid ferroresonance
Switch TX at single phase underslung links	Switch TX at air-break switch
Switch TX at drop-out fuses	

Figure 17 Switching overhead network with tee'd cable to transformer

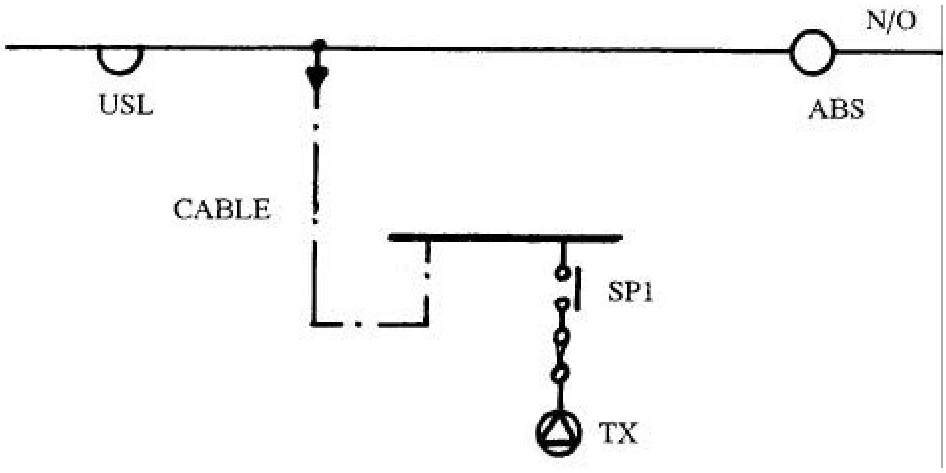


Figure 18 Switch overhead network with tee'd cable to padmount substation

Ferroresonance occurs	Recommended to avoid ferroresonance
Switch TX at single phase underslung links	Switch TX at SP1
	Switch TX and cable with 3phase air-break switch

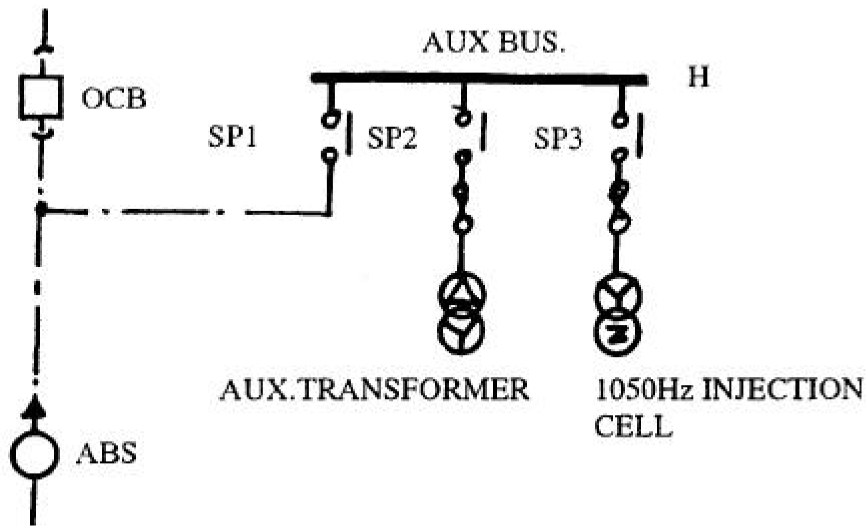


Figure 19 Single phase switching zone sub auxiliary bus with frequency injection cell

Ferroresonance occurs	Recommended to avoid ferroresonance
Switch Aux Transformer and 1050 Hz injection cell at SP1	Switch TX at SP2 and 1050 Hz injection cell at SP3

4 MAXIMUM ALLOWABLE VOLTAGE

4.1 Nature of the overvoltage

For the fundamental mode ferroresonance, the overvoltage is a power frequency overvoltage persisting for the full duration of the switching period. The overvoltage appears between the core and sheath for two phases of the cable for the full length of the cable. It also appears between the full length of one of the windings of the transformer and earth. The overvoltage occurs across the terminals of each of the two open phases of the switchgear.

The excitation voltage of the transformer is equal to the vector difference between the ferroresonant voltage and the applied voltage.

The wave shape of the voltage is not sinusoidal and contains harmonics.

4.2 Maximum overvoltage

Guidance can be obtained from AS 1824.1 – 1995 (IEC 71-1:1993*) "Insulation co-ordination. Part 1:P Definitions, principles and rules"* as to the voltage withstand level of equipment connected to the electrical network.

In accordance with Table 2 of AS 1824.1 – 1995 the "Standard short-duration power-frequency withstand voltage kV (rms value)" and "Standard lightning impulse withstand voltage" is shown in Table 1.

Table 1 Standard insulation levels from AS 1824.1 - 1995 (Table 2)

Highest voltage for equipment U_m kV (r.m.s. value)	Standard short-duration power-frequency withstand voltage kV (r.m.s. value)	Standard lightning impulse withstand voltage kV (peak value)
12	28	60 75 95
24	50	95 125 145

Furthermore, in accordance with Clause 4.9 "for phase-to-phase insulation, range 1, the standard short duration power-frequency and lightning impulse phase-to-phase withstand voltages are equal to the relevant phase-to-earth withstand voltages". The short-duration power frequency is a sinusoidal voltage with frequency between 48 Hz and 62 Hz and duration of 60 s.

The insulation co-ordination standard provides guidance to the various equipment technical committees as to the withstand voltage that should be specified for various items of equipment.

Referring to AS1429.1-2000 *"Electric Cables – polymeric insulated Part 1: For working voltages 1.9/3.3 (3.6kV up to and including 19/33 (36)kV"* the high voltage test voltage applied for 5 minutes is 21kV for 6.35/11 (12) kV cables and 42kV for 12.7/22 (24) kV cables.

For AS 3599.1 – 1988 *"Electric Cables – Aerial bundled polymeric insulated voltages 6.35/11 (12) kV and 12.7/22 (24) kV Part 1 – Metallic screened"* as well as AS3599.2 – 1999 *"Electric Cables – Aerial bundled polymeric insulated voltages 6.35/11 (12) kV and 12.7/22 (24) kV Part 2 – Non-Metallic screened"* the high voltage a.c. test for 5 min is as follows:

a) 6.35/11 (12) kV cables 15kV
b) 12.7/22 (24) kV cables 30kV

Tests specified in the various standards mostly provide for tests on either completely new equipment prior to its installation or on new equipment only recently installed. There are normally no overvoltage test values specified for equipment which had been in service for a considerable period and which might well have deteriorated in the process. It must be assumed, therefore, that an adequate margin of safety is incorporated in test values to ensure trouble-free service. Since life expectancy of power distribution equipment is in the range of 30 to 50 years, an effort should be made to prevent application of excessive overvoltages.

Ferroresonant overvoltages can occur at any switching operation during the life of an installation.

A further issue that needs consideration is that with oil-impregnated paper-insulated cables, if an overvoltage was to initiate partial discharge within the cable, the characteristic of the oil-insulated paper-insulated cable is that the partial discharge is “self healing”. However, with polymeric insulated cables, which are now almost universally used, should the presence of an overvoltage trigger inception of a partial discharge as a result of the overvoltage exceeding the inception voltage of discharge, the partial discharge is not “self healing”. This can result in premature failure at the point of discharge inception, be it within the cable itself or at a termination.

In the work undertaken by the author in the 1970’s, it was concluded that the overvoltage should not be allowed to exceed $(1 + \sqrt{3})$ times phase-to-earth voltage (ie 2.73 times phase voltage). Ideally, the overvoltage should not occur at all.

5 CRITICAL CABLE LENGTH

As referred to in Section 2.2, utilising the graphical analysis technique it is necessary to establish characteristic curve for the cable and for the transformer.

As the cable is a linear device, its characteristic curve is readily determined.

For the transformer, the characteristic curve is a function of the design parameters of the transformer which establish the exciting current. The parameters that affect the curve include the normal flux density, steel type, iron loss and “knee point” of the excitation curve.

As the only known characteristic of the transformer from standard test results is the three-phase exciting current at rated voltage and the iron loss of the transformer at rated voltage. It is not possible to establish the shape of the magnetisation curve from this one value.

However, by utilising the graphical technique the author has been able to establish a relationship between the cable characteristics and the transformer exciting current at rated voltage at which the expected ferroresonant voltage is $(1 + \sqrt{3})$ times phase-to-earth voltage (ie 2.73 times phase voltage).

Refer to Figure 20 for the construction to determine what is referred to as the “Critical Cable Length”.

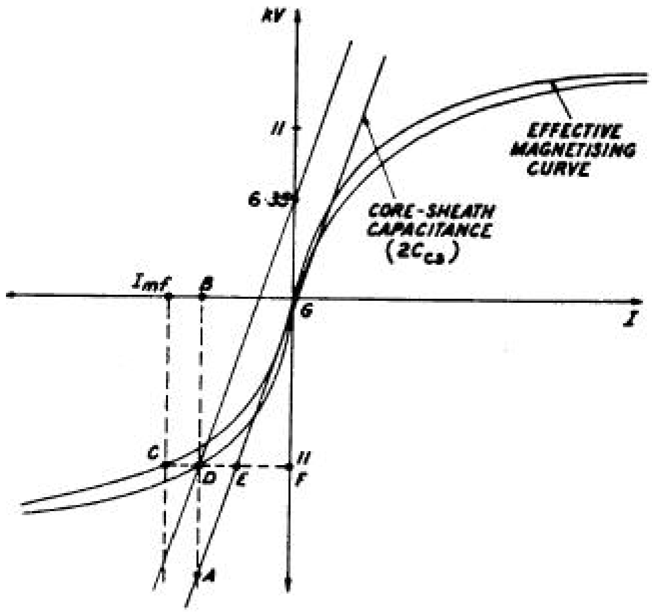


Figure 20 Critical Cable Length

The magnetising current under ferroresonant condition (I_{mf}) with rated system voltage across the winding of the transformer is related to the three-phase magnetising current as follows:

$$I_{mf} = \frac{y \;.\; I_{mag}\;\% \;.\; kVA_R}{100 \;.\; kV_R}$$

Where y is the % of the core that is being excited under ferroresonant conditions. Typically, this is 0.6.

From the graphical construction in Figure 20, voltage across the cable core-to-sheath capacitance is equal to (1 + √ 3) times phase-to-earth voltage (ie 2.73 times phase voltage) at the point where the voltage across the transformer winding is rated voltage.

$$CF = CD + DE + EF$$

$$I_{mf} = V_R \; w \; C_C + \left(\frac{1}{\sqrt{3}}\right) V_R \; w \; C_{S(Crit)} + V_R \; w \; C_S$$

Substituting the formula for the exciting current, and expressing cable length in terms of the characteristic core-to-sheath capacitance of the cable (C'_{CS} (µF /km) results in the Baitch Ferroresonance Critical Cable Length formula:

$$L_{crit} = \frac{0.6 \;.\; I_{mag\%} \;.\; kVA_R \;.\; 1000}{(1.58 + C'_{CC}/C'_{CS}) \;.\; 62.8 \;.\; (kV_R)^2 \;.\; C'_{CS}} \;(m)$$

Where:

L_{crit} = *Critical Cable Length*
$I_{mag\%}$ = *Transformer magnetising current (%)*
kVA_R = *Transformer Rating (kVA)*
kV_R = *Rated Voltage (kV)*
C'_{CC} = *Specific cable core - to - core capacitance (mF / km)*
C'_{CS} = *Specific cable core - to - sheath capacitance (mF / km)*

Inspection of this formula shows that the critical cable length is:

- Directly proportional to transformer capacity
- Directly proportional to transformer magnetising current
- Inversely proportional to Square of rated voltage
- Inversely proportional to specific cable capacitance.

Assuming that the average transformer magnetising current is 0.8%, the critical cable lengths, as a function of transformer rating are shown in Table 2.

It will be noted from the cable lengths in Table 2 that the maximum allowable cable length is very short. For a typical example where a 120 sq mm cable supplies a 300 kVA transformer, the maximum cable length is only 31m if XLPE cable is used and 40m if belted paper-insulated cable were to be used.

Table 2 Critical Cable Lengths

(Based on Transformer exciting current = 0.8%)

	Cable Length (m)					
Cable Size and Voltage Rating			**Transformer Rating (kVA)**			
	Cable core-to-sheath capacitance mF/km	**Cable core-to-core capacitance mF/km**	**300**	**500**	**750**	**1000**
6.35/11kV XLPE Screened Cables						
16 sq mm	0.17	0	70	117	177	235
25 sq mm	0.19	0	63	105	158	210
70 sq mm	0.27	0	45	74	111	148
120 sq mm	0.34	0	35	59	88	118
185 sq mm	0.40	0	30	50	75	100
240 sq mm	0.45	0	27	45	66	89
300 sq mm	0.49	0	24	41	61	82
500 sq mm	0.64	0	18	31	46	62
6.35/11kV Paper Insulated Belted Cables						
0.06 sq in (38sq mm)	0.161	0.044	63	106	159	212
0.10 sq in (64 sq mm)	0.166	0.051	55	92	138	184
0.20 sq in (128 sq mm)	0.234	0.065	40	66	100	133
0.40 sq in (258 sq mm)	0.270	0.080	34	57	85	114
22kV Cables XLPE screened Cables						
150 sq mm	0.25	0	12	20	29	39
240 sq mm	0.31	0	10	16	24	32
11kV Aerial Bundled Conductor (ABC)						
50 sq mm	0.255	0	47	78	117	157
150 sq mm	0.382	0	31	52	78	104
	Phase-E Capacitance pF/m	**Phase-phase Cap pF/m**				
11kV Covered Conductor						
120 sq mm Vertical Construct	9.457	9.160	800	1300	2000	2600
22kV Covered Conductor						
120 sq mm Vertical Construct	9.758	9.974	200	300	450	600

6 CONTROLLING FERRORESONANCE

The options for controlling ferroresonance can be broadly classified into two groups:

- inherent in the design of the network elements
- requiring action on behalf of the operating staff

6.1 Three phase switching

The use of three phase switching on the underground and on the overhead network avoids the occurrence of ferroresonance.

6.2 Switching at the transformer

Providing a switch at the transformer terminals rather than use of tail-ended transformers which are controlled by drop out fuses or remote single phase operating switch avoids the possibility of ferroresonance if the switching is carried out at the substation. The cable should not be switched at the same time as the transformer.

6.3 Limiting the cable length switched

Limiting the cable length to be less than the length established by the Baitch Ferroresonance Critical Cable Length will result will limit the overvoltage that may occur to $(1 + \sqrt{3})$ times phase-to-earth voltage. The effect of iron losses will tend to result in the overvoltage being less that $(1 + \sqrt{3})$ times phase-to-earth voltage.

6.4 Applying a resistive load

A resistive load of approximately 3% is sufficient to suppress the occurrence of ferroresonance. Customer connected load can be used to suppress ferroresonant overvoltages. The use of portable resistors, while a possibility, has not been found to be practical.

6.5 Use of star-connected transformers

Without the presence of a delta winding, ferroresonance will not occur. Accordingly, if it was possible to utilise star-star connected transformers, this would provide a solution. However, in practice, there are other more fundamental reasons for not utilising star-star connected transformers.

7 CONCLUSION

The phenomenon of ferroresonance can readily occur on the 11kV or 22kV distribution system. It is a phenomenon that occurs whenever a cable and an unloaded transformer are switched with the use of single phase switching. Practical measures can be implemented in terms of switching practice to avoid the occurrence of the ferroresonant overvoltages. These involve the switching of the transformer separately to that of the cable, providing a switch at the transformer terminals or by utilisation of three phase switches.

8 REFERENCES

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