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The Impact of Ferroresonance and Low Frequency Phenomena on Power Transformers and Transmission systems

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SUMMARY

Ferroresonance is a low frequency phenomenon that can occur when one side of a double circuit transmission line connected to a transformer is switched out. This can result in the transfer of power from the adjacent circuit through mutual coupling into the de-energised circuit. This can lead to saturation of the transformer and stressing of the disconnector during opening. More typically, ferroresonance will affect control and protection functions preventing circuit operations and possibly requiring an unplanned double circuit outage to safely isolate the distressed transformer.

In the UK a number of power transformers are exposed to ferroresonance and remote switching where they are connected to mesh corner and circuit tee configurations. Ferroresonance will continue for a few minutes until it can be detected and quenched. In cases where it cannot be detected, this can be much longer until the transformer is fully isolated. There are a number of ferroresonance modes, which may affect the unit differently, little is known to what degree this is damaging the transformer.

This paper briefly discusses the results of system tests carried out to investigate the effect of ferroresonance and subsequent modelling work. The validation of a detailed transient model has been carried in an attempt to understand the effect of ferroresonance and quantify the energy injected into the transformer core during various ferroresonance modes. The article concentrates on the early stages of this work and the impact of ferroresonance on network infrastructure including transformers, switchgear, protection and control.

KEYWORDS

Ferroresonance, switching, transformer modelling, saturation, power systems, system tests.

BACKGROUND

The UK transmission network is a highly integrated system, containing many double circuit lines, terminating in some cases, with mesh design substations [1]. During the 1970's, when the transmission network was built, the prohibitively high cost of circuit breakers drove the development of the mesh substation (Fig. 1). This design maximised the use of the circuit breaker, which was comparable in

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cost to the transformer. The air blast circuit breakers were very complex units requiring highly skilled engineering and resource. This cost factor resulted in a design compromise and the mesh substation was established. The banking of transformers with lines exposed transformers to more frequent and higher stresses from remote end switching over-voltage effects, compared to that of transformers in a double busbar substation.

Although technology has changed over the last few decades, substations with mesh corners or circuit 'tees' still exist and experience the problems of remote energisation overvoltages and ferroresonance. Remote energisation is more likely to cause a failure mode, but can be managed to some degree by surge arresters. Ferroresonance tends to cause switching complexity issues, albeit damage is possible. As the issue of ferroresonance became more of a problem, intricate control schemes were developed, based on automatic quenching schemes using disconnectors to isolate the transformer from the line to remove the ferroresonance. While this was acceptable for the older and more robust committee design disconnectors, present day equipment with tighter design margins proved less robust and effective as quenching devices and as a result quenching performance has deteriorated.

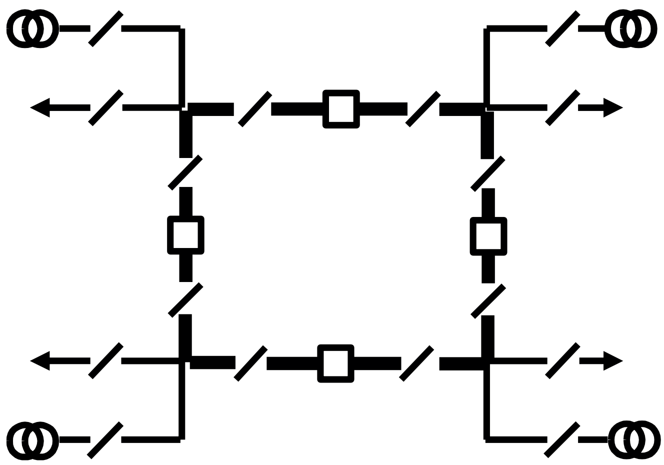

Figure 1. A typical mesh substation layout

FERRORESONANCE

Ferroresonance is an electromagnetic phenomenon which occurs as a result of the interaction between an iron core inductance and shunt capacitance. This non-linear condition can arise on the transmission system under specific network configurations (Fig. 2). The effect can weaken the security of the network and ultimately damage primary equipment, including power transformers, wound voltage instrument transformers and switchgear exposed to the electro-mechanical stress during the ferroresonance condition [2].

There are three categories of ferroresonance, and in each case mechanical duty will be imposed onto the transformer winding and core, in addition to the consequential dielectric and thermal stress on the insulation materials.

- **Unstable Quasi-Periodic Oscillation (Chaotic)** where a given excitation forces a move between more than one stable equilibrium state. The effect is characterised by a sudden jump of voltage or current from one stable state to another.
- **Fundamental Mode Ferroresonance** can only be sustained in the presence of fundamental excitation (from an adjacent source). Both odd and even harmonic oscillations can occur depending on the system parameters and initial conditions. However, the region of existence of such oscillations is very sensitive to losses in the circuit.
- **Sub-Harmonic Mode Ferroresonance** can occur at an integral sub-multiple of the fundamental frequency, but only in the presence of fundamental excitation. Both odd and even sub-harmonic oscillations are possible. It is also very sensitive to losses in the circuit.

There are two typical scenarios where ferroresonance occurs within the UK Transmission network:

- Power transformer ferroresonance – where the unit is connected to a double circuit overhead line (this can also affect quadrature boosters and shunt reactors),
- Wound electromagnetic voltage transformer (EMVT) ferroresonance – where the unit is connected to an isolated section of busbar and circuit breakers fitted with grading capacitors.

This paper concentrates on the impact associated with power transformers, the issue of electromagnetic voltage transformer ferroresonance is covered in greater detail by other references [3].

This paper examines where power transformer ferroresonance can arise as a result of the following circumstances (Fig 2):

- De-energisation of one circuit of a double circuit over-headline with a transformer feeder
- A live adjacent overhead circuit on the same tower (i.e. part of a double circuit typically longer than 10km)
- Transformer connected with a disconnector (no HV circuit breaker between the transformer and line).

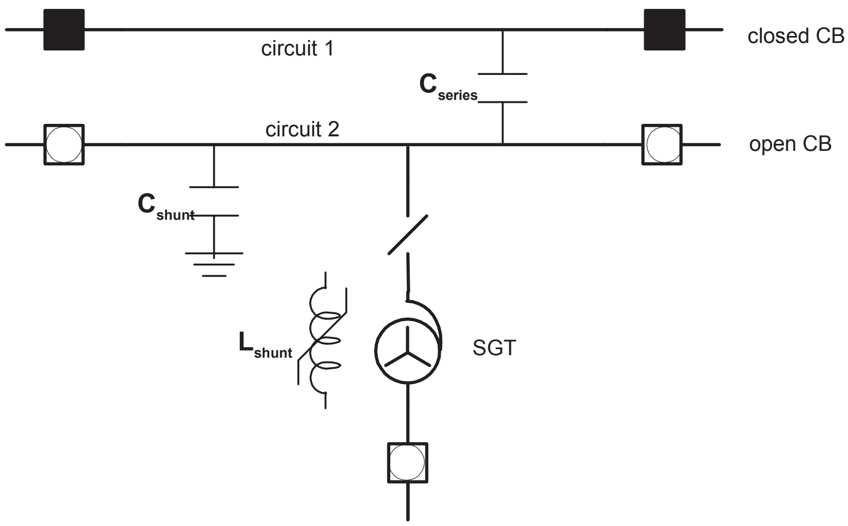

Figure 2. Typical circuit configuration which can exhibit ferroresonance.

The energised adjacent line (on a double circuit tower) is capable of indefinitely supporting an established ferroresonance condition between the non-linear inductance of the transformer and the de-energised line circuit capacitance to ground. This forcing function can cause the transformer magnetic flux to saturate, failure of the core to contain magnetising current, results in stray current flowing into metallic elements of the transformer other than the iron core (such as core bolts or the tank). These components have a higher resistance and rapidly heat up due to the stray currents. This could potentially cause internal thermal damage to insulation local to the parts, this will result in a subsequent reduction in the dielectric strength.

SYSTEM TESTS

In 1998 a number of system tests were performed on a 400kV circuit which was known to ferroresonate. The feeder circuit is composed of a 1000MVA 400/275kV interbus transformer connected to a double circuit overhead line with only a disconnector. The purpose of these tests was to establish the likelihood of ferroresonance and the quenching performance of the disconnector. The tests successfully established different states of ferroresonance through control of the point on wave switching of the circuit breaker which discharges the circuit containing the transformer.
The results indicated that quite onerous conditions could be generated on a relatively short circuit (37km) if the ideal conditions for ferroresonance prevail. In the case of fundamental mode

ferroresonance, voltages in excess of 1 per unit were established (Fig. 3) and associated non sinusoidal currents with peak values over 200A (Fig. 4). Other tests produced sub-harmonic mode ferroresonance where the voltages and currents were much lower, typically of the order 100kV and 50A.
The disconnectors opened successfully to quench and remove the ferroresonance condition and safely isolated the transformer.

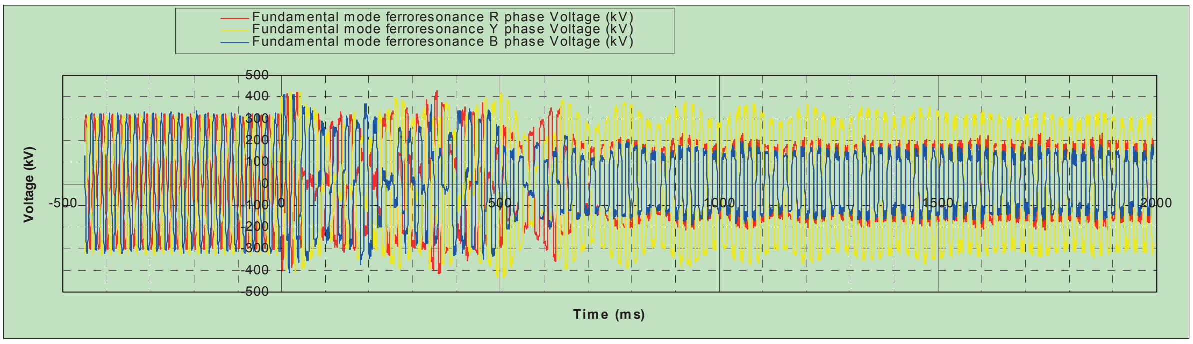

Figure 3. Fundamental mode ferroresonance – voltage (measured)

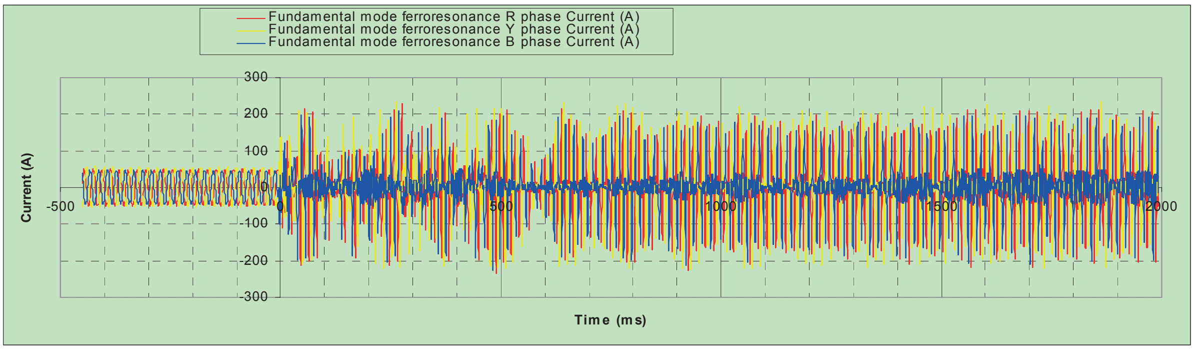

Figure 4. Fundamental mode ferroresonance – current (measured)

MODELLING FERRORESONANCE

The system tests were replicated in EMTP (ATP) to understand the impact that ferroresonance has on both the switchgear and transformer. This will help to gain further insight into the conditions which increase the likelihood of ferroresonance occurring and the amount of energy being transferred into the transformer.
The overhead line circuit was modelled using the geometric transmission line characteristics. The transformer model adopted the BCTRAN transformer matrix model using data from manufacturer test results. Saturation effects were considered by attaching the non- linear characteristics externally in the form of a non-linear inductive element branch [4]. The results replicated the measured voltage (Fig. 5) and currents (Fig. 6) waveforms to a very good degree [5].

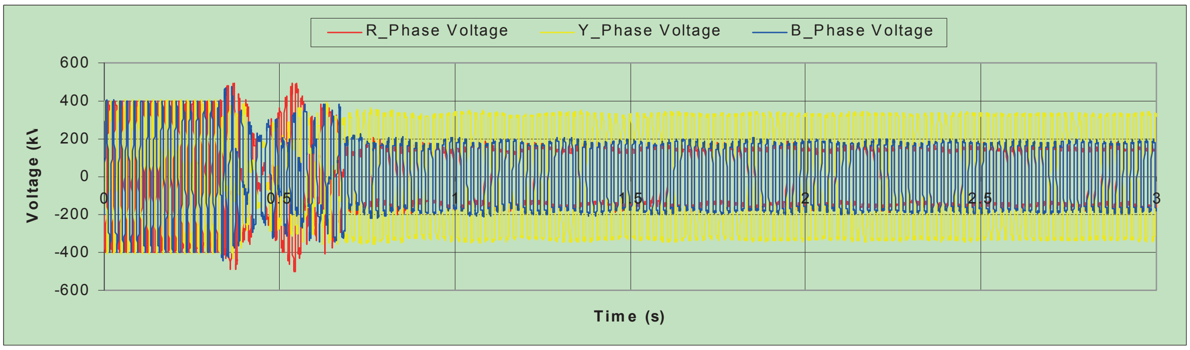

Figure 5. Fundamental mode ferroresonance – voltage (simulated)

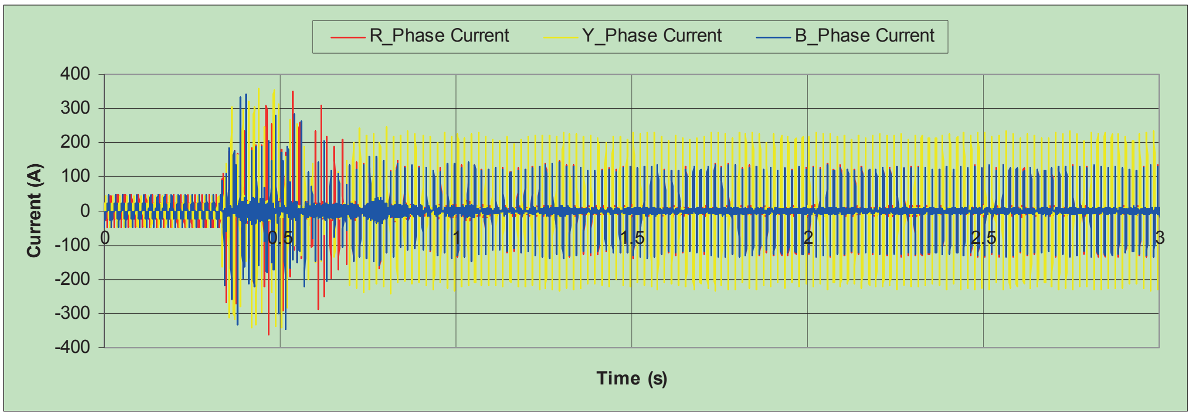

Figure 6. Fundamental mode ferroresonance – current (simulated)

Numerous studies were performed considering various sensitivities including the interaction between point on wave switching, transformer core losses and line length. From this analysis a ferroresonance map (Fig. 7) was developed, which identifies the likely type of ferroresoance to be experienced when a feeder circuit with the relevant conditions is switched. The map suggests that point on wave switching and transmission line length dominates the susceptibility of a transformer to sustain ferroresonance. These results support the concept of energy transfer in the transformer being a likely cause of insulation stressing and possible ageing. Switching studies suggest that, in addition to ferroresonance, large magnitude overvoltages and inrush currents will worsen the condition of the transformer, by further reducing the dielectric strength.

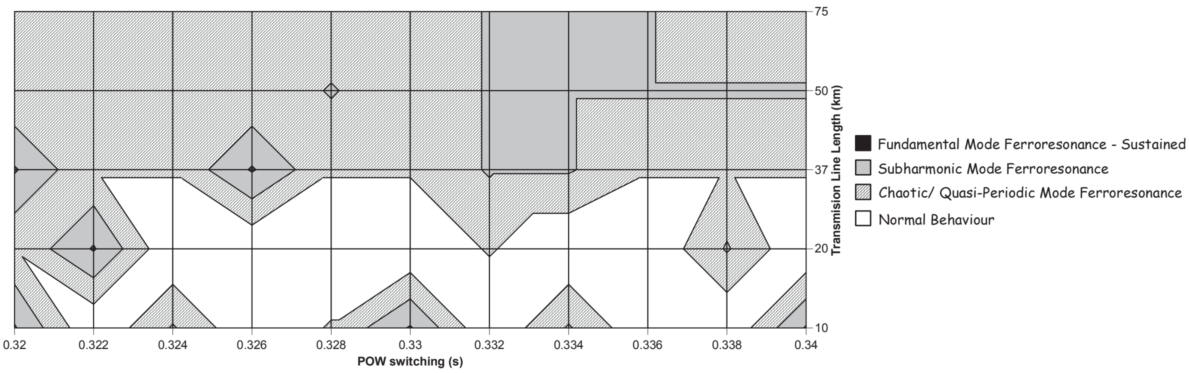

Figure 7. Ferroresonance map - Interaction of point on wave and line length

The information gained from this work can be used in conjunction with fine element analysis to develop a detailed transformer model to understand the magnetic field distribution within a transformer under ferroresonance and any degrading mechanisms on the transformer. This model will help to determine the likelihood of transformer ferroresonance and other low frequency effects including geomagnetically induced currents (GIC) and switching surges.

IMPACT THE TRANSMISSION SYSTEM

Ferroresonance does not only affect transformers and the effect on the transmission systems is widespread stressing switchgear and interfering with protection and control operation.

Transformers

The key concern for plant with magnetic iron cores such as transformers, reactors and quadboosters is whether the energy transferred into the transformer body during core saturation by the non-sinusoidal currents is damaging. Saturation and failure of the transformer core to contain the flux, manifests itself

as current induced in parts of the transformer body not designed to conduct current. The ferroresonance fundamental current pulses (up to $500A_{pk}$) can continue indefinitely causing heating in the core bolts and tank. This can thermally damage insulation, creating weaknesses, which cannot be spotted before a failure occurs.
A transformer experiencing ferroresonance generates an uncharacteristic audible grumbling, the fundamental frequency mode is loud and can be heard up to 50m away. Evidence of ferroresonance causing internal heating is indicated by gassing and tripping of the Bucholtz protection.

Switchgear

During the field tests the disconnectors experienced significant arcing during quenching of the fundamental mode ferroresonance. This caused some erosion of the contacts, which suggests that closer inspection and possible replacement is likely should they see frequent ferroresonance quenching duty.
New disconnectors are not rated for ferroresonance quenching duty and are not ideal devices as they draw the arc slowly and in an uncontrolled manner. A modified earth switch is used instead as it is the only other mechanical switching device remaining (other than an expensive circuit breaker). The method is a closing operation which will not draw an arc (although one will be created). Operationally, a standard earth switch is not suitable for ferroresonance quenching, so an enhanced duty device is necessary.

Surge arresters can also be affected if the voltages associated with ferroresonance exceed the rated TOV and cause the arrester to operate and conduct current for long periods (in surge arrester terms). This is a particular issue if an arrester is subject to heating and then exposed to a switching over-voltage when the transformer is remotely energised. This can only be avoided through design by ensuring the MCOV and TOV is greater than anticipated ferroresonance voltages.

Control & Protection

There are a number of problems caused by ferroresonance, firstly it is very difficult to reliably detect and initiate automatic quenching, and secondly ferroresonance can interfere with circuit protection and control operations.
Detection is difficult, especially sub-harmonic modes. The bulk of ferroresonance modes involve current values typically of 100A and below. These are quite low values to detect in terms of protection reliability and dependability and could lead to spurious tripping. Voltage detection is more suitable, however three phase detection is necessary and the frequency response of the CVT can make sub-harmonic ferroresonance detection uncertain. The relay looks for a three phase condition typical of fundamental mode ferroresonance, sub-harmonic mode detection is more variable.

Interference with schemes is probably the main concern surrounding ferroresonance from the Control room perspective. The main problem is lockout of autoreclose schemes following a transient fault. The presence of a ferroresonance voltage inhibits the synchronisation relay, which detects a voltage on what should be a dead circuit. Non routine switching is necessary to quench the ferroresonance before the circuit can be re-energised. If operation of the disconnector is prevented then the adjacent circuit will need to be switched out, creating a double circuit outage. This is quite a serious situation, since what started out as a simple transient fault (e.g. lightning) can start to compromise system security by creating an N-2 condition. Consequently, where ferroresonance can be identified in advance an automated detection and quenching scheme is installed in an attempt to prevent the risk of a double circuit outage.
Mesh corner and transformer tee control schemes require bespoke engineering solutions and are resource intensive, involving significant site-specific functionality. The risks are difficult to quantify at a design stage. Although switchgear costs are reduced, the engineering cost can be significant and introduce problems at commissioning, where various circuit configurations must be tested. Mesh corner protection is complex, adding ferroresonance to this introduces another unreliability factor. The complexity associated with this type of connection should not be dismissed, since any circuit changes throughout the connection lifetime will need to be carefully assessed to identify any interactions or inter-tripping.

CONCLUDING REMARKS

Ferroresonance is a complex electro-magnetic condition. Through system tests and analytical studies it has been demonstrated that ferroresonance is a stochastic function, dependent upon the initial conditions and circuit parameters. Simulations suggest that the transformer may be exposed to higher energy transfers with long transmission lines or where the core losses are low. The impact of ferroresonance on transmission assets has been discussed and although no transformers have failed during ferroresonance activity, accelerated ageing is likely, but to what extent we do not know at this time.

Ferroresonance has a complex and cumulative impact, since not only do you get the ageing of assets, but there is the problem of reliably detecting the condition and then the interference from ferroresonance on protection and control systems which make secure operation of the system increasingly difficult. In summary utilities should avoid configurations which will create ferroresonance and increase the risks to the system and assets.

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