High Technology Solutions
for the Producers, Distributors
and Users of Electric Power

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Abstract - This paper describes the phenomenon of ferroresonance, the conditions under which it may appear in electric power systems, and some techniques for avoiding ferroresonance or mitigating its effects.

INTRODUCTION

Ferroresonance is a complex electrical phenomenon that, though identified since the early 1920s, remains little understood today. It is characterized by the sudden onset of very high sustained overvoltages concurrent with high levels of harmonic distortion. Ferroresonance has been known to be responsible for equipment damage and protection malfunctions

Ferroresonance is hard to analyze, in part because it does not occur regularly or predictably in response to a particular stimulus. More than one stable steady state response can result from the same set of initial circuit parameters. In response to a voltage transient, phase to ground fault, circuit breaker opening, equipment energization or de-energization, lightning induced overvoltages, or any number of other sudden changes, the system can take a sudden non-linear jump from its normal steady state response to a steady state condition of severe harmonic distortion and high (several per-unit) overvoltages that can severely damage power system equipment.

All is not lost however. Enough is known about ferroresonance to enable power system engineers to design systems that avoid the problem, or to mitigate its effects should it occur.

BACKGROUND ANALYSIS

In order to understand ferroresonance, a nonlinear phenomenon, it is necessary to distinguish it from regular and well understood resonance in electrical circuits, what we will refer to as linear resonance.

Linear Resonance

In a linear resonance the impedance values represented by the circuit components are predictable; they change predictably with frequency. When operated within its designed ranges, a given capacitance will always present a capacitive reactance of

$$Z_C = \frac{1}{j\omega C}$$

and a given inductance will always present an inductive reactance of

$$Z_L = j\omega L$$

where ω is the frequency of the sinusoidal voltage and current.

The relationship between a voltage across an impedance and a current through it is given by Ohm's Law:
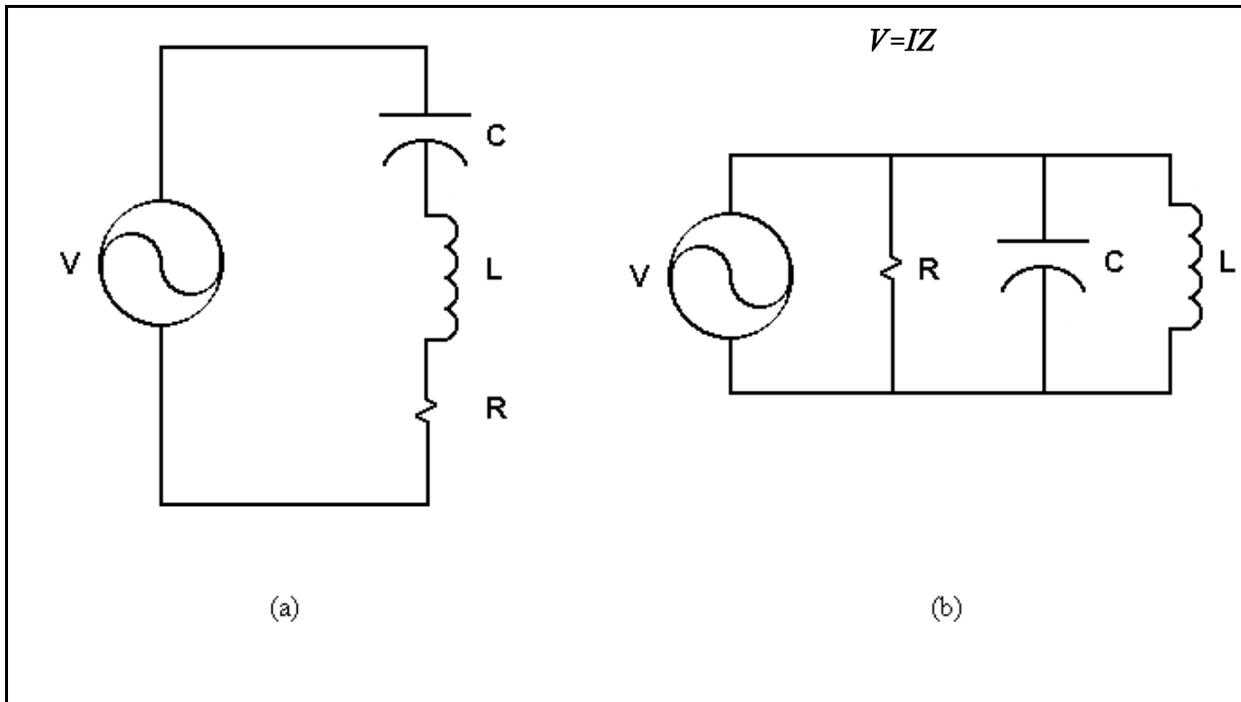
$$V = IZ$$

$$V=IZ$$

Figure 2   Series and Parallel Resonance

Resonance, linear or otherwise, occurs when the inductive and capacitive reactances of a circuit exactly balance. As shown in the equations, inductive reactance is proportional to frequency, rising with rising frequency, while capacitive reactance is inversely proportional to frequency, and so drops with rising frequency. For a given electrical circuit a resonant frequency can be found in which the inductive reactance and the capacitive reactance exactly cancel. In a series resonant circuit (Fig. 1a) this results in a total impedance Z that is a minimum. And because
the current is a maximum. In a parallel resonant circuit (Fig. 1b) the total impedance is a maximum at the resonant frequency. For a given current flowing through the circuit, the voltage across the circuit

will also be at a maximum.

In both series and parallel resonance, the extreme effects of voltage and current are mitigated by the introduction of pure resistance, because the value of a pure resistance is the same at all frequencies.

Linear resonant circuits as shown above exhibit regular and predictable responses to the applied voltage. A steady-state sinusoidal voltage will result in sinusoidal voltages and currents everywhere in the circuit; and though at different magnitudes, they will be at the same frequency. Applying twice the voltage will result in doubling the magnitude of voltages and
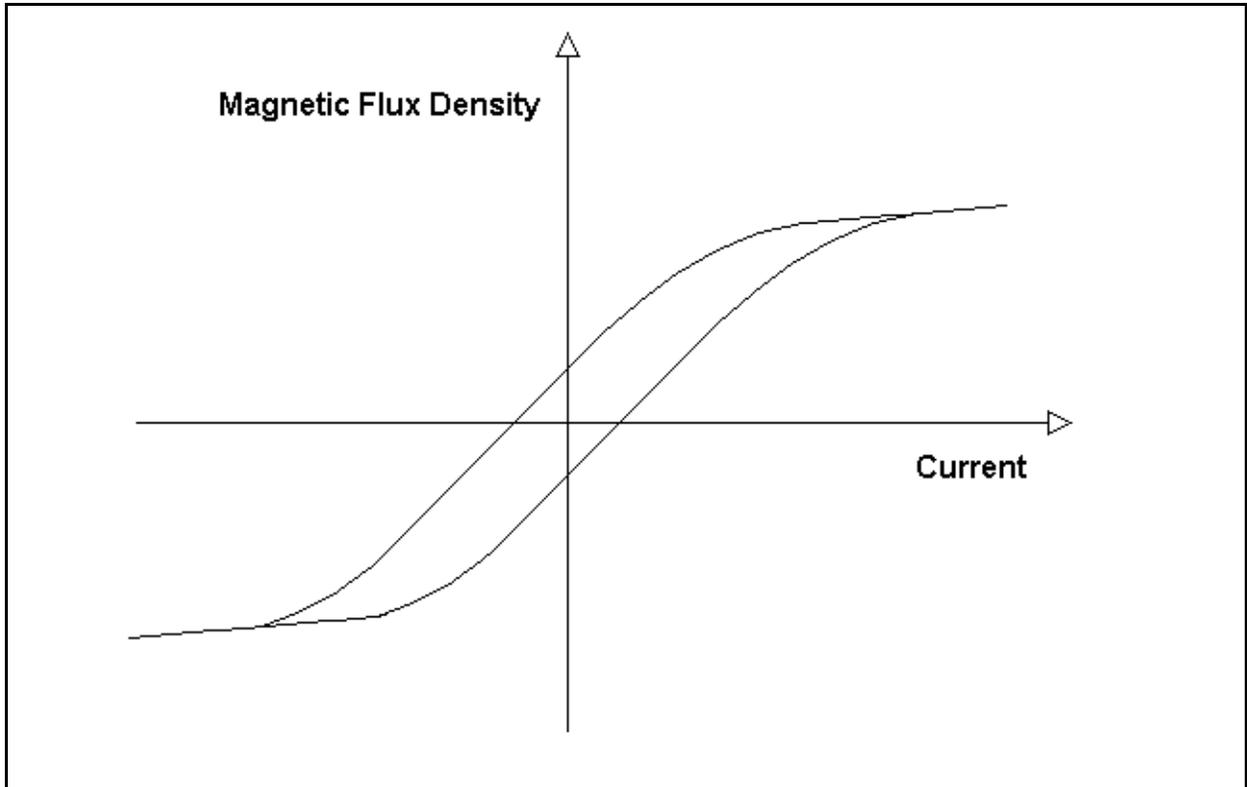
$$I=\frac{V}{Z}$$

Figure 3 Magnetic Hysteresis

currents elsewhere in the circuit. Even the circuits response to transients, though somewhat more complicated, is theoretically predictable and repeatable.

Ferroresonance

With ferroresonance the rules change. Ferroresonance is distinguished from linear resonance in that:

- there exist several stable steady state responses to any given change of parameters.
- Which particular response occurs is very dependant on the initial conditions.
- resonance at a given frequency can occur over a wide range of parameter values.

- the resonant frequency can be different for each stable response.

Ferroresonance occurs because the inductance in the circuit is ferromagnetic, meaning that it has a core made of a ferromagnetic material, usually iron. A transformer is an excellent example of a ferromagnetic inductance.

In ordinary, non-ferromagnetic inductance, as in a simple coil of wire, the value of inductance is determined by geometry; the dimensions of the coil, the number of turns, the cross sectional area, etc. When a ferromagnetic material such as iron is introduced into the core of such a coil, the inductance value is changed. This is because ferromagnetic materials have the property of causing an increase the magnetic

flux density, and therefore the magnetic induction.* The amount of magnetic induction attributable to the iron in the center of the solenoid can be much larger than the induction associated with the current in the coil by itself.

There are two additional properties of ferromagnetic materials that are important in understanding the phenomenon of ferroresonance. Ferromagnetic materials can saturate, and they exhibit hysteresis.

A typical magnetization curve of an iron core coil is shown in Figure 2. As the current increases, the magnetic flux density increases. A point is reached, however, where further increases in current yield smaller and smaller increases in flux density. This is called the saturation point, and is characterized by a dramatic change in the slope of the current - flux density curve. The slope of this curve is proportional to the inductance of the coil, which indicates that the inductance value itself is different for current magnitudes above the saturation point. This is key to understanding ferroresonance. *As the current in a ferromagnetic coil increases beyond the saturation point, the inductance of the coil changes rather suddenly.*

Figure 2 further shows two current-flux density characteristics. The bottom curve indicates the the flux that occurs when increasing from a negative current. The top curve indicates the flux that occurs when decreasing from a

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*In nonmagnetic materials the magnetic effect of electron spin in one direction is completely offset by equal electron spin in the opposite direction. In ferro-magnetic materials, compensation is not complete, and tiny, completely magnetized domains exist in the crystals of such materials. The application of a magnetic field (as when in the presence of an electrical current) causes an orientation of the domains in the direction of the applied field. [5]

positive current. This is a characteristic of ferromagnetic materials, and also very important to understanding ferroresonance. *The magnitude of current that causes the iron to go into saturation is not the same as the magnitude at which the iron comes out of saturation. The boundary between linear operation and saturated operation is not a fixed value of current, but is dependant on the previous values of that current.* This is called hysteresis, and is due to residual flux density stored in the iron, and which must be overcome when the current changes direction.

As with any resonance, the resonant frequency is that at which the capacitive and inductive reactances exactly cancel. At resonance extreme values of voltage and current can occur. With ferroresonance however, the inductance is not fixed. It changes due to saturation, and this changes the inductive reactance, so that the resonant frequency is a moving target. As the iron goes into saturation, the sudden change in inductance brings about a sudden change the frequency at which resonance will occur.

Another way of looking at this is to focus on the value of capacitance required to bring about a resonance. In a linear resonance this value can be (theoretically) identified precisely. With ferroresonance however, sudden and unpredictable changes in inductance will mean that a wide range of capacitances can potentially lead to resonance at a given frequency.

Once the ferromagnetic inductance "pops" into saturation, it remains saturated until the current magnitude decreases. If the inductance when saturated causes a resonance (i.e. results in an inductive reactance that matches the capacitive reactance in the circuit), the current magnitude can increase dramatically, further driving the iron into saturation, and thus making the resonant point stable.

If the current is able to drop below the saturation point, the inductance "pops" out of saturation, and again the inductance value changes. As previously described, magnetic hysteresis causes the precise points where the inductor goes into and out of saturation to be different, as shown in Figure 2.

These dramatic changes in inductance account for the multiple stable responses characteristic of ferroresonance. Hysteresis explains how the particular response that occurs is very dependant on the initial conditions.

As with linear resonance, the introduction of significant resistance in the circuit will tend to mitigate the extreme values of voltage and current.

POWER SYSTEM FERRORESONANCE

Ferroresonance in a power system can result in any of the following, alone or in combination:

- high sustained overvoltages, both phase to phase and phase to ground, (a maximum of 4.5 per unit in one typical example [2].)
- high sustained overcurrents,
- high sustained levels of distortion to the current and voltage waveforms,
- transformer heating and excessively loud noise,
- electrical equipment damage (thermal or due to insulation breakdown)
- Apparent mis-operation of protective devices.

If this occurred randomly without warning it would be quite disconcerting. Armed with our "circuit level" understanding of ferroresonance, however, we can identify the conditions under which ferroresonance is likely to occur.

- A sinusoidal voltage source - A power system generator will do quite nicely.
- Ferromagnetic inductances - these can be power transformers or instrument transformers.
- Capacitance - this can come from installed power system capacitors, the capacitance to ground of transmission lines, the large capacitance of underground cable, or the capacitance to ground of an ungrounded system.
- Low resistance - this can be lightly loaded power system equipment, (unloaded transformer for example), low short circuit power source, or low circuit losses.

A further requirement [1] is the existence of at least one point in the system whose potential is not fixed. This can be an isolated neutral, or can be created by a blown fuse or during single phase switching. This one "degree of freedom" can allow the system to "reposition" itself into a ferroresonant condition.
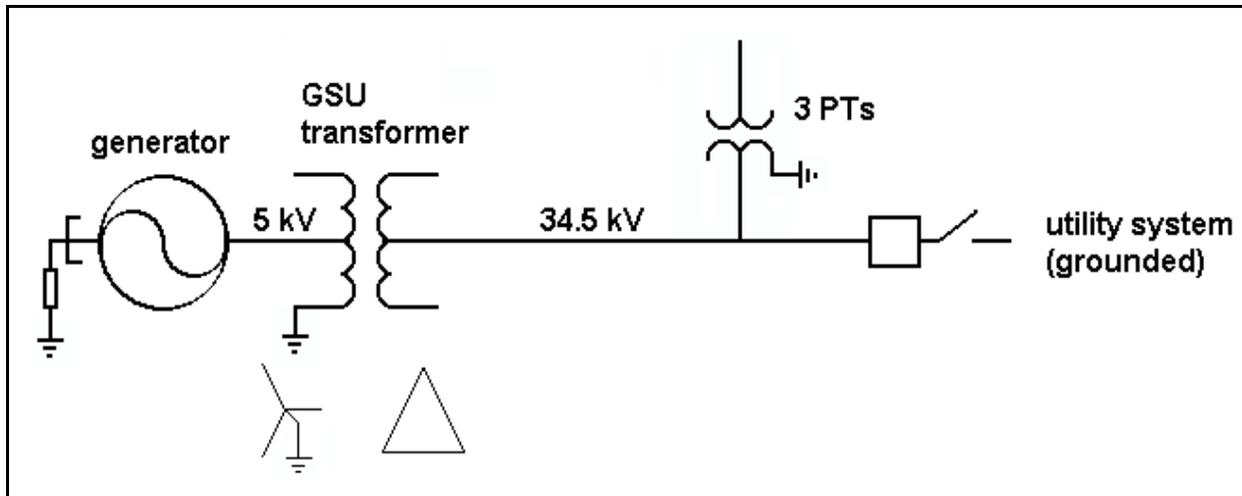
Figure 4 Typical Power System Configuration Favorable to Ferroresonance

The research [1] on ferroresonance indicates that if any one of these conditions does not exist, ferroresonance is highly unlikely.

The number of power circuit configurations which meet the conditions described above and therefore could conceivably support ferroresonance are endless. Through experience, however, several typical circuit configurations can be identified that have been known to give rise to ferroresonance. [1]

TYPICAL NON-UTILITY POWER PLANT

This paper now concentrates on the circuit presented by an actual industrial cogeneration project. The connection of this generator into the utility distribution system typifies one of the configurations known to give rise to ferroresonance: a grounded voltage transformer connected to an isolated neutral system.

As shown in Figure 3, the scenario features a voltage transformer whose wye grounded primary is connected to a 34.5 kV system that could become ungrounded.

One side of the circuit is fed by a generator,

through a wye grounded to delta generator step up (GSU) transformer. The GSU transformer provides no ground to the 34.5 kV system, and isolates it from what ever ground connection is provided by the generator itself. The utility source feeds the other side of the circuit, and even assuming it is grounded, may become ungrounded during some switching contingencies. A recloser or the gang operated switch can isolate the cogenerator from the utility source, and if the plant is running with this switch open, the 34.5 kV section of line will be entirely ungrounded.

Ferroresonance is a possibility during the time the 34.5 kV line section is not adequately grounded. Each of the necessary pre-conditions described will be met:

● A sinusoidal voltage source - in this case the normal utility source or the power plant generator.
● Saturable ferromagnetic inductance - the voltage transformer
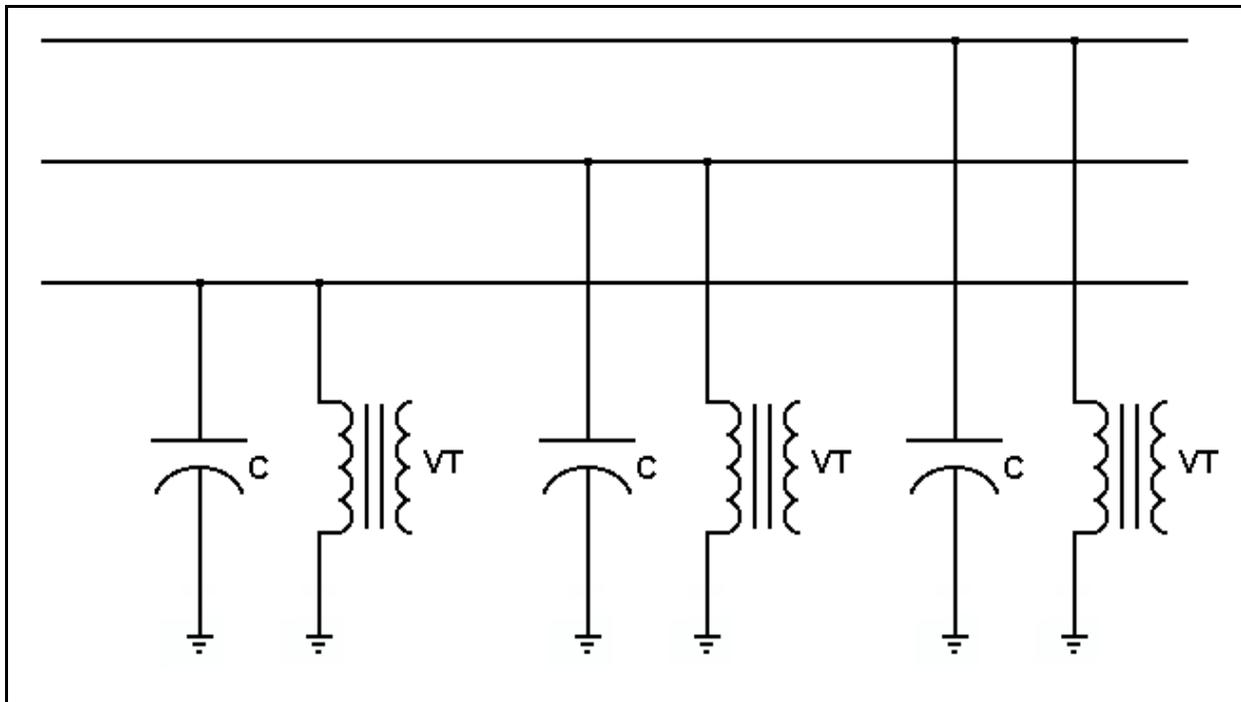● Capacitance - capacitance to ground of the 34.5 kV lines.

Figure 5 Parallel Ferroresonant Circuit

- Low resistance - the voltage transformer only is probably very lightly loaded, as it feeds voltage sensing devices. The generator may also be very lightly loaded.
- The existence of at least one point in the system whose potential is not fixed - the neutral point of the ungrounded or inadequately grounded section of the system.

The ferroresonant inductance of the voltage transformer is in parallel with the system capacitance, as shown in Figure 4. An initiating event, such as a transient overvoltage due to switching or fault clearing on the utility system, or a phase to ground fault on the inadequately grounded system, can drive one or several phases of the VT into saturation. The saturation of the iron core results in a sudden change in the inductance presented to the system by the voltage transformer. The ferromagnetic circuit can "lock" onto a level of saturation that provides an inductive reactance exactly canceling the capacitive reactance, and ferroresonance results. Overvoltages, caused by the parallel resonance, will sustain the saturation, and thus stabilize the ferroresonant condition. Steady state overvoltages can exceed normal phase to phase voltage and destroy electrical equipment. Extreme harmonic distortion may confuse protective relays and prevent tripping.

PREVENTION OR MITIGATION

Ferroresonance is prevented by eliminating one of the pre-conditions. Several alternatives, of various practicality, present themselves:

- avoid by design: use a delta connected primary VT. (This may not be practical in this case because one of the purposes of the VT is to detect ground faults using an open corner delta

secondary.)

- prevent the system from becoming ungrounded under any conditions. (This may not be entirely possible.)
- purchase a VT designed to operate at much lower induction values, so that the saturation point is at least twice the system voltage. (This may an expensive alternative.)
- Introduce losses by means of load resistances. (This is the alternative chosen.)

In wye-wye connected VTs 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 VT 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 in "Ferroresonance of Grounded Potential Transformers on Ungrounded Power Systems" (AIEE Power Apparatus & Systems, August 1959) as

$$100 \times \frac{L_a}{N^2}$$

where L_a is the voltage transformer primary inductance in millihenries and N is the

transformer turns ratio. [3]

CONCLUSIONS

Though ferroresonance may be complex and hard to analyze, it need not be mysterious. Ferroresonance has been shown to be the result of specific circuit conditions, and can be induced predictably in the laboratory. Power system ferroresonance can lead to very dangerous and damaging overvoltages, but the condition can be mitigated or avoided by careful system design.

REFERENCES

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[3]   Elmore,W.A., ed., "Protective Relaying Theory and Applications", ABB Power T&D Company, Blackburn, J.L., Kresseler,J.V., Chp. 7., New York, Marcel Dekker, Inc., 1994.

[4]   "Protective Relays", GEC Alsthom Measurements, Stafford England, 1990

[5]   Masch,L.W., "Electromagnetic & Electromechanical Machines", 2nd ed., New York, Harper & Roe, 1972