Examples of Ferroresonance in a High Voltage Power System

David A. N. Jacobson, *Member, IEEE*

***Abstract*—Catastrophic equipment failures continue to occur today due to ferroresonance even though this phenomenon has been extensively studied over the past ninety years. This paper is concerned with describing practical examples of ferroresonance in a high voltage transmission system. Methods of mitigating ferroresonance are discussed.**

***Index Terms*—Ferroresonance, power transformers, capacitors, power system transients, power system modeling, nonlinear circuits.**

I. INTRODUCTION

BOUCHEROT [2] originally coined the word *ferroresonance* in 1920 to describe the phenomenon of two stable fundamental frequency operating points coexisting in a series resistor, nonlinear inductor, capacitor circuit. The first published work, a 1907 paper by Bethenod [1], simply described the phenomenon as transformer resonance. Today, the term ferroresonance is firmly established in the power system engineer's vocabulary and is used to not only describe the jump to a higher current fundamental frequency state but also bifurcations to subharmonic, quasi-periodic and even chaotic oscillations in any circuit containing a nonlinear inductor.

A special publication is being prepared by the Practical Aspects of Ferroresonance IEEE Working group. One of the tasks of the Working Group is to provide a comprehensive survey of the ferroresonance issues reported in the literature. To date, 129 papers have been reviewed and categorized as practical. The following categories or classes of ferroresonant circuits have been reported:

1. Transformer supplied accidently on one or two phases (39 papers) [3]-[5],
2. Transformer energized through the grading capacitance of one or more open circuit breakers (25 papers) [6], [7],
3. Transformer connected to a series compensated transmission line (15 papers) [8], [9],
4. Voltage transformer connected to an isolated neutral system (14 papers) [10]-[13],
5. Capacitor voltage transformer (11 papers) [14], [15],
6. Transformer connected to a de-energized transmission line running in parallel with one or more energized lines (6 papers) [16], [17],
7. Transformer supplied through a long transmission line or cable with low short-circuit power (14 papers) [18]-[21].

Of the many excellent papers available, a few have been chosen above to enable the practicing engineer an opportunity to read further. For a better understanding of the phenomenon, including methods of identifying, modeling and preventing ferroresonance, the paper by Ferracci [22] and by the Slow Transients Task Force are recommended [23].

The key similarities between the different categories of circuits identified above are that each circuit has:

- a nonlinear saturable inductance (i.e. transformer),
- a capacitor,
- a voltage source,
- and low losses.

Ferroresonance is normally initiated after some type of switching event such as load rejection, fault clearing, transformer energization, single-phase switching or loss of system grounding.

The main objective of this paper is to document a set of system configurations that have experienced ferroresonance or are likely to experience ferroresonance in a high voltage power system (i.e. 33 kV or greater). Typical system parameters and means to mitigate ferroresonace are discussed.

Two examples are given for a transformer energized through the grading capacitance of open circuit breakers. The first example discusses a single-phase voltage transformer and the second discusses a three-phase station service transformer.

The final two case studies investigate a voltage transformer connected to an isolated neutral system and a capacitor voltage transformer.

II. WOUND PT-CB GRADING CAP.

A. Grading Capacitance

Circuit breaker technology involving the use of advanced interrupting mediums has evolved significantly over the past 50 years. Bulk oil breakers were the only choice for high voltage applications in the 1940s. Between 1950 and 1980 air blast breakers were common on MH's transmission system. Minimum oil breakers were most common between 1970 and 1990. Since 1988, all circuit breakers purchased by MH are SF_6 mixed with CF_4 in order to meet a -50³° C low temperature specification.

For high voltage applications, multiple interrupting chambers connected in series are required to interrupt the current and withstand the high recovery voltage. Grading capacitors are installed in parallel with each break to obtain an equal voltage distribution.

The author is with the System Planning Department, Manitoba Hydro, 12-1146 Waverley Street, P.O. Box 815, Winnipeg, Manitoba, R3C 2P4, Canada (e-mail: dajacobson@hydro.mb.ca).

As the interrupting medium has improved, the requirement for multiple interrupting chambers has diminished. At 230 kV, for example, air blast breakers required four to six chambers, minimal oil required two to four and SF_6 require two. Typical grading capacitance applied across each break is 30 to 800 pF for an air blast breaker, 800 to 1350 pF for a minimum oil breaker and 1500 to 1600 for an SF_6 breaker.

B. Description of Disturbance

The Dorsey HVdc converter station 230 kV ac bus is comprised of four bus sections on which the converter valves and transmission lines are terminated. At 22:04, May 20, 1995, bus A2 (Fig. 1) was removed from service to commission replacement breakers, current transformers and to perform disconnect maintenance and trip testing. At approximately 22:30, a potential transformer (V13F) failed catastrophically causing damage to equipment up to 33 m away. The switching procedure resulted in the deenergized bus and the associated PTs being connected to the energized bus B2 through the grading capacitors (5061 pF) of nine open 230 kV circuit breakers. A station service transformer, which is normally connected to bus A2, had been previously disconnected. A ferroresonance condition caused the failure of the PT.

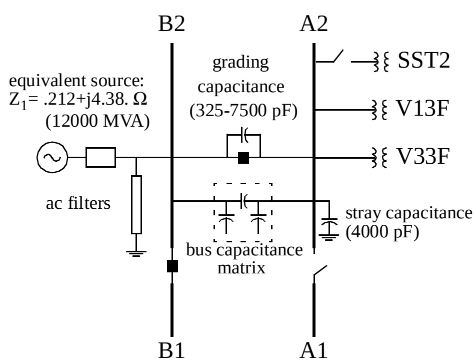

Fig. 1. Wound PT circuit model single line diagram.

C. Typical Oscillations

An oscillogram was located that shows the A2 Bus voltage for the Dorsey ferroresonant event of 95/05/20 at 22:04, after the last breaker cleared the bus. The trace is included in Fig. 2 for reference. The oscillogram shows phase A and B experienced random jumps between subharmonics and normal 60 Hz oscillations for the first 700 ms before settling into a steady state fundamental frequency ferroresonant state. Phase C did not experience ferroresonance.

The initial transients shown in the oscillograph are almost impossible to duplicate because they are a function of the breaker opening times, pre-switch voltage and the exact values of all parameters in each phase. Simulation tests showed for example that by varying the time step either all phases could jump into the final ferroresonant state immediately or any phase or combination of phases could remain at low voltage. A typical EMTP simulation is shown at the bottom of Fig. 2.

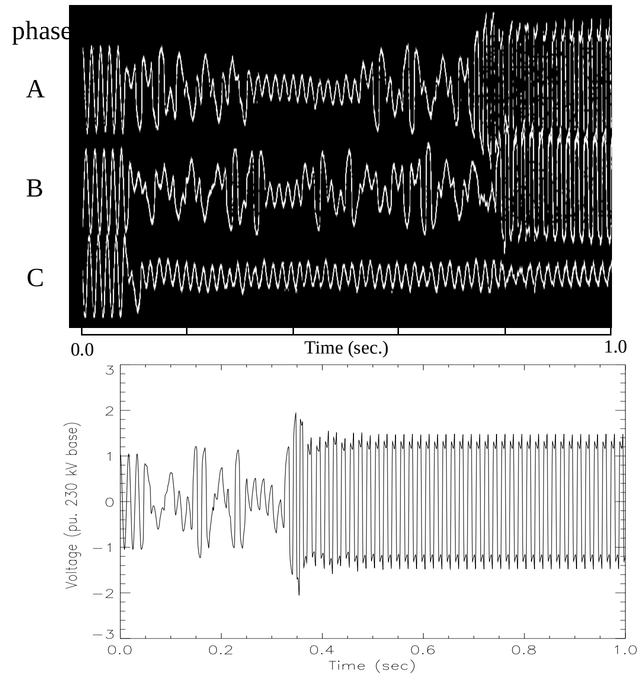

Fig. 2. Benchmark case results. Top: recording. Bottom: EMTP.

D. Mitigation Options

Revised manual bus clearing guidelines were implemented to reduce the risk of ferroresonance by minimizing the grading capacitance coupling the two buses. Disconnects on all but two breakers are opened thus limiting the maximum grading capacitance to 1500 pF. Damping resistors are not required in this case if the SST is in-service.

Permanently connected 200 ohm damping resistors connected to the secondary of the SST were found to be the most suitable short term mitigation measure to prevent ferroresonance following automatic bus clearing. Resistors were installed in September, 1995. Trip testing (Fig. 3) has shown the resistors prevent ferroresonance.

Other options that would also work include: a permanently bus connected 2 MVAr air-core reactor or filter (i.e. existing 80-100 MVAr), automatic disconnection of PT/SST via motor operated disconnects or a three phase grounding switch. The decreased system security, reduced reliability, operating inflexibility and cost preclude the use of these options. Bus surge arresters are not feasible as large overvoltages did not occur.

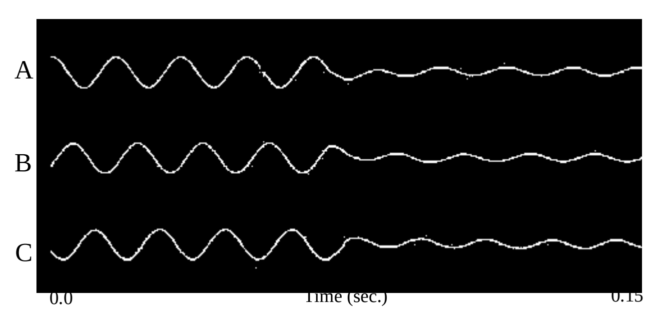

Fig. 3. Trip testing with 200 ohm resistors. Bus A2 voltage.

Permanently connected resistors on the PT secondaries are not feasible since the minimum required per phase load is at least double the 4 kVA thermal rating. The continuous losses associated with a permanent resistor can be avoided by switching a resistive load upon detection of a bus isolation signal. The degraded reliability associated with switched elements makes this option unattractive. As well, the resistive load needs to be increased (up to 40%) in order to extinguish an established ferroresonant state. The damping resistor needs to dissipate energy faster than the system can supply energy in order for the ferroresonant state to collapse into a non-ferroresonant 60 Hz operating mode.

III. TRANSFORMER-CB GRADING CAP.

A. Description of Disturbance

On August 5, 1995, at 14:18, a 4.16-kV breaker failed to latch while attempting to energize a 1500 kW induction motor at the Dorsey Converter Station in Manitoba [7]. As a result, eleven 230-kV breakers opened to clear bus B2 to which the 230-kV/4.16-kV transformer (SST1) was connected.

Noise levels coming from SST1 were noticeably higher than normal and higher than the nearby loaded SST2 immediately following the 230-kV bus de-energization.

The Dorsey synchronous condenser joint var controller responded to the ferroresonant overvoltage on the B2 bus and reduced the var output from the on-line synchronous condensers to near zero. The Dorsey 230-kV voltage on the in-service A2 bus stabilized at approximately 0.91 per unit after 30 minutes. Filter bank F9 was manually switched onto bus B2 at 14:58, eliminating the ferroresonant condition, after other attempts at regaining control of the Dorsey voltage had failed.

B. Typical Oscillations

Recordings given in Fig. 4 show high distortion and overvoltages near 1.5 pu. A steady-state asymmetric fundamental frequency mode of ferroresonance had developed. The asymmetry results in even harmonics being present.

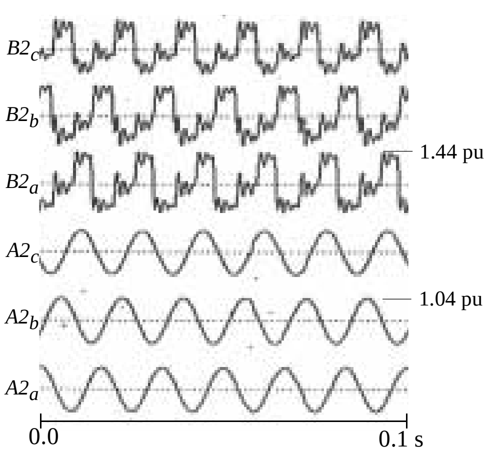

Fig. 4. Field recordings of bus voltages.

An EMTP model was developed and successfully modified to match field recordings of the disturbance [7]. A detailed three phase transformer model is required to generate the asymmetric fundamental frequency ferroresonant state. If three single phase transformers are used then a symmetric mode develops (i.e. Fig. 2). A single-line diagram of the EMTP model is given in Fig. 5.

C. Network Parameters

The approach taken in modelling the transformer's magnetization curve is to find a polynomial that closely follows the manufacturers data and best represents recordings from an inrush or ferroresonance test. A 13th order two-term polynomial is found to be a reasonable representation. The parameters used are: a_1=.002, a_{13}=.0024, n=13, i_b=35.5 A.

Iron-core losses of the station service transformers are 17 kW at nominal voltage. A more detailed model of iron-core losses is required to match the recorded transients. At the same instant that the oscillation mode changes to ferroresonance, additional resistance is switched on in parallel with the existing linear iron-core loss resistor. A more detailed discussion of iron-core loss modelling can be found in [7].

When bus B2 is de-energized, it remains capacitively coupled to the 443 m parallel A2 bus. A bus capacitance matrix is used to model the capacitive coupling [6]. The equivalent phase-to-ground capacitance (C_{pg}) is 5316 pF and the mutual capacitance (C_m) is 1108 pF. The equivalent positive sequence capacitance to ground is C_{pg}+C_m or 6424 pF. Therefore, the effective stray capacitance (C_b) is 12424 pF.

D. Mitigation Options

Since the May 20, 1995, destruction of wound potential transformer V13F [4], all wound potential transformers of concern at the Dorsey Station have been replaced with capacitor voltage transformers. Permanently connected 200-Ω loading resistors are installed on the 4.16-kV secondary bus of station service transformers SST1 and SST2.

The manual de-energizing operating procedure described earlier in the paper is no longer required with the addition of loading resistors and replacement of wound PTs.

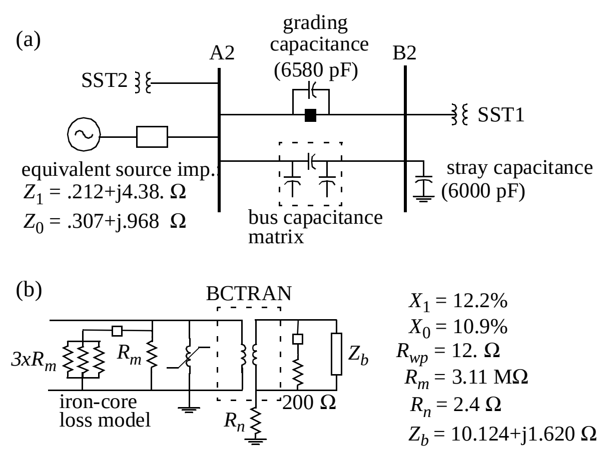

Fig. 5. Single-line diagram of the August 5, 1995, Dorsey disturbance showing (a) main circuit components and (b) model of station service transformer.

E. Bus Enhancement Project

A plan is in place to enhance the reliability of the station by adding a third bus and several new bus tie breakers and disconnects. By October 2003, the Dorsey station will be modified as indicated by the single-line diagram given in Fig. 6. The long buses have now been split into three shorter sections. Buses A1 and B1 remain unchanged.

Because of the bus configuration change, there may be an opportunity for removing the loading resistors if the potential for period-1 ferroresonance is eliminated.

Estimates of the possible combinations of stray and grading capacitance in which the station service transformers may operate are shown in Fig. 7.

The specific configurations correspond to:

i. normal clearing of SST1
ii. normal clearing of SST2
iii. normal clearing of SST3 or SST4
iv. breaker fail clearing of SST1
v. breaker fail clearing of SST2
vi. breaker fail clearing of SST2
vii. breaker fail clearing of SST3
viii. breaker fail clearing of SST4
ix. normal clearing of SST2 (existing configuration)

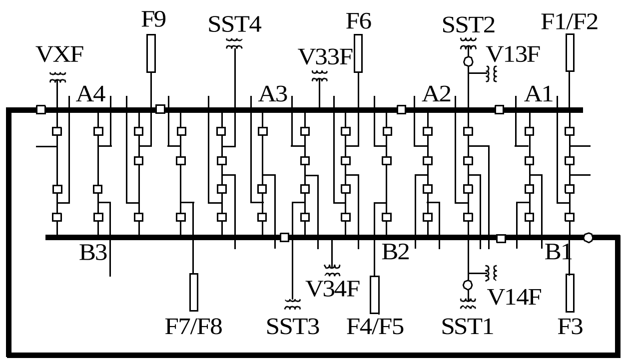

Fig. 6. Dorsey bus enhancement project.

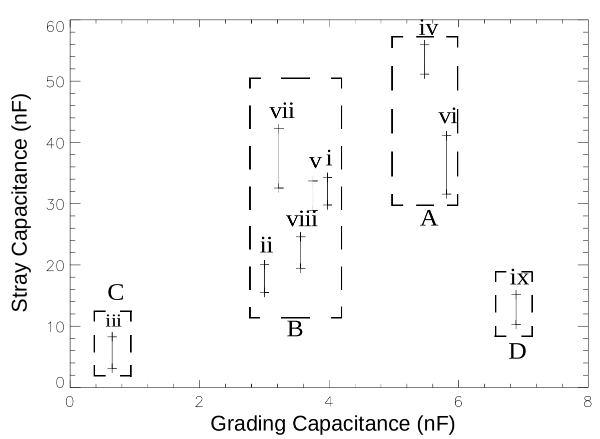

Fig. 7. Dorsey station service transformer stray and grading capacitance operating environment.

Using some modern analysis techniques, a decision was made to switch the 200 Ω resistors rather than have them permanently connected [7].

IV. Open-Delta PT

A. Network Problems

Concerns for ferroresonance in open-delta PTs exist:

- during energization of the unloaded stepdown transformer
- following interruption of a single line-to-ground fault on the low side of the transformer.

During normal operation, the system voltages are balanced and virtually zero volts occurs across the break in the broken-delta winding. Ground faults will cause sufficient unbalance for a voltage to appear across the break. Overvoltage relays connected across the break serve as ground-fault detectors and will trip the low voltage breakers.

During severe unbalanced conditions, the resulting overvoltages cause PT saturation. If the stray capacitance on the secondary of the step-down transformer is within a particular range, ferroresonance can result.

Depending on the value of capacitance, different ferroresonance modes can be excited. Based on a review of the literature [10]-[13], three modes of ferroresonance have been observed in an open-delta PT. Low values of stray capacitance may cause a third harmonic mode of ferroresonance to develop. Medium values of capacitance result in an unbalanced fundamental mode of ferroresonance being excited. Quite often ground-fault relays may trip, resulting in a so-called faked earth-fault. Higher values of capacitance may result in subharmonic modes of ferroresonance (period-2 or period-4). The subharmonic modes may result in dangerous overheating in the PT due to high core losses resulting from elevated flux levels.

B. Network Parameters

A typical 33 kV or 66 kV station single line diagram with two radial feeders is shown in Fig. 8.

The critical elements to be modeled are:

- potential transformer (PT)
- stray capacitance
- grounding bank (GB)

The purpose of the GB is to provide zero sequence current during single line-to-ground faults for ground fault protection relays to operate. The open-delta PT serves as a backup to allow the GB to be taken out-of-service for maintenance.

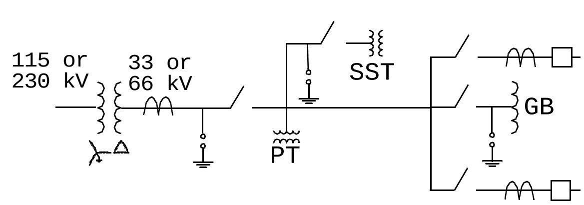

Fig. 8. Typical station layout.

A lumped capacitor, representing the stray capacitance of the various components, can be calculated using data given in [24]. Assuming a 66 kV station, the stray capacitance can range from 4000 pF to 17000 pF. The lower value is possible if the station service transformer (SST) and grounding bank (GB) are disconnected.

A zig zag winding configuration is used to create the low zero sequence impedance of the grounding bank. Grounding banks connected to the Manitoba Hydro 33 kV and 66 kV are specified to have a zero sequence impedance of 120 ohms.

C. Typical Oscillations

Fig. 9 shows the simulated open-delta voltages following clearing of a nine-cycle SLGF.

Typical waveforms were generated by EMTP simulations of SLGF clearing rather than transformer energization. Transformer energization requires long duration simulation times or special initialization techniques in order to reach steady-state, whereas the ferroresonant mode is immediately apparent following interruption of a fault.

In Fig. 9a, the unbalanced fundamental mode of ferroresonance is shown. A damping resistor (25% of thermal rating of PT) is effective at eliminating ferroresonance as is a zig-zag grounding bank.

The third harmonic mode could be excited if the stray capacitance was approximately 500 pF and subharmonic modes if the stray capacitance was greater than 50000 pF.

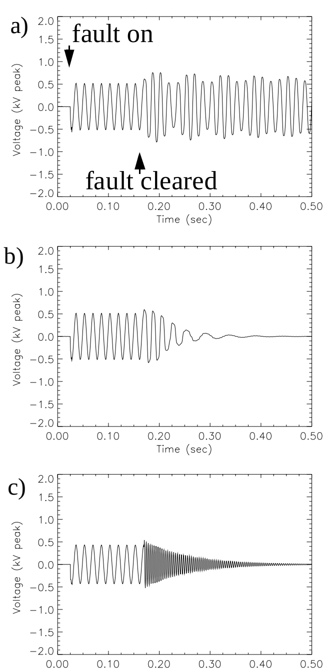

Fig. 9. Example of voltages oscillations across open-delta with 15000 pF, a) no mitigation, b) 83 ohm resistor (25% of PT thermal rating), c) GB connected.

D. Mitigation Options

There are several possible solutions. Crane and Walsh [11] recommend one of the following:

1. replacing PTs with capacitive coupled voltage transformers (CCVTs).

2. installing PTs that are rated for line-to-line system voltage. Minimal saturation occurs during ground faults, thus limiting the susceptibility to ferroresonance.

3. installing a resistor in the broken-delta. The paper discusses a calculation method. A 3 ohm resistor (43 kJ) was recommended for their application. Under worst case conditions, up to twice rated current could flow in the PT. However, the PT is designed to handle twice rated current for up to 30 seconds which is must greater than a typical fault clearing time of 1 second. The damping resistor is expected to eliminate any ferroresonant oscillations within 0.1 to 0.2 seconds.

Ritz instrument transformers recommend installing an inductor in parallel with a resistor. The inductor is used to eliminate subharmonic oscillations and the resistor is used to damp period-1 ferroresonance. It’s not clear what thermal rating corresponds to each PT they discuss, however, the damping resistors are in the range 500-2000 watts with a 5 second rating (10 kJ max).

Damstra [12] also recommends a saturable reactor-resistor scheme. At KEMA labs in the Netherlands, several Holec PTs in the 50, 100 and 150 kV classes were tested. The saturable reactor tended to eliminate subharmonic modes and a 50-100 ohm resistor eliminated period-1 modes of ferroresonance.

Van Craenenbroeck *et al.* [13] are investigating modern techniques of analysis and their application to a 6.6 kV ungrounded network. Energizing the PT through a cable feeder could excite ferroresonance oscillations. Their analysis techniques can determine a minimal value of damping resistance.

For typical 33 kV and 66 kV delta stations, Manitoba Hydro installs ballast resistors across the open-delta of all PTs and installs grounding banks. The ballast resistor has a power rating of 25%. Specialized studies are used to determine appropriate ferroresonance mitigation when the stray capacitance becomes excessive (i.e. due to underground cables).

V. CAPACITOR VOLTAGE TRANSFORMER

A. Network Problems

The phenomenon of ferroresonance is of particular concern during capacitor voltage transformer (CVT) or coupling capacitor voltage transformer (CCVT) transients, and can cause noticeable deviation of CVT response from the actual input waveform. The Canadian Standards Association requires CVTs to be designed such that it does not develop continuous subharmonics or stable overvoltages at system frequency.

CSA requires ferroresonance tests to demonstrate that transients damp out within 10 cycles when the CVT is supplied at 1.2 pu or less than 2 s when supplied at 1.5 pu [25]. The latest ANSI C93.1 standard has no requirements for ferroresonance suppression and only requires a test at 1.1 pu voltage [26].

Specialized equipment may require more stringent specifications than CSA. For example, a CVT used for voltage measurement at an SVC terminal may be required to damp transients within 2 cycles [15]. Because of the deviation from the actual commutating bus voltage, only wound PTs are permitted to be used for valve timing at Manitoba Hydro's HVdc converter stations. High speed protective relays can be impacted by the transient response which can cause overreaching, underreaching or directional errors [27].

Nonlinear burdens such as auxiliary potential transformers can impact the CVT. For the circuit shown in Fig. 10, a 230:230 volt auxiliary PT is chosen in the 115-volt circuit to avoid any problems. Smaller auxiliary PTs (i.e. 115:115 volt) have gone into ferroresonance before the intermediate transformer leading to overvoltages and protective gap flashovers.

B. Network Parameters

A typical CVT single line diagram is given in Fig. 10. Parameters vary widely between manufacturers and as a function of the voltage level. A complete set of data for a 161 kV CVT is given in [15].

C. Typical Oscillations

Simulations of a ferroresonance test (i.e. secondary short-circuit test) for the circuit in Fig. 10 is given in Fig. 11. The impact of the ferroresonance suppression circuit (FSC) is clearly seen.

D. Mitigation Options

Manufacturers are aware of the ferroresonance problem and install various types of suppression circuits. The FSC shown in Fig. 10 has a constant burden and a saturable reactor. Tuned RLC filters are also used but this type of circuit affects the frequency response of the CVT. Special arrangements of triacs/spark-gaps can be used to achieve ferroresonance suppression within 2 cycles.

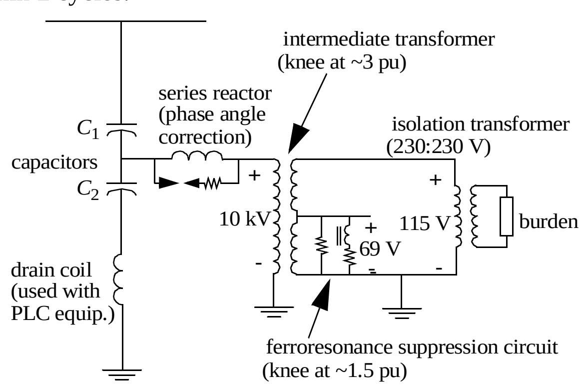

Fig. 10. Typical CVT single line diagram.

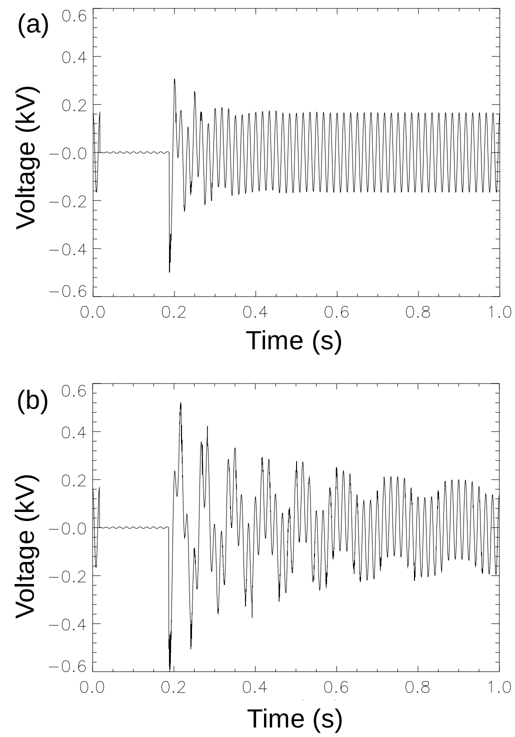

Fig. 11. CSA ferroresonance test comparison with, (a) ferroresonance suppression circuit (FSC) enabled and with, (b) FSC disabled.

VI. CONCLUSIONS

Four examples of circuit configurations that can experience ferroresonance have been presented. The impact of ferroresonance can vary from relay or control misoperation to catastrophic equipment failure. By being aware of the various situations where ferroresonance can occur, appropriate mitigation strategies can be designed before equipment is put into service and problems develop.

As the first two examples show, an innocent circuit breaker replacement project created a ferroresonance situation where there was none prior. Advances in circuit breaker interrupting medium technology led to an effective increase in the amount of grading capacitance connected to a de-energized voltage transformer and station service transformer. Loading resistors and replacement of the voltage transformers with capacitor voltage transformers were required to mitigate the problem.

Open-delta voltage transformers are well protected with loading resistors across the open delta or by nearby grounding transformer banks in most situations. However, high values of capacitance due to the presence of underground cables requires special studies to determine if additional facilities are required to mitigate ferroresonance.

Capacitor voltage transformers are protected by ferroresonance suppression circuits installed by the manufacturer. Depending on the application, high speed suppression of the transient ferroresonant oscillations may be needed, which requires a more sophisticated FSC.

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VIII. BIOGRAPHIES

David A. N. Jacobson (S'84-M'90) received the B.Sc. degree in electrical engineering (with distinction) and the M.Sc. and Ph.D. degrees from the University of Manitoba, Winnipeg, MB, Canada, in 1988, 1990, and 2000 respectively. He joined Manitoba Hydro, Winnipeg, in 1990, where he is currently the Interconnections and Grid Supply Planning Engineer. He was a visiting researcher with the Siemens Power System Planning group in Erlangen, Germany, in 1994. His research interests include nonlinear dynamics, power system control and FACTS devices. He is active in CIGRE Study Committee C6 Distribution Systems and Dispersed Generation. Dr. Jacobson has been a registered Professional Engineer in the province of Manitoba since 1992.