Modeling Ferroresonance in a 230 kV Transformer-Terminated Double-Circuit Transmission Line

D. A. N. Jacobson
Manitoba Hydro
820 Taylor Ave.
Winnipeg, Manitoba, R3C 2P4, Canada
dajacobson@hydro.mb.ca

Dr. L. Martí
Ontario Hydro
700 University Avenue
Toronto, Ontario, M5G 1X6, Canada
luis.marti@hydro.on.ca

Dr. R. W. Menzies
Dept. of Electrical and Comp. Eng.
University of Manitoba
Winnipeg, Manitoba, R3T 5V6, Canada
menzies@ee.umanitoba.ca

Abstract - **One possible ferroresonant circuit occurs when an unloaded transformer is connected to a de-energized transmission line that is capacitively coupled with a parallel energized line. An example from Manitoba Hydro's 230 kV power system is investigated through EMTP simulations and field tests. The transformer model is shown to greatly influence the final state. The possibility of fictitious ferroresonant states can result when a piecewise-linear saturation curve with too low a kneepoint is used. The damping of subharmonics is influenced by the iron-core loss representation. Proposed solutions include isolating the transformer automatically via an overvoltage relay or line reactor switching.**

Keywords: ferroresonance, EMTP, power transformer, magnetic saturation, modeling, transients, field testing.

I. INTRODUCTION

Recently, Ontario Hydro reported on examples of ferroresonance occurring in their Dual Element Source Network (DESN) stations [1], [2]. The close coupling of parallel circuits with similar or higher voltage increases the risk of ferroresonance in the disconnected transformer. An example is shown in [2] where 59 km of parallel 230 kV and 32 km of parallel 500 kV transmission were sufficient to cause ferroresonance in a 230-115 kV transformer. Electricité de France (EDF) have reported on experiences with their 400 kV network [3]. Ferroresonance has been reported following uneven breaker pole operation (i.e. stuck breaker during single-pole switching operations). An example of a 113 km double-circuit 400 kV transmission line with a 150 MVA transformer tapped off one line is discussed in [3].

Some examples from Britain are given in [4] and [5]. These examples are slightly different, because one of the double-circuit lines is not tapped. Instead, the lines are terminated by one or two step-down transformers. The simulation results for a 45 km, 400 kV double-circuit line terminating in a 1000 MVA transformer is described in [4], while field observations of a 150 km, 400 kV double-circuit line terminating in a 500 MVA transformer are reported in [5]. German and Davies [5] observe that the length of the coupled lines tends to influence the type of oscillations observed. Very short lines (i.e. less than 20 km) do not experience ferroresonance. Period-1 ferroresonance (i.e. the ratio of the natural period of the dynamic system to the base period of a 60 Hz source is equal to one) is prevalent for medium length lines, while subharmonic (period-3) oscillations dominate long lines (i.e. >150 km). Diseko *et al.* [4] notices the zero sequence impedance of the transformer is a critical parameter in determining the probability of ferroresonance.

The first reported occurrence of ferroresonance in a transformer caused by capacitive coupling with a parallel energized line took place at the Big Eddy Station of Bonneville Power Administration (BPA) in the U.S. [6]. The circuit consisted of 31 km of parallel 525 kV circuits. One circuit was terminated by a 1000 MVA 525-241.5 kV autotransformer. Ferroresonance (period-1) lasted for 16-22 minutes in phase C but did not cause any damage to the transformer. Subsequent measurements showed that the magnetizing current in phase C was 30% lower than in phases A and B. Both period-1 and period-3 ferroresonance were observed in subsequent field tests.

In summary, transformers can ferroresonate when connected to an open transmission line which is capacitively coupled to an energized line. It is assumed at least 10 to 20 km of parallel high voltage transmission lines (i.e. 115 kV or greater) coupled with an unloaded transformer are necessary before ferroresonance can be initiated. The literature indicates ferroresonance will be excited only for a narrow band of initial conditions. Hence, the probability is low even if the configuration is of high risk.

In order to avoid any surprises at Manitoba Hydro, a search for candidate 230 kV configurations that might be susceptible to this form of ferroresonance was made. To date, Manitoba Hydro has only one tapped parallel circuit transmission line with a length in excess of 10 to 20 km. The paper will discuss an EMTP and field study investigation of this circuit.

II. SYSTEM DESCRIPTION

A single-line diagram representing the studied system is given in Fig. 1.

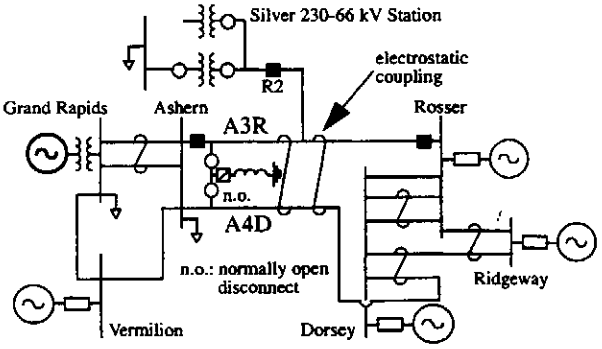


Fig. 1. Circuit model single line diagram.

Based on the literature review, the Silver 230-66 kV transformer may be susceptible to ferroresonance if it is unloaded and remains connected to the de-energized line A3R. Manual clearing or energization procedures currently in place will not place the Silver transformers and line A3R in a configuration which is susceptible to ferroresonance.

In order for the Silver transformer to remain connected to the de-energized 230 kV line, two scenarios have been identified:

- automatic clearing of 230 kV line A3R.
- automatic clearing of Silver station.

Each scenario will be described in more detail.

A. De-energizing line A3R

A fault on the 230 kV line will be detected by impedance relays and cleared by opening breakers at Rosser and Ashern. Breaker R2 at Silver is not equipped with line protection or communication and therefore will not open automatically for faults on line A3R.

The 66 kV breakers will open via an undervoltage relay after 200 milliseconds assuming the 66 kV is not networked (normal case). The purpose of sectionalizing the 66 kV bus automatically following undervoltages is to avoid the pickup of full station load current in addition to transformer inrush current following re-energization of line A3R.

Ferroresonance may develop if the transformer is unloaded. During a recent winter storm, crossarms were damaged on both 66 kV feeders leaving Silver resulting in a three hour outage. If the 230 kV line A3R had also tripped during the storm, the Silver transformers may have gone into ferroresonance and remained undetected.

B. De-energizing Silver Station

The transformers at Silver station are protected against internal faults by fast gas, pressure relief, temperature and differential relays. These relays trip and lockout breaker R2 and the 66 kV breakers. Normal clearing of Silver station disturbances will not result in a configuration which is prone to ferroresonance.

In the event of one or more phases of R2 failing to open (e.g. loss of gas pressure), line A3R will trip as a backup (i.e. by zone 2 protection - 250 ms delay). Because the bank is unloaded before A3R trips, there is a risk of ferroresonance. The concern with this disturbance is that ferroresonance will not be removed by automatic protection. Existing overvoltage or neutral overcurrent relays may operate; however the failed phases of breaker R2 cannot be opened.

Some possible alternatives available to remove this condition are:

- reclose circuit breaker at Rosser or Ashern.
- trip line A4D.
- install transformer loading resistors.
- permanently connect a line reactor to A3R.
- switch the existing line reactor onto A3R.

There is a risk that a reclose at Ashern or Rosser will not be successful if a permanent fault exists in the Silver station. Tripping line A4D is possible; however, this results in a double-circuit outage which can have stability implications.

The use of switched [2] or permanently connected loading resistors [10] is sometimes the only feasible method which can be used to prevent ferroresonance. However, the method is costly and should be avoided if other techniques are available.

The existing line reactor cannot be connected permanently to A3R because it reduces operating flexibility. A smaller line reactor (e.g. 25 MVAr) could be connected to A3R, but this is also a costly method. Temporarily switching the existing line reactor onto A3R to remove a ferroresonant condition is feasible if the reactor is available and inserted in a timely manner.

Field tests and further analysis in later sections will address the concerns for ferroresonance posed by this circuit configuration.

III. FIELD TESTS

Tests were conducted on July 4, 1997, to assess the risk of ferroresonance occurring at Silver station. Preliminary EMTP studies showed a risk of ferroresonance if the line A3R trips and one or two unloaded transformers are connected at Silver. Controlled field tests were used to verify the accuracy of the EMTP model. Once the EMTP model is validated, simulations can be confidently carried out to design the appropriate mitigating procedures, if the risk of ferroresonance is verified. As well, the effectiveness of the Silver transformer's neutral current protection and overvoltage protection under distorted conditions had to be tested.

Several switching events were investigated. Fig. 2 represents the transients following de-energization of the Ashern reactor. Prior to the reactor circuit switcher opening, line A3R was open. The high coupled voltage (i.e. 20 kV) is due to parallel line resonance [7], [8] between the reactor and line charging capacitance. After the reactor is removed, the coupled voltage reduces to 3.2 kV.

Tripping line A3R with the Ashern reactor connected was also tested. The trapped charge on the line was dissipated through the Ashern reactor in three seconds. The frequency of the line discharge oscillations was 56 Hz. During the discharge, a 240 kV (1.27 pu) transient voltage appeared at the terminals of the Silver transformer without significantly saturating the core.

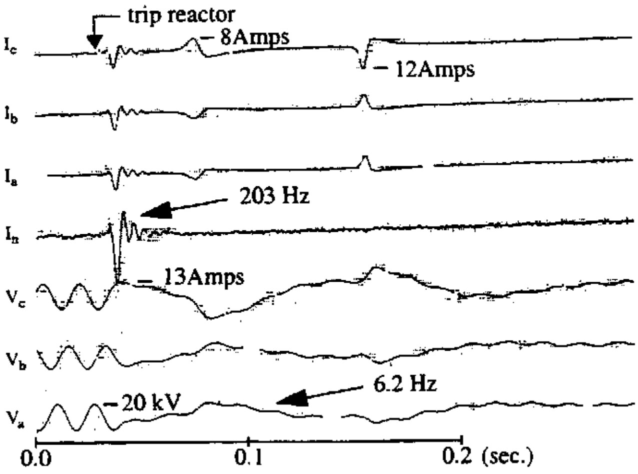


Fig. 2. Field test: reactor switching.

Tripping line A3R without the Ashern reactor connected could not be tested because the open-ended line voltage exceeds the steady-state rating of line-end equipment.

IV. EMTP MODEL

The EMTP (DCG/EPRI ElectroMagnetic Transients Program version 3.0F) was used for circuit simulation. Details of the modeling techniques of various components follow.

A. Transmission Line Model

The critical lines to be modeled are A3R, A4D and the Silver tap. Frequency dependent line models are necessary if accurate transient recovery voltages are to be calculated or if a broad spectrum of transients are expected. Based on previous research [1]-[6], periodic signals based on 60 Hz or subharmonics of 60 Hz are expected, however, there is always the possibility of quasi-periodic or chaotic signals being excited. A frequency dependent line model was used as it is more accurate for signals that deviate widely from 60 Hz.

The transposition scheme must be explicitly modeled. Transpositions in each circuit have the effect of balancing the phase-to-neutral capacitance and phase inductance between each phase over the entire transposition cycle. By transposing phases in a double-circuit line at the same locations, the positive sequence coupling between circuits can be reduced. A pictorial representation of the A3R/A4D transposition scheme and conductor configuration is shown below in Fig. 3. The average separation between the two transmission lines A3R and A4D is 28.26 meters.

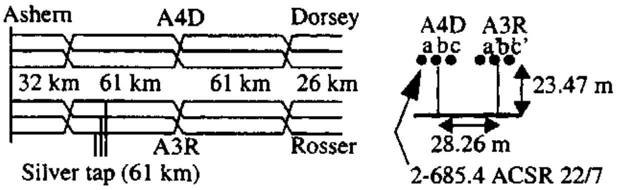


Fig. 3. A3R/A4D transpositions and tower configuration.

The peripheral lines to the study area do not need frequency dependent modeling as they don't affect switching surges in the study area to a great extent. Therefore, all external lines were modeled as untransposed distributed parameter lines.

The line discharge oscillation frequency predicted from linear frequency scans using the parameters given in Fig. 3 is 58 Hz and the coupled voltage with the reactor connected is 30 kV. If the transmission line length is increased by 5%, the discharge frequency decreases and the coupled voltage decreases to match field measurements shown in Fig. 2.

B. Ashern Reactor Model

The Ashern 50 MVAr reactor is constructed in a three-phase three-legged core configuration. The positive and zero sequence impedances given by the manufacturer are: X_1=100.71%, X_0=34.87%, and R_1=0.266% (all values on 230 kV, 50 MVA base). The X_0/X_1 ratio (0.35) is lower than typical values (0.5-0.7) [8]. The positive sequence quality factor (Q_1=379) is within typical ranges of 300 to 500. The zero sequence resistance was not given. Typically, Q_0 lies between 10 and 40 [8]. A value of 23 was chosen based on one author's 60 MVAr reactor [7]. The positive and zero sequence data was entered in a three phase coupled R-L branch in EMTP. The zero sequence data is necessary to determine the effect of faults on coupled voltages.

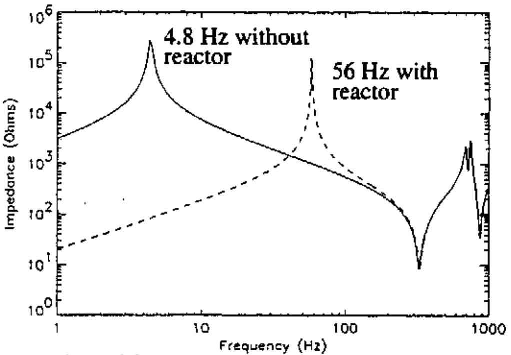
Saturation data was not given by the manufacturer. The knee point of a reactor's saturation curve is normally near 150-160%, therefore a linear reactor model was used since study voltages were not expected to exceed the reactor knee-point.

Field tests indicate the reactor impedance is 1100 Ohms which compares well with the digital model (1069 Ohms).

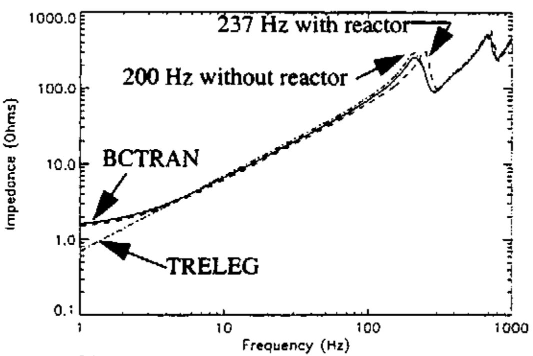
C. Silver Transformer Model

The Silver transformer is a 230-66 kV grounded wye-delta three-phase transformer rated 50 MVA constructed in a three-legged core configuration. Since 1995, a second 230-66 kV transformer has been in-service as a hot standby (i.e energized but not connected to the 66 kV). The second transformer was modeled with parameters identical to the first bank.

Because of the direct magnetic coupling between phases, a three phase transformer model must be used. Two models are currently available for use in EMTP: TRELEG and BCTRAN. Both models consist of coupled R-L branches that reproduce standard short circuit tests at 60 Hz power frequency. For frequencies up to 1 kHz both models behave similarly, however for zero sequence frequencies approaching dc the BCTRAN model correctly degenerates to a simple resistance (see Fig. 4b). The BCTRAN model was used in the paper.



a) positive sequence



b) zero sequence

Fig. 4. Frequency scans. A3R open. Two Silver transformers.

A frequency dependent transformer model and frequency dependent eddy-current model [9] are available in EMTP. The additional accuracy above 2-3 kHz is not required for ferroresonance studies.

Several changes were required in the transformer's saturation and iron-core loss models in order to match field recordings. The next section will discuss transformer saturation modeling in more detail.

Subharmonic damping could only be matched if hysteresis losses were included. A constant resistance is normally used to approximate the iron-core losses [10]. This model is voltage dependent and not flux dependent which causes inadequate damping of low voltage subharmonics.

Historically, the hysteresis losses have been assumed to be 1/3 the eddy-current losses for modern transformers constructed using grain-oriented silicon-steel sheets [11]. The subharmonic damping shown in Fig. 2 was duplicated when this loss ratio was used.

The EMTP simulation of the reactor switching test is shown in Fig. 5 and includes breaker R2 current (i.e. sum of two banks), neutral current and 230 kV bus voltages.

A current transformer (CT) model was required in the simulation in order to match the recorded current transients. The subharmonic current saturates the CT which distorts the measured current. An ideal CT model produces the transients shown in Fig. 8. The large current pulse at 0.16 seconds indicated by field tests was not duplicated with the final EMTP model.

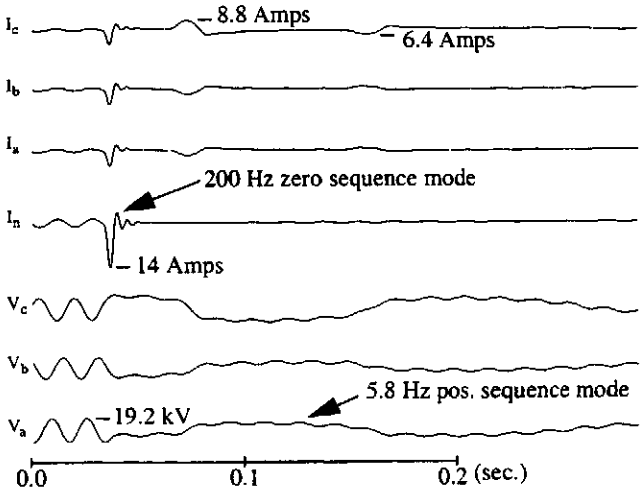


Fig. 5. EMTP simulation of reactor switching. Type-96 model.

V. SATURATION MODELS

The location of the saturation curve is important. Of importance is the ability to match the transient flow of current in the neutral. With saturation modeled on the delta winding, all zero sequence current is trapped in that winding. With saturation modeled on the high-side wye winding, some third harmonic current will flow transiently through the neutral, for example. The best match to field measurements resulted when saturation was modeled on the low side as shown in Fig. 6.

There are three models available in EMTP to represent saturation in an inductor. Each will be described briefly.

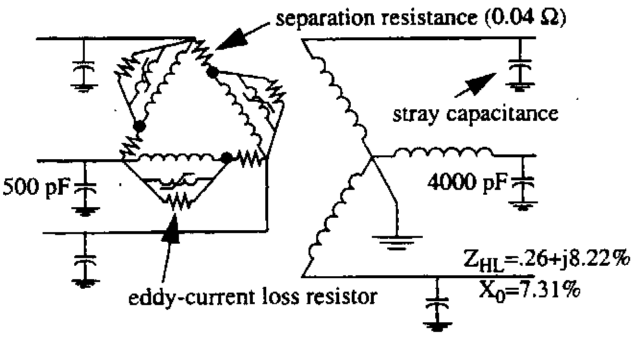


Fig. 6. Silver transformer model.

A. Type-98: Piecewise-Linear Inductance

A normal piecewise-linear saturation curve was used in the initial modeling stages. Test data was given by the manufacturer for 90%, 100% and 110% open-circuit voltage. The air-core reactance was assumed to be twice the leakage reactance (Z_{HL}). Since the flux contained by the core under full saturation was unknown, a worst case was obtained by extrapolating the last measured point. The resulting four-segment piecewise-linear curve did not match field tests. Fictitious oscillations resulted because of too low a knee-point and too abrupt a transition between curve segments.

An alternative model was developed using a two-term polynomial relation (1).

$$i_L(\phi) = a\cdot\phi + b\cdot\phi^n \qquad (1)$$

An 11th order polynomial (a=.0028, b=.0001) served as a starting point and was discretized into 28 segments. The flux coordinate points were scaled (i.e. 80%) until the first transient current peak in the reactor switching test matched field tests.

A linear parallel resistor modeled the 50 kW iron-core losses.

B. Type-96: Pseudo-Nonlinear Inductance with Hysteresis

The Type-96 reactor model was setup to have roughly the same transient flux-current loop shape as the Type-98 reactor shown in Fig. 7a. By using the default 22 segment hysteresis shape (Armco M4 grain-oriented silicon steel) and by modifying the slope through the linear region by adjusting the excitation current to 0.2% in the BCTRAN transformer model, this was achieved.

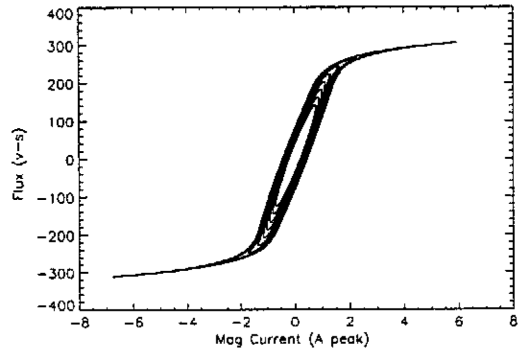
One input required in the hysteresis data setup routine is the coordinates where the saturation characteristic changes from being multivalued to single-valued. The flux coordinate can be estimated from the Type-98 flux-current loop to be 290 Volt-seconds. The current coordinate is adjusted until the total measured open-circuit losses is 50 kW. A linear eddy-current loss resistor is included representing 75% of the total iron-core losses.

C. Type-92: True-Nonlinear Inductance with Hysteresis

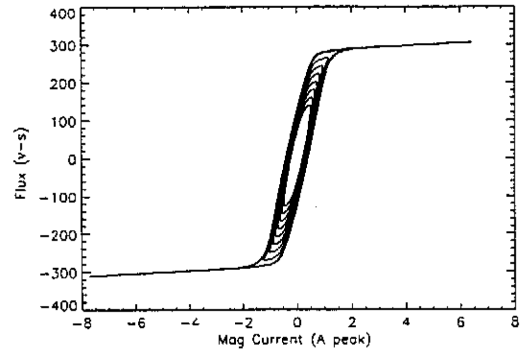
The new Type-92 nonlinear inductor with hysteresis model [9] is not a piecewise-linear model but rather a closed-form nonlinear function. This closed-form function takes the form of a two-term polynomial.

The closed-form functions are calculated using an auxiliary EMTP subroutine. A 10 segment single-valued saturation curve taken from the Type-98 reactor is input and the coercive current is adjusted until the total measured open-circuit losses is 50 kW. As with the Type-96 reactor, a linear eddy-current loss resistor representing 75% of the total iron-core losses was used.

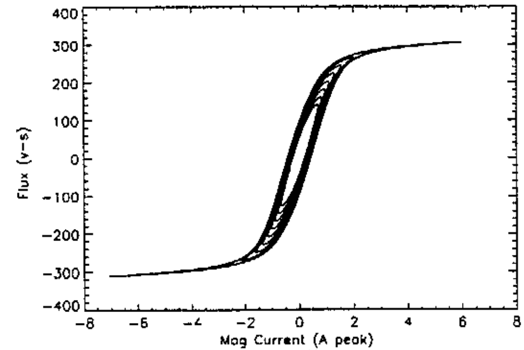
The DCG/EPRI version of the EMTP, type-92 (or true nonlinear models) are solved using the compensation method [15]. Because of the way the compensation method is implemented in this version of the EMTP, delta-connected loops of Type-92 elements result in a singular matrix (the Microtran version of the EMTP formulates the compensation-based solution somewhat differently and does not have this particular problem). One way of eliminating this problem is to separate the nonlinear elements by a small impedance. For this problem, a resistor was used as shown in Fig. 6. A value equivalent to 15% of the measured delta winding resistance was required to eliminate the singularity and allow for rapid convergence.



a) Type-98 piecewise-linear



b) Type-96 pseudo-nonlinear

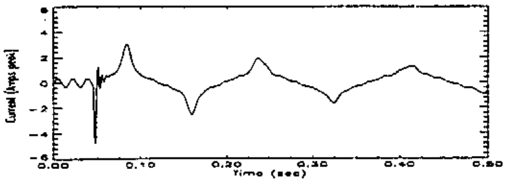


c) Type-92 true-nonlinear

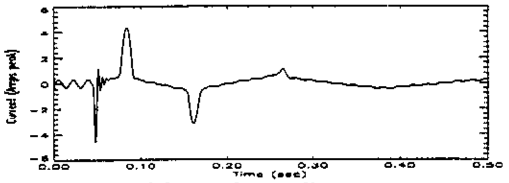
Fig. 7. Transient flux-current loops.

D. Comparison of the Models

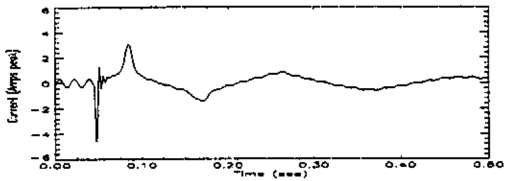
As mentioned earlier in the paper, subharmonic damping is improved by including hysteresis losses. A comparison of the damping performance of the three models is shown in Fig. 8.



a) Type-98 piecewise-linear



b) Type-96 pseudo-nonlinear



c) Type-92 true-nonlinear

Fig. 8. Comparison of subharmonic damping.

Sustained numerical oscillations can be introduced following transitions between segments in piecewise-linear inductors. A small time step (10 µsec.), large number of segments and inclusion of a linear parallel eddy-current loss resistor effectively eliminated any oscillations. The "Critical Damping Adjustment" feature of EMTP was not enabled in these simulations.

In terms of cpu time, the Type-92 inductor requires approximately 25% more computation time than the Type-98 and Type-96 inductors.

VI. EMTP FERRORESONANCE STUDY

Several cases which could not be field tested were investigated using the benchmarked EMTP model. In general, ferroresonance did not develop for any case which had the Ashern reactor connected or had loaded transformers. Ferroresonance did develop for the following cases:

- single-pole breaker failure at Rosser or Ashern.
- tripping A3R.

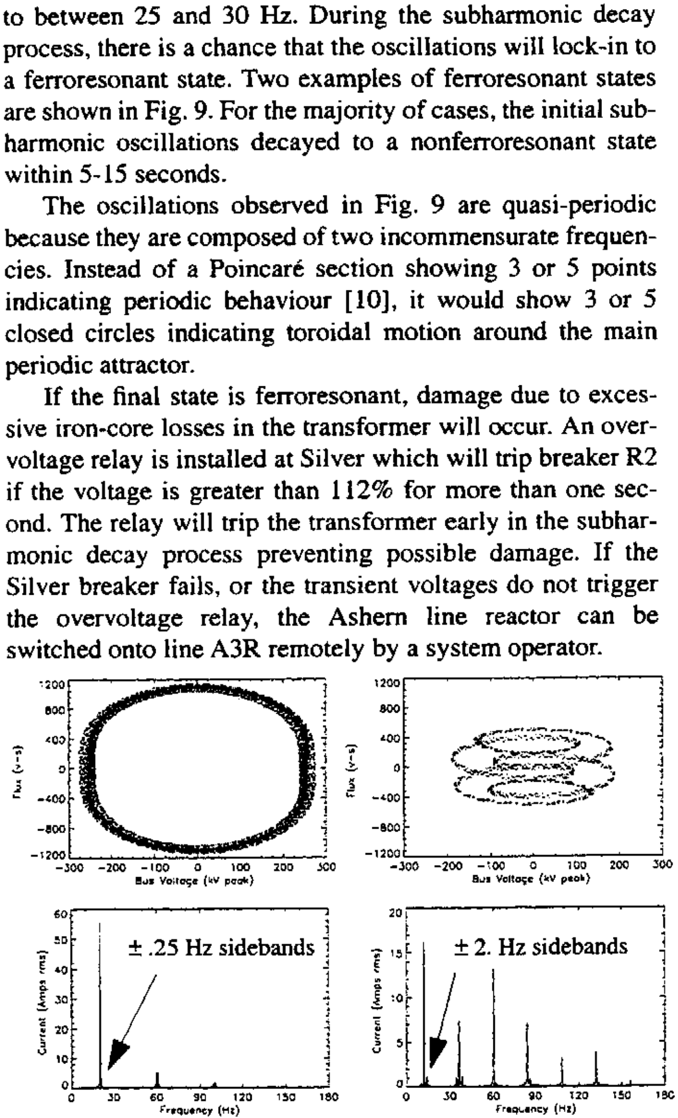
The parallel transmission line can be ignored in the case of single-pole failure at Rosser or Ashern as the energy required to sustain ferroresonance is derived from the remaining healthy phases on line A3R. This phenomenon has been extensively studied using laboratory models and field tests at distribution level voltages up to 35 kV originally by Hopkinson [12] and later by Walling *et al.* [13]. For distribution systems, single-pole failures are a real concern because there may be no backup protection. At transmission voltage levels, breaker failures are cleared within 250 milliseconds by backup breakers. The only concern is whether the transient recovery voltage (TRV) capability of the backup breaker is sufficient or whether ferroresonance will be sustained following breaker clearing. For this system, standard ANSI 230 kV TRV ratings were not exceeded and no ferroresonance modes were sustained.

Tripping A3R with no reactor and with no load at Silver also results in ferroresonance. The oscillations were predominantly subharmonic which supports the observations made by German and Davies [5]. Long duration simulations (i.e. up to 10 seconds) are required to determine whether the ferroresonance oscillation mode is permanent.

Immediately following the trip of A3R, the transformer saturates and the first positive sequence resonance mode bends to the right. Wrate *et al.* are developing techniques for predicting the frequency shift [14]. The new "resonant" frequency depends on a number of factors but typically shifts to between 25 and 30 Hz. During the subharmonic decay process, there is a chance that the oscillations will lock-in to a ferroresonant state. Two examples of ferroresonant states are shown in Fig. 9. For the majority of cases, the initial subharmonic oscillations decayed to a nonferroresonant state within 5-15 seconds.

The oscillations observed in Fig. 9 are quasi-periodic because they are composed of two incommensurate frequencies. Instead of a Poincaré section showing 3 or 5 points indicating periodic behaviour [10], it would show 3 or 5 closed circles indicating toroidal motion around the main periodic attractor.

If the final state is ferroresonant, damage due to excessive iron-core losses in the transformer will occur. An overvoltage relay is installed at Silver which will trip breaker R2 if the voltage is greater than 112% for more than one second. The relay will trip the transformer early in the subharmonic decay process preventing possible damage. If the Silver breaker fails, or the transient voltages do not trigger the overvoltage relay, the Ashern line reactor can be switched onto line A3R remotely by a system operator.



a) Quasi-Period-3. A3R trip. Type-96 reactor

b) Quasi-Period-5. A3R trip with single-pole breaker fail at Rosser. Type-92 reactor

Fig. 9. Subharmonic attractors. Top: state space trajectory (flux vs. 230 kV bus voltage). Bottom: secondary current spectrum.

VII. CONCLUSIONS

This paper has focused on double-circuit transmission lines and how ferroresonance can result in a de-energized transformer through capacitive coupling with a parallel energized transmission line. Field tests are essential for improving modeling techniques and validating digital models. The study has confirmed the probability of a permanent ferroresonant state exists and can be mitigated.

VIII. REFERENCES

[1] Mork, B.A., Morched, A.S., and Walling, R.A.,"Modelling and Analysis Guidelines for the Investigation of Slow Transients in Power Systems: Part III-Study of the Phenomenon of Ferroresonance", *Slow Transients T.F. of IEEE WG on Modelling and Analysis of System Transients Using Digital Programs*, July 27, 1996.

[2] Brierly, R.H., Morched, A.S., and Grainger, T.E.,"Compact Right-of-Ways with Multi-Voltage Towers", *IEEE Trans. on Power Delivery*, Vol. 6, No. 4, pp. 1682-1689, Oct. 1991.

[3] Bornard, P., Collet Billon, V., and Kieny, C.,"Protection of EHV Power Systems Against Ferroresonance", *1990 CIGRE*, paper 34-103, pp. 1-8, Sept. 1990.

[4] Diseko, N.L., and Bickford, J.P.,"A Method of Simulating Linear and Nonlinear Resonant Phenomena Associated with Transformer Feeders", *IEE Proceedings*, Vol. 127, Pt. C, No. 3, pp. 169-178, May 1980.

[5] German, D.M., and Davies, A.E.,"Ferroresonance on EHV Transmission Systems", *1978 IEEE PES Winter Meeting*, Paper No. A78 116-6, Feb., 1978.

[6] Dolan, E., Gillies, D., and Kimbark, E.,"Ferroresonance in a Transformer Switched with an EHV Line", *IEEE Summer Power Meeting*, Paper 71 TP 533-PWR, T-PAS-91, No. 3 pp. 1273-1280, May/June, 1972.

[7] Colapret, E.E., and Reid, W.E., "Effects of Faults and Shunt Reactor Parameters on Parallel Resonance", *IEEE Power App. and Systems*, Vol. PAS-100, No. 2, pp. 572-584, Feb. 1981.

[8] Reid, W.E., Gustin, R.F., and Zylstra, P.V.,"Guidelines for Determining Parallel Resonance on EHV Transmission Lines", *IEEE Trans. on Power App. & Systems*, Vol. 102, No. 9, pp. 3196-3204, Sept. 1983.

[9] Tarasiewicz, E.J., Morched, A.S., Narang, A., and Dick, E.P.,"Frequency Dependent Eddy Current Models for Nonlinear Iron Cores", *IEEE Trans. on Power App. and Systems*, Vol. 8, No. 2 pp. 588-597, May 1993.

[10] Jacobson, D.A.N., Swatek, D., and Mazur, R., "Mitigating Potential Transformer Ferroresonance in a 230 kV Converter Station", *Computer Analysis of Electric Power System Transients: Selected Readings*, IEEE Press: Piscataway, N.J., pp. 359-365, 1997.

[11] Swift, G.W.,"Power Transformer Core Behavior Under Transient Conditions", *IEEE Trans. on Power App. and Systems*, Vol. PAS-90, No. 5, pp. 2206-2210, Sept./Oct. 1971.

[12] Hopkinson, R.,"Ferroresonance During Single-Phase Switching of 3-Phase Distribution Transformer Banks", *IEEE Trans. on Power App. & Systems*, Vol. 84, No. 10, pp. 1258-1265, April 1965.

[13] Walling, R., Hartana, R., and Ros, W.,"Self-generated Overvoltages due to Open-Phasing of Ungrounded-Wye Delta Transformer Banks", *IEEE Trans. on Power Delivery*, Vol. 10, No. 1, pp. 526-533, Jan. 1995.

[14] Wrate, G.T., Mork, B.A., and Mustaphi, K.K.,"A New Method to Determine Frequency Characteristics of a Power System Including Nonlinear Effects", *Proc. of the 1997 Intl. Conf. on Power Systems Transients*, pp. 11-16, June 1997.

[15] Dommel, H.W., *The EMTP Theory Book: Second edition*, Microtran: Vancouver, B.C., April 1996.