765 KV POWER TRANSFORMER LOSSES UPON ENERGIZATIONS: A COMPARISON BETWEEN FIELD TEST MEASUREMENTS AND EMTP-RV SIMULATIONS

C. Morin (*) B. Khodabakhchian

Abstract **-- Transformer energization tests were performed in Hydro-Québec Chateauguay substation on a 300 MVA single-phase 765/125/12.5 kV Yg-Yg-Δ power transformer in order to improve power transformer modeling for harmonic over-voltage evaluations upon energizations and fault removals close to HVDC converters with associated filters and capacitor banks. From these results, an enhanced transformer model has been developed in EMTP-RV Software. Subsequent simulations show that accurate modeling of the power transformer losses does only have minor influences on harmonic over-voltages damping. It is shown however that the usage of the proposed model is essential to predict adequately the risks of ferroresonance and generated over-voltages in power systems.**

Keywords**: Transformer saturation - Eddy current losses, Hysteresis losses, harmonic over-voltages, ferroresonance, EMTP-RV.**

I. INTRODUCTION

HYDRO-QUÉBEC transmission system, one of the largest in North-America, delivers over 35,000 MW of hydro-electric power to its customers in the south (Montreal and Québec city) from large generation centers situated very far in the north of the Province (up to 1,200 km). It delivers also large amount of green power to neighboring utilities via HVDC interconnections. Consequently, the system is vulnerable to the generation of severe harmonic over-voltages due to the interaction of large transformers saturation currents with long transmission lines during events such as load rejections and system restorations following a partial/major black-out.

This paper reports the field tests performed on a 765 kV power transformer in order to evaluate the saturation losses under different levels of the core flux, describes the developed EMTP-RV model and its validation to finally conclude on the influence of these losses on the phenomena of harmonic over-voltages damping and creation of ferroresonance.

II. DESCRIPTION OF THE FIELD TESTS

The Chateauguay substation configuration during the tests is shown in Fig. 1. An air-blast 8 chambers circuit-breaker was used to switch the single-phase transformer situated at the end of 400 meters of 765 kV bus-bars. High voltage instruments were set-up next to the power transformer to measure voltages on both sides. A one mΩ shunt resistance was installed between transformer neutral and earth on 765 kV side to measure the current circulating through the winding.

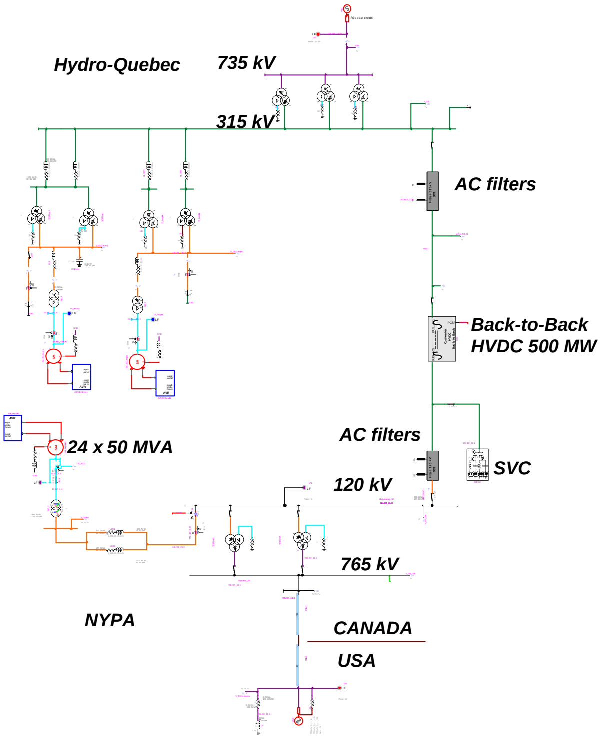


Figure 1. Chateauguay substation configuration during tests

Residual fluxes needed to be set before energizing the transformer in order to have a better control of the saturation level in the core of the transformer. Flux adjustment was done by traveling on the hysteresis curve using a DC source connected on the HV winding. A special device was built to change the polarity of the source, to protect against over-voltages and to measure the voltage and the current. From the voltage reading, the magnetic flux was calculated in real time and a flux-current curve was drawn. This method helps to

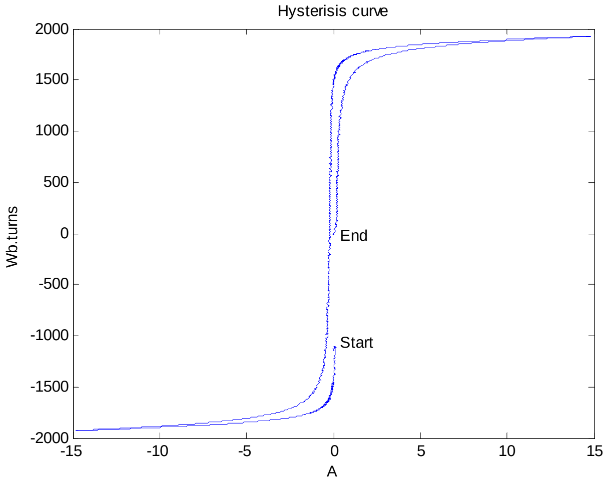
---

(*) Charles Morin, corresponding author, is with System Studies, Hydro-Québec TransÉnergie Complexe Desjardins, Tour de l'Est, 10e étage, case postale 10000, Montréal (Qc), Canada, H5B-1H7. Phone: 1-514-879-4100 (Ext. 5229). Fax: 1-514-879-4482. Email: morin.charles.r@hydro.qc.ca

Bahram Khodabakhchian is also with System Studies, Hydro-Québec TransÉnergie. Phone: 1-514-879-4100 (Ext. 5237). Fax: 1-514-879-4482. Email: khodabakhchian.bahram@hydro.qc.ca

Paper submitted to the International Conference on Power Systems Transients (IPST2013) in Vancouver, BC, Canada July 18-20, 2013

evaluate the initial residual flux and to set it to a desired value. Fig. 2 shows the magnetic flux adjustment during the DC source injection. In this case, a magnetic flux of 0 *wb·turns* was desired.



. Fig. 2. Adjustment of the residual flux on the hysteresis curve

It is worthy to mention that according to the manufacturer test report for this particular transformer, the no-load losses were 277 kW at an applied voltage of 1.15 pu. The hysteresis losses calculated on a complete cycle of the measured DC hysteresis curve of fig. 2 are 175 kW. This means that no-load losses are composed of 63% of hysteresis losses and 37 % of Eddy current losses.

Four tests with different saturation levels have been performed. Table I shows the parameters associated to these tests.

TABLE I

PARAMETERS OF THE PERFORMED FOUR FIELD TESTS

Test #	Residual Flux (pu)	Max Flux (pu)	Current (A) 1st crest	1st cy. Loss (kW)
1	-0.62	+1.33	+284	850
2	+0.47	-1.43	-596	982
3	-0.13	-1.88	-1615	1786
4	+0.62	+2.25	+2996	4450

Figure 3, which corresponds to test # 2, shows the measured 765 kV voltage and the inrush current of the transformer. On the voltage signal, one may notice the followings:

- before the closing instant of the circuit-breaker, the 4% transfer voltage through its 3 nF grading capacitor is not purely capacitive, the lead angle depends on the magnetizing inductance and the no-load losses of the transformer at low voltages (4%);
- following the closing of the circuit-breaker, the harmonic contents of the inrush current creates slight voltage distortions;
- the slight instantaneous jump of the 765 kV voltage near the end of the third cycle is due to the current chopping of the air-blast circuit-breaker [1];
- the voltage oscillation amplitude and frequency after current chopping are again mainly governed by the transformer magnetizing inductance and the no-load losses at low voltages.

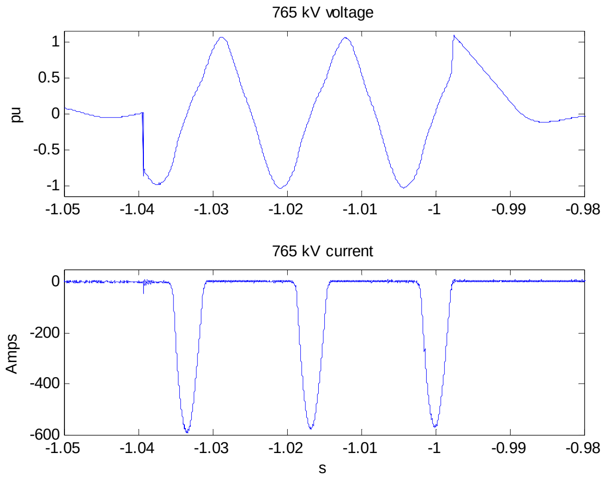


Figure 3. Measured current and voltage during test # 3

Another interesting information which may be deducted from figure 4 (test # 4) is the variation of the saturation slope between 1.15 pu (50%) and 1.55 pu (33%) of the flux. It is therefore suggested in electromagnetic studies to model the saturation characteristic of the power transformers with three segments instead of widely used practices of two.

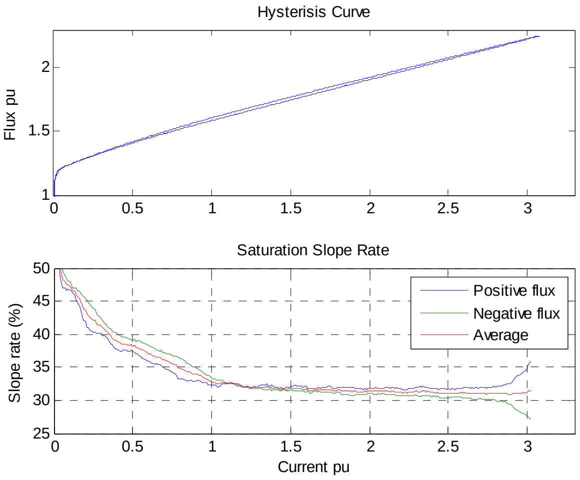


Figure 4. Measured saturation characteristic during test # 4

III. DESCRIPTION OF THE SIMULATION EFFORTS

A. *Transformer Model*

An EMTP-RV transformer model based on overexcitation tests performed at Hydro-Québec in 2001 on a 370 MVA single-phase transformer was developed [2]. This model takes advantage of the controlled resistance element in EMTP-RV library to vary the transformer core losses as a function of the flux (Fig. 5). Figure 6 shows the loss characteristics of the 300 MVA 765 kV transformer at three different overexcitation voltage levels. The fact that the simulated no-load core losses of figure 7, if compared on a per MVA basis, match very well those reported by tests is an indication of a satisfactory model development.

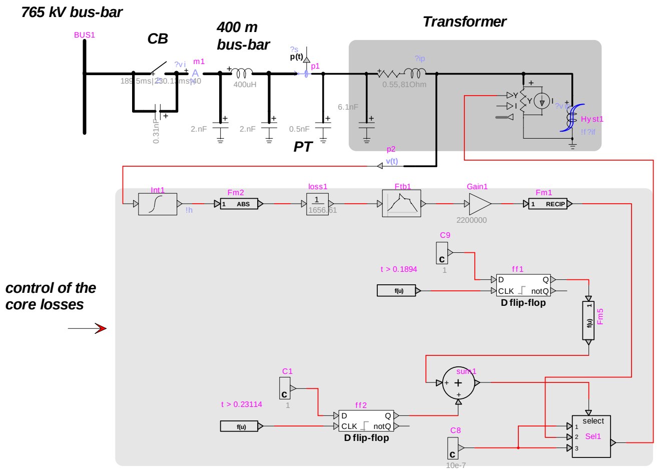
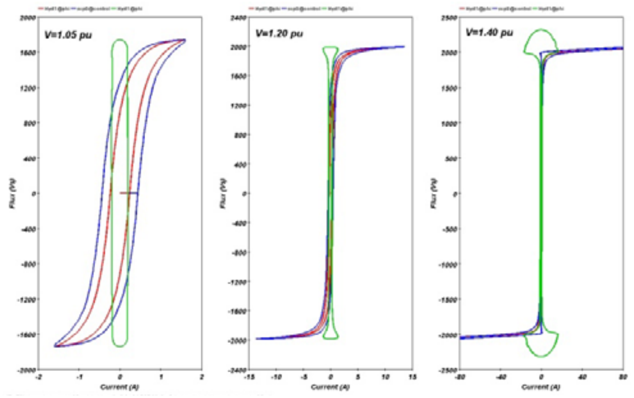


Figure 5. EMTP-RV simulation of the switched 765 kV transformer



Green: Eddy losses, Red: Hysteresis losses, Blue: total core losses

Figure 6. Simulation results of the core loss characteristics of the 765 kV transformer at three different overexcitation voltage levels: a) 1.05 pu, b) 1.20 pu and c) 1.40 pu

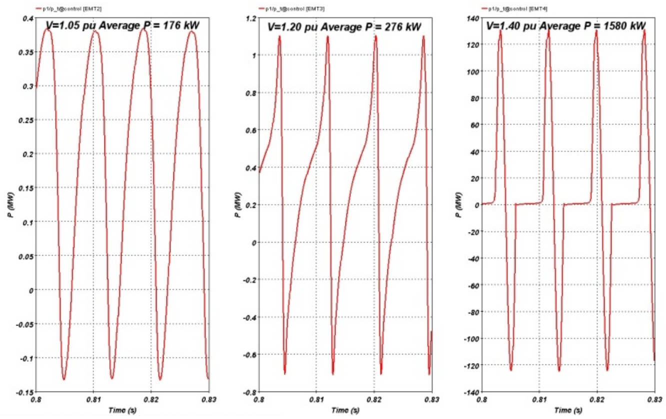


Figure 7. Simulation results of the 765 kV transformer no-load core losses, 1.05 pu, 1.20 pu and 1.40 pu

B. Network Model

The network of figure 1 was modeled in detail in EMTP-RV [3] with synchronous machines, excitation systems and saturable transformers models. The back-to-back HVDC digital controller Software was implemented directly in EMTP-RV by its flexible DLL capability. The analog controller of the SVC was modeled by the control library elements of the Software.

The 765 kV circuit-breaker was represented by an ideal switch with a 0.3 nF capacitance. The 400 meters bus-bar was modeled by a Pi section equivalent and the PT with its known value of 0.5 nF. In order to reproduce correctly the 4% transfer voltage and its lead angle, a 6.1 nF of capacitance was added to the transformer model as its HV winding capacitance. The total losses of the transformer at 4% transfer voltage (open circuit-breaker) was represented by a resistance of 10 MΩ. Finally, a 40 A chopping current characteristic was assumed for the air-blast circuit-breaker in order to reproduce correctly the slight instantaneous jump of the 765 kV voltage in the last cycle.

C. Simulation Results

Figure 8, 9 and 10 compare the simulations results versus field tests number 2, 3 and 4 respectively. An almost perfect match is obtained even in the area of harmonic distortions of the 765 kV voltages and following transformer disconnection by the circuit-breaker. The latter is particularly an important argument to affirm that the model can correctly predict the transformer's trapped core flux following its de-energization by a circuit-breaker.

In terms of losses, figure 11 compares the measured first cycle losses with those obtained by simulations. The slightly lower simulated losses are most probably due to the fact that, in the performed simulations, the transformer model does not take into account the Eddy current losses increase with the frequency (i.e. harmonic contents of the 765 kV voltages).

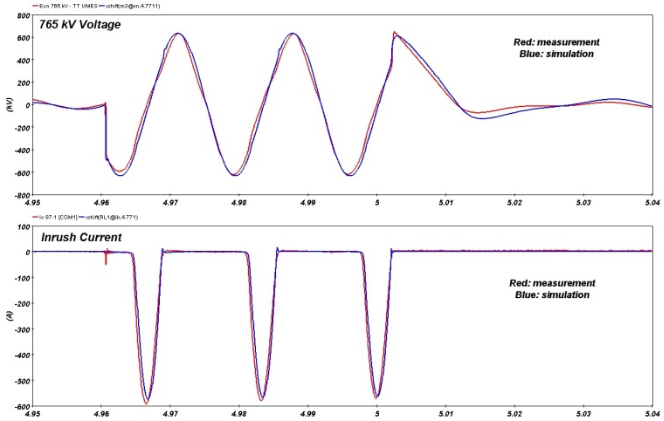


Figure 8. Test # 2: Comparison of simulation results vs field test measurements: Voltage and Inrush current. Red: measurements, Blue: simulations

IV. MODEL APPLICATIONS

A. Harmonic Over-voltages

In order to investigate the influence of core losses on harmonic over-voltages, a third-harmonic resonant circuit was created (fig. 12) in which the proposed 900 MVA transformer model influence on harmonic over-voltage damping was compared with a conventional one.

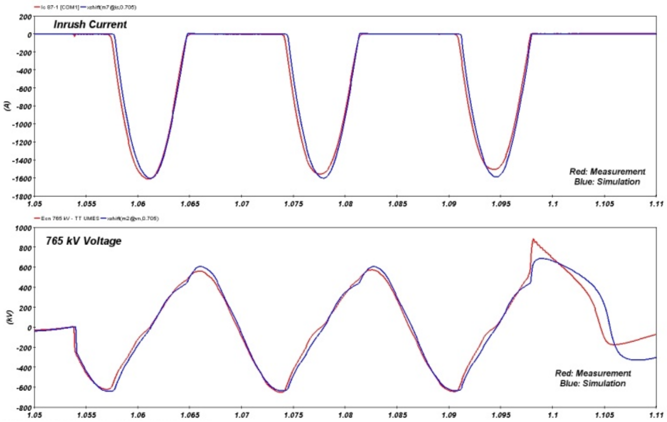


Figure 9. Test # 3: Comparison of simulation results vs field test measurements: Voltage and Inrush current. Red: measurements, Blue: simulations

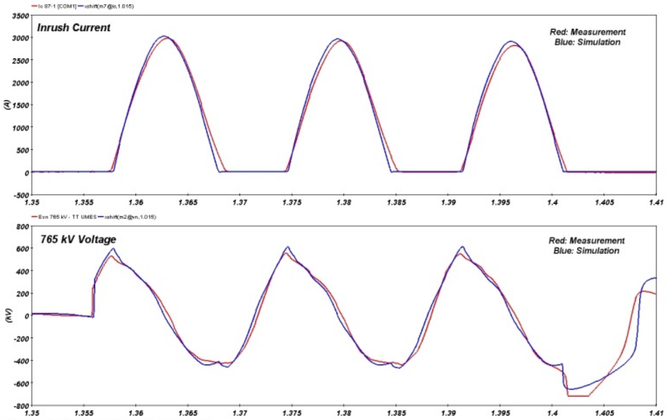


Figure 10. Test # 4: Comparison of simulation results vs field test measurements: Voltage and Inrush current. Red: measurements, Blue: simulations

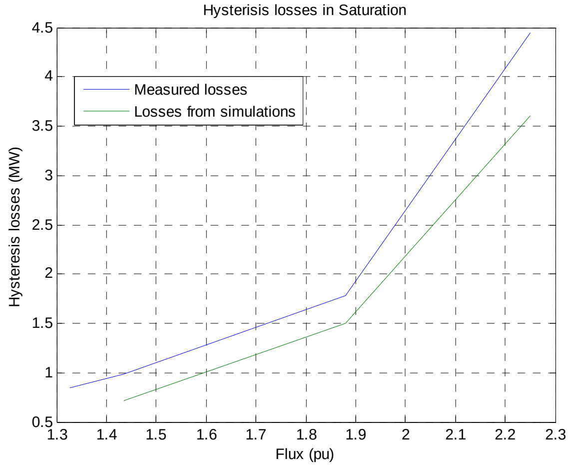


Figure 11. Comparison of simulation results vs field test measurements.

Even though the harmonic over-voltages reach crests up to 2.0 pu, figure 13 shows that the additional core losses presented by the proposed model have almost no influence on their damping.

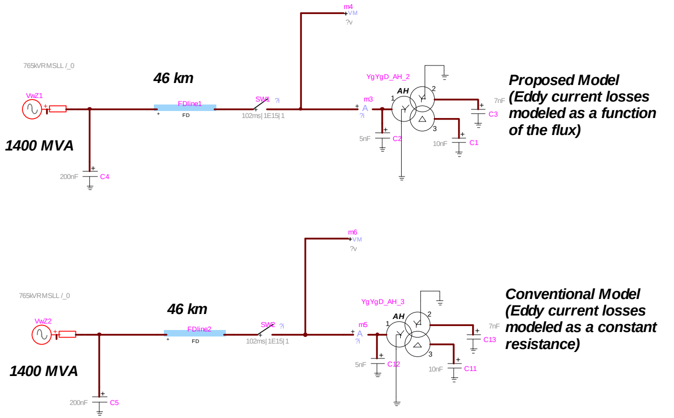


Figure 12. EMTP-RV simulation of harmonic over-voltages with two different transformer models; proposed model and conventional model

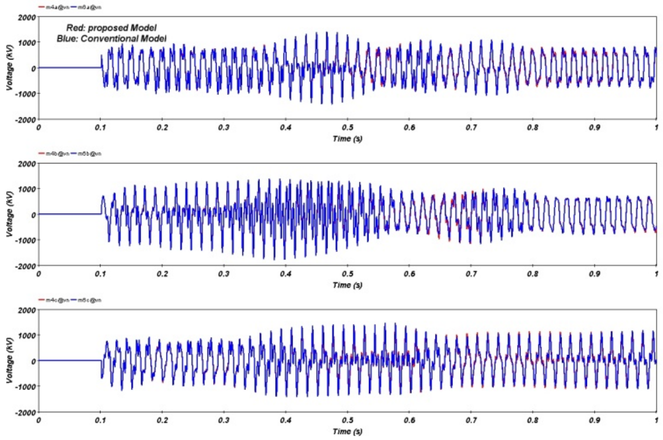


Figure 13. Simulation results of harmonic over-voltages with two different transformer models; Red: proposed model, Blue: conventional model

B. Ferroresonance

Ferroresonance is a complex non-linear phenomenon with its creation and stability very much dependant to the circuit losses. Figure 14 shows an EMTP-RV circuit created with the aim to investigate the influence of the proposed transformer modeling with realistic losses on ferroresonance.

Figure 15 shows the results. Interestingly, the proposed model with more realistic losses creates a sustainable regime of ferroresonance which is not the case when a conventional transformer model is used. This may be explained by the fact that in the proposed model, the losses vary with the flux therefore the losses are almost non-existent at crest values of the voltage.

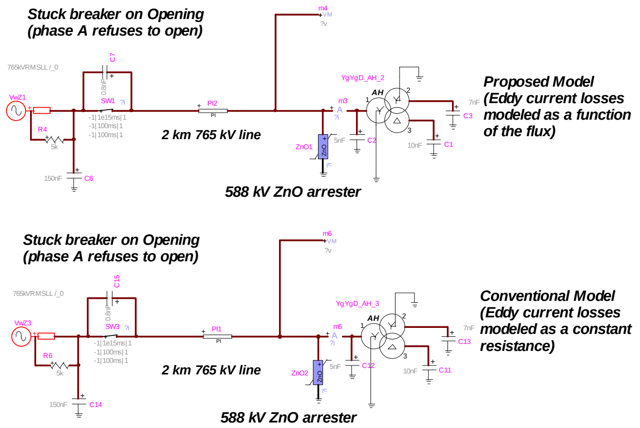


Figure 14. EMTP-RV simulation of ferroresonance with 2 different transformer models; proposed model and conventional model.

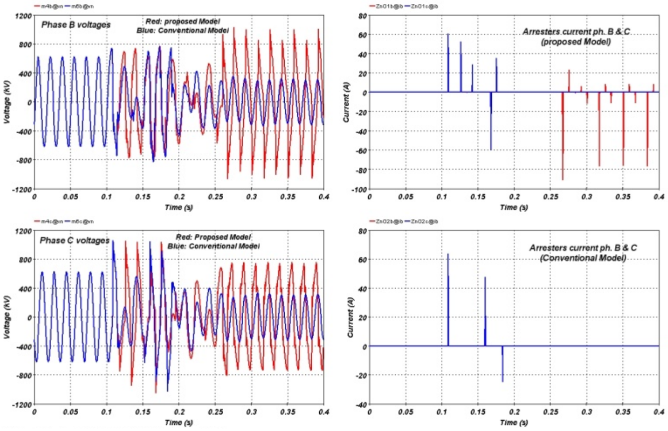


Figure 15. Simulation results of ferroresonance with two different transformer models; Red: proposed model, Blue: conventional model.

V. CONCLUSIONS

Transformer energization tests performed at Chateauguay substation confirmed the adequacy of a new transformer model with core losses varying as a function of the flux.

It is shown that the transformer core losses have almost no influence on the damping of harmonic over-voltages created in resonant circuits upon large transformer energizations. On the other hand, ferroresonance investigations need to be performed with better transformer models such as the one proposed in this paper.

VI. REFERENCES

[1] S. Okabe et al., "Steep Fronts at Transient Recovery Voltages Appearing with the Interruption of Inrush Currents of Transformers", *Journal of Electrical Engineering in Japan,*,vol. 135, pp. 24-32, 2001

[2] A. Gaudreau et al., "No-load Losses in Transformer under Overexcitation/Inrush Current Conditions: Tests and a New Model", *IEEE Trans. Power Delivery*, vol. 17, pp. 1009-1017, Oct. 2002.

[3] see www.emtp.com

VII. ACKNOWLEDGMENT

The authors would like to thank Hydro-Québec TransÉnergie for the permission to publish the results of this scientific work.