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A Comparison Between Some Used High Frequency Transformer Models

مقارنة بين بعض النماذج المستخدمة للمحولات عالية التردد

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ملخص

تتسبب ظاهرة الرنين عموما والرنين الحديدي خصوصا في حدوث أخطاء وكوارث بالمحولات. وهذه الظاهرة تنشأ من توصيل المحول مع الكابل. وفي هذا البحث يتم مقارنة بعض نماذج المحولات المستخدمة في دراسات الرنين عموما والرنين الحديدي خصوصا. وقد تم استخدام برنامجين لهذه المقارنة هما EMTP/ATP و EMTDC/PSCAD. أيضا تم دراسة تأثير الكابلات على نماذج المحولات المستخدمة في بحث هذه الظاهرة. وأثناء الدراسة تم تطبيق صاعقة على الوجه A للطرف الثانوي للمحول المختبر وذلك من خلال ثلاث توصيلات هي : 1- المحول بدون كابلات متصلة ، 2- المحول موصل مع كابل على الطرف الابتدائي ، 3- المحول موصل مع كابلان احدهما على الطرف الابتدائي والآخر على الطرف الثانوي. وقد أظهرت المقارنة أن هناك اختلاف بين النماذج المختبرة للمحول ولذا فانه يجب العناية أثناء اختيار نموذج المحول المناسب لدراسة ظاهرة الرنين الحديدي المغناطيسي. وقد وجد أن النموذج HYBRID في برنامج EMTP/ATP يعطي أفضل النتائج وأدقها وهو المطلوب لتحليل ظاهرة الرنين الحديدي المغناطيسي بدقة.

ABSTRACT

Catastrophic transformers failures continue to occur today due to resonance stresses in general and specially ferroresonance. These resonances are initiated due to the cable-transformer connection. In this paper a comparison between high frequency transformer models for resonance studies in general as well as for ferroresonance studies is introduced. Two electromagnetic transients programs are used in this comparison; EMTP/ATP and EMTDC/PSCAD. The study is performed by applying an impulse on phase A of the secondary side of the tested transformer. Three connection cases are used in this investigation; separate transformer, a connected cable with the primary side, and an additional connected cable with the secondary side of the tested transformer. These cases are used to investigate the effect of cable connection on the transformer model response. The comparison shows how the model types vary in their results that care should be taken by the choice of the correct model by the investigation of the ferroresonance phenomenon.

Keywords - Transformer, Overvoltage, Ferroresonance, EMTP/ATP, PSCAD/EMTDC.

I. INTRODUCTION

Ferroresonance is a complex nonlinear dynamic electrical phenomenon, which frequently occurs in a power system that comprises no-load saturated transformers, transmission lines (or cables) due to unsymmetrical switching operations with the three-phase supply. Ferroresonance phenomenon causes dielectric and thermal problems, which may not be suppressed in some cases and thus repeated and sustained causing great damages [1].

The connection of three-phase transformers through underground cables is becoming more common in industrial, commercial and residential systems. Due to this situation, the possibility of establishing a series connection between the capacitance and the transformer non-linear inductance, which leads to the occurrence of ferroresonance, is favorable. Ferroresonance is in simple terms a series resonance that involves a non-linear inductance and capacitance [1]. Its

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occurrence is more frequent in the absence of adequate damping and within low or medium resonance frequency range of the treated cable-transformer combination [2]. At such frequencies, the behavior of a transformer is dominated by the magnetic coupling among windings and by the core saturation.

Consequently, among the power system components, the transformer is undoubtedly the equipment that requires the most detailed modeling for the analysis of ferroresonance. If the model is not sufficiently precise the simulation may not reproduce the real behavior of the system resulting in inaccurate or false results. The intrinsic difficulty in transformer modeling is due to several factors, among which the type of transformer under study. The transformer type dominates the important characteristics that should be correctly represented such as core configuration, self and mutual inductances between windings, leakage fluxes and the magnetic core saturation [2].

Transformer models can be divided into two main categories, namely; the black box and the gray box models. The black box models are necessary for insulation co-ordination of power system and can be employed to evaluate current and voltage wave shapes at the terminals of the power transformer. These models are normally based on the results of measurements in time or frequency domain. Thus, it is possible to develop this kind of models after transformer construction. Whereas, the gray box models are used by the designers to study the resonance behavior of transformer winding and the distribution of electrical stresses along the transformer windings. These models are based on the physical layout and construction details of the transformers [3].

Nowadays, computer models have been created to study the transient phenomena in the transformer. The most famous and currently used models are contained by the EMTP/ATP and EMTDC/PSCAD programs. This work aims to compare the capabilities of both of these software packages, specially in regard to the ferroresonance behavior in transformers. It may be worthy to note that, both programs are block-oriented simulators with a user graphical interphase.

II. TRANSFORMER MODELS IN EMTP/ATP

The transformer is modeled in EMTP/ATP using different transformer models; Saturable, BCTRAN, and HYBRID. These models vary in their capabilities from simple transformer model to complex transformer representation [4].

A. Saturable Transformer Component (STC Model)

This model is based on the representation of the transformer through single-phase circuits. Saturation and hysteresis effects may be modeled with the inclusion of a non-linear inductance in the wye point [5]. The STC model is used for three-phase units by adding a zero-sequence reluctance parameter. In this model, the parallel magnetizing inductance and resistance is not connected to the correct point and so, some numerical instability has been reported when using this model for three-winding transformers [2].

B. BCTRAN

BCTRAN model is a linear representation of single- and three-phase transformers in the form of branch impedance in the admittance matrix. In this model, the core type is not supported; however, simple nonlinear core model can be added externally [6].

The non-linear behavior is not directly included in the BCTRAN model. This behavior (saturation and/or hysteresis) may be taken into account with the inclusion of an external magnetizing branch connected to the appropriate transformer terminals. This external connection of the magnetizing branch is not, in general, topologically correct [2]. This is the main disadvantage of BCTRAN transformer model, which may lead to incorrect results when simulating ferroresonance. Moreover, the external connection does not take the inter-phase coupling into consideration [2].

C. HYBRID Model

This model has been recently developed to overcome the disadvantages of the exceeding models [6-7]. The model combines the matrix representation from BCTRAN for the winding modeling and the duality principle for the representation of the correct core magnetization topologically in legs and yokes. The model supports three-phase, two and three winding transformers, autotransformers, and wye and delta couplings. Although it is an extremely powerful model, it is still seldom used by the scientific community in part due to its complexity and in part due to the quantity of data to be informed [2].

The main difficulty in this model is the adjustment of the parameters of the Frolich equation which models the behavior of the *BH* curve of the material that constitutes the magnetic core [8].

III. TRANSFORMER MODELS IN EMTDC/PSCAD

There are two transformer models available in EMTDC /PSCAD; XFMR and UMEC. These models are varied in their capabilities from simple transformer model to complex transformer representation.

A. XFMR Model (The Classical Model)

The XFMR model is also defined as the classical model. This model represents the transformer windings on the same leg; i.e. each phase is separated and there is no interaction between phases. The saturation characteristic is represented with a single valued continuous function that converges to the vertical flux axis at low currents, and asymptotically to the air core reactance line at high currents. This is a reasonable modeling technique since the true saturation characteristic of a transformer is rarely known with any degree of precision [9].

The saturation in this model is represented in one of two ways; using a varying inductance across the winding wound closest to the core, or using a compensating current source across the winding wound closest to the core where the magnetic effects are occurring. Core losses are represented internally with an equivalent shunt resistance across each winding in the transformer. These resistances are varied by the model for each winding in order to maintain a uniform distribution across all windings. The value of this shunt resistance is based on the no-load losses inpu parameter [9].

B. UMEC Model

Unified Magnetic Equivalent Circuit model o the transformer is defined as UMEC model. This model considers the core geometry and also represents inter-phase coupling and the core non-linearity [9]. The winding resistance is added as an external resistance. The UMEC transformer model provides the option of selecting either a three-limb core or a five-limb core configuration which is inherent to the model. The UMEC transformer model has a distributed saturation characteristic defined in straight line segments by ten pairs of entered points. Thereby, it is not necessary to place the saturation across a specific winding because the saturation is distributed to all windings [9].

The UMEC transformer model treats the core saturation differently than the classical model. The piecewise linear technique is used to control the model equivalent branch conductance. The non-linearity of the core is entered directly into the model as a piece-wise linear V-I curve, which makes full use of the interpolation algorithm for the calculation of exact instants in changing of state range [9-10].

IV. SIMULATION OF TRANSFORMER ENERGISATION

The transformer energization study is carried out by applying a 1.2/50 µsec. standard lightning impulse to the test system. The 6.7/60 kV, 15 MVA transformer used for this investigation is picked from [8]. In this study, the two transformer models in EMTP/ATP; namely, BCTRAN and HYBRID, and the other two transformer models in EMTDC/PSCAD; namely, XFMR and UMEC, are used and compared.

The investigation is performed by applying the standard impulse on the secondary side of the transformer through three cases:

i- Energization of the transformer without connected cables

ii- Energization of the transformer with its primary connected to a 25 m cable.

iii-Energization of the transformer with its primary connected to a 25 m cable and its secondary connected with a 100 m cable.

The investigated system, which is chosen to represent some typical practical cases, is given in the appendix.

A. Simulation Using EMTP/ATP Models

Fig. 1 illustrates the test system model in EMTP/ATP; ATPDraw version, where the transformer is connected to a 25 m cable on the primary and a 100 m cable on the secondary. The lightning impulse is implemented to phase A at the secondary side end of the connection. Two transformer models in EMTP/ATP; namely, BCTRAN and HYBRID, are used in this comparison.

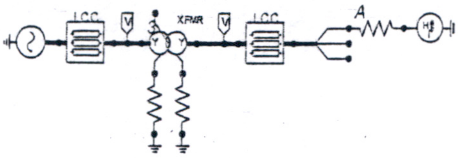

Fig. 1: EMTP/ATP Investigation System Model

Fig. 2 shows the output voltage of phase A of the primary side terminals of the transformer for the three investigation cases. It is clearly seen from Fig. 2 that the same voltage profiles result from the two models (BCTRAN and HYBRID) when the transformer is struck without connection to cables (case i). Whereas, when a 25 m cable is connected to the primary side of the transformer, the behavior is changed as shown in Fig. 2 (case ii). It is shown that the connection of cable to the transformer leads to a noticeable resonance behavior. However, it is seen that the peak voltage which resulted from the HYBRID model is 11.19 kV and 6.99 kV from the BCTRAN model.

Also, after the connection of a 100 m cable to the secondary side of the transformer a resonance behavior have been noticed, which is less oscillating due to the additional resistance and capacitance of the cable. It is also noticed in this case that the peak voltage results of the HYBRID model are higher (6.97 kV) than that of the BCTRAN model (5.94 kV), as shown in Fig. 2 (case iii).

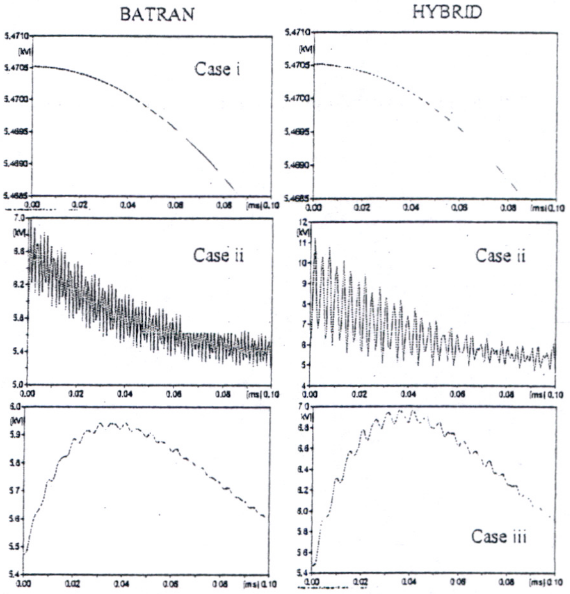

Fig. 2: Phase A Voltage of the Tested Transformer Primary side

Fig. 3 and Fig. 4 illustrate the voltage at phase B and phase C (non-struck phases) of the transformer primary side, respectively. It is clearly seen that the interphase coupling actively reflects the resonance of the cable transformer interaction in HYBRID model whereas in BCTRAN model is not.

Fig. 5 shows the secondary side voltage for all phases of the transformer in case iii where the primary and secondary cables are connected. It is shown that the same voltage profiles are resulted at the transformer terminals with the same magnitudes. Although the ferroresonance appears on the secondary side (injected side) in both models, it is not transferred to the other side of the transformer in case of BCTRAN model. It partially appears in BCTRAN model due to the cable model inter-phase mutual coupling. Therefore, it is evident that the HYBRID model is the suitable EMTP/ATP transformer model for high frequency ferroresonance studies.

The neglecting of the nonlinear magnetic behavior may not only lead to false results but also to mis-underestimating peak resonance voltage values.

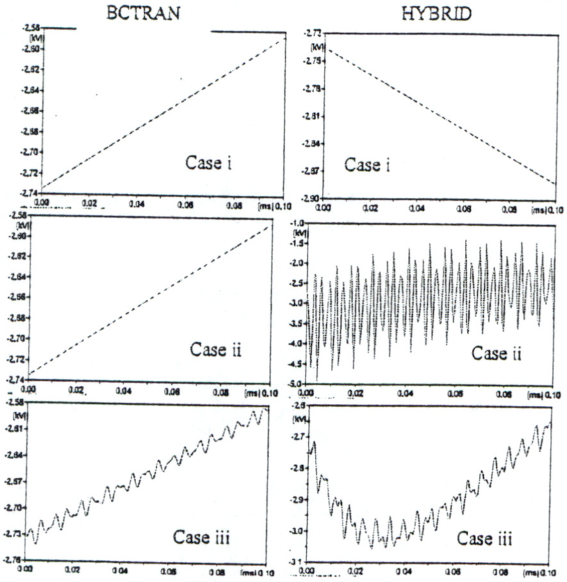

Fig. 3: Phase B Voltage of the Tested Transformer Primary side

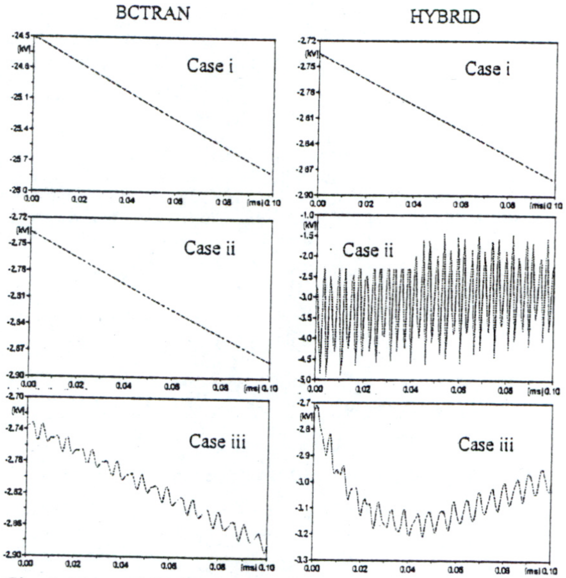

Fig. 4: Phase C Voltage of the Tested Transformer Primary side

B. Simulation Using EMTDC/PSCAD Models

Fig. 6 illustrates the test system model in EMTDC/PSCAD where the transformer is connected with a 25 m cable on the primary and a 100 m cable on the secondary. The lightning impulse is implemented to phase A at the secondary side of connection end. Two transformer models in EMTDC/PSCAD; namely, XFMR and UMEC, are used in this comparison

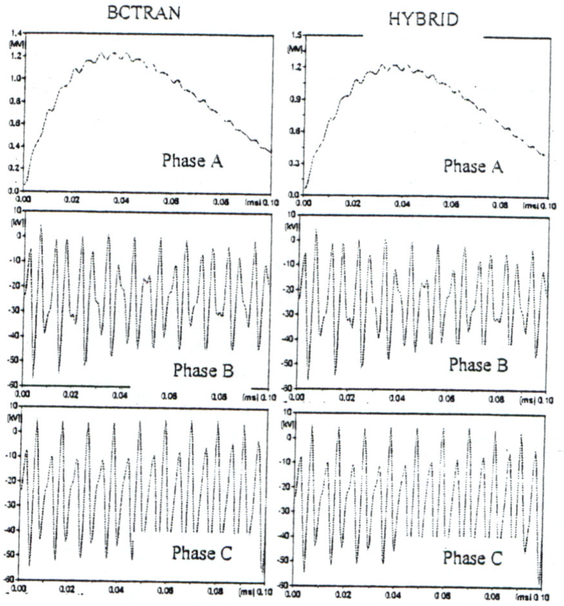

Fig. 5: Voltage of all Phases of the Transformer Secondary side in case iii

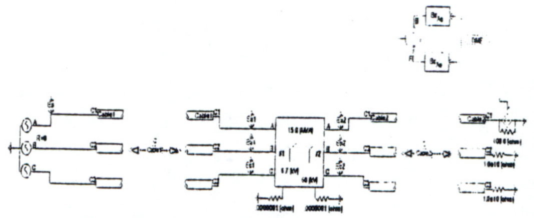

Fig. 6: EMTDC/PSCAD Investigation System Model

Fig. 7 shows the output voltage of phase A of the primary side terminals of the transformer for the three investigation cases. It is clearly seen from Fig. 7 that the same voltage profiles result from the two models (XFMR and UMEC) when the transformer is struck without connection to cables (case i). Also, when a 25 m cable is connected to the primary side of the transformer (case ii) and at the addition connection of a 100 m cable to the secondary side of the transformer (case iii), it is shown that the XFMER model and the UMEC model act as an ideal transformer which transform the impulse voltage without the core nonlinearity action representation. This linear behaviour of these transformer models reduces the chance to use EMTDC/PSCAD transformer models in high frequency ferroresonance studies.

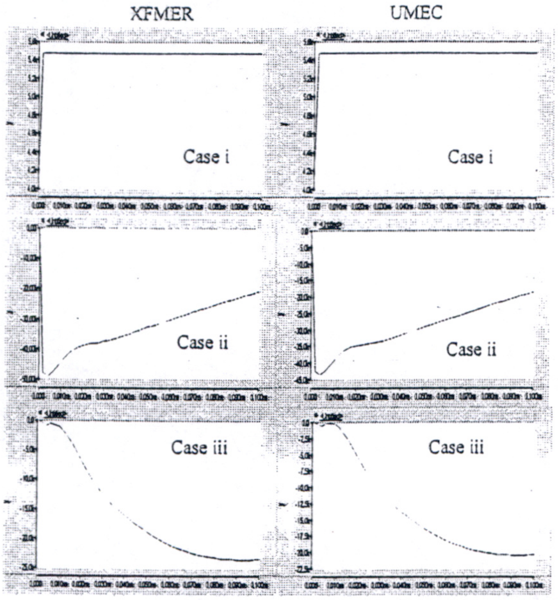

Fig. 7: Phase A Voltage of the Tested Transformer Primary side

V. CONCLUSION

In this paper, a comparison of high frequency transformer models for resonance studies is introduced. Two electromagnetic transients programs are used in this comparison; EMTP/ATP and EMTDC/PSCAD. The study is performed by applying an impulse on phase A of the secondary side of the tested transformer. Three connection cases are used in this investigation; separate transformer, a connected cable with the primary side, and an additional connected cable with the secondary side of the tested transformer. These cases are used to investigate the effect of cable connection on the transformer model response.

It can be noted that, for the separate transformer test the core of the transformer does not affect the results. When the cable is connected resonance and/or ferroresonance behavior appears clearly and it has been shown that the HYBRID model in EMTP-ATP is the only one, which represents the right behavior on all phases, whereas, the EMTDC/PSCAD transformer models act as linear models in all cases. The HYBRID model is very worthy to be used in spite of its complexity, because it gives better and more real results which are needed by the insulation coordination.

VI. REFERENCES

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VII. APPENDIX

A. Insulated Cables

a) The Transformer Primary Side Connected Cable

The underground primary circuit is a 3.6-6.0 kV, high temperature, single core sheathed cable. The cable information is:

- Nominal cross sectional area (mm^2) = 150
- Conductor diameter (mm) = 15.8
- Min. Mean thickness of insulation (mm) = 2.2
- Mean average sheath thickness (mm) = 1.6
- Over all diameter min- max (mm) = 22.3-26.1

b) The Transformer Secondary Side Connected Cable

The underground secondary circuit is a 60 kV, single core sheathed cable. The cable information is:

- Nominal cross sectional area (mm^2) = 2000
- Diameter of conductor (mm) = 56
- Insulation thickness (mm) = 9
- Diameter over insulation (mm) =78
- Cross section of screen (mm) = 35
- Diameter of the cable (mm) = 91

B. Power Transformer

The 15 MVA, 6.7/60 kV power transformer is used in this investigation. It is a wye-earthed/wye-earthed connected, three stacked core. The no-load and short-circuit tests information are given in Table 1 and Table 2.

Table 1: Transformer No load test (low voltage)

Volt [%]	Losses [kW]	I_{av}[%]
80.597	10.716	0.1316
85.0746	12.09	0.1563
89.0299	13.776	0.195
94.0299	15.684	0.2539
100	18.84	0.4087
102.985	20.773	0.5721
107.4627	23.97	1.0348

Table 2: Transformer short-circuit test (high-voltage)

Imp [%]	Power [MVA]	Loss.[KW]
7.9	15	97.3