AN IMPROVED TRANSFORMER MODEL FOR TRANSFER VOLTAGE STUDY

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ABSTRACT

This paper proposed an improved model to simulate the transfer voltage of a power transformer. This model consists of the TRANSFORMER model of EMTP with some capacitances.

The power frequency TRANSFORMER model of EMTP can not be used for high frequency transfer voltage study. In high frequency transfer voltage study, transformers are simulated as capacitances only. This representation is very simple and less accurate. Recently, the high frequency transformer models have been reported. These models are based on the numerical calculations for wide range of frequency response of the transformer, and the users have to deal with the model as a black box, the physical meaning of which is unknown.

In this paper, the measurement of transfer voltages for an actual transformer (11/154kV, 68.3MVA) was performed in various conditions. The value of various parameters of the proposed model are calculated from the actual measurements entailing no numerical calculations and help in understanding their physical relevance. The accuracy of the proposed model is confirmed by comparing the simulated results with the actual measurements.

Keywords: Transfer voltage, Transformer model, EMTP

1. INTRODUCTION

In the insulation design for power stations and substations, it is necessary to study the over-voltage of high voltage class and also the transfer voltage which penetrates in the low voltage class through transformer. For this purpose, an accurate transformer transfer voltage model is necessary. As a model for power transformer, a model intended for a transient phenomenon of the commercial frequency domain(1)(2) is widely employed. However, this model cannot be used for studying the transfer voltage including MHz order high frequencies. Conventionally, therefore, models consisting of capacitances between high/low voltage winding and ground, and high and low voltage windings were employed. This model was simple but was not advantageous in that the transfer voltage was excessive with respect to the measured value. Recently, various transformer models have been proposed for accurately simulating the transients in the high frequency domain.(3)-(6) These models are based on a wide range of frequency response, complicated numerical calculations are required for determining the constants and knowing the physical meanings of these constants is difficult. The paper proposes a new model of simulating a transfer voltage of 3 phase transformer using a equivalent circuit of the transformer model in EMTP plus capacitances between winding and ground and between windings based on measured results in actual fields.

2. MEASUREMENT OF TRANSFER VOLTAGE

2.1 Measuring procedure

The object under test is the main transformer (rated 11/154kV, 68.3MVA, star/delta connection, core type) in a hydraulic power plant. An impulsive voltage of approximately 10kV has been applied to the high voltage side of the transformer and voltages generated at the transformer neutral, low voltage side and open end of generator circuit breaker (CB) have been measured. Fig. 1 shows a typical test circuit.

Table 1 gives the test conditions. The input waveforms are 2/70 μs, 4/10 μs and also attenuating oscillatory wave almost matched to the resonance frequency of the transformer. As circuit conditions, in addition to the transformer (Tr) singly, it has been connected with cable(Tr+cable) and cable and surge absorber C(0.3 μF)

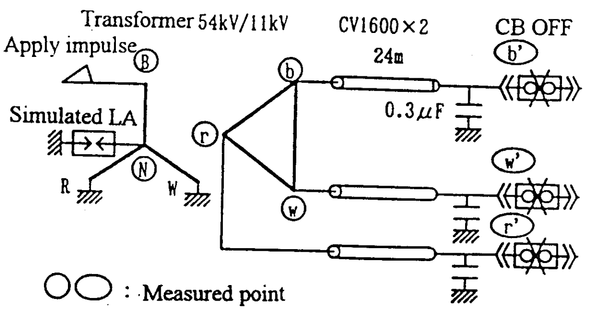


Fig. 1. An example of test circuit to measure transformer transfer voltage

(Tr + cable + C) have been measured. Further, to study the influence by the neutral arrester, the neutral arrester has been simulated by ZnO element of 1/40 of actual rated value (V_{100A} = 6.3kV) and the transfer ratio at various neutral conditions has been measured.

2.2 Tested results

Fig. 2 exemplifies measured waveforms. When an impulse is applied on the high voltage side, the neutral voltage normally becomes a waveform which oscillates at the resonance frequency of the high voltage winding. If the waveform has a resonance frequency component, the neutral voltage will further rise by resonance (Fig. 2 (b)). To the low voltage side, on the other hand, the voltage of the same oscillating period as the neutral transfers.

Table 1. Test conditions

Input phases	1 phase (B) or 3 phases
Input waveform	2/70 μs, 4/10 μs, attenuating oscillatory wave (approx. 10kHz)
Circuit	Tr singly, Tr + cable, Tr + cable + C
Neutral	Not grounded, simulated arrester (LA), grounded

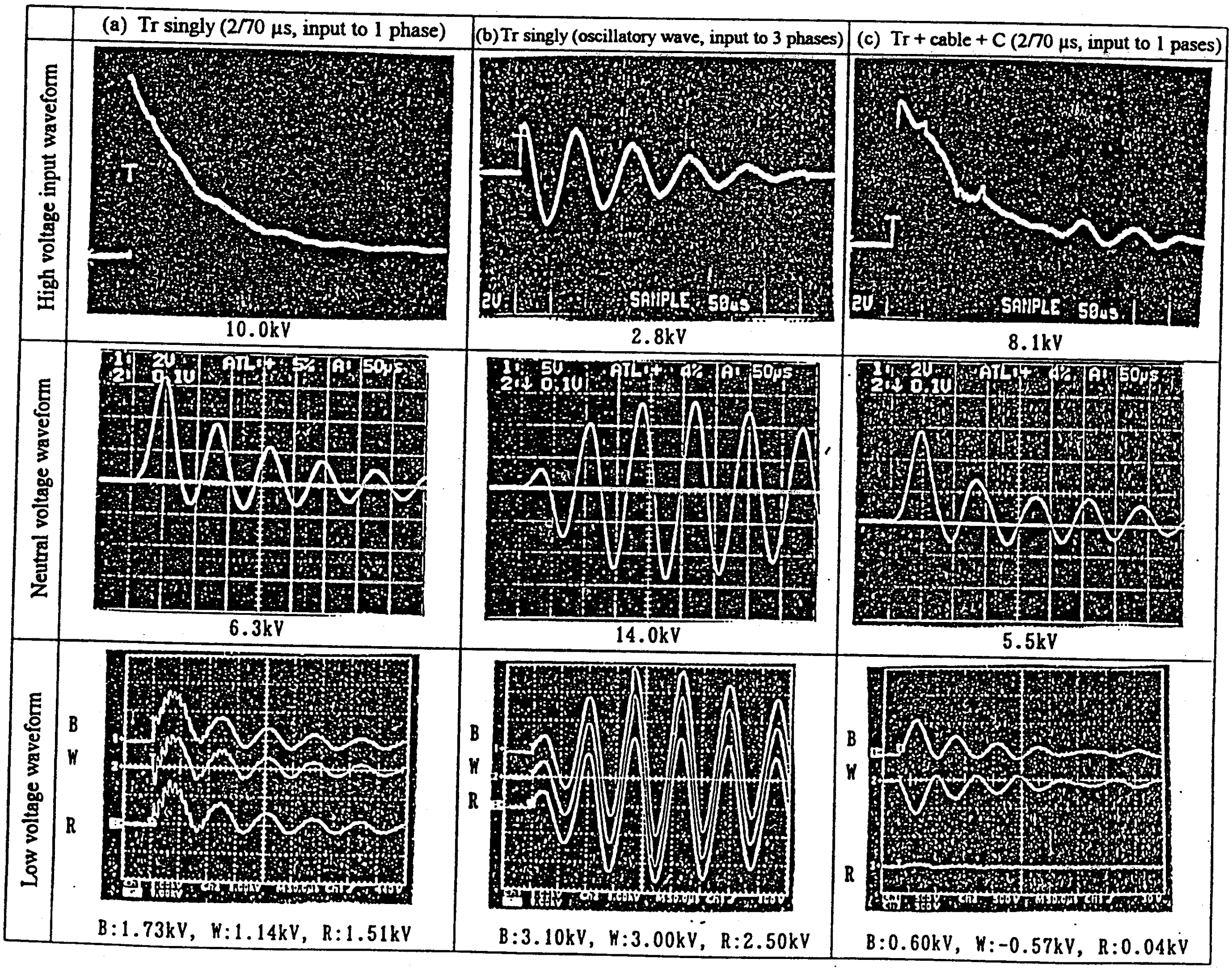


Fig.2. Examples of measured waveform

Besides, fine oscillating periods may appear on the wavepeaks sometimes (Fig. 2 (a).) These periods are determined by the low voltage winding constant. Thus, the low voltage winding constant can be estimated. How to derive the winding constant will be stated in detail later.

3. STUDY OF MODEL

3.1 Proposal of model

We will propose a model for accurately simulating a transformer transfer voltage based on the above measured results. Fig. 3 illustrates the proposed model. Basically, it is the transformer model in the commercial frequency domain (EMTP TRANSFORMER model) simulating the electromagnetic transfer component plus capacitances between windings and between winding and ground simulating the electrostatic transfer component. As a way of deriving each constant of the model, different constants are divided into ones (estimated values) which can roughly be estimated from measured results and others (adjusted values) which are finely adjusted based on the measured results, several simulations are carried out and then respective constants are determined. The procedure of deriving model constants is summarized as follows.

1) Derive estimated values (L_1, L_2, C_{HG}, C_{NG}, C_{LG}, C_{NL}.) These values can roughly be estimated from measured results. Measured values referred to are listed below.
   Peak value of low voltage transfer voltage
   Peak value of high voltage level
   High/low voltage oscillating period

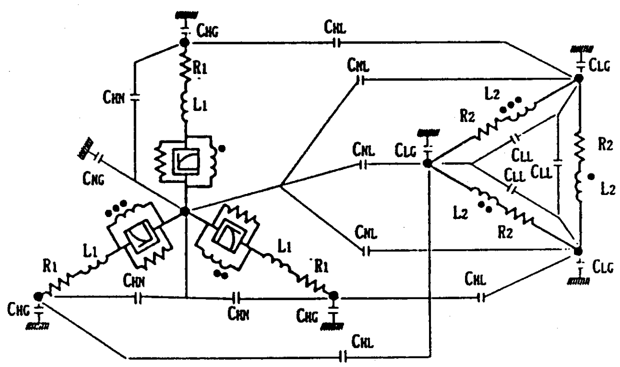
2) Simulate estimated values several times and finally determine the estimated values.

3) Derive adjusted values (C_{HN}, C_{LL}, C_{HL}.) These values are finely adjusted based on measured result.

4) Simulate adjusted values several times and finally determine adjusted values.

5) Determine estimated values/adjusted values.

Table 2 exemplifies concrete transformer model constants (estimated) derived. Referred to for deriving constants are test cases with 2/70 μs applied and with neutral not grounded. For example, out of estimated values, L_1 and L_2 are basically half the inductance obtained from %Z of transformer. C_{NG}, C_{LG} and C_{NL} are determined by the oscillating period of waveform referred to and ratio between neutral voltage and low voltage. Adjusted values are not given in the table. As C_{HN} and C_{LL} out of them, 74pF and 7.4pF have been obtained by several simulation. However, they can be omitted because of small values. As C_{HL}, 100pF has been obtained likewise but, because the transfer from neutral is supposed to be large (C_{NL} >> C_{HL}) considering the winding arrangement of the transformer (neutral is on both ends of high voltage winding), it can be omitted. R_1, R_2, core saturation characteristics (i-ϕ characteristics), etc. may be ordinary values because they do not affect analyzed results.



L_1:High voltage leakage inductance
L_2:Low voltage leakage inductance
R_1:High voltage winding resistance
R_2:Low voltage winding resistance
C_{HG}:Capacitance between high voltage winding and ground
C_{NG}:Capacitance between neutral and ground
C_{LG}:Capacitance between low voltage winding and ground
C_{NL}: Capacitance between neutral and ground
C_{HN}: Capacitance between high voltage windings
C_{LL}: Capacitance between low voltage windings
C_{HL}: Capacitance between high and low voltage windings

Fig.3. Proposed transformer transfer voltage model

Table 2. Estimated value

Constant name	Test case referred to	Waveform referred to	Calculation	Estimated value
L_1	—	—	Halve 11.1%Z (Note 1)	51.1mH
L_2	—	—	Halve 11.1%Z (Note 2)	0.66mH (0.73mH)
C_{HG}	—	—	Note 3	3700pF
C_{NG}	Tr singly: Input to 1 phase	Neutral waveform Oscillating period: T=74μs	$T = 2\pi\sqrt{L_1 \bullet C_{NG}}$	2700pF
C_{LG}	Tr singly: Input to 1 phase	Low voltage waveform Oscillating period: T=8.7μs	$T = 2\pi\sqrt{L_2 \bullet C_{LG}}$	2900pF
C_{NL}	Tr singly: Input to 3 phases	Neutral voltage: V_N=16kV Low voltage: V_2 = 4.1kV	$V_2 = \frac{C_{NL}}{C_{NL}+C_{LG}} V_N$	1000pF (Note 4)
Z_S	Tr + cable: Input to 1 phase	Low voltage waveform Oscillating period: T=23μs	$T = 2\pi\sqrt{L_2 \bullet C_C}$ $Z_s = \frac{1}{C_R \bullet v} l$	C_C=20800pF Z_S=6.4Ω (Note 5)

Notes

1. L_1

Halve the leakage impedance from the winding method. Halving is said to well coincide on other transformers also. Error is approximately 10% at most.

$$L_1 = 0.111 \times \frac{\left(154/\sqrt{3}\right)^2}{68.3/3} / 2\pi f / 2 = 51.1mH$$

If there are measured results where a capacitance greater than that between neutral and grounded is connected at high voltage neutral, further detailed constant can be determined.

2. L_2

$$L_2 = 51.1 \times \left(\frac{10.6}{154/\sqrt{3}}\right)^2 = 0.73mH$$

In case of Tr + cable + C, the low voltage capacitance with respect to ground is regarded almost determined by C_{SA} (0.3 μF) of surge absorber and L_2 is corrected by the case of Tr + cable + C: Input to 1 phase.

Low voltage waveform: T = 88 μs

$$T = 2\pi\sqrt{L_2 \cdot C_{SA}} \quad \rightarrow L_2 = 0.66mH$$

where cable capacitance is ignored

3. C_{HG}

Indifferent to transfer voltage. 3700pF/phase (measuring side).

4. C_{NL}

In case of input to 3 phases, the electromagnetic transfer component can almost be ignored. Therefore, it can be determined by the calculation expression for the electrostatic transfer voltage.

5. Cable capacitance C_C and cable surge impedance Z_S (for 2) can also be determined by the case with Tr + cable: Input to 1 phase.

Cable transmission speed: v= 180.0m/μs

Cable length: l = 24.0m

3.2 Comparison of analyzed results with measured results

To verify the adequacy of the model, we compared the results analyzed on the proposed model with measured waveforms on the low voltage side. For reference, we also compared results analyzed on TRANSFORMER model of EMTP(L model) and C model (Fig.4) where C is arranged in π form generally used for analyzing the transformer transfer voltage currently.

Fig. 5 indicates the results. Each case shows a good coincidence with the transfer ratio and oscillating period of measured waveform, thereby proving the model adequacy. On the other hand, C model does not reproduce the oscillating component and, in case of Tr + cable + C, the value is calculated considerably lower than measured since the electromagnetic transfer component is not taken into account. With L model, cases with Tr + cable and Tr + cable + C show a coincidence to a certain degree with measurements but case of Tr singly where the electrostatic transfer component is the most part suffers from errors. All these facts prove the adequacy of the present proposed model combining C model and TRANSFORMER model. This modeling technique has been applied to the shell type transformer also and actual waveforms have accurately been simulated, thereby indicating that this arrangement is applicable for general purposes.

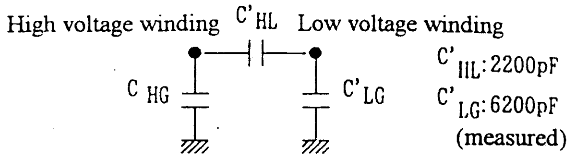


Fig.4. Conventional C model

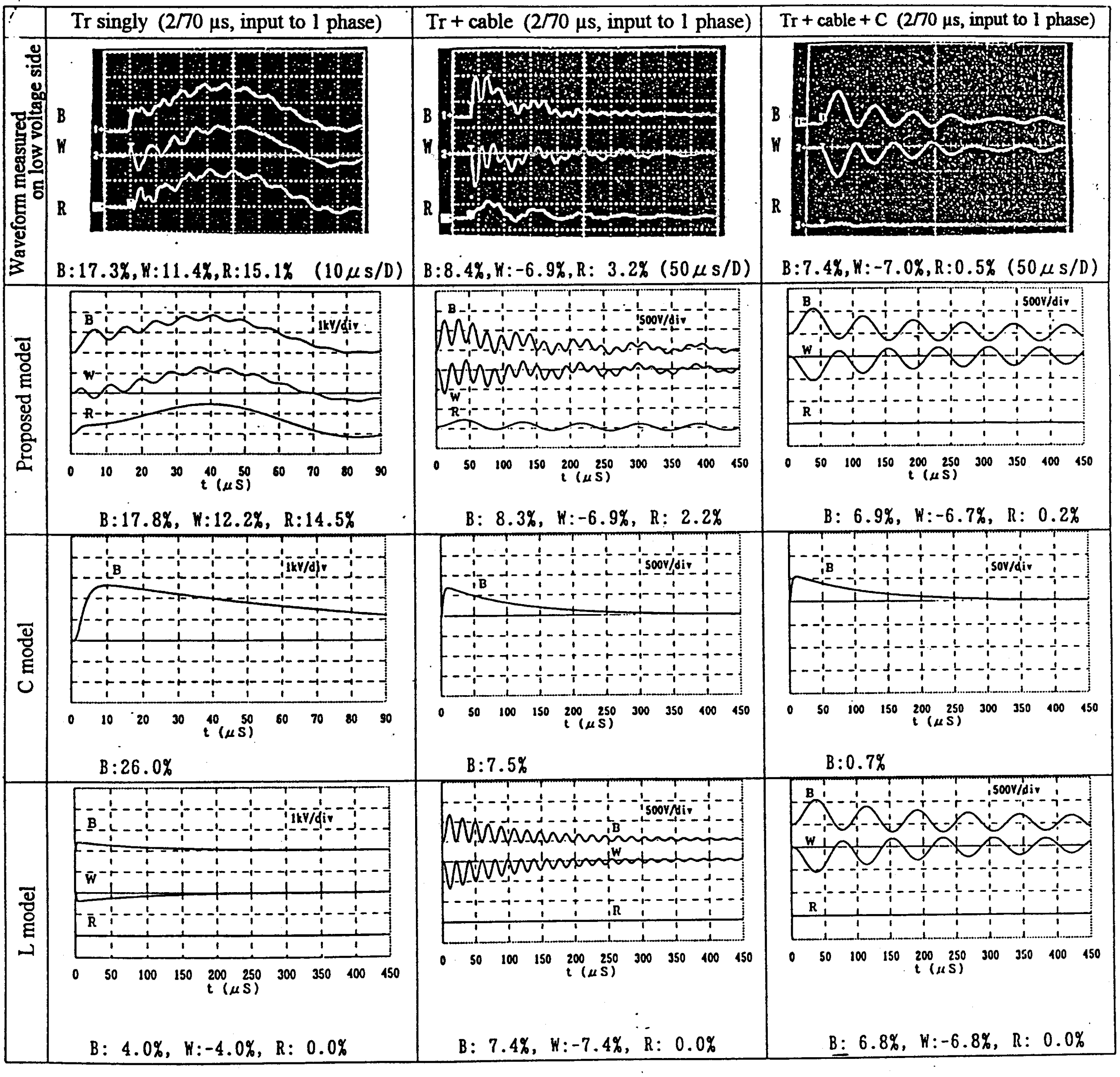


Fig.5. Comparison of waveform between measurement and analysis

4. CONCLUSIONS

In actual fields, we measured transformer transfer voltages under various conditions and, based on the results, proposed an accurate transformer transfer voltage model. Results of the present paper can be summarized as follows.

(1) We prepared a transformer transfer voltage model for simulating a transfer voltage based on the measured results. The transformer transfer voltage model consists of transformer model in the commercial frequency domain simulating the electromagnetic transfer component plus a simple equivalent circuit of several capacitances simulating the electrostatic transfer component. It facilitates to know the physical meaning of constants.

(2) The procedure for preparing a transformer transfer voltage model is to determine constants which can be estimated based on measured oscillating period and peak value, then finely adjust them according to measured and calculated results and obtain the constants. To create a model basically, several simulations are necessary.

According to the measured results, however, the constants may be determined rather easily.

(3) The model proved adequate upon comparing the results analyzed by the model with measured results of transformer transfer voltage. Basically, they can apply to transformers of other structures (shell type, etc.), thereby making this model usable for different purposes.

Although neutral and low voltage levels must be measured for several cases in order to determine model constants, it may be fulfilled by a simple transfer voltage measuring test when manufacturing transformers.

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