A Frequency-Dependent Transformer Model for Transfer Voltage Study

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Abstract - We have already proposed a transformer model for transfer voltage, which consists of the EMTP TRANSFORMER model simulating the electromagnetic transfer component and some capacitances simulating electrostatic transfer component. In the subsequent discussion, however, we found it important to consider the frequency dependence of leakage inductance and core loss. This paper shows frequency dependence from tested results for many transformers, and studies the validity of the new transformer model by comparing the transformer model based on the frequency dependence with the tested results. The model is represented in the MODELS language description.

Keywords: Frequency dependence, Transformer model, Transfer voltage, EMTP, MODELS

I. Introduction

In the insulation design for power stations and substations, it is necessary to study transfer voltage [1] which transfers to the low voltage class through a transformer, in addition to study the overvoltage in high voltage class. The transfer voltage is an important factor for protection of the lower voltage side equipment of the hydraulic power plant. Transformer modeling was directly treated as one of circuit analysis [2]. For transfer voltage study models shown in [3],[4] or capacitance-model consisting of capacitance between low voltage winding and ground and that between high and low voltage winding, are widely applied for studying the transfer voltage which includes MHz order high frequency components. In many cases, however, the calculated results by these models, do not agree with the measured result. An idea of taking frequency dependency of transformer into account was presented from earlier times. To present frequency response of transformers, simple linear equivalent circuit [5],[7], transfer function [6],[9], and state equations [8] were used. As another kind of modeling method, using modal theory is unique approach [10]-[12]. These methods mentioned above [5]-[12] seems to be rather complex and may not be general, because they are focusing on internal winding representation. In recent year, CIGRE has proposed simple terminal type transfer model based on the TRANSFORMER model shown in [3],[4] and adding above-mentioned capacitance to this model. This type of model is comparatively simple and clear in its physical meaning of electrostatic and electromagnetic transfer components[13].

On the basis of the CIGRE's model, authors have proposed a transfer voltage model for 3-phase/2-winding transformer and its constant derived using the field measured results, and reported that the analyzed results were found to be comparative with the measured results [14]. Afterwards we found that the discrepancy observed between measured and analyzed result may be due to non-consideration of frequency dependence of transformer. To obtain the analyzed result which are well-agreed with the measured result of the transfer voltage, the frequency dependence must be taken into account on the previously proposed model.

At the first stage in this paper, we compare the measured results with the analyzed results obtained by the previously proposed model for the transfer voltage when varied capacitance is added to the low voltage side. As a result, we make it clear that frequency dependence must be considered together with leakage inductance and core loss in analyzing transfer voltage using the previously proposed model. Secondary, we represent the frequency dependence with approximate curve assembled into MODELS [15] to propose a new model. At the last part, we compare the analyzed results with measured results.

II. Measured results of transfer voltage and analyzed results of previously proposed model

A. Measurement condition

A measurement circuit to measure the voltage transferring into the low voltage side is shown in Fig.1. The measurement conditions is as shown in Table 1. There are three types of the input waveform. The various capacitances are applied in the low voltage side to study the frequency dependence of transfer voltage. Table 2 shows the specifications for Y-Δ transformer of 4 types used to measurement.

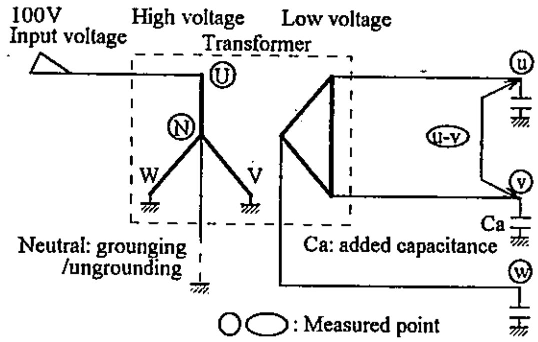


Fig.1. A measurement circuit to measure transfer voltage.

Table 1. Measurement conditions.

Input phase	1 phase (U)
Input voltage	100 V
Input waveform	1.2/700μs, 1.2/50μs, AC voltage(1 - 450kHz)
Neutral	Grounding / Ungrounding
Low voltage side	Added capacitance: Ca(0, 1, 2, 3, 6, 10, 20, 30, 50, 100, 300, 500nF)

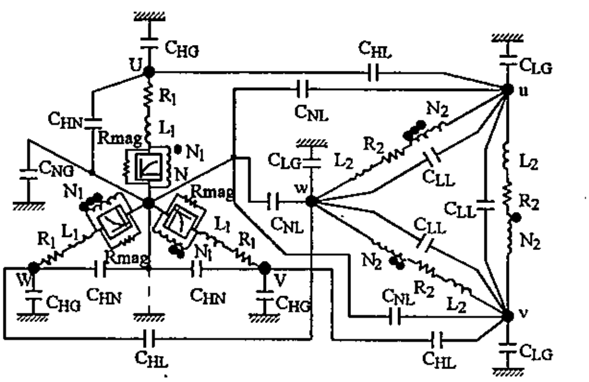
Table 2. Specifications for Y-Δ transformer of 4 types. (3-phase/2-winding transformer)

Rated capacity: P	120MVA	45MVA	25MVA	10MVA
Rated voltage: V_H/V_L (V_H minimum tap)	275/34.9kV (247.5kV)	154/10.5kV (150.5kV)	64.5/6.9kV (57.0kV)	154/3.3kV (140kV)
Rated frequency: f	50Hz	50Hz	60Hz	50Hz
Leakage inductance: %IZ	15.56%	11.07%	17.36%	10.96%
Capacitance between high voltage winding and ground: C_{HG}	1720pF/phase	2080pF/phase	1300pF/phase	1200pF/phase
Capacitance between low voltage winding and ground: C_{LG}	2320pF/phase	4250pF/phase	2700pF/phase	2430pF/phase
Capacitance between high and low voltage winding: C_{HL}	4020pF/phase	2250pF/phase	2300pF/phase	1070pF/phase
Neutral	Grounding	Ungrounding	Ungrounding	Ungrounding

Note; Leakage inductance: %IZ is measurement value when minimum tap is used.
Capacitances: C_{HG}, C_{LG}, C_{HL} are measurement values.

B. Previously proposed model

As shown in Fig. 2, we have proposed a model based on CIGRE's model. The model can simulate the electromagnetic and electrostatic transfer components.



L_1, L_2: high, low voltage leakage inductances
Rmag: core loss
R_1, R_2: high, low voltage winding resistances
N_1, N_2: high, low voltage turns
C_{HL}: capacitance between high and low voltage winding
C_{HG}: capacitance between high voltage winding and ground
C_{LG}: capacitance between low voltage winding and ground
C_{NG}: capacitance between neutral and ground
C_{NL}: capacitance between neutral and low voltage winding
C_{HN}, C_{LL}: capacitance between high, low voltage windings

Fig.2. Previously proposed model.

The parameter's values of the previously proposed model are derived using the values in Table 2. L_1 and L_2 can be obtained by sharing %IZ of the transformer as shown in equation (1).

$$\begin{cases} L_1 = \dfrac{V_H^2}{P}\cdot\dfrac{\%IZ}{100}\cdot\dfrac{1}{2\pi f}\cdot 0.5 \\ L_2 = L_1\cdot(N_2/N_1)^2 \end{cases} \quad (1)$$

Rmag can be easily calculated with capacity and voltage [4], hereby 12kΩ is provided as the resistance value when frequency of transfer voltage is about 10kHz. R_1 and R_2 can be obtained by the measured result. But, those values can be neglected as they are very small. C_{NL} is a half value of C_{HL} by the winding location. Therefore, C_{HL} has to be varied as half as it was. C_{NG} is a 2/3 times value of C_{HG}. C_{HN} and C_{LL} can be neglected as enough to small.

C. Comparison of measured and analyzed results

Fig.3 shows the measured and analyzed results in case of applying parameter's values derived in the section B to the previously proposed model on the 120MVA transformer. Fig.3 (a) is an input voltage waveform of 1.2/700μs (long tail), and Fig.3 (b) is a transfer voltage waveform between u-v phase. In order to vary the frequency (1/Tm) of transfer voltage, the added capacitance Ca of 100nF and 30nF are used. As shown in Fig.3 (b), when Ca is comparatively large, the analyzed result almost agree with the measured result. But if frequency of transfer voltage is increased by means of decreasing Ca, the peak values and periods of the analyzed results disagree with the measured results. Then we have to consider the frequency dependence included in winding and core of the transformer on analysis with the previous model. Therefore, it is necessary to compare the analyzed and the measured results of transfer voltage for the cases of setting Ca to several kinds of values.

In order to coincide the analysis with the measurement, L_1 and L_2 have been multiplied by corrected coefficient K and Rmag has been adjusted. Fig.4 shows the comparison of the measurement and the corrected analysis. Fig.5 shows the relation between K and measured frequency of transfer voltage f and relation between Rmag and f. On analysis with the previous model, K has to be decreased and Rmag has to be increased as frequency of transfer voltage increases.

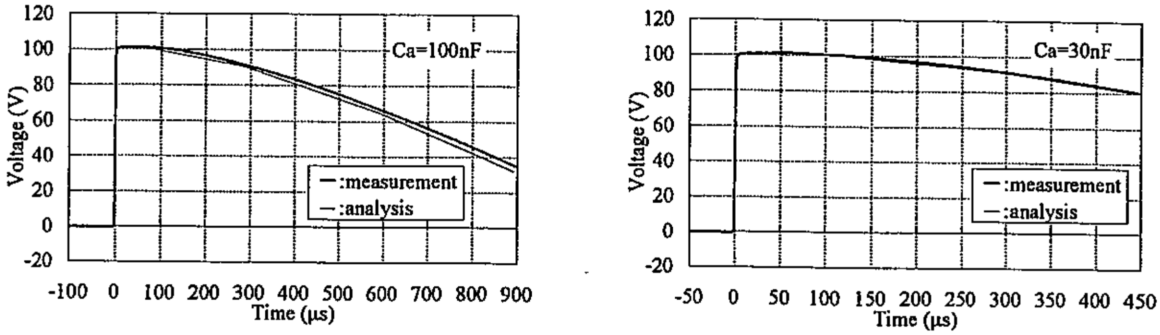
D. Frequency dependence of transfer voltage

In order to study frequency dependence of transfer voltage, the amplitude of transfer voltage was measured when Ca used were 3nF and 100nF and AC voltage of 1-450kHz was inputted. Resonances occur above 10kHz. Resonant frequencies are numerous if low voltage side capacitance is small and the peak value at resonant frequency is larger if low voltage side capacitance is large.

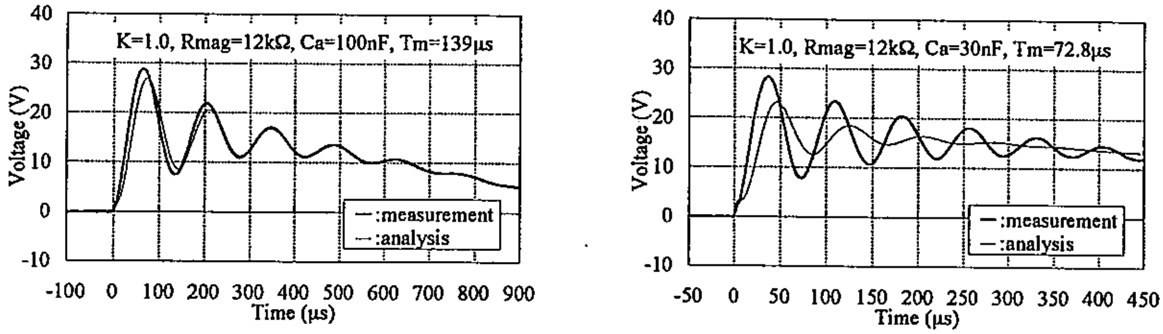
III. Transformer model account for frequency dependence

A. Approximate curves representing frequency dependence

The approximate curves, representing the frequency-dependent L_1, L_2 and Rmag, can be derived from the



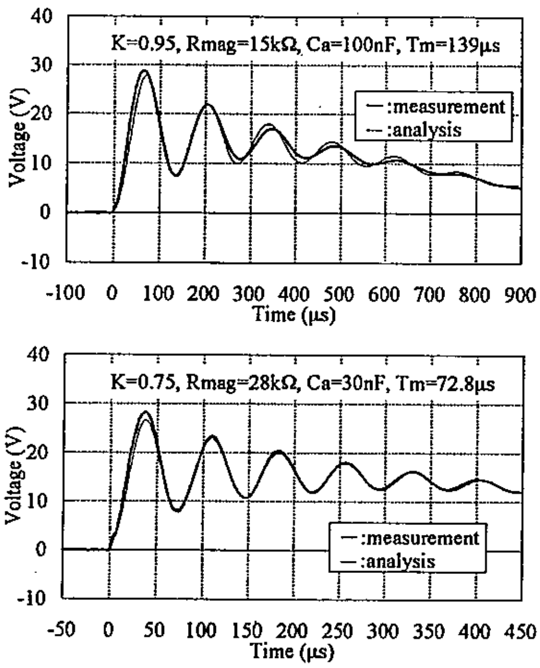
(a) Input voltage. (1.2/700μs)



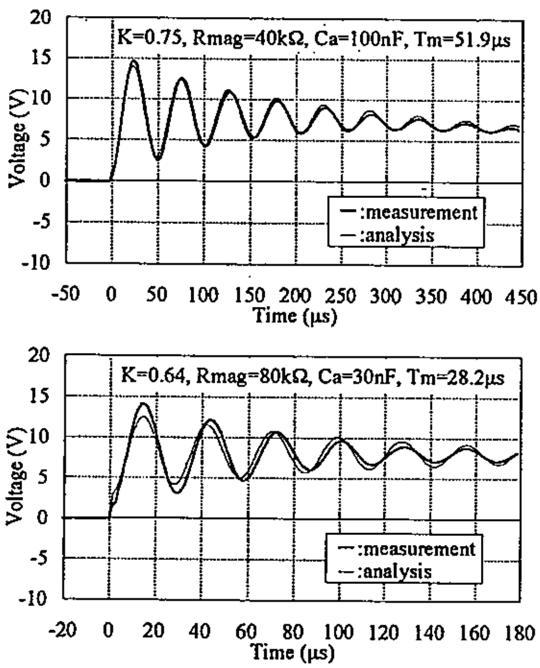
(b) Transfer voltage. (u-v phase)

120MVA transformer

Fig.3. Comparison of measured results and analyzes results of previously proposed model.



120MVA transformer



45MVA transformer

Fig.4. Comparison of measurement and corrected analysis.

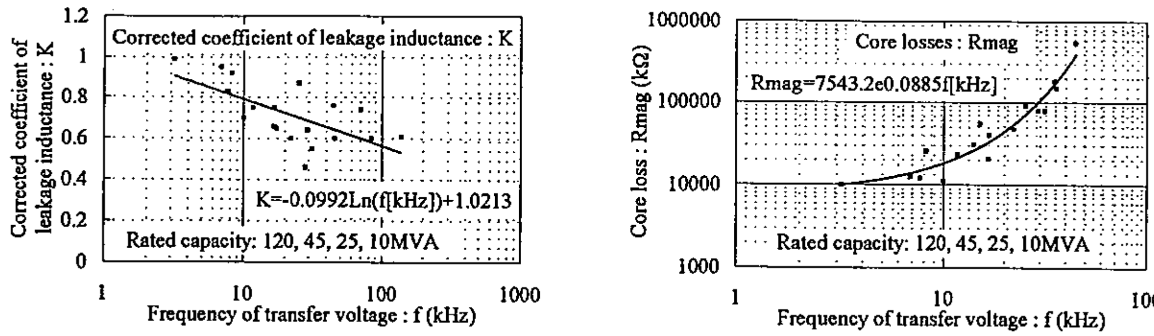


Fig.5. Relation of K and Rmag with frequency of transfer voltage.

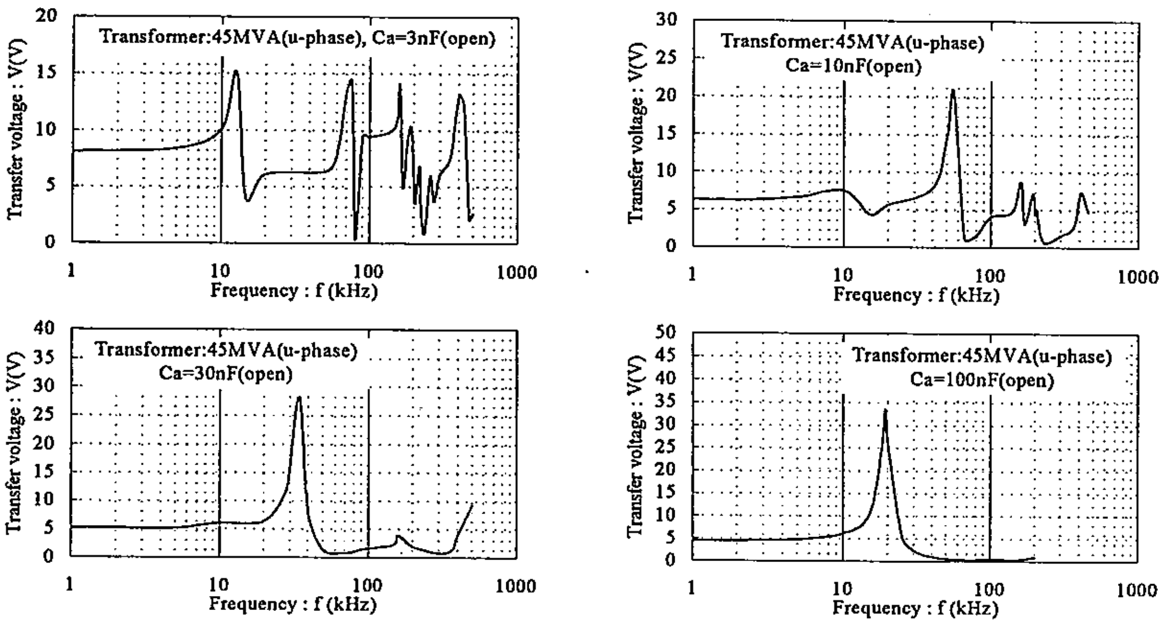


Fig.6. Frequency dependence of transfer voltage. (measurement)

measured transfer voltages of 4 transformers when varied Ca is added.

As shown in Fig.7, low voltage leakage reactance L_2' seen from high voltage side is represented by the following equation (2).

$$L_2' = \frac{2}{3} L_2 \tag{2}$$

By using equation (2), capacitance between high and low voltage windings C_{HL} and other capacitances, theoretical period T_t (period before correction) of transfer voltage, taking no account of frequency dependence of transformer, is represented by the equation (3).

$$T_t = 2\pi\sqrt{L_2' \cdot (C_{HL} + C_{NL} + C_{LG} + C_a)} \tag{3}$$

Corrected coefficient K for L_1, L_2, as shown in equation (4), can be expressed by the square of the ratio of the period T_t obtained from equation (3), whereas Rmag can be derived from calculated result agreed well with measured result.

$$K = \left(\frac{T_m}{T_t}\right)^2 \tag{4}$$

In Fig.5, Rmag has been converted by the base capacity 45MVA and base voltage 154kV due to correct the difference of core volumes of each transformers. these relationships are approximated by the equation (5).

$$\begin{cases} K & = -0.0992 Ln(f[kHz]) + 1.0213 \\ Rmag & = 7543.2 \exp^{0.0885 f[kHz]} \end{cases} \tag{5}$$

Therefore, frequency-dependent L_1 and L_2 can be corrected by multiplying K by equation (1). Frequency-dependent Rmag can be derived from converting the value of Rmag at frequency of transfer voltage by the base capacity and voltage inversely.

As a result of above discussion, more accurate transformer transfer voltage model applied in wide frequency range can be made by representing from equation (1) to (5) in MODELS.

B. Modeling

A frequency-dependent transformer model for transfer voltage study is shown in Fig.8. Since the frequency-dependent L_1, L_2 and Rmag cannot be represented directly in

TRANSFORMER model described in [3] and [4], these elements are in outside of the TRANSFORMER model.

IV. Comparison of analyzed and measured results

To verify the adequacy of this proposed model, we compared the results analyzed on the proposed model with measured waveforms on 4 transformers when varied Ca is added. Analyzed results agree with measured results relatively well. However, when the accuracy of the approximate curves decreases, namely, measured K or Rmag separate from the approximate curves, the error becomes larger.

V. Conclusion

We have proposed a frequency-dependent transformer model for transfer voltage study. Results of the present paper can be summarized as follows.

(1) We have measured the transfer voltages of transformers, whose rated capacity and voltage are different from each other, varying the value of low voltage side capacitance. As a result of comparing the measured waveformes with the result analyzed on the model already proposed in [14], for more accurate calculation, frequency-dependent leakage inductance and core loss have to be considered.

(2) We have measured the frequency dependence of transfer voltages. Resonances occur above 10kHz.

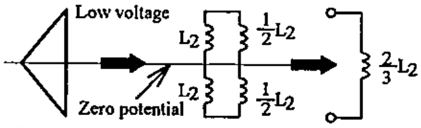


Fig.7. Low voltage leakage reactance seen from high voltage side.

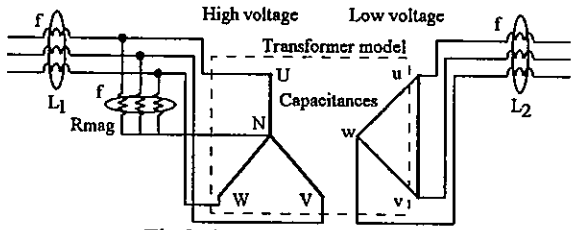
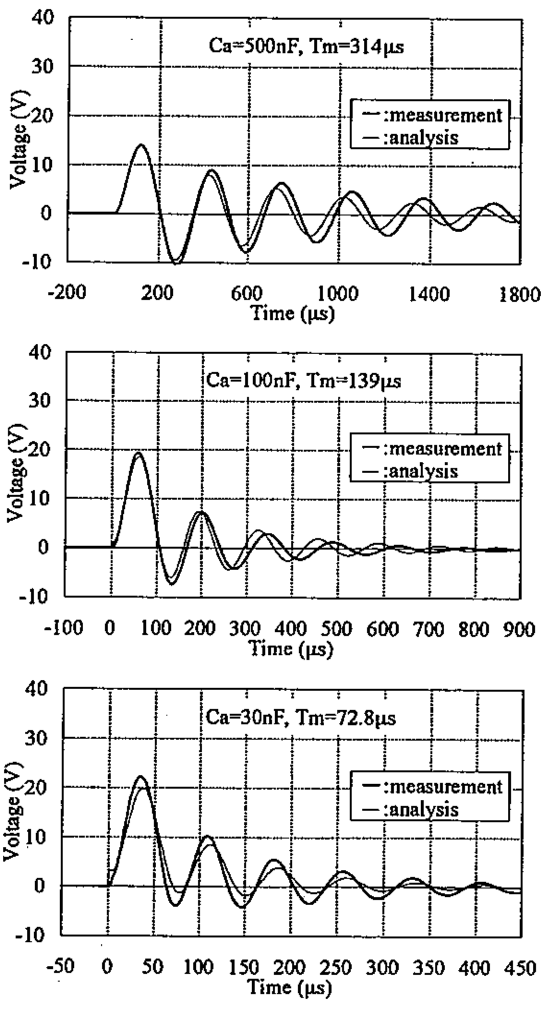
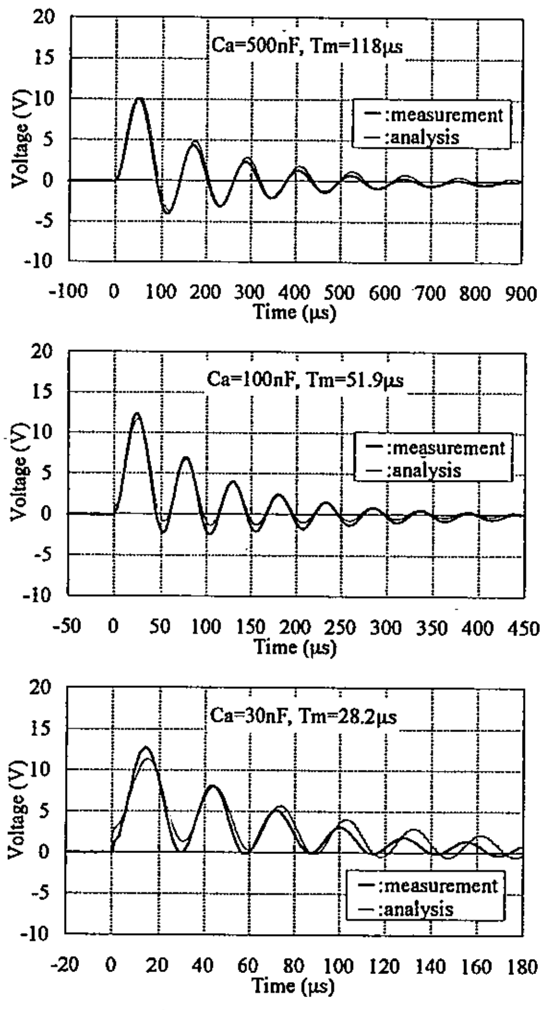


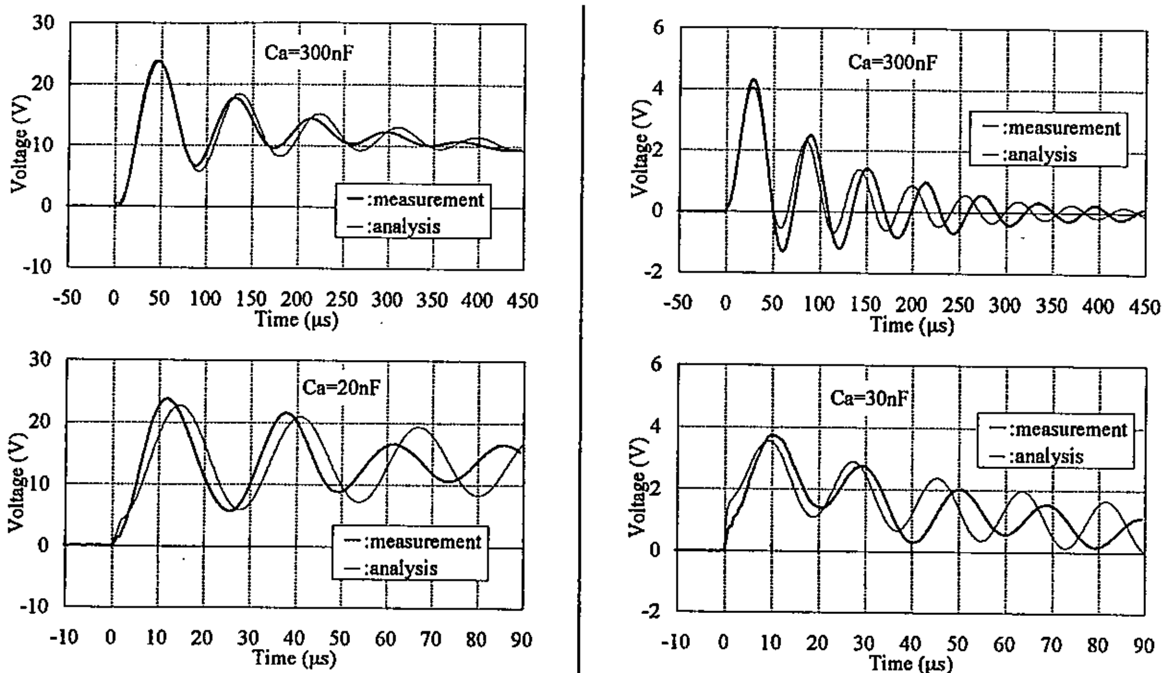
Fig.8. A new proposed model.



(a) 120MVA transformer.



(b) 45MVA transformer.



(c) 25MVA transformer.

(d) 10MVA transformer.

Fig.9. Comparison between measured results and analyzed results used to new proposed model. (u-v phase transfer voltage)

Resonant frequencies are numerous if low voltage side capacitance is small and the peak value at resonant frequency is larger if low voltage side capacitance is large.

(3) A new transformer model, whose frequency dependence are represented by approximate curves assembled into MODELS, has been developed. The validity of this model has been indicated by comparing the measured results with analyzed results.

(4) When this proposed model is compared with the previous model, it dose not need to repeat simulation for determination of model parameters and it can be applied to the various transformer.

Hereafter, we would like to continue accumulating the measured data on the various transformer and investigating high reliable transformer model for transfer voltage study.

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