Digital Time-Domain Simulation of Ferroresonance of Potential Transformer in the 154 kV GAS Insulated Substation

Eung-Bo Shim, Jung-Wook Woo and Sang-Ok Han

Abstract - This paper reports a set of digital time-domain simulation studies conducted on 154 kV wound Potential Transformer(PT) in the 154 kV Gas Insulated Substation(GIS). The Electro-Magnetic Transient Program(EMTP) is used to develop the PT model and conduct the transient studies. The accuracy of the PT model is verified through comparison of the EMTP simulation results with those obtained from the field test results. The investigations shows that the developed model can accurately predict PT transient resonance, especially, the phenomenon of ferroresonance. The model is developed not only to determine impact of transients on PT response but also to design ferroresonance suppressor devices of PT. And it can also be used to predict PT transient response on power system monitoring and protection scheme.

Keywords - Potential Transformer, Ferroresonance, Simulation, EMTP, Damping Reactor

1. Introduction

Potential Transformer is a well known apparatus to transform high voltage input to lower voltage levels output at which monitoring devices and protection relay operates. Theoretically, the output waveform should be identical of the input waveform under all operating conditions. Under steady state conditions, this requirement can be satisfied based on the proper design and tuning of the PT. However, under transient situations such as faults and switching incidents, the PT output waveform may different from the input waveform due to the impacts of capacitive, inductive and nonlinear components of the PT. Therefore, the characteristics of PT during transient must be analyzed and quantified. The other concern is thermal overstress and consequently deterioration of PT components due to its internal transient phenomena, especially the phenomenon of ferroresonance.

The PT burned out in the KEPCO's 154 kV GIS due to ferroresonance during the commissioning test was reported recently, and necessity of developing a analysis model was proposed to get proper countermeasures. The model was developed based upon the use of the EMTP. The objectives of this studies are;

- To evaluate, compare and quantify impacts of PT component parameters and protective/suppressive device on its transient response, e.g. the phenomenon of ferroresonance.
- To predict and quantify impact of PT ferroresonance occurrence according to the combination of circuit breaker capacitance and bus capacitance.

In this paper we represent an EMTP model of the KEPCO 154 kV PT, investigation of the circumstances in which the ferroresonance may occur and the examination of the damping reactors connected to the secondary winding of the PT in order to accelerate the damping of the ferroresonance or avoid it. It is hoped that this model will benefit the manufacturer to get proper countermeasure of ferroresonance.

2. Ferroresonance and Suppressive Device

The ferroresonance phenomenon may occur and persist when the following operational circumstances duplicate simultaneously.

- The isolated circuit meets the resonance conditions, between one PT characterized by its nonlinear inductance and the capacitance of the isolated bus section.
- The opened circuit breaker has grading capacitors, and the disconnecters are closed.
- The switching transient overvoltage is high enough to initiate the PT core saturation.

The ferroresonance is not a new phenomenon, and the theoretical aspect of the ferroresonance are described in many papers.[2, 4, 5, 6, 7]

The ferroresonant circuit shows the oscillations characterized by frequency, which according to the voltages applied on it and circulating current through the components. The dominant frequency of these periodic oscillations could be the network frequency (fundamental ferroresonance)and DC component due to trapped charge (sub-harmonic ferroresonance).[8]

Manuscript received: Mar. 14, 2001 accepted: Sep. 13, 2001.

Eung-Bo Shim and Jung-Wook Woo are with Power System Lab., Korea Electric Power Research Institute, 103-16, Munji-Dong, Yousung-Gu, Taejon 305-380, South Korea.

Sang-Ok Han is with the Department of Electrical Engineering, Chungnam National University, 220 Kung-Dong, Yousung-Gu, Taejon 305-764, South Korea.

One of the well known effective countermeasure for ferroresonance is connecting a damping reactor and series resister to the secondary winding of the PT. The damping reactor behaves as a magnetic switch with its nonlinear characteristics. Under the normal operating conditions, the damping reactor has a high impedance in order to prevent the disturbances of the measuring devices. When ferroresonance occurs, the damping reactor inductance reaches its saturated state before the saturation of the PT core, thus serial resister acts as secondary burden which damps the phenomenon.[5, 6, 7, 8, 9]

3. Emtp Simulation Model

Fig. 1 shows the single line diagram of the KEPCO's 154 kV GIS and Fig. 2 represents the equivalent circuit diagram of the substation when the last breaker(bus-tie CB) was opened to deenergize the #1 bus section.

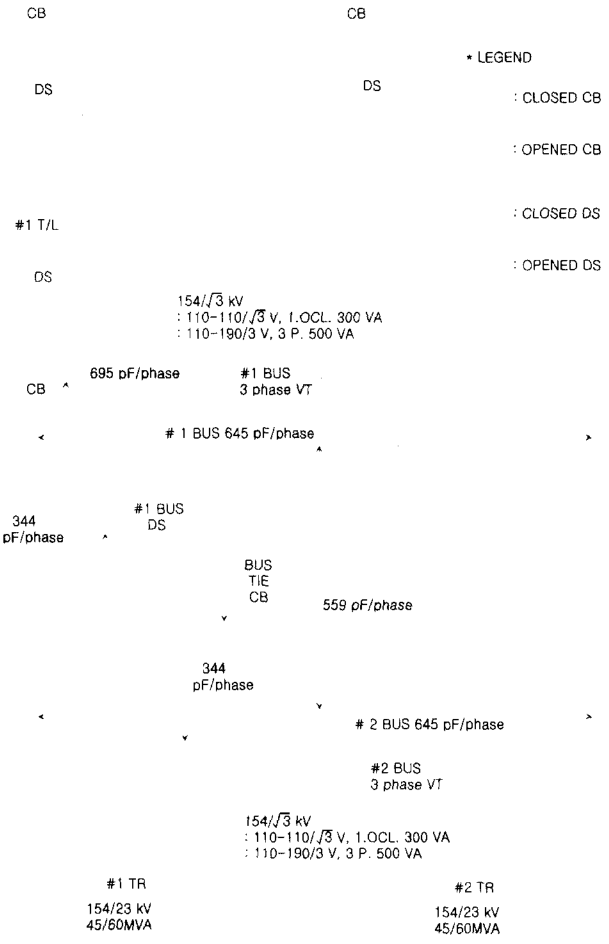

Fig. 1 Single Line Diagram of KEPCO 154 kV GIS

3.1 Equivalent Source

The short circuit strength at 154 kV GIS does not influence the onset of ferroresonance because the impedance is not of the same order as the saturated PT impedance. However, the actual system data from PSS/E program was used in the simulations.

3.2 Bus Capacitance and Grading Capacitors

An accurate model of the bus capacitance is required to simulate ferroresonant condition reliably. The calculated value is represented in Fig. 1, and the deenergized bus voltage through the capacitive coupling between circuit breaker capacitance and bus equivalent capacitance was confirmed in the field test. The capacitance of one section of GIS bus(C_E in Fig. 2) is 1,269 pF for the manufacturer A whereas the capacitance of one circuit breaker(C_B in Fig. 2) is 695 pF. Thus, approximately 0.35 p.u. of voltage is applied to the deenergized bus. The capacitance C_E, C_B for the manufacturer B is 4,664 pF and 1,165 pF, respectively.

3.3 Potential Transformers

The wound potential transformers involved in the ferroresonant disturbance is 300 VA(secondary) and 500 VA(tertially) of rated burden, 88,900 Volt ground wye-110V/66.4V 808/1,404:1 voltage transformer. Critical parameters for the wound PT include core loss, winding resistance and exciting current.

The losses measured in an excitation test are the iron-core losses which are due to the cyclic changes in flux. The iron core losses are composed of both hysterisis and eddy current losses. A constant resistance was chosen to model the iron core losses. A value of 140 watts(no-load loss) per phase at nominal voltage was used for PT. The corresponding value for R_{mag} reflected to the primary is 56 MΩ. In region of high saturation, the value of resistance(R_{mag}) is no longer constant but is greatly reduced thus increasing the effective iron core losses.

The leakage inductance of the primary winding is assumed to be negligible and is set at 0.001 ohms. A burden of 50 VA is assumed to be normal PT loading. Manufacturer's data was used to model the PT saturation characteristics as shown in Fig. 3. The fully saturated(air-core) inductance was not available from the excitation test, so the designed value from the manufacturer was used for the fully saturated inductance, which matched field test recordings.

3.4 Benchmark Case Results

An oscillation was observed after the deenergization of bus #1 by opening the bus-tie circuit breaker in Fig. 1 and Fig. 2. The trace is included in Fig. 4 for reference.

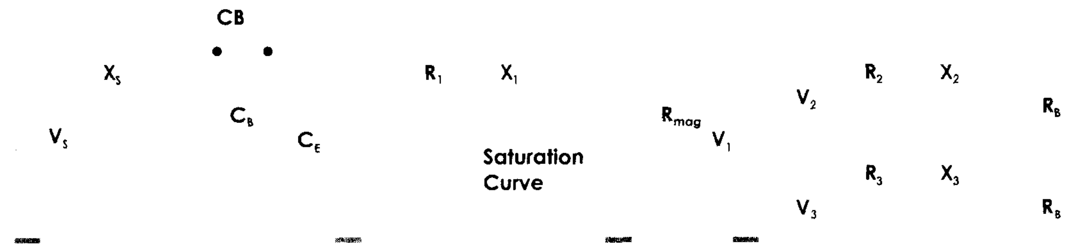

Fig. 2 Equivalent Circuit for EMTP Simulation

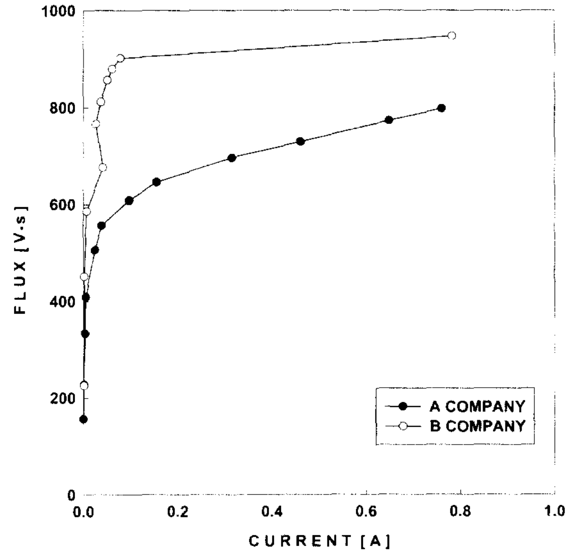

Fig. 3 Iron Core Saturation Characteristics

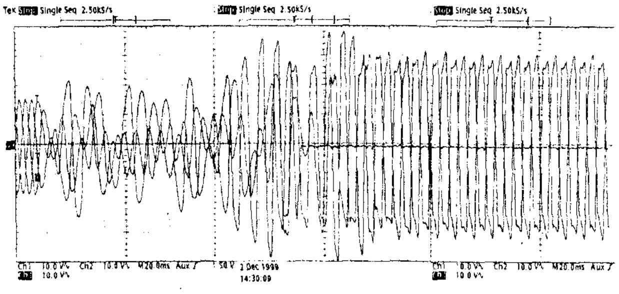

Fig. 4 Ferroresonance Recordings(Field Test)

Fig. 5 is the simulated oscillogram for the same situation. The field test oscillogram shows three phases experienced chaotic oscillations for the first 250 ms before settling into a steady state fundamental frequency ferroresonance state. However the EMTP results shows 150 ms chaotic oscillations, the magnitude and steady state resonance has good agreement.

The particular chaotic pattern shown in the oscillograph is almost impossible to duplicate. It is a function of the breaker opening times, pre-switch voltage and the exact values of all parameters in each phase.

Fig. 6 and 7 show the simulated result of PT primary voltage and exciting current during the ferroresonance state. From this oscillograph, we can understand the energy during the ferroresonance state is much greater

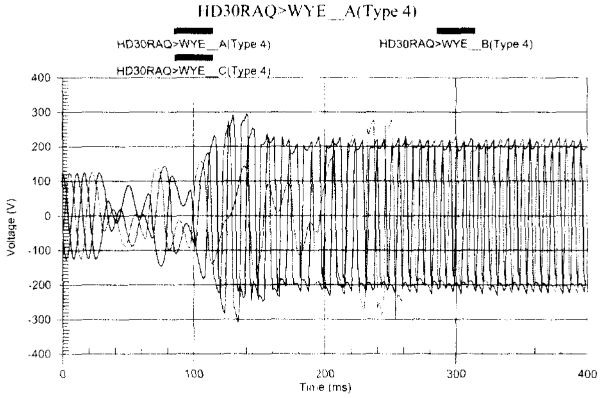

Fig. 5 EMTP Simulation Result

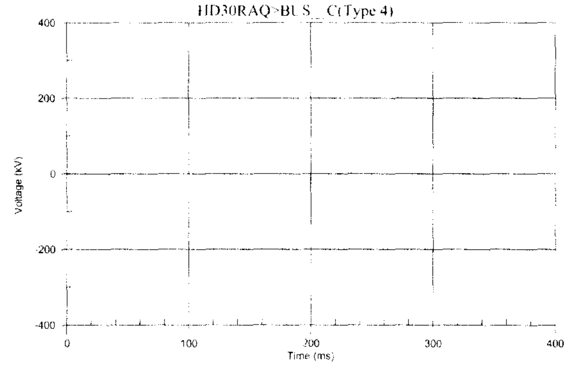

Fig. 6 PT Primary Voltage(EMTP)

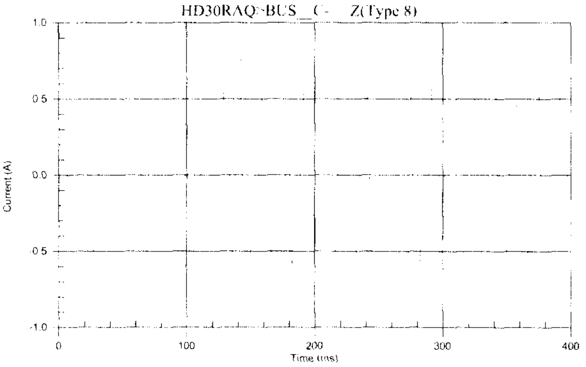

Fig. 7 PT Excitation Current(EMTP)

than the normal state by several hundred times, which lead to PT burnt out.

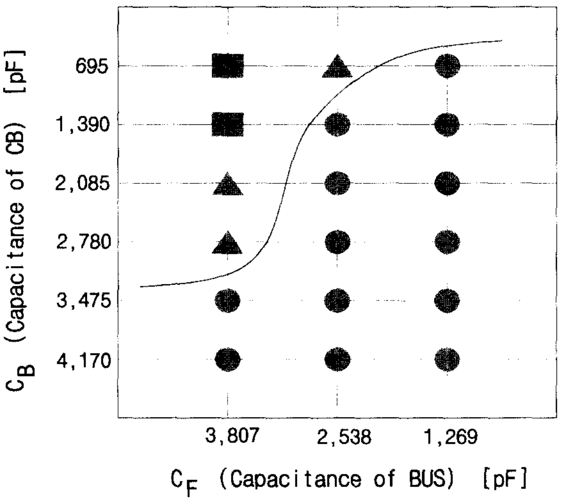

Fig. 8 Ferroresonance Domain(Manufacturer A)

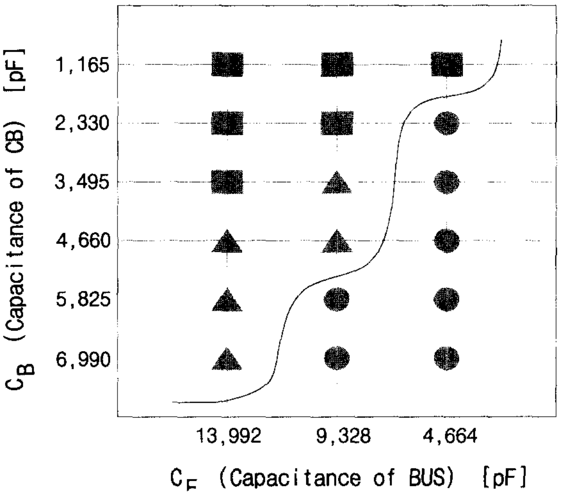

Fig. 9 Ferroresonance Domain(Manufacturer B)

4. Consideration of Damping Reactors

4.1 Ferroresonance Occurrence Domain

Fig. 8 demonstrates the ferroresonance domain according to the number of circuit breakers and length of the isolated bus for the manufacturer A. The remark ■ is the ferroresonance safe region, remark ▲ is the ferroresonance occurrence with lower voltage and remark ● is the strong ferroresonance occurrence region. Fig. 9 and 10 are the same case for the manufacturer B and C respectively. This data will be very useful to the ferroresonance suppressive design of PT.

4.2 Ferroresonance Suppression by Damping Reactor

Fig. 11 shows the saturation characteristics of damping reactor for the manufacturer A. The fully saturated inductance was not available by the manufacturer test, so proper assumption was added.

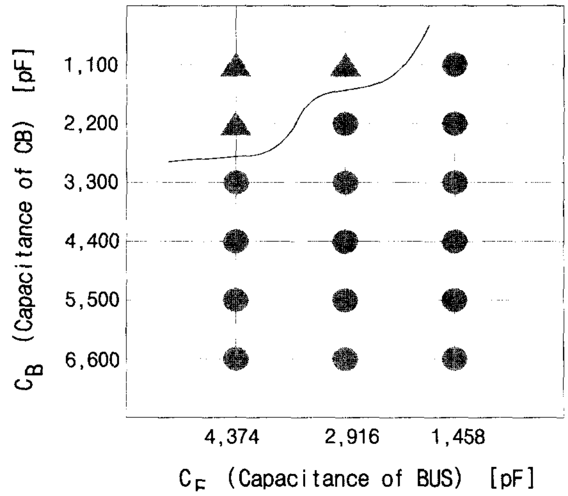

Fig. 10 Ferroresonance Domain(Manufacturer C)

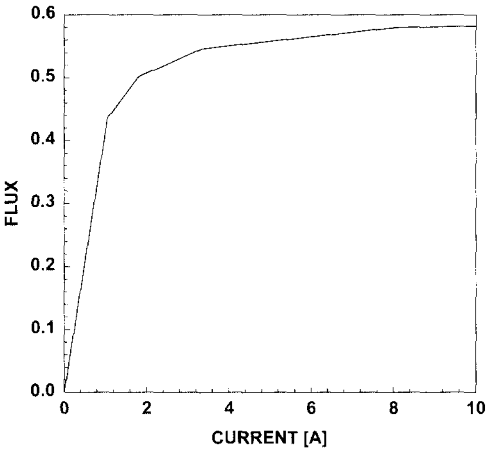

Fig. 11 Saturation characteristics of Damping Reactor

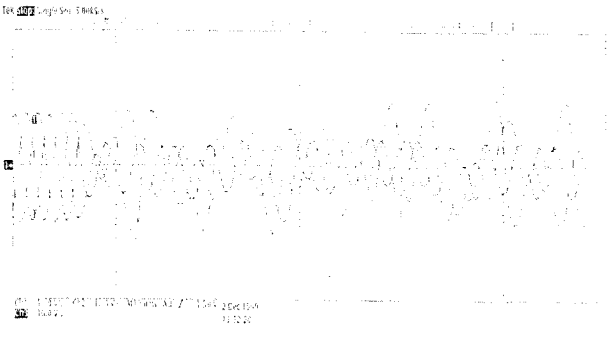

Fig. 12 Damping Effect(field test)

Fig. 12 and 13 demonstrate the damping effect with 2.0 ohms of resistor in series to the secondary winding of PT, field test case and EMTP simulation result respectively.

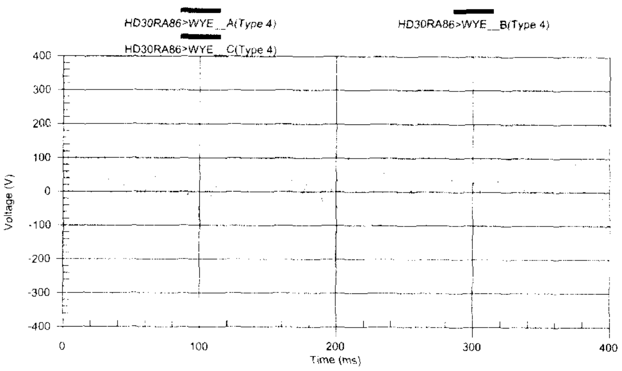

Fig. 13 Damping Effect(EMTP Result)

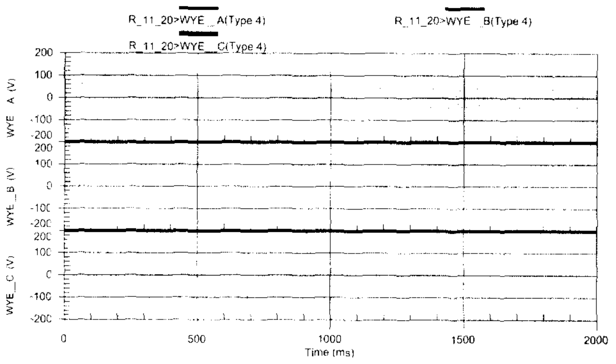

Fig. 14 Well-damped case(EMTP Result)

4.3 Damping Resister Efficiency

In order to check the damping resister efficiency, many computations were performed for different values of the serial damping resister from 0 to 5 ohms.

From the calculated result, we have known that the damping reactor is efficient only for specific values of serial resistor, which depend on the operational schemes and on the secondary loading of PT, in a very sensitive way.

Table 1 shows the effective region of damping resister value according to the combination of capacitance between circuit breaker and GIS bus for the manufacturer A.

The remark ○ shows the well-damped case (ferroresonance was damped within 2 second), △ shows the half-damped case(ferroresonance was not damped within 2 second but with low voltage) and × shows the strong ferroresonance case.

Fig. 14 to 16 demonstrate the well-damped, half-damped and not-damped case of manufacturer A.

We do not need any damping device for the manufacturer B, because the chaotic ferroresonance was disappeared naturally during the field test, which matches the digital simulation result as shown in Fig. 9.

Table 2 illustrates the effective damping region according to the combination of capacitance between circuit breaker and GIS bus for the manufacturer C. From the study result, we found the effective range of damping resistances are from 1.0 ohms to 3 ohms, though the optimal values are 2.0 ohms for the manufacturer A and C.

Table 1 Effective Damping Resistance Value(Manufacturer A)

No	C_B [pF]	C_F [pF]	DV* (p.u.)	Damping Resistance [Ω]					
				0.5	1.0	2.0	3.0	4.0	5.0
1	695	1269	0.35	×	△	○	○	×	×
2	695	2538	0.21	○	○	○	○	○	○
3	1390	2538	0.35	△	△	△	△	△	○
4	2085	2538	0.45	△	△	△	×	×	×
5	2085	3807	0.35	○	○	○	△	△	△
6	2780	3807	0.42	×	×	×	×	×	×

Remark : DV= Devided voltage of the de-energized bus

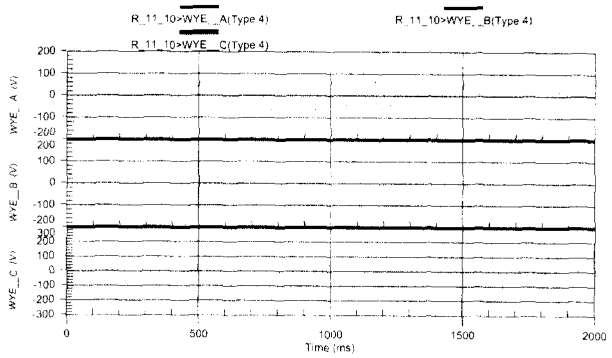

Fig. 15 Half-damped case(EMTP Result)

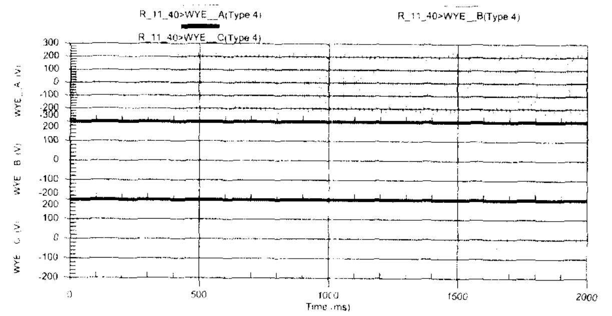

Fig. 16 Not-damped case(EMTP Result)

Table 2 Effective Damping Resistance Value(Manufacturer C)

No	C_B [pF]	C_F [pF]	DV* (p.u.)	Damping Resistance [Ω]					
				0.5	1.0	2.0	3.0	4.0	5.0
1	1,100	1,458	0.43	×	○	○	○	○	×
2	1,100	2,916	0.27	○	○	○	○	○	×
3	2,200	2,538	0.43	○	○	×	×	○	○
4	3,300	2,538	0.53	×	○	○	×	×	×
5	3,300	4,374	0.43	×	○	○	○	×	×
6	4,400	4,374	0.50	○	×	○	○	○	×

Remark : DV= Devided voltage of the de-energized bus

5. Conclusion

This paper represents the results of digital time-domain studies conducted on 154 kV wound PT. The Electro-Magnetic Transient Program(EMTP) is used for digital time domain simulation of the PT transient response. Comparison of the EMTP results with those of field test results verifies the accuracy of the EMTP model of the PT.

The investigations conclude that:

1) Time domain analysis of PT provides complementary information to accurately predict steady state and transient behavior of PT system, and to properly design its protective and suppressive devices.
2) The ferroresonance phenomenon is very sensitive to operational schemes and circuit parameters. The EMTP model of PT can accurately demonstrate ferroresonance of a PT circuitry.
3) The EMTP model of PT can identify characteristics and rating of protective and ferroresonance devices. The model also predicts thermal stresses imposed on such devices.
4) The EMTP model of PT also can be used to investigate impacts of system transients and burden characteristics on the PT transient response.
5) The damping reactor efficiency depends on the series resistor value and on the operational schemes. In this case, we could damped out the ferroresonance successfully by using a damping reactor in series with a 2.0 ohms external resistor.

Reference

[1] "Alternative Transient Program Rule Book. Salford Version" Leuven EMTP Center (LEC). 1987.
[2] EMTP Primer, EPRI EL-4202, Project 2149-1, Final Report, September 1985
[3] EMTP Case Study Workbook I ~ IV, Electrotek Concept, Inc, January 1997
[4] R. P Aggarwal and others, "Failure of Electromagnetic Voltage Transformer due to Sustained Overvoltage on Switch-Off. Preventive measures", IEEE Trans. On PAS, Vol. PAS-101, pp.4536-4541, Dec.1982
[5] N. Janssens and others, "Elimination of Temporary Overvoltages Due to Ferroresonance of Voltage Transformers : Design and Testing of Damping System", CIGRE, Session, Report 33-204, 1990
[6] R. mareachen, A. cristen, G. Poletto, "Ferroresonance on 345 kV bus kills PT", Electrical World, No.4, pp.69-70, 1986
[7] D. Shein, S. Zissu, W. Schapira, "Voltage Transformer Ferroresonance in one 400 kV GIS Substation", IEEE The Sixteenth Conference of Electrical & Electronics Engineers in Israel, March 7-9, 1989
[8] D. A. N. Jacobson, D. R. Swatek, R. W. Mazur, "Mitigating Potential Transformer Ferroresonance in a 230 kV Converter Station", IEEE Conference on Transmission and Distribution, pp.269-275, 1996
[9] M. R. Iravani, W. Wang, J. Ribero, A. Sarshar, et al, "Digital Time-Domain Investigation of Transient Behavior of coupling Capacitor Voltage Transformer", IEEE Transactions on Power Delivery, Vol.13, No.2, pp.622-629, 1998

Eung-Bo Shim (Member, KIEE) received his B.S. degree of Electrical Engineering from Hanyang University, Seoul, Korea in 1982. He has been worked for Korea Electric Power Research Institute of KEPCO. His research interests include the analysis of power system overvoltage, insulation design and lightning observation

Jung-Wook Woo (Member, KIEE) received his B.S. and M.S. degree of Electrical Engineering from Kyungpook National University, Taegu, Korea in 1992 and 1994 respectively. He has been worked for Korea Electric Power Research Institute of KEPCO since 1994. His research interests include the analysis of power system overvoltage, insulation design and lightning observation.

Sang-Ok Han (Member, KIEE) received his B.S. degree of Electrical Engineering from Chungnam National University in 1974, M.S. degree of Electrical Engineering from Dankuk University in 1978, and Ph.D. degree of Electrical Engineering from Inha University in 1986, Inchun, Korea. He was a visiting professor of Electrical Engineering at Nagoya University in 1989. Currently, he is a professor of Electrical Engineering dept. of Chungnam National University. He has special interest in insulation material of ultra high voltage.