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Investigation and Mitigation of Overvoltage Due to Ferroresonance in the Distribution Network

Preecha Sakarung†, Teratam Bunyagul* and Somchai Chatratana**

Abstract – This paper reports an investigation of overvoltages caused by ferroresonance in the distribution system, which consists of a bank of open-delta single-phase voltage transformers. The high voltage sides of the voltage transformer are connected to the distribution system via three single-phase fuse cutouts. Due to the saturation characteristic of the transformer cores, ferroresonance can occur in the condition that the transformer is energized or deenergized with single-phase switching operation of the fuse cutouts. The simulation tool based on EMTP is used to investigate the overvoltages at the high side of voltage transformer. Bifurcation diagrams are used to present the ferroresonance behavior in ranges of different operating conditions. The simulation results are in good agreement with the results from the experiment of 22 kV voltage transformers. The mitigation technique with additional damping resistors in the secondary windings of the voltage transformers will be introduced. Brief discussion will be made on the physical phenomena related to the overvoltage and the damage of voltage transformer.

Keywords: Ferroresonance, Voltage Transformer, Bifurcation Diagram, EMTP, PSCAD/EMTDC

1. Introduction

In recent years, the Provincial Electricity Authority (PEA), Thailand which supplies the electricity to all parts of the country except Bangkok Metropolitan area, is at higher risk of ferroresonance. There are many reports on damages of three-phase distribution transformers with single-phase energization/de-energization operation at no load. An abnormally high number of cases were also reported on the damages of voltage transformers (VT) used for supplying measuring instrument. Insulation of the high side of transformer coil was often burnt particularly at the area of top windings of the coil. Deformations of the tank and the damages near the base of the bushings of VT were found in general. The damages occurred when the VTs were operated for 8 to 10 hours after energization.

2. Description of PEA's Distribution System

The Provincial Electricity Authority (PEA) uses Supervisory Control and Data Acquisition (SCADA) system for its network control. Due to very large service area, the problem of voltage collapse has been taken very seriously by PEA. Therefore, on-line operation with SCADA is essential for PEA operation. In SCADA system, many voltage transformers (VTs) are needed to supply the power to the measuring systems with low voltage ratings. Due to low power consumption of the measuring system, open-delta connection is normally used for banking the two single-phase transformers to form three-phase configuration. The two single-phase transformers are normally put in the same tank for the sake of economy. The problem of damaged VT occurred mostly in the area which VT was already installed but SCADA system was not yet put in operation.

The circuit diagram of a typical supply system for measuring equipment is shown in Fig.1 Three-phase distribution system supplies voltage to VT via short transmission lines and three single-phase fuse cutouts (a, b, c).

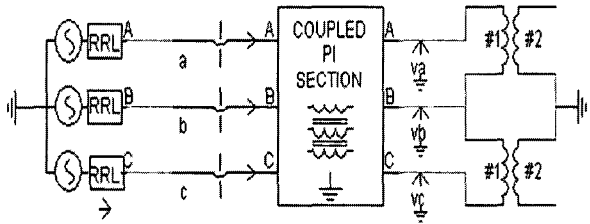

Fig. 1. Typical circuit diagram of the distribution system with voltage transformer connection

For economic reason, the three-phase VT is built from two single-phase transformers connected in open-delta. The center tap of the low side of the transformer is connected to the ground. The physical structure of the voltage transformer is shown in Fig. 2.

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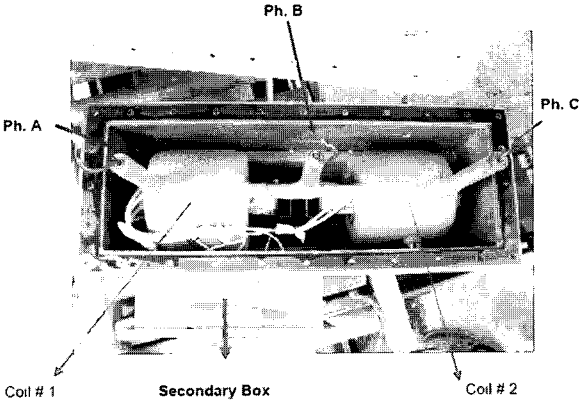

Fig. 2. The physical structure of VT

3. System Modeling

In standard PSCAD/EMTDC simulation tool, the model for two single-phase transformers with different magnetic cores, which are connected in open-delta and put together in the same tank, is not available. It is therefore necessary to build the approximate model from the single-phase transformer and the configuration of VT as shown in Fig.1.

Three-phase voltage source is 22 kV, 50 Hz, and its positive sequence impedance is 2.8086 ohm with 83.979 degree phase angle. The voltage rating of the single-phase voltage transformer is 22 kV on high side and 110 V phase on low side. The power rating is only 25 VA. The core losses in the magnetic component are 22 watt. Copper loss is very low and can be neglected. The approximate characteristic of saturation is obtained from the experiment and the compensating current source for core saturation in EMTDC is used. The parameters for the saturation curve are Air Core Reactance (XAIR) = 0.001 p.u., Rated Magnetizing Current (IMR) = 1.29 p.u. and Knee Point (XKNEE) = 45.0 %. To verify the saturation model of the transformer, an actual curve of saturation curve was compared with approximate saturation characteristic shown in Fig. 3.

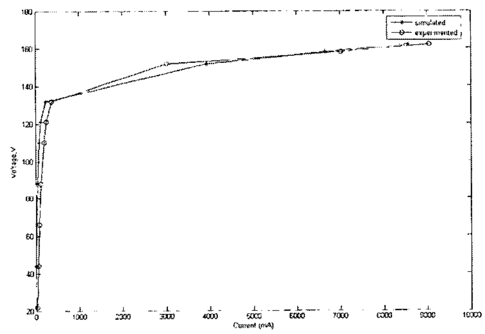

Fig. 3. Comparison of actual saturation v-i curve and approximate saturation curve (low side of transformer)

If the length of distribution line is less than 20 km. and the time step used in the calculation is 50 μsec., Pi section type of transmission line model is recommended in EMTDC. In this case, the length of the line is approximately a few meters only (~3 meters). Therefore, modeling the line with Pi section can produce good results.

4. Experiment Result

The objective of the experiment is to observe ferroresonance phenomenon. The test circuit is shown in Fig. 4. Three single-phase circuit breakers were connected with VT (SW1a, SW1b and SW1c). The measuring equipment represented by V_C was made from 30 MΩ resistor connected in series with a 30 kΩ resistor and a 500 pF capacitor connected in parallel. Simple test procedure involved the random of single-phase switching of the circuit breaker at different angles of the voltage waveform. It was found that overvoltages occurred several times. The overvoltages caused by de-energization of VT of phase C at the angles of 90 degrees and 270 degrees are shown in Fig.5 and Fig.6, respectively. From Fig. 5 and Fig. 6, it can be seen that ferroresonance occurred with fundamental mode (50 Hz) and the highest magnitude of overvoltage was 3 p.u.

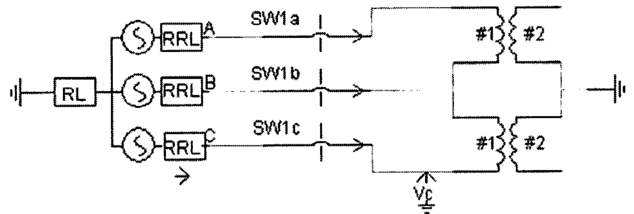

Fig. 4. Circuit diagram of experimental set up

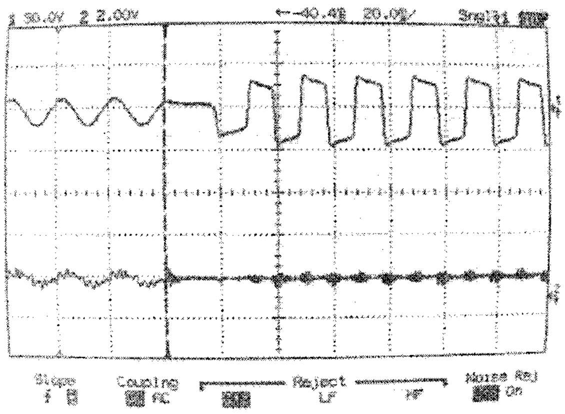

Fig. 5. Voltage (top) and current (bottom) waveforms of phase C resulting from de-energization at 90 degrees (scale: 50 kV/Div and 4.5 mA/Div.)

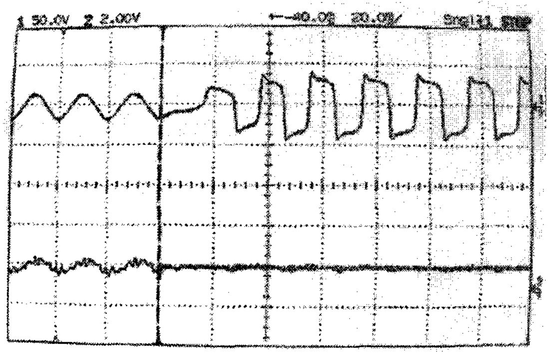

Fig. 6. Voltage (top) and current (bottom) waveforms of phase C resulting from de-energization at 270 degrees (scale: 50 kV/Div and 4.5 mA/Div.)

5. Mitigation Technique

Ref. [2] presents a technique for ferroresonance mitigation by installing of a damping resistor at the secondary side of the transformer. However the resistance value was selected by the trial and error method. Approximate results when a burden resistor was used to damp ferroresonance are shown through the field test and EMTP simulation as in [3]. Serial resistor and damping reactor were used to reduce overvoltage demonstrated in [4]. Saturation characteristic allows the reactor to act like magnetic switch. In normal operation, the impedance of reactor is high, but with overvoltage, the impedance of the reactor reduces significantly due to the saturation. The reactor must be designed to reach saturation level before the core of the voltage transformer does. With this design, the serial connected resistor and the reactor become the burden resistor during overvoltage. Simulation was carried out several times in [5] to determine the optimum resistance value to be installed at the secondary side of VT. Burden resistor or damping resistor is a popular mitigation technique introduced in [2-5]. It is simple, effective, and easy to install in the field.

The resistance value should effectively damp the ferroresonance but with constant secondary voltage, it should be high enough to keep the loss in the burden resistor low. If damping resistor is installed permanently on secondary side of VT, loss of energy occurs continuously. The combination of advantages of not only suppressing overvoltage but also of saving of energy, the power electronic switch is recommended to connect the burden resistor with the secondary side of VT only when overvoltage occurs.

6. Application of Bifurcation Diagrams for Ferroresonance Investigation

Optimal values of burden resistor can be determined from bifurcation diagram. It is more effective and more time saving than the trial and error method reported in the past. Bifurcation diagrams are also useful for investigation of ferroresonance due to other parameters and operating conditions.

6.1 Simulation of single-phase switching

Fig. 7 shows the result of simulation of single-phase switching of the circuit in Fig. 1. The energization sequence was: switching of only phase A at 0.1 second, followed by switching of phase B at 0.5 second and switching of phase C at 0.7 second. It can be seen that the highest overvoltage occurred at phase C only after a single cycle of switching time. The overvoltage reached the peak at 4.5 p.u. and maintained at 4 p.u. with fundamental mode. When phase B was energized, the overvoltage at phase C was decayed with subharmonic mode. The overvoltage disappeared when phase C was energized and all three lines were connected to the supply.

6.2 Bifurcation diagrams for ferroresonance investigation

The bifurcation diagrams can be created from the plot of collection points obtained from the Poincaré Sections with 20 ms sampling time. Three system parameters were investigated to determine their effects on ferroresonance.

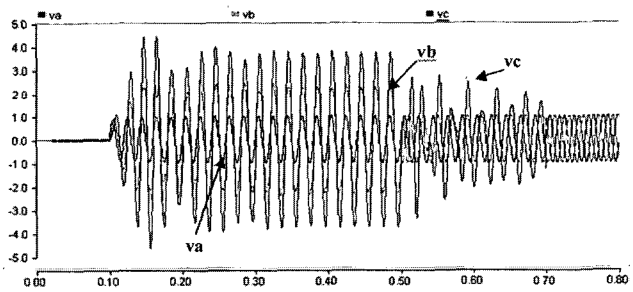

Fig. 7. Waveforms of phase voltages resulting from single phase switching of voltage transformer

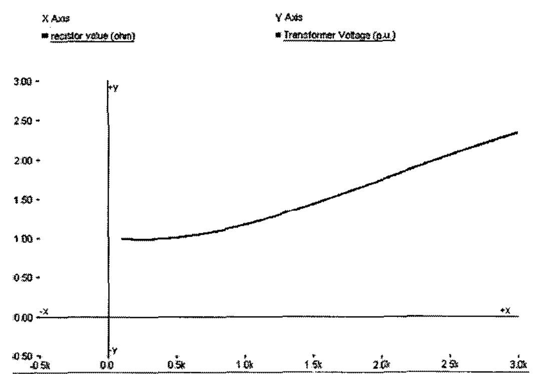

Fig. 8. Bifurcation diagram with varying resistance of burden resistor

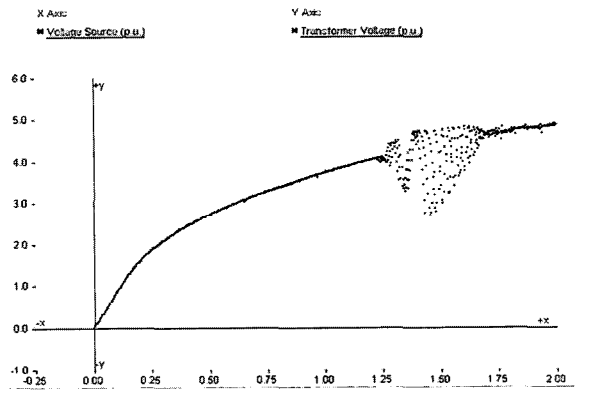

Fig. 9. Bifurcation diagram with varying magnitudes of voltage source

Fig. 8 shows the effect of damping resistance on the overvoltage. The resistance value was varied from 100 Ω up to 3000 with 1 varying step. It can be seen that overvoltage did not occur when the value of resistance was between 100 and 500. Fig. 9 shows the bifurcation diagram of the magnitude of system voltages with varying source voltage from 0 p.u. to 2.0 p.u. It can be seen that, without damping resistor, overvoltage occurred even at the very low magnitude of voltage source (0.1 p.u.). The mode of ferrorresonance changed from fundamental mode to chaotic mode at the source voltage from 1.22 p.u. to 1.7 p.u. The effect of de-energization angles on overvoltages is shown by the bifurcation diagram in Fig. 10. From the bifurcation diagram, ferroresonance occurred at all de-energization angles with single-phase switching operation at 1 p.u. source voltage and without damping resistor.

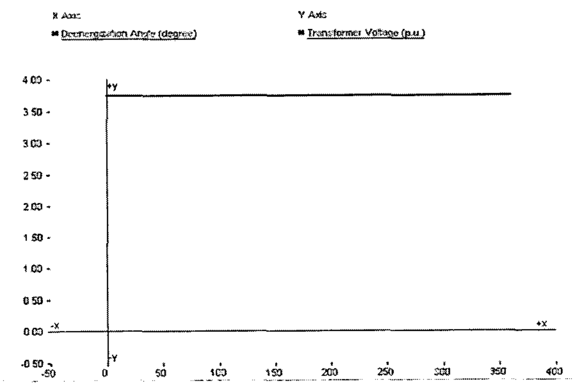

Fig. 10. Bifurcation diagram with varying de-energization angles

6.3 Simulation of single-phase switching with damping resistor

From bifurcation diagram in Fig.8, the resistance value from 100 to 500 can be used to damp the overvoltage at VT. Fig. 11 shows the simulation result of the circuit in Fig. 1 with the damping resistance of 440. The value of 440 was chosen to optimize both the power loss and the common value of resistance to be easily obtained over the counter. In comparison with Fig. 7, for the same switching conditions, it can be seen that there is no overvoltage. No ferroresonance occurred from the first instant of switching at 0.1 second until the end of the energization process at 0.7 second.

6.4 Experimental result of single-phase switching with damping resistor

The result of the investigation was confirmed by installing 440 damping resistors in the VT. Then Fig. 12, the VT was tested with the same conditions as in Fig. 6 (270 degrees de-energization angle).

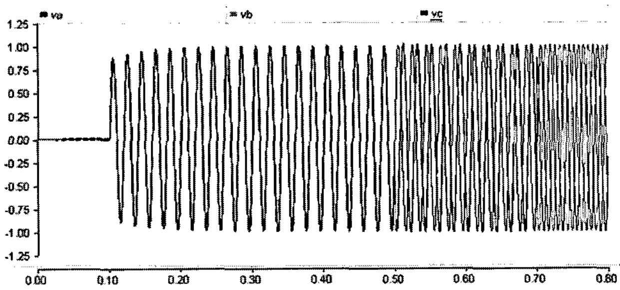

Fig. 11. Waveforms of phase voltages resulting from single-phase switching of voltage transformer with damping resistor of 440 Ω

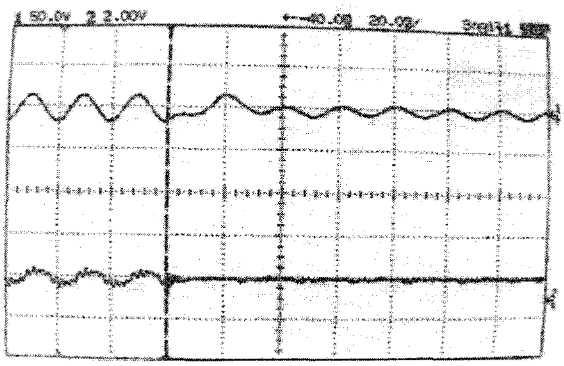

Fig. 12. Voltage (top) and current (bottom) waveforms of phase C resulting from de-energization at 270 degrees with 440 ohm damping resistors at secondary side

7. Practical Aspect of Overvoltage on Voltage Tramsformer

Manual single-phase energization/de-energization of three phase network by operator usually takes about 15 minutes. This is due to the fact that the receptor part of the fuse cutout is rather tight. When ferroresonance occurs, the magnitude of overvoltage can be as high as 3 to 4 p.u. High electrical stress can occur at the insulation close to the transformer tank. During overvoltage, the insulation characteristic of transformer coil deteriorates. Complete damage of VT was reported after being put into operation for 16 hours or in some cases even within shorter operation time.

Coils at phase B and C also face with higher risk from overvoltages if the sequence of energization is A-B-C. Overvoltages damage the insulation of the transformer coils. Insulation failure leads to high current due to short circuits between the windings turns. Burnt insulation was found at groups of high side coil particularly at top position of the coil. Tears between high side terminal and connector were also reported. High internal pressure resulted from high temperature distorted the oil-filled transformer tank and broke the bushing at the base position.

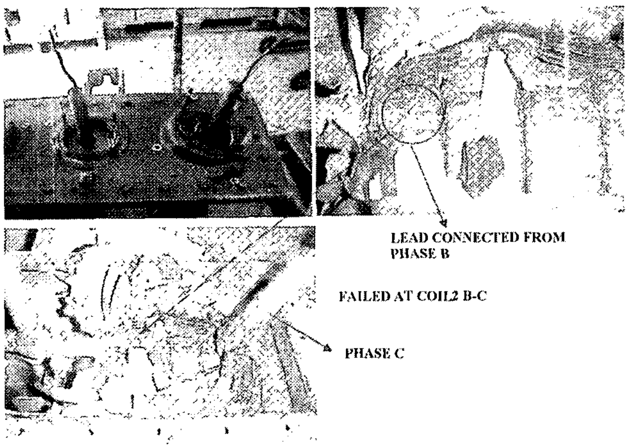

Fig. 13. Internal view of the damaged VT

8. Conclusion

Single-phase energization and deenergization of no-load saturable voltage transformer can cause ferroresonance in the distribution system. The overvoltages caused by ferroresonance can last several minutes after energization process. Overvoltages lead to insulation failure and high short circuit currents. Insulation failure and short circuit current finally destroy the voltage transformer.

EMTP is a popular simulation tool for ferroresonance investigation. With the help of Poincare' sections, bifurcation diagrams can be produced to demonstrate various effects of operating parameters on ferroresonance. In this paper, bifurcation diagrams were produced to study the effects of damping resistors, magnitude of the source voltages, and de-energization angles on the ferroresonance caused by single-phase operation.

The results obtained from the simulation of damping resistor were confirmed by the test in which the damping resistor was installed with the secondary circuit of the VT.

Test result confirms that the damping resistor of 440 can successfully eliminate ferroresonance. This procedure can be used to determine ferroresonance suppression circuit in the future.

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Appendix

Table 1. Pi section line data

	Positive sequence	Zero sequence
Resistance	.21435E-3 [ohms/m]	.39186E-3 [ohms/m]
Inductive reactance	.33976E-3 [ohms/m]	.15538E-2 [ohms/m]
Capacitive reactance	289.695 [Mohms*m]	647.332 [Mohms*m]

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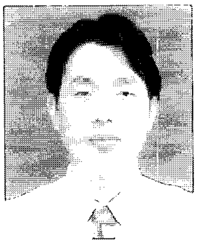

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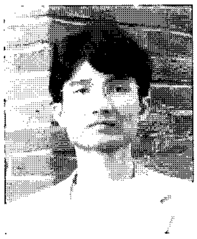

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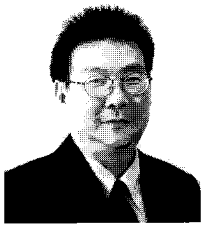

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