Failure of Riser Pole Arrester due to Station Service Transformer Ferroresonance

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Abstract--This paper presents the explosive problem of riser pole arresters during the operations of disconnector switches in the feeder having a station service transformer. In order to determine the cause and the practical solutions, field tests and computer simulations with ATP/EMTP program were conducted. The field tests revealed that in the case of switching without arrester installation, chaotic transient and 3rd sub-harmonic overvoltages appeared in the opened phase during switching. In the case of switching with arrester installation, the restricted spike overvoltages were found. The arrester on the last closed phase exploded because it suffered ferroresonant overvoltages for a long time. The simulation results agree with the results of field test. They show that the switching angle has significant effects on ferroresonant initiation, and associated overvoltages. To avoid and mitigate ferroresonant overvoltages, alternation of switching procedures and application of a resistive load were considered. The results of counter-measures were verified by using both simulations and field tests.

Keywords: Station Service Transformer, Riser Pole Arrester, Underground Cable, Ferroresonance, ATP/EMTP

I. INTRODUCTION

ONE of the recognized causes of metal oxide arrester failures in distribution systems is ferroresonant overvoltage. As a result of complication and difficulty to predict, ferroresonance has still occurred in various situations such as the single-phase switching, blowing out of a fuse and line rupture. There have been several reports on ferroresonant overvoltages [1]-[5] and their effects on the power system equipment, especially the arresters [6]-[10]. Ferroresonance in term of power system transients is a nonlinear resonance occurring in the electric circuit consisting of a capacitance and an iron-core saturable inductance in a condition of low losses [11]. The main causes of its occurrence in distribution feeders are designs of the network configuration and the switching sequences without comprehension of ferroresonant and factors which excite a jump phenomenon.

In Thailand, the explosion of riser pole arrester during switching operations has been found in distribution networks. It directly effects on the system reliability because of fault clearing. As a result of arrester failure, the power system equipment face the risk of damage due to surge overvoltages. To avoid and mitigate these problems, the causes and their practical solutions are studied.

The purpose of this paper is to report a study on the explosive problem of riser pole arresters during the operation of disconnector switches in a 12 kV distribution feeder. The damage of arresters and its cause were investigated by using both field tests and computer simulations. Moreover, the practical solutions are also considered.

II. SYSTEM CONFIGURATION

Fig. 1 shows a simplified one line diagram of the case studied. The distribution feeder circuits leave the substation from circuit breakers via substation exit underground cables. The cables connect to the overhead lines outside the substation at riser poles where arresters are installed. The length of each cable is more than 300 metres. The feeder deenergization is normally performed to maintain the equipment or to manage emergency situation. For deenergization of the underground cable, the circuit breaker will be opened after customer loads are transferred to another feeder by closing the tie switches. Then, the disconnector switches at the riser pole are opened in the last step. The feeder energization is conducted in the reverse order.

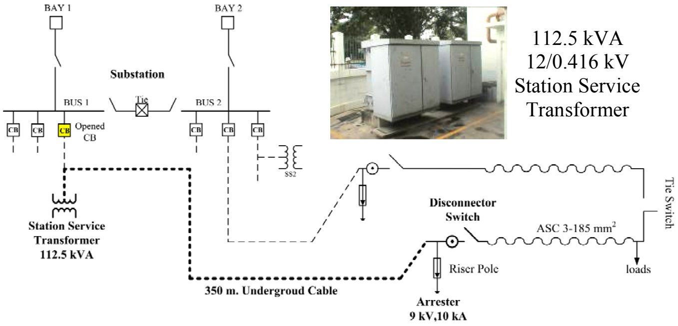

Fig. 1. A simplified one line diagram of the case studied

It is found that the riser pole arresters sometime exploded during the operations of disconnector switches. The primary investigation revealed that the explosive events occurred to the feeders having a station service transformer. It is possible that temporary overvoltages due to ferroresonant phenomena may involve with these events. While the disconnector switch is operated, ferroresonant phenomenon involving a nonlinear inductive core of the station service transformer and a capacitive component of the cable can be produced. The nonlinear resonant overvoltages may lead to thermal runaway of arrester.

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III. FIELD TESTS

The field tests were conducted to verify the cause of riser pole arrester failure by measuring and recording waveforms of phase system voltage on the underground cable side. The 12 kV distribution feeder consists of a cable of 350 metres in length. The power rating of the station service transformers is 112.5 kVA. The installed arresters are riser pole type with polymer housing rated for 9 kV, 10 kA. Fig. 2 shows the measuring circuits and waveform recorder. The capacitor voltage dividers with a digital storage oscilloscope were used to measure phase voltages which are the voltages across arresters. The voltage waveforms on the secondary side of the transformer were simultaneously recorded by another oscilloscope. Furthermore, the eventful movies during tests and the audible noises of the transformer were also recorded. Table I shows the field test procedures and the phase sequence of switching, same as the actual procedures.

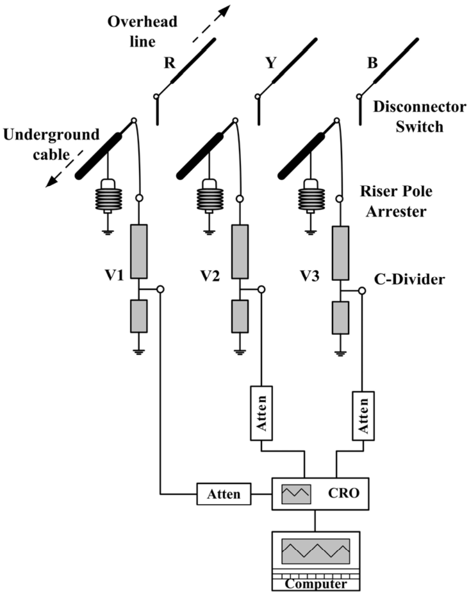

Fig. 2. Measurement of phase system voltage on underground cable side

TABLE I
FIELD TEST PROCEDURES AND PHASE SEQUENCE OF SWITCHING

Procedure	Switch	Action	Phase sequence
deenergization	circuit breaker	open	simultaneous
	disconnector switch	open	R → B → Y
energization	disconnector switch	close	Y → B → R
	circuit breaker	close	simultaneous

A. *Field Tests without Arrester Installation*

In case of switching without arrester installation, the overvoltages of two ferroresonant modes appeared in the opened phases during switching. First, a chaotic oscillation temporarily appeared in the condition of single-phase opening. Its peak voltage was greater than 4.0 per unit. Second, the 3rd sub-harmonic mode continuously occurred in the condition of double-phase opening.

Fig. 3 demonstrates an example of chaotic mode appeared on phase R after closing phases Y and B. The peak value of overvoltages was about 4.14 per unit. The 3rd sub-harmonic overvoltages appeared on phases R and B after opening phases R and B are shown in Fig. 4. They had a peak value of about 2.69 per unit. The peak value of overvoltages from both modes was high enough for arresters to operate, if they were installed.

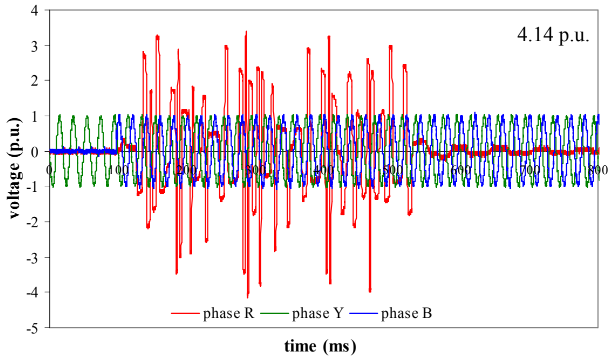

Fig. 3. Chaotic waveform of voltage on the cable side

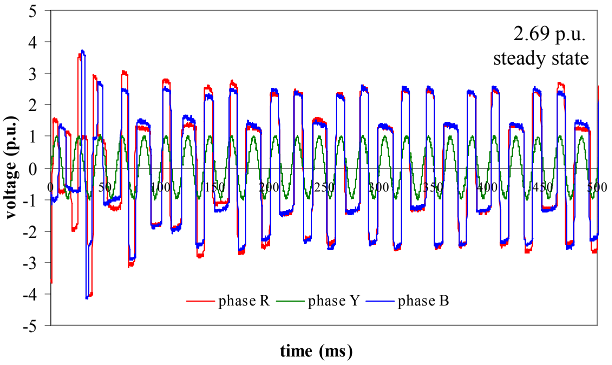

Fig. 4. 3rd sub-harmonic waveforms of voltage on the cable side

The tests were repeated several times. The different results of overvoltages were obtained. These imply that the point on wave of switching has effects on the peak and duration of overvoltages. It is also found that the overvoltages on the secondary side of the transformer, were transformed from the primary side by the transformer ratio and its vector group. The transformer made loud noises during ferresonant phenomena like the sounds of a crack and raced engine in periods of the chaotic and sub-harmonic modes, respectively.

B. *Field Tests with Arrester Installation*

After the riser pole arresters were already installed on the cable side, the tests with the same procedures were repeated. For closing operation, the spike overvoltages appeared on phases R and B after closing phase Y. The waveform of overvoltages changed to a fundamental mode. As shown in Fig. 5, the peak value of overvoltages was restricted about 1.50 per unit. Fig. 6 shows that the restricted voltage was about 1.0 per unit in phase R, after subsequently closing phase B. The overvoltage restriction with fundamental mode was due to the effect of arrester behavior operating in ferroresonant conditions, as explained in [12].

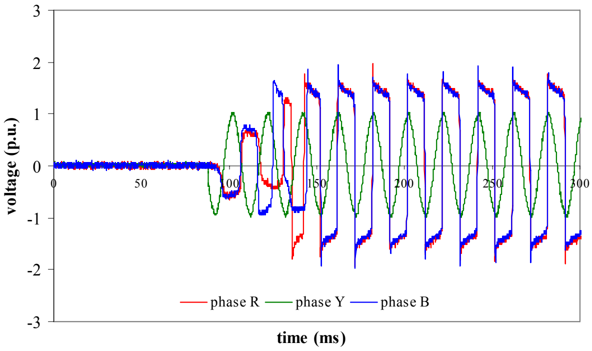

Fig. 5. Spike overvoltage in phase R and phase B due to the arrester operation

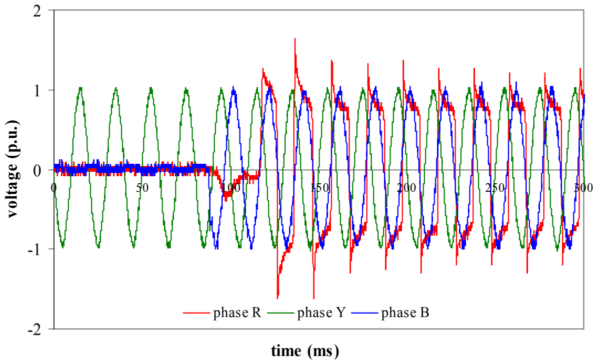

Fig. 6. Spike overvoltage in phase R due to the arrester operation

After closing all phases, the phase voltage of each phase became the normal level, but the arrester on phase R, the last closed phase, exploded within less than 30 seconds. The detonation of a ground lead disconnector, attached at the bottom of the bracket, and the ruptures of the polymer housing were observed. Fig. 7 shows a photograph of the event during the arrester failure. However, the arrester on phase B, which also suffered ferroresonant overvoltage, was still in the acceptable condition by verification of the discharge-voltage test.

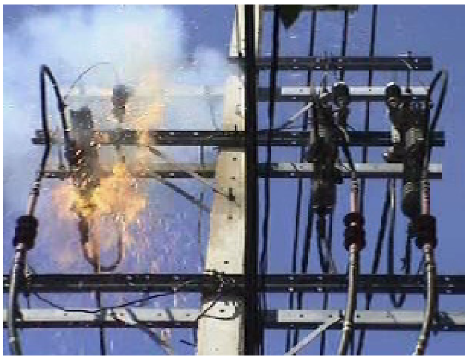

Fig. 7. A photograph during arrester failure of phase R

IV. ATP/EMTP SIMULATIONS

To confirm the causes of these problems, the computer simulations with ATP/EMTP program were performed. Moreover, the model was also applied for analyzing the effects of circuit parameters and determining the solutions.

A. Modeling

For a study on ferroresonance, the transformer model is the most important component to correctly obtain the results. Refer to ATPDraw version 4.0 p2, the linear elements of transformer were be represented by using the three phase general saturable transformer model (SatTrafo) with the Dyn1 vector connection [13]. The external delta-connected nonlinear current-dependent inductors with hysteresis (Hevia98) were added to SatTrafo on the high voltage side in order to represent the saturable cores of transformer. For the V-I magnetization curve, it is not normally the technical data in type tests and difficult to obtain from the experiments. Therefore, it was reasonably approximated to the nonlinear characteristic of the grain oriented steel by exactly fitting the rated voltage with the designed maximum flux density on the curve. Furthermore, the zero sequence reluctance of air-return path was considered, as stated in [14].

For other components, the overhead lines and cables were lumped as a pie model which was built by the line/cable module in the program. Because, ferroresonant phenomenon is a kind of the slow transients, the three phases metal oxide varistor (MOV) model without the high frequency components were used. The customer loads were included at the middle point of the overhead lines. Fig. 8 shows the ATP/EMTP schematic diagram of case study.

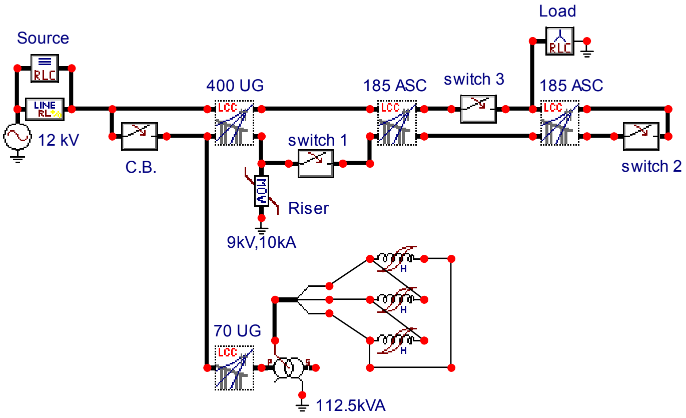

Fig. 8. ATP/EMTP schematic diagram of case study

B. Simulation Results

First of all, the ATP model was validated by comparing with the test results in the same switching conditions. The simulation results showed a good agreement with the test results about ferroresonant phenomena. The chaotic and the 3rd sub-harmonic waveform could be produced in the simulations as found in the field tests. Fig. 9 and Fig. 10 show the instances of the simulation waveforms in the same conditions as Fig.3 and Fig. 4, respectively. It is difficult to exactly obtain the same waveforms as the field tests because of the inaccurate input data and the effects of time step. The later has sensitive and random effects on the waveform and peak of overvoltages.

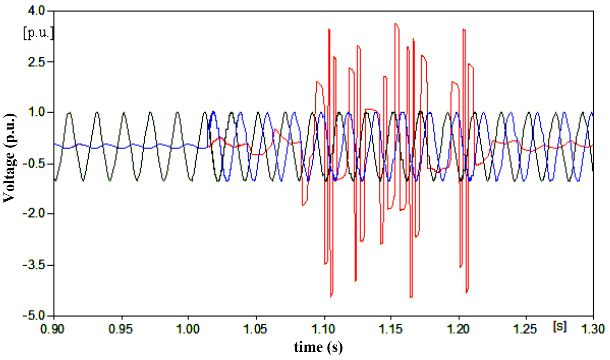

Fig. 9. Simulation waveforms in the same condition as Fig. 3

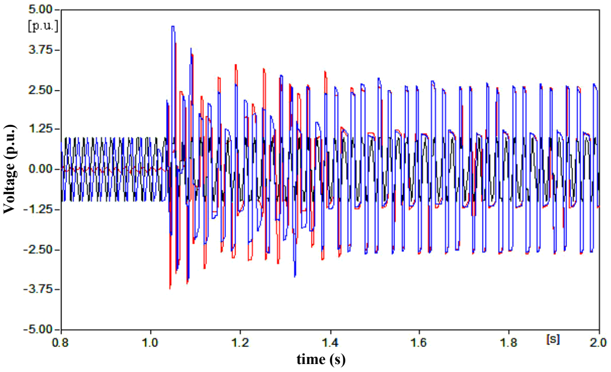

Fig. 10. Simulation waveforms in the same conditions as Fig. 4

In the case of arrester installation, the spike overvoltage could be simulated as shown in Fig. 11. The peak voltage of nearly 1.50 per unit is close to the results of field tests.

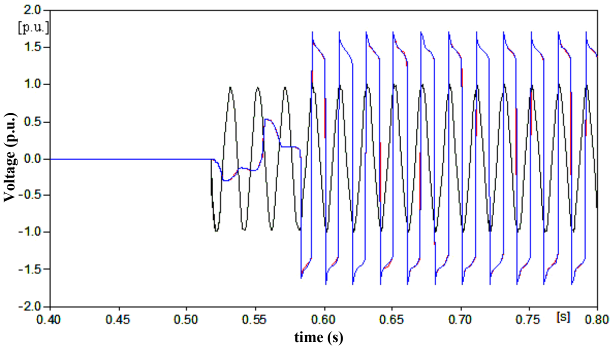

Fig.11. Simulation waveforms in the same condition as Fig. 5

Then, the Pocket Calculator Varies Parameters (PCVP) is used for an automatic variation to study the effects of point on wave of switching. The point on wave when switching or switching angle was varied between 0 and 350 deg on a sinusoidal waveform with a step of 10 deg. All procedures follow the phase sequence of switching, as detailed in Table I. The results showed that the point on wave of switching had significant effects on ferroresonant occurrence. Fig 12 shows an example of the effect of closing angle. Phase Y is closed, while phases R and B are still opened. It can be seen that the switching overvoltage appears on phase Y is maximum when closing at 90 deg, which is the crest of voltage. Its peak value is less than 2.0 per unit. On the other hand, the ferroresonant overvoltages appear on opening phases R and B when closing at angle ranges near the zero crossing point of the voltage. This result is supported by the field test that ferroresonance did not take place when closing at 256 deg.

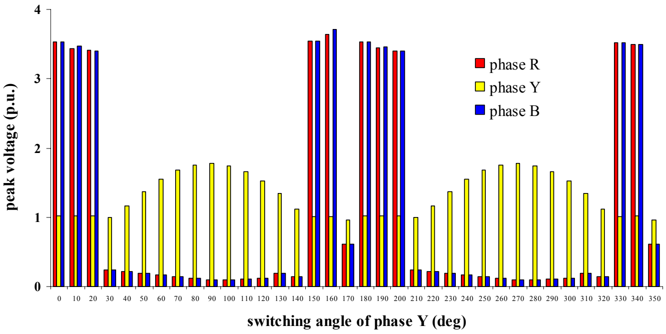

Fig. 12. Effect of point on wave of closing (phase Y)

To simply explain above results, the graphical solution of a single phase circuit, neglecting the reluctance of air-return path, was plotted. There are three intersections between the capacitive linear line and the saturable curve. So, when the circuit is energized near zero crossing point and has no residual flux, a magnetic flux in the core will be driven to the saturation area. This area is above knee point and it is the unstable point, resulting in the divergent oscillation of flux and the jump behavior. In this condition, the chaotic transient oscillation will be produced and changed to the stable states which can maintain until next disturbance. These situations can be observed from the lead-lag conditions and the magnitude comparison of capacitive and inductive voltages.

V. RISER POLE ARRESTER FAILURE

According to field tests and simulations, ferroresonant overvoltages can cause arrester operation. The operating point of the arrester depends on its V-I characteristic curve, which is strongly temperature dependent, and the strength of source. Ferroresonance is a kind of overvoltage phenomena which has high equivalent impedance (weak source). So, when the riser pole arrester is shunted to the capacitive element of the underground cable, the maximum operating point of the arrester is near the knee point on V-I characteristic curve. It is in the region of low resistive current. From the simulation, the peak of discharge current is just about 8.5 A. It is not high enough to detonate the ground lead disconnector.

Although, the riser pole arrester is designed for suffering the high impulse current, it can not withstand the temporary overvoltage (TOV) existing in a long time. When the arrester conducts ferroresonant current, a heat generated in a ZnO block will transfer through the cover materials and the polymer housing to the environment. The thermal energy may accumulate in the arrester, if a rate of heat transfer to surrounding is less than a rate of ZnO power dissipation. Refer to the field test results, the explosion of riser pole arrester during ferroresonant sustention was not observed. This event shows that the riser pole arrester could keep a thermal stability. However, its temperature is gradually increased. After the last phase switch is closed, the high temperature arrester is directly connected to the system source which has low equivalent impedance (stiff source). Then, the discharge current is quickly increased, until a thermal runaway occurs. As a result, the riser pole arrester explodes, or its housing is ruptured. The ground lead disconnector and pressure relief operate.

VI. PRACTICAL SOLUTIONS

To avoid and mitigate the explosive problem, several countermeasures were practically and financially considered. Two solutions, the alternation of switching procedures and the application of a resistive load, were studied by using the simulations and the field tests.

A. Alternation of Switching Procedures

As shown in Fig. 1, if the circuit breaker is in the closed circuit condition, ferroresonance can not occur during the operations of disconnector switches. Because all phase of the underground cables and the station service transformer are still in energetic condition with bus system voltage. Therefore, the switching order is alternated between the circuit breaker and the disconnector switch. This solution was verified by the field tests and the simulations. They show good results. This solution is convenience and no cost.

B. Application of a resistive load

To mitigate ferroresonant overvoltages, the application of a resistive load to the secondary side of the transformer was considered. Because resistive components in the circuit can limit an operative region of ferroresonance. For this study case, the simulation results showed that ferroresonant overvoltages no longer appear when the resistive load is more than 1% of the power rating of the transformer.

VII. CONCLUSIONS

The explosive problem of riser pole arresters during the operations of disconnector switches were studied by using field tests and computer simulations. It can be summarized as follows:

1. Ferroresonance involving the station service transformer and the underground cables can occur on the opened phases during asymmetrically switching of disconnector switches with the appropriate conditions.
2. The chaotic and the 3rd sub-harmonic overvoltages appear in case of switching without arrester installation. On the other hand, the restricted overvoltages in fundamental mode appear, when riser pole arresters are installed.
3. The point on wave of switching has significant effects on ferroresonant occurrence.
4. The arrester on the last closed phase explodes because it suffers ferroresonant overvoltages for a long time.
5. The alternation of switching order or the application of a resistive load to the secondary side of the transformer can suppress ferroresonant overvoltages.

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IX. BIOGRAPHIES

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