Analysis of lightning-caused ferroresonance in Capacitor Voltage Transformer (CVT)

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Abstract

Power networks contain capacitances and inductances that can saturate, presenting opportunities for ferroresonance to occur. Most power equipment is designed through linear theory but ferromagnetic materials are highly non-linear and when they resonate, the non-linearity produces currents and voltages that are larger than usual. Ferroresonance is a complex, non-linear electrical phenomenon. It can cause dielectric and thermal problems through overvoltage, an intrinsic phenomenon present in all networks. A network dynamic response to lightning and switching will be energy storage and release. The transfer of energy will propagate an overvoltage through the network and damage substation equipment when lightning strikes near the substation. Application of conventional mathematics is inappropriate to ferroresonance study in which actual events are simulated. Lightning strikes that occurred near a substation and that led to explosion of CVTs have been reported, so this study investigates the effect of a lightning strike on a tower with a 132 kV Capacitor Voltage Transformer (CVT). Alternative Transient Program (ATP) was used for the simulation which duplicated the lightning-strike effect that causes a CVT to explode.

1. Introduction

Capacitive voltage transformers are predominant sources of voltage signals for monitoring, protection and control applications at transmission level. High-speed protective relays are expected to make decisions based on signal produced by CVT, to preserve system stability and minimize damage to equipment. There have been recent reports in Malaysia on CVT failures and explosions at substations. They are:

(1) No output on the secondary side of the transformer.
(2) Hot spot on CVT main tank detected through thermo vision.
(3) CVT explosions.

Owing to energy stored in the capacitive, inductive and non-linear components of the CVT, under transient conditions the CVT may not follow closely its input waveform. A redistribution of the electric and the magnetic energies cannot occur instantly and the power system must go through a transient state before a new steady-state condition occurs.

Proper design of CVT components will ensure that under steady-state condition, the required output duplicates the input. During transients, CVT’s energy-storage element and magnetic-saturation non-linearity however causes its output waveform to deviate from its input waveform. CVT ferroresonance during transients may cause thermal overstress, consequently deteriorating CVT components through over-voltage.

Application of conventional mathematics is not appropriate in studying ferroresonance [1] because analysis of the characteristic forced non-linear differential equations results in considerably complex algebraic equations. A ferroresonance study simulates actual events.

This paper investigates the effect of lightning on a 132 kV tower near the substation where several CVT explosions had been reported. Over-voltages induced in the phase conductor caused by strikes close to ground may happen too but they generally are below 200 kV and matter only to lower voltage systems. In Malaysia the minimum transmission voltage is 132 kV and its minimum BIL is 650 kV.

Owing to this and also to Malaysia’s lightning current being typically more than 20 kA (up to the maximum 200 kA) the simulation thus investigates the actual CVT explosions that had occurred at the substation due to lightning.

2. Lightning strike and ferroresonance

2.1. Lightning strike

Peninsular Malaysia experiences frequent lightning strikes, regarded to be among the highest in the world with thunder-days averaging 200 according to the Malaysian Meteorological Department. Lightning occurrences vary with month, occurring frequently from April to June, and less so from December to
February. Lightning also varies with time of day, peaking from 1700 to 1800 h, with 34.5 kilo amperes (kA) mean discharge current [2].

Types of flashovers occurring when lightning hits transmission lines are back flashover and shielding failure. Back flashover occurs when lightning strikes tower and the resultant voltage across the insulator is large enough to cause flashover from tower to line conductors. Shielding failure occurs when lightning strikes conductor. Magnitude of current shielding failure is 20 kA or less. Since mean current is higher than 20 kA, the simulation considers back flashover only.

### 2.2. Ferroresonance

Ferroresonance are non-linear dynamic systems and as such their behaviour can be analysed using tools available in chaos theory. Four basic types of ferroresonance have been indentified such as fundamental frequency mode, subharmonic mode, where the period of oscillation is an integral multiple of the period of the supply system, quasi-periodic mode and chaotic mode ferroresonance in which the oscillations appear to be random [3]. In this study, ferroresonance due to lightning is of fundamental mode ferroresonance type.

For a ferroresonance to occur, a series LC circuit is excited at or near its natural frequency. A transformer inductance and a system capacitance may sometimes be placed in series. Ferroresonance occurs when components in the series circuit reach critical values. System voltage may surpass rated values, leading to equipment damage or failure.

Ferroresonance modes have various physical and electrical displays. Some have very high voltages and currents, while others have voltages close to normal. There might have been or might not have been ferroresonance failures, so in many cases whether or not ferroresonance had occurred is difficult to know, unless there had been witnesses or fault-recording instruments. Conditions considered causes of ferroresonance.

#### 2.2.1. Switching

Switching transient in power systems have always been of concern in studies of power-equipment insulation coordination. They are commonly caused by arcing faults and static discharge. Also major power-system switching disturbances initiated by utilities to correct line problems may happen several times a day. These trigger ferroresonance inside the power system and the equipment. Fig. 1 shows the voltage waveform through ATP simulation, ferroresonance that had been caused by switching transient.

In this figure, the ferroresonance occurs after the fault clearing time at 0.9 s for several cycles before it becomes stabilized.

#### 2.2.2. Lightning strike

Direct lightning strike on a structure, could cause it to catch fire and severely damage electronic, electrical and even mechanical
equipment. Lightning strikes are common sources of over-voltage, which also can trigger ferroresonance inside equipment or power system. Fig. 2 shows the voltage waveform through ATP simulation, ferroresonance due to lightning strike.

3. Simulation by using ATP

Current study is on ferroresonance due to lightning strikes near the substation [4]. Fig. 3 shows a typical layout of the substation.
The arrangement for the CVT that is the focus of this research is its location which is after the lightning arrester and before the transformer.

There are several current-surge models, but the Heidler surge model was chosen. This is due to the fact that the Heidler lightning model is a channel-base current which permits easy modelling of usually measured lightning current quantities at strike point: current peak, current rise time, maximum of current steepness and the charge transfer.

The Bergeron tower model was considered because the overhead transmission line is modelled on frequency dependent (Phase) model, which uses curve fitting to duplicate the frequency response of a line or a cable. The Bergeron model is based on distributed LC parameter travelling wave-line, with lumped resistance. It represents in a distributed manner the L and the C elements of a PI Section and it also roughly equals use of an infinite number of PI Sections except that the resistance is lumped (1/2 in the middle of the line, 1/4 at each end).

The CVT model uses a voltage-controlled switch as available in the ATPDraw. The CVT model consists of coupling capacitor, compensating reactor, step-down transformer and ferroresonance-suppression circuit. The ferroresonance circuit is a resistor–inductor series circuit, which is normal ferroresonance-suppression circuit. A typical 132 kV model is shown in Fig. 4.

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A typical 132 kV model is shown in Fig. 4.

Table 1

<table>
<thead>
<tr>
<th>Description</th>
<th>Parameters</th>
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<tbody>
<tr>
<td>System voltage</td>
<td>132 kV</td>
</tr>
<tr>
<td>Frequency</td>
<td>50 Hz</td>
</tr>
<tr>
<td>Capacitive voltage divider</td>
<td>C1 = 5348.8 PF, C2 = 76666.6 PF, Ce = 5000 PF</td>
</tr>
<tr>
<td>Drain coil [LD]</td>
<td>10 mH</td>
</tr>
<tr>
<td>Step down transformer (SDT)</td>
<td>Rpr = 220 Ω, Lpr = 1.745 H, Rmt = 6500000 Ω, Lmt = 8841 H, R1a–1n = 0.007 mH, Trans. ratio n = 78.74</td>
</tr>
<tr>
<td>Compensating series reactor (SR)</td>
<td>RpSR = 220 Ω, LpSR = 1.745 H, RsSR = 6500000 Ω, LsSR = 8841 H, Rsr = 0.04 Ω, Lmr = 0.007 mH</td>
</tr>
<tr>
<td>Note: the reactor considered as an autotransformer having N1 [primary turns] 6160 and N2 [secondary turns] 220</td>
<td></td>
</tr>
<tr>
<td>Ferroresonance suppression filter (FSF)</td>
<td>Lf = 4.62 H, Rf = 12.3 Ω</td>
</tr>
<tr>
<td>Stabilizing burden (Rsb)</td>
<td>75 Ω</td>
</tr>
<tr>
<td>Series gap resistance (Rgap)</td>
<td>11.2 Ω</td>
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<tr>
<td>Gap firing voltage</td>
<td>250 V</td>
</tr>
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Table 2

<table>
<thead>
<tr>
<th>Type of FSC</th>
<th>Ferroresonance cycle</th>
<th>Peak voltage value (V)</th>
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<tbody>
<tr>
<td>Normal filter</td>
<td>12</td>
<td>318.6</td>
</tr>
<tr>
<td>Active filter</td>
<td>12</td>
<td>260.81</td>
</tr>
<tr>
<td>Passive filter</td>
<td>11</td>
<td>252.43</td>
</tr>
</tbody>
</table>

Fig. 9. Simulation of 34.5 kA lightning strike.
4. Results and discussion

Simulations done to predict and mitigate the ferroresonance were:

(i) Ferroresonance suppression circuit (FSC).
(ii) Various magnitudes of lightning current.
(iii) Improvement to overvoltage protection device.

Fig. 5 shows a normal filter used in the CVT is usually a resistor in series with an inductor. Active and passive filters were also used in the simulations. A 34.5 kA current, the mean value injected between the second and the third spans of the substation’s transmission tower as an injection towards the first tower near the substation is considered a direct hit to the CVT. The simulation result is as shown in Fig. 6 for normal filter, Fig. 7 for active filter.

<table>
<thead>
<tr>
<th>Spark gap improvement</th>
<th>Ferroresonance cycle</th>
<th>Peak voltage value (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without improvement</td>
<td>15</td>
<td>11728</td>
</tr>
<tr>
<td>Series resistor</td>
<td>14</td>
<td>11715</td>
</tr>
<tr>
<td>Parallel resistor</td>
<td>2</td>
<td>27</td>
</tr>
<tr>
<td>Parallel resistor and capacitor</td>
<td>7</td>
<td>125</td>
</tr>
</tbody>
</table>

Table 3
Results of ferroresonance oscillation due to spark gap improvement.

Fig. 10. Simulation of 100 kA lightning-strike.

Fig. 11. Simulation of 200 kA lightning strike.

Fig. 12. Waveform at the overvoltage protection device for 200 kA, without spark-gap improvement.

Fig. 13. Waveform at the overvoltage protection device for 200 kA, with 40 Ω series resistor.

Fig. 14. Waveform at the overvoltage protection device for 200 kA, resistor parallel with spark gap.

Fig. 15. Waveform at the overvoltage protection device for 200 kA, resistor series with capacitor and parallel with spark gap.
and Fig. 8 for passive filter respectively. Table 1 shows the data description of the CVT diagram.

The results of ferroresonance oscillation of FSC type in Table 2 show that the oscillation of the lightning strike improved by one cycle from 12 cycles to 11 cycles when passive filter is used [5]. Figs. 9–11 simulate 34.5 kA (the mean value), 100 kA and 200 kA respectively. These values are lightning magnitudes recorded in Malaysia. The results also show that the higher the magnitude, the more severe the ferroresonance.

Figs. 12–15 show the waveform taken from the overvoltage protection device of the CVT system which is located at the primary side of the CVT system. The waveform shows the result of re-model spark gap system by putting a passive element of RLC.

As for the overvoltage protection device, the previous design is just a spark gap. A suggested improvement is for a 40 Ω resistor to be inserted in series with the spark gap resulting in slight improvement from 15 cycles to 14 cycles as shown in Table 3. A parallel resistor with spark gap would improve the oscillation to two cycles, however oscillation still persist. A design proposed in this study is for the resistor in series with a spark gap to be replaced by parallel connection of a 5 Ω resistor in series with a 47 μF capacitor. The improvement is from 15 cycles to 7 cycles. Of three designs, the one that mitigated ferroresonance and also the oscillation was the design proposed.

5. Conclusions

This paper presents dynamic simulations of ATP/EMTP that analysed the contribution of lightning-caused ferroresonance to the CVT explosions in Malaysia. The following are concluded:

(i) A lightning strike can cause ferroresonance in a CVT.
(ii) The primary side of the CVT is most severely affected.
(iii) To mitigate ferroresonance on the primary side, an improved overvoltage protection device can be considered. Presently the overvoltage circuit uses spark gap. The addition of a resistor does not fully mitigate ferroresonance.
(iv) A new design proposed for the overvoltage protection device is for the spark gap to be parallel with the resistor and in series with the capacitor. Ferroresonance and its oscillation can then be mitigated.

This study shows that CVT components matter to CVT’s transient response. A CVT properly designed for a particular power system will enhance performance and eliminate expensive equipment failure caused by ferroresonance.

References