Over-Voltage Prevention Solutions for 220 kV Distribution Substation to Enhance Power System Stability: A Case Study in Vietnamese Power System

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Abstract
This paper proposes the solutions to prevent over-voltage for the 220 kV distribution substations with several different voltage levels. The motivation comes from the failures of surge arrester number 2 of phase B at the transformer number 2 (CS2BAT2) of the Vietnamese 220 kV Thainguyen substation due to the over-voltage. The main objective is to enhance the operating stability of a scattered connected power network between substations. The Vietnamese 220 kV Thainguyen substation has the complexity structure, operates on three voltage levels of 220/110/35/22 kV, and connects the Chinese 220 kV Malutang. During the operating period, the operating voltage at the 220 kV bus is equal to 1.15 p.u.. This high voltage will put the transformer into magnetic saturation, so that the CS2BAT2 has been faced with serious failures. This paper proposes the solutions for preventing over-voltage located CS2BAT2 to enhance the Thainguyen substation stability. These proposed solutions are developed from the operating ideas based on the flexibility in instantaneously changing the system configuration. The effectiveness of the proposed solutions are confirmed by the simulation results based on (i) using Electromagnetic Transients Program-Restructured Version (EMTP-RV) to calculate and re-analyze the practical event at 0 : 12 AM on June 17, 2015, (ii) comparing the obtained results between the use of EMTP-RV and the recorded relay, on those bases to continue making other necessary case. It was observed that the proposed solutions could apply to immediately solve the difficulties encountering in the Vietnamese 220 kV Thainguyen substation.

Keywords: Surge arrester (SA), over-voltage, Vietnamese system, 220kV distribution substation, Electromagnetic Transients Program-Restructured Version (EMTP-RV)

INTRODUCTION
In early days, the demand to the electric energy is little, so that the small power station was built to supply the heating and lighting loads. However, when the social, political, and technological aspects develop, the demand of electricity power grows rapidly, resulting in building big power station at favorable places. The long transmission distances over weak grids, highly variable generation patterns, and heavy load, resulting in the increase of the scale and complexity of power systems and the large network of conductors between the power station and the consumers, continuously face the disturbances like sudden change in load, sudden thrown of load, transient, switching etc. [1]

The distribution substation is an important electrical part for the electric power supply system used to transfer the electric power from the transmission system to the distribution system of an area. In a scattered connected power network between substations, the series inductances and shunt capacitances long the long transmission lines can cause significant voltage variations between high and low load periods [2]. When the transmission line is loaded below the surge impedance load, the line experiences a voltage rise due to the natural shunt capacitance drawing charging current through the series inductance [3], leading to the bus at receiving-end also experiences a voltage rise. During the periods of light loading on the transmission line, the bus at receiving-end happen over-voltage. Moreover, the over-voltage caused by lightning or switching surges [4].

Over the years, there has been a growing concern about the issue of over-voltage for distribution substation [5]. The over-voltages can be classified as the transient over-voltage, harmonic resonance over-voltage, over-voltage resulting from ferro-resonance, and sustained over-voltage, in which the transient over-voltage is an outcome of witching operations on the long transmission line or the capacitive devices, and may result in the surge arrester failures, leading to the damage of transformers and other power system equipments [6–8]. As well as preventing damage to the equipments in substation due to fault current, the over-voltage protection is also necessary to ensure that, the excessive voltage do not cause damage or lead to unnecessary outages.

In recent years, the economic tempo in the Vietnam has been developed rapidly; the total load has increased continuously. Therefore, the Vietnamese power system has been faced with the serious power system blackouts, such as on Dec. 27, 2006; July 20, 2007; Apr. 09, 2007; and the latest event on May 22, 2013 [9]. Therefore, this study proposes the solutions to prevent over-voltage for the Vietnam 220 kV Thainguyen substation to project the equipments as the surge arrester, transformers, and so on and to enhance the system stability. The motivation comes from the failures of surge arrester number 2 of phase B at the transformer number 2 (CS2BAT2) (denoted the red symbol in Figure 1) of the Vietnamese 220
kv Thainguyen substation due to the transient over-voltage. The substation has complexity structure, operates on several different voltage levels of 220/110/35/22 kV with the total capacity of 626 MVA, placed at Quangtrieu, Thainguyen urban area, playing an important role in the electric distribution and transmission of the North area. It is received the electrical power from the several different substations through the long transmission lines and most notably the line connects between Malutang substation of China and Thainguyen substation of Vietnam, as shown Figures 1 and 6.

During the operating period, the recorded results from relay is provided by Power Transmission Company 1 (PTC1), the operating voltage at the 220 kV bus is equal to 1.15 p.u.. This high voltage will put the transformer into magnetic saturation [10], causing core heating and harmonic current. SA called upon to operate at excessive sustained energy during periods of high voltage will have reduced tripping capability [11]. However, for the Vietnamese 220 kV Thainguyen substation, the CS2BAT2 has been faced with serious failures, such as on April 22, 2012; July 17, 2014; and June 17, 2015. Typically, the event is at 0 : 12 AM on June 17, 2015, the damage has occurred on the CS2BAT2, the voltage and current at the bus C22 before and after producing the fault are plotted in Figures 10 and 11, resulting in the broken CS2BAT2. The scene after fault shows in Figure 2.

The 220 kV bus of Thainguyen substation is connected to the Chinese Malutang substation through transmission line between Thainguyen and Malutang (Thainguyen-Malutang) about 347.9 km. During the operating period, the sending-end voltage (220 kV bus of Malutang substation) is not controlled despite the operating structure at Thainguyen substation. In addition, the line Thainguyen-Malutang can cause significant voltage variations between high and low load periods. It can be realized that the main case occurs this damage due to the over-voltage bus at receiving-end (220 kV bus of Thainguyen substation) due to the system that receives power from the Malutang station.

In this paper, solutions for preventing over-voltage of CS2BAT2 are proposed to enhance the 220 kV Thainguyen substation stability. These proposed solutions are developed from the operating ideas based on the flexibility in instantaneously changing the system configuration. The effectiveness of the proposed solutions are confirmed by the simulation results based on (i) using Electromagnetic Transients Program-Restructured Version (EMTP-RV) to calculate and re-analyze the practical event at 0:12 AM on June 17, 2015, (ii) comparing the obtained results between the use of EMTP-RV and the recorded relay, on those bases to continue making other necessary case study. The main new contributions of this paper is to propose an optimal solution for preventing over-voltage of the 220 kV substation that receives the power from two different countries.

The remaining part of this paper is organized as follows: Section 2 presents the description and modeling of main components used in the work described in the paper. The case simulation and impacts analysis when producing the danger to SA are described in Section 3 and 4, respectively. Section 5 proposes the solutions for preventing the over-voltage of SA. Lastly, the conclusions are presented in Section 6.

Figure 1: One Line Diagram of the Vietnamese 220 kV Thainguyen substation.
DESCRIPTION AND MODELING FOR MAIN COMPONENTS OF POWER SYSTEM

Substation structure

The 220 kV Thainguyen substation consists of two automatic transformers (AT) of 250/250/85 MVA-220/110/22 kV, two transformers (T) of 63/63/63 MVA-110/35/22 kV, seven feeders (switching bays) of 220 kV, fourteen switching bays of 22 kV, a 220 kV series capacitor unit with fixed series compensation (FSC) of 35-Ohm, and a static var compensator (SVC) of \( \pm 50 \) MVAR. The one line diagram and location of substations are shown in Figures 1 and 3, respectively.

Surge arrester

The over-voltage protection to high voltage network is performed by the combination of several different devices, in which SA is a protective equipment placed at the electrical station to protect the equipment against over-voltage caused by the lightning and switching surge and alternating current (AC) voltages [12–13], as shown in Figure 1. The SA has two types, the first one is the resistor element made of the silicon-carbide (SiC); there contains the air gap in the SiC. Another one is the non-linear resistor element made of the metal-oxide (MO); there is no air gap in the MO. Nowadays, the SAs with the MO is selected to install into the electrical power system to be more than the SiC because of the its highly non-linear voltage-current (V-I) characteristic [13]. MO surge arresters are used to protect the medium- and high-voltage system and the insulation of equipment against over-voltage [14]. SAs are often subjected to the high-voltage stresses because of the high earth resistance of the grid grounding system. Assessment of the dynamic characteristic of MO surge arrester under such over-voltage stresses to be therefore an important aspect of insulation coordination [15–16].

For the 220 kV Thainguyen substation, the MO surge arrester PEXLIM Q192-XH245 [17] is used and placed at CS2AT2 location having the voltage-current (V-I) characteristic [18] and temporary over-voltage (TOV) strength factor, as shown in Figure 4a and the parameters are listed in Table 1[17].

For using this AS, the highest energy absorption capability of SA at the TOV condition is about 4.5 kJ/ kV, as shown in Figure 4b. Therefore, the highest absorption energy of the surge arrester PEXLIM Q192-XH245 is 0.864 MJ at the TOV's endured time of 17 minutes and this absorption energy after enduring the over-voltage time of 28 hours is equal to 0.8 MJ.

### Table 1. Parameters of surge arrester PEXLIM Q192

<table>
<thead>
<tr>
<th>Max. system voltage</th>
<th>Rated voltage</th>
<th>Max. continuous operating voltage</th>
<th>TOV capability</th>
<th>Max. residual voltage with current wave</th>
</tr>
</thead>
<tbody>
<tr>
<td>Um</td>
<td>Ur</td>
<td>Uc</td>
<td>MCOV</td>
<td>30/60 ( \mu ) s</td>
</tr>
<tr>
<td>kV</td>
<td>kV</td>
<td>kV</td>
<td>kV</td>
<td>kV</td>
</tr>
<tr>
<td>245</td>
<td>192</td>
<td>154</td>
<td>220</td>
<td>211</td>
</tr>
</tbody>
</table>
Transformer

The over-voltage will cause the magnetic saturation of transformer [10], leading to this serious damage for the equipments in substation. The Thainguyen substation has four transformer, in which two 250 MVA-220/110/22 kV automatic transformers; group of winding Y_0\text{-}\Delta-11; short-circuit voltage \( U_{\text{HV-Ter}} \) of 10.27, \( U_{\text{LV}} \) of 30.53\%, and \( U_{\text{Ter-LV}} \) of 17.9\% at the temperature 75\^\circ C; no load loss of 57,797 kW; and another two 63 MVA-110/35/22 kV transformers; group of winding Y_0\text{-}\Delta-11/Y_0; short-circuit voltage \( U_{\text{HV-Ter}} \) of 11, \( U_{\text{HV-LV}} \) of 34.8\%, and \( U_{\text{Ter-LV}} \) of 21.6\% at the temperature 75\^\circ C; no load loss of 45 kW. The equivalent “T” of transformers shown in Figure 5a; in which, for 250 MVA, the impedances are \( Z_{\text{HV}} \) of \( 0.2 + j10.9 \) Ohm, \( Z_{\text{LV}} \) of \( 0.2 + j14.1 \) Ohm, and \( Z_{\text{Ter}} \) of \( 0.2 + j15.2 \) Ohm; and for 63 MVA, the impedances are \( Z_{\text{HV}} \) of \( 1.57 + j103 \) Ohm, \( Z_{\text{LV}} \) of 1.11 – \( j10 \) Ohm, and \( Z_{\text{Ter}} \) of 6.69 + \( j191 \) Ohm. Figure 5b plots the saturation characteristic. The transformers are modeled using EMTP-RV.

Static Var Compensator

The SVC is one of the most notable series of the FACTS devices. The basis control scheme is designed on the basis of the quick an reliable means of exchanging capacitive and/or inductive to regulate the voltage, control reactive power, and dampen oscillation [19]. In this paper, SVC can be installed at the buses to maintain and/or control particular parameters of the electrical power system by exchanging capacitive and/or inductive current. As seen in Figure 1, A 50 MVA SVC, including of a thyristor controller reactor (TCR) unit of -108 MVAr and three harmonic filter units of the frequencies 3\text{rd}, 5\text{th}, and 7\text{th} having the reactive powers 26 MVAr, 19 MVAr, and 15 MVAr, respectively, is placed at bus C46 of Thainguyen substation. For this proper, the dynamic and transient stability will be enhanced. The TCR provides continuously controllable lagging VARs [20]. The harmonic filters are used to filter the frequencies 3\text{rd}, 5\text{th}, and 7\text{th} and to prove the reactive power. The modeling of SVC control is modeled by EMTP-RV, as shown in Figure 6a. The voltage-current characteristics of a SVC are shown in Figure 6b, describing the variation between the voltage and current or reactive of the installed SVC bus.
transmission line with another one. The lines Malutang-Hagiang, Hagiang-TDTuyenquang and Hagiang-Baccan used the aluminum conductor steel reinforced (ASCR)400/51 and 2xASCR 330/41 types [21]. The line TDTuyenquang Tuyenquang used 2xASCR 330/43 and transposed. The line Tuyenquang-Thainguyen did not transposed. The tower structure of the transmission line shows in Figure 6b.

Transmission tower is modeled in EMTP-RV using philosophy of lossless line, in this loss line model each section of tower in represented with a calculated surge impedance and transmission line is modeled with a frequency dependent J marti model based on the geometrical data of the tower, the surge impedance, and the insulator details. In addition, the earth resistance of the tower was approximated with a current depending relation. The resistance and inductance of the positive sequence are constant up to approximately 1.0 kHz that cover the frequency range of harmonic over-voltage phenomena.

**SIMULATION**

The simulation cases are reported in this section to illustrate the suitability of the obtained results of using EMTP-RV software compared to that of actual relay. These actual results provided by the Operation Unit. Here the result is represented as four figures, (i) Normal condition (Figures 8 and 9) and (ii) Transient condition (Figures 10 and 11). The representation of figures are shown below:

*Under Normal Condition* This simulation was done on the normal condition. Three phase voltages at the bus CC22 and three phase currents on circuit breaker 272 using AMTP-RV are shown in Figure 8, whereas that are recorded by Relay as shown Figure 9.

*Under Transient Condition* This simulation was done on the fault development at 0:12 AM on 17 Dec., 2016, this damage resulted in opening circuit breaker 232. This fault represents below: (i) The SVC is outage after time 0.3 sec. (ii) The circuit breaker 171 is opened after time 0.5 sec, resulting with the interruption of loads at bus 110 kV, so that the transformer AT2 operated no load. (iii) The circuit breaker 232 will be opened when the CS2BAT operates the energy over its rated energy, in other words, the CS2BAT is broken.

Figure 10 plots three phase voltages at the bus CC22 and three phase currents on circuit breaker 272 using AMTP-RV, whereas figure 11 plots that using the recorded Relay.

Observing the obtained results from using EMTP-RV analyses and the recorded Relay in Figures 8–11, their effectiveness seems to be similar all over the time. Therefore, we can be concluded that the model, simulation, and analyses, using EMTP-RV software, have reasonable grounds for making next steps.
Figure 12 plots the highest energy absorption capability of some of surge arresters in the station. Observing from figures, it can be shown that the energy in phase B of surge arrester CS2AT2 is higher than its other two phases and the surge arresters at locations of lines and buses.

As simulated result in Figure 12a, the energy absorption capability in phase B of surge arrester CS2AT2 at started surges is equal to 0.238 MJ. This energy continues to increase and reaches a value 0.88 MJ at time 17 sec, whereas the highest energy absorption capability of the surge arrester PEXLIM Q192-XH245 is 0.886 MJ, according to the TOV’s endured time of 5 minutes. Therefore, this phase B of surge arrester CS2AT2 is broken after 5 minutes.

Figure 7: The 220 kV line from Malutang to Thainguyen: (a) the block diagram of transposing line; and (b) the tower base mounting detail.

Figure 8: Test result under normal condition using EMTP-RV: (a) three phase voltages at the bus C22; and (b) three phase currents on circuit breaker 272.
Figure 9: Recorded result of Relay under normal condition: (a) three phase voltages at the bus C22; and (b) three phase currents on circuit breaker 272.

Figure 10: Test result under transient condition using EMTP-RV: (a) three phase voltages at the bus C22; (b) three phase currents on circuit breaker C272.

Figure 11: Recorded result of Relay under transient condition: (a) three phase voltages at the bus C22; (b) three phase currents on circuit breaker 272.

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Figure 12: Energy absorption capability of some surge arresters in the station: (a) CS2AT2; (b) CSC22; and (c) CS272.

Figure 13: The 3rd harmonic: (a) voltage at bus 220 kV; and (b) Current in transformer AT2.

ANALYSIS

Considering the conductor

The 220 kV line connects between Chinese Malutang and Vietnamese Thainguyen substations, denoted the pink trace, as shown in Figure 6, having total length 347.9 km. When this line is loaded, the voltage at bus 220 kV of Thainguyen substation is high because of generating large reactive power, as shown in Figure 11c, the phase B voltage is 257.2 kV after opening the 110 kV load. This over-voltage will cause the magnetic saturation of transformer [10]. Why did only the phase B of surge arrester CS2AT2 break, it may be explained as follows:

The 220 kV transmission line from Malutang to Thainguyen station mounted on the supporting structure of the transmission line with another transmission line, in other words, it is dual circuit line system, as shown in Figure 7, in which a part line from Hagiang to Thainguyen station was not transposed for a cycle. Therefore, the operating voltage between phases is difference [22–25].

Considering the capacitance

For the transposed lines, based on Figure 14a, the conductor capacitance per phase can be calculated as follows [22]:

\[
C = C_s + 3C_m,
\]

where \(C_s\) is the phase-to-ground capacitance, and can be calculated as:

\[
C_s = \frac{0.02413}{\log_{10} \frac{8h^3}{r_{eff} s_{ll}}},
\]

and \(C_m\) is the phase-to-phase capacitance and it can be calculated as:

\[
C_m = \frac{0.02413}{\log_{10} \frac{8h^3}{r_{eff} s_{ll}}} \frac{2h^3}{\log_{10} \frac{8h^3}{r_{eff} s_{ll}}} \frac{s_{ll}}{r_{eff}},
\]

in which \(s_{ll}\) is the averaged phase-to-phase distance, \(h\) is the average height to ground, \(r_{eff}\) is the equivalent radius in case of the multi-bundled conductor lines, \(n\) is the radius of conductor, and \(w\) is the geometrical averaged distance of bundled conductors.
The reactive power to each phase can be calculated as [23]:

\[ Q = |U_1|^2 \times B \times l \]  

(4)

where \( l \) is the conductor length, \( U_1 \) is the sending-end voltage, and \( B \) is the inductor susceptance. Note that the line susceptance is fixed and the sending-end voltage is relatively constant.

The reactive power per phase of the line Maluting-Thainguyen can be calculated using Equation (4) as follows:

\[ Q_a = 25.89 \text{ MVAr}, \]
\[ Q_b = 27.34 \text{ MVAr}, \]
\[ Q_c = 26.54 \text{ MVAr}. \]  

(5)

As obtained result in Equation (5), we can conclude that the total capacitance of phase B is higher than other two phases. Furthermore, since the phase B has a length \( 176.0 \) km compared to the total length of line \( 347.9 \) km is mounted low to ground, so that the above conclusion is satisfied and it can be verified by Eqs. (1)–(3).

Considering the conductor inductance. The self-inductance of conductor A can be calculated based on Figures 7 and 15b as follows [22,26]:

\[ L_{aa} = 0.4605 \log \left( \frac{h_a + H_a}{r_{eff}} + 0.05(1 + \frac{1}{n}) \right), \]

(6)

and the mutual inductance between conductors A and B is:

\[ L_{ab} = 0.4605 \log \left( \frac{h_a + H_a}{S_{ab}} + 0.05 \right), \]

(7)

where \( h_a \) is the distance between conductor A and ground, \( H_a \) is the distance between ground and image of conductor A, \( S_{ab} \) is the distance between conductors A and B, \( r_{eff} \) is the equivalent radius in case of the multi-bundled conductor lines \( n \) determined in Equation (3).

The inductance of conductor A, considering the mutual inductance, can be calculated as follows:

\[ L_a = L_{aa} - L_{ab}. \]

(8)

Similarly, \( L_{bb}, L_{cc}, L_{bc}, L_{ca}, L_{cb}, \) and \( L_c \) can be derived in the same way, where subscripts \( a, b \) and \( c \) denote the conductor A, B, and C, respectively.

The numerical check to the line Maluting-Thainguyen by using Eqs. (6)–(8) and considering the 110 kV load of Thainguyen station of \( S = 95 + j5 \) MVA, we have:

The total reactive power loss per phase is

\[ \Delta Q_a = 6.55 \text{ MVAr}, \]
\[ \Delta Q_b = 8.54 \text{ MVAr}, \]
\[ \Delta Q_c = 7.18 \text{ MVAr}. \]  

(9)

The total inductance of conductor per phase is

\[ L_a = 0.971 \times 10^{-3} \text{ H/km}, \]
\[ L_b = 1.265 \times 10^{-3} \text{ H/km}, \]
\[ L_c = 1.064 \times 10^{-3} \text{ H/km}. \]  

(10)

Therefore, the reactive power per phase, considering the loss, is

\[ Q_a = 19.43 \text{ MVAr}, \]
\[ Q_b = 18.80 \text{ MVAr}, \]
\[ Q_c = 19.38 \text{ MVAr}. \]  

(11)

As obtained results in Equation (11), it can be shown that the reactive power on phase B, caused by inductance of conductor when it carrying the load, is lower than compared to other two phases. So that the phase B voltage is slower than that of other two phases, leading with the phase B current is higher than that of other two phases since the powers per phase is equal.

Beside the maximum current impulse in the process of operation, the over-voltage on the phase B is high when load is lost, leading to the leakage current of this phase higher than that of other two phases. After the interruption load, the current per phase is just the magnetization current of transformer, so that the power loss per phase is no negligible, but the reactive power on phase B is higher than that on other two phases resulting from the stay capacitances, as the above-mentioned Equation (5).

Furthermore, the impact of harmonic current increases highly, resulting from the effects of the series capacitor unit of 220 kV and the magnetization current of transformer since these effects may cause the current impulse fluctuations having the great voltage amplitudes, as shown Figure 15, so that it leads to the temporary over-voltage at time after disconnecting the 110 kV load.

Figure 15 plots the magnetization current of phase B of transformer AT2 with or without bypass the 35-Ohm series capacitor unit at time \( 0.6 \) sec, the other word, after suddenly disconnecting the 110 kV loads.
Figure 14: The geometric configuration of the transmission line system [22]: (a) the stray capacitances of dual circuit line; and (b) the earth–ground as conductor pass.

Figure 15: The magnetization current of phase B of transformer AT2: (a) with bypassing the 35-Ohm series capacitor unit; and (b) without bypassing one.

Figure 16: The energy absorption capability of some surge arresters in the station with bypassing the 35Ω series capacitor unit at time 0.6 sec: (a) CS2AT2 and CSC272; and (b) CS22.

PROPOSED SOLUTIONS

Impacts of SVC

Generally, the main purpose of the SVC is to increase the transmission capacity. This can be achieved by increasing the stability margins and providing voltage support. The aim of this study leads with the over-voltage at the receiving-end of Maluting-Thainguyen transmission line, thus the SVC is operated essentially as a voltage regulator. The reactive output being varied to reduce and rapidly damp the bus voltage variations [27]. The representation of this problem is simulated below:

Solution 1: Reasonably SVC Disconnection In reality, the SVC has the capability to maintain the voltage, so that the transformer AT2 set voltage is at a safe level after interrupting the load of 110 kV bus and, therefore, it can be reduced the current impulse fluctuations that produced the TOV at start time. In order to examine this problem, this study presents the first solution that is to interrupt the load of 110 kV bus at time 0.5 and 0.3 sec later, SVC disconnects.

Figure 17a depicts the energy absorption capability of CS2BAT2. Observing from this figure, it can be seen that the energy absorption capability of CS2BAT2 when disconnecting the SVC after the interruption of load is slower than that before one.

As known, due to the maintaining of SVC connection to the grid when interrupting the load, the transformer AT2 now operates normally and supplies the power for a load that is the
reactive power due to the absorption power of SVC, so that the secondary voltage of AT2 is not too large. Therefore, the current impulse fluctuations does not has, such that, the AT2 is not the magnetic circuit saturation of transformer AT2 and thus, the energy absorption capability of CS2BAT2 is small. However, the SVC disconnected out the gird later, the transformer has operated no the load, so that the voltage at 220kV bus increases, happening the magnetic circuit saturation of transformer AT2 and resulting to the TOV, and that the surge arrester CS2BAT2 continues to absorb the energy.

Figure 17: Switching the SVC out after and before disconnecting the 110 kV load: (a) the energy absorption capability of CS2BAT2; and (b) the phase B voltage the Thainguyen substation.

Figure 18: The SVC non-disconnection when interrupting the 110 kV load: (a) the energy absorption capability of CS2AT2 and CS272; (b) the out reactive oscillations of the SVC; and (c) the voltage at 220kV bus of the Thainguyen substation.

Impacts of shunt reactor placements

The Thainguyen substation is received electrical power from the Malutang substation through the transmission line having the total length of line 347.9 km. For such long line, during the low demand and disconnection periods of load, the CS2BAT2 can reach to the highest value 0.75 kJ at time 5 sec with the absorption velocity is slow, as seen in Figure 18a. The reactive power oscillations of the SVC and the voltage at the 220 kV bus of Thainguyen station under condition after and before disconnecting the 110 kV load are respectively depicted in Figure 18b,c. As seen in Figure 18c, the voltage value at 220 kV bus of the Thainguyen substation is 0.96 p.u., such obtained voltage is because of supporting the reactive power from SVC and this may be seen from Figure 18b. Therefore, we could conclude that SVC is kept connected to the grid after disconnecting the 110kV load; the system is stable and continuous receiving the power from the Malutang substation.
excessive reactive power produced by the natural shunt capacitance between line and line and between lines and ground drawing charging current through the series inductance [3] and this that we are also mentioned in Section 4, so that it causes over-voltage at Thainguyen substation. The over-voltage at 220 kV bus is recoded by Relay over 1.15 p.u. For such problem, in this Section, we propose solutions is that it should install the additional shunt reactor at Thainguyen and Hagiang substations for purpose of maintaining the voltage at Thainguyen 220 kV bus in the allowed operating condition in spite of either connected SVC or not into the grid. Once the shunt reactor is connected the receiving end of the transmission line to offset the capacitive effect of this transmission line and to regulate theVolt/VAr of the power system.

Let us look at the equivalent circuit transmission line, as shown in Figure 19 and see the effect of the shunt reactor on its parameters, in which \( \tilde{U}_s \) and \( \tilde{l}_s \) are respectively the sending-end voltage and current, \( \tilde{U}_r \) and \( \tilde{l}_r \) are respectively the receiving-end voltage and current, \( Z \) is the impedance of line, \( Y \) is the admittance of line.

\[
\begin{bmatrix}
\tilde{U}_s \\
\tilde{l}_s 
\end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix}
\tilde{U}_r \\
\tilde{l}_r 
\end{bmatrix},
\]

(13)

The Equation (12) can be rewritten under the following form:

\[
\begin{bmatrix}
\tilde{U}_s \\
\tilde{l}_s 
\end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix}
\tilde{U}_r \\
\tilde{l}_r 
\end{bmatrix},
\]

(14)

Assuming that the shunts reactor unit is connected at both ends of the transmission line with length \( l \) during the light load conditions, providing 80% compensation (shunt reactor unit is removed during the heavy load conditions). In this case, the components in equation (14) can be rewritten as follows:

\[
A = D = (1 + \frac{\sqrt{Z}}{2}), \quad B = \sqrt{Z}, \quad C = (1 + \frac{\sqrt{Z}}{4}).
\]

Equations (13) and (14) summarize a result, showing a high receiving-end voltage at no-load and a low this voltage at full load. This voltage regulation issue becomes more difficult as the line length increase. It may be concluded from Equations (13) and (15) that the shunt reactor reduces over-voltage during the light or no load conditions. Therefore, the representation of this problem is simulated below:

**Solution 3:** The 220 kV bus of Thainguyen substation As recorded results of Relay, the receiving-end voltage value (at the 220 kV bus of Thainguyen substation) is 1.12 p.u. In order to maintain this voltage within the sustainable limit, the shunt reactor bank proving 80% compensation must place at the 220 kV bus of Thainguyen substation that is the power receiving-end placement from the Malutang substation.

Figure 20 depicts the voltage response from Malutang substation to Thainguyen one with and without 80% compensation placed at the 220 kV bus of Thainguyen substation when transformer AT2 operates no load. As shown in this figure, the voltage at receiving-end is approximately 1.182 p.u. without compensation, whereas that is approximately 1.056 p.u. with 80% compensation, so that when transformer AT2 operates no load, leading to the core saturation, and happening harmonic component with high amplitude. This is major reason happened the failure of surge arrester CS2BAT2.

In order to demonstrate the better support capability of the additional shunt reactor, the simulation was done under the scenario is that the SVC is disconnected at 0.3 sec and later, the load of 110 kV bus is interrupted at 0.5 sec.
Figure 21 is a plot of the voltage at the 220kV bus of the Thainguyen substation and the energy absorption capability of the surge arresters CS2AT2 and CS272. As obtained result from Figure 21a, when shunt reactor connected at the 220 kV bus of Thainguyen substation, during operational process, the voltage at the 220kV bus is approximately 1.05 p.u. For such voltage value, the magnetic circuit saturation phenomenon of AT2 does not occur. As a result, the energy absorption capability of CS2BAT2 is slow, in particular, after switching the 110 kV load out, the maximum energy that CS2BAT2 drawn is approximately 16.5 kJ at 0.75 sec, as seen in Figure 21b.

**Figure 21:** The shunt reactor placed at 220 kV Thainguyen substation: (a) The voltage at the 220kV bus; and (b) The energy absorption capability of CS2AT2 and CS272.

**Solution 4:** The 220 kV bus of Hagiang substation  The fact that, we want to build the shunt reactor system need to have a large area. However, the area at the Thainguyen substation is enough large to place the shun reactor system. The Malutang-Thainguyen transmission line is indirectly connected thought the 220 kV Hagiang substation, the distance from this substation to Thainguyen one is 269.8 km, as shown in Figure 6 and thanks to it, we propose the fourth solution is that the shunt reactor bank proving 80% compensation placed at the 220 kV bus of Hagiang substation.

Figure 22 depicts the voltage response from Malutang substation to Thainguyen one with and without 80% compensation placed at Hagiang substation.

In order to demonstrate the better support capability of the additional shunt reactor placed at 220 kV bus C21 of Hagiang, the simulation was done under the scenario is that the SVC is removed at 0.3 sec and later, the load of 110 kV bus is removed at 0.5 sec.

Figure 23 is a plot of the voltage at the 220kV bus of the Thainguyen substation and the energy absorption capability of the surge arresters CS2AT2. As can be seen Figure 23b, when shunt reactor is connected, the CS2TA2 absorbs the energy reduced greatly in the process of operation and after removing the 110 kV load, the phase B of surge arrester CS2AT2 absorbs with the maximum energy 93.25 kJ at 1.05 sec.

**Figure 22:** The voltage response from Malutang substation to Thainguyen one with and without 80% compensation placed at Hagiang substation.

**Figure 23:** Placing the shun reactor at 220 kV Hagiang substation: (a) The voltage at the 220kV bus; and (b) the energy absorption capability of CS2AT2.
For placing the shunt reactive at 220 kV bus of Hagiang substation, the failure of surge arrester CS2BAT2 may be prevented. But on issue like over-voltage prevention, this solution really do not optimize compared with the placed shunt reactive at Thainguyen substation to be because the energy that CS2BAT2 absorbs is high and the voltage at bus of transformer AT2 is very high when the transformer AT2 operates no load. This is become, the distance between Thainguyen and Hagiang substation is too long.

CONCLUSIONS

The operational process to the electrical power system is an important task. It requires a completely approach in accord with rules of the national power system. The Thainguyen 220kV substation is required to satisfy the conditions as, firstly, removed the 22 kV voltage side; secondly, removed the 110 kV voltage side; and then removed the 220 kV voltage side when operating. As such, for the transformer AT2 of this substation, switching SVC out, removing 110 kV load, and then disconnecting the 220 kV voltage side, such that it satisfies rules of the national Vietnam’s power system. However, this substation is connected to the Chinese power system; this case could create temporary over-voltage (TOV) due to the action of series capacitor, transformer magnetization, and receiving-end over-voltage, leading to the magnetic circuit saturation of transformer and causing the failure to equipments and especially to the 220 kV side surge arresters of transformer AT2. Furthermore, when the phenomena of the transformer magnetic circuit saturation causes, the incremental overall energy of primary current will change to the heat losses, this case is so dangerous for transformer or even explosion.

For the surge arresters in the Thainguyen substation, the phase B surge arrester of CS2TA2 is just broken to be because the transmission line Thainguyen-Malutang is mounted as dual line with other line of Vietnamese power system in the same tower, in which the phase B is mounted blow above the ground, so that the current of this phase has a tendency to increase much faster than other two phases. When the 110 kV load was cut off out of the blue, the discharge pulse to the phase B surge arrester of CS2TA2 is high in the first place since the phase B current is maintaining a current having the high resonance amplifier. Further, after removing the load, the transmission line Thainguyen-Malutang was operated no load, causing the phase B voltage higher than other two phases due to the influence of the conductor capacitance, leading to the energy storage in the phase B surge arrester of CS2TA2 higher than other two phases.

If we use the approach that is either to set up more the surge arrester or to replace another surge arrester, this solution really is not reasonable since when replacing surge arrester, it just increases the good ovenproof efficiency, but it is not solving the issue about the over-voltage causing to the magnetic circuit saturation of transformer. For the surge arrester having high-energy absorption ability, just endures the prolonged period of failures, but it is not preclude them. If we choose surge arrester on the condition of the continuous operating voltage to be higher than to replace, it has to endure the over-voltage, but the residuals voltage in equipments after cutting surge is high, so that it may be caused the discharge to equipments that the surge arrester protects.

This paper has proposed four solutions to prevent over-voltage and to insure safe operating for equipments and power system, specially is the phase B surge arrester of CS2AT2 based on the operational process of Thainguyen substation, and specially is the transformer AT2. When asking this transformer AT2 to disconnect, firstly we cut out the 110 kV side load, secondly the 220 kV side, and then 22 kV (disconnect SVC), these proposed solutions are highly effective. But if the SVC was disconnected for either maintenance or fault, the proposed solutions 1 and 2 are not feasible. The optimal solution is to place the shunt reactor for the long transmission line Thainguyen-Malutang at Thainguyen 220 kV substation, so that it will ensure safety for both the disconnected SVC and feeder 171 cases. Besides, if area of the Thainguyen 220 kV substation is not big enough to place the shunt reactor unit, it could consider to place at the Hagiang substation.

APPENDIX

The event was happened at 00 : 12 AM on June 17, 2015 with the following whole process:

The method of operation and connection before occurring fault

Bus C21 (received the power from Vietnamese system) supplied the power for the feeders 271, 273, 274, 275, and 231.

Bus C11 (received the power from Vietnamese system) supplied the power for the feeders 131, 133, 134, 172, 173, 174, 715, 176, 177, and 178.

Bus C31 (received the power from Vietnamese system) supplied the power for the feeders 333, 373, 377, and 381.

Bus C32 (received the power from Vietnamese system) supplied the power for the feeders 334, 376, 380, and 231.

Bus C43 (received the power from Vietnamese system) supplied the power for the feeders 433, 471, and 473.

Bus C44 (received the power from Vietnamese system) supplied the power for the feeders 434, 472, 474, and 444.

Bus C91 (received the power from Vietnamese system) supplied the power for the feeders 931 and 941.

Bus C22 (received the power from Chinese system) supplied the power for the feeders 272 and 232.
Bus C12 (received the power from Chinese system) supplied the power for the feeders 132 and 171.

Bus C42 (received the power from Chinese system) supplied the power for the feeders 432 and 402.

Circuit breaker 212 was opened.

Circuit breakers 112 and 100 were opened.

Circuit breakers 312 and 372 were opened.

Circuit breaker 412 was opened.

The developments of event

At 00:05 AM, the SVC has generated the reactive power \( Q = -4 \text{ MVAr} \) and the voltage at received bus of Chinese system is 232/115 kV. It has been ordered to disconnect SVC and to open Circuit breaker 171.

At 00:08 AM, feeder 171 is disconnected, the voltage at Thainguyen substation is 240/119 kV.

At 00:10 AM, the voltage that transformer AT2 is underwent is 250/120 kV, the CS2BAT2 is broke as shown in Figure 2. The differential protection relay RET521 is operated, so that the opened circuit breakers 232, 123, and 432 are opened.

At 00:43 AM, the feeder 171 is connected to the Vietnamese system.

At 00:47 AM, the transformer AT2 disconnected out.

At 01:10 AM, it has been ordered to disconnect circuit breaker 272.

At 01:20 AM, it has been ordered to connect the received 220 kV buses from China and Vietnam together.

At 01:40 AM, it has been ordered to close circuit breaker 272.

At 01:50 AM, checking, the transformer AT2 did not see anything unusual and the CS2BAT2 is broke as shown in Figure 2.

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REFERENCES


[14]. Vita, V.; Mitropoulou, A.D.; Ekonomou, L.; Panetsos,


