Study on Surge Voltage Mitigation of Evolving Close-in Fault in HV Substations

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Voltage surges are sudden and short-term increases in voltage that can potentially damage electrical equipment, cause data loss, or disrupt operation. Surge voltage mitigation is crucial for the reliability of power systems and the protection of sensitive electronic equipment. By implementing effective surge protection strategies, power system operators can minimize the risk of damage and improve the overall stability of the electrical infrastructure. In this paper, the surge voltage caused by an evolving close-in fault in the 20 kV busbar of a sub transmission station is investigated. According to the results of the measurements made by recorders at the location of the substation, the reason for happening of the incident is elaborated. Using a simulation by PowerFactory software (DIgSILENT/2022 version), the occurred disturbances and relevant cases are investigated. Focusing on the role of shunt capacitor banks, the necessary solutions to mitigate the surge voltage are presented and their effectiveness are analyzed with the help of simulation.

keywords: *Close-in Fault, Evolving Fault, Opening Surge, Damper Resistance, Snubber Filter, Surge Suppressing Technique.*

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NOMENCLATURE

SCB	Shunt Capacitor Bank
PQA	Power Quality Analyzers
FR	Fault Recorder
ER	Event Recorder
SOE	Sequence of Events
CB	Circuit Breaker
SC	Short Circuit
PT	Potential Transformer
GTR	Grounding Transformer
CT	Current Transformer
OC	Overcurrent
OLD	One Line Diagram
TDD	Total Demand Distortion
$PWTR$	Power Transformer
LA	Lightning Arrester
LT	Line Trap
DS	Disconnector Switch
TMS	Time Multiplier Setting
I_{KSS}	Initial symmetrical (sub transient) short circuit current

1. INTRODUCTION

In power systems, studies and investigations are generally categorized into three main types: steady state, dynamic state, and transient state. Transient state studies focus on disturbances of very short duration, such as lightning, switching, and transient faults. These disturbances can cause over voltages of various natures and origins, negatively impacting equipment insulation. Therefore, the insulation resilience and withstand capacity of high-voltage equipment must be selected with these factors in mind [1]. Today, shunt capacitor banks (SCBs) are essential elements in substations. However, SCBs can pose certain challenges to power systems, especially in transient states, and their effects must be studied thoroughly [2]. One phenomenon extensively discussed in the literature is the close-in fault, which occurs near the relay [3],[4]. This fault type can cause protective relay malfunctions and may also generate transient surge overvoltage. Such over voltages can damage equipment installed at the capacitor bank's neutral point, including CTs and PTs, and may adversely affect the insulation of auxiliary transformers

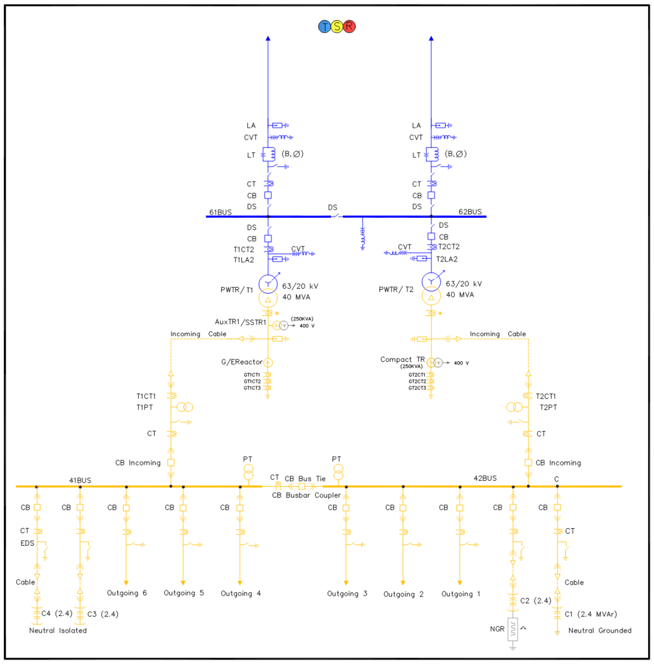

Fig. 1. One line diagram (OLD) of the substation under study with different sections

(GTR/compact) or busbar PTs. Given the high cost of high-voltage equipment, it is essential to establish protective measures to mitigate over voltages, using devices like lightning arresters and limiting devices such as neutral grounding resistors [5],[6],[7],[8]. Surge suppression techniques have demonstrated varying degrees of effectiveness, depending on the case. This work also examines faults with an evolving nature, in which a fault begins in one phase and spreads to others. Such faults have been studied in [9],[10],[11], highlighting the challenges they present, which require detailed analysis and thoughtful management. Two electrical incidents with similar results occurred in AJ 63/20 kV substation (see Fig. 1). At the fault instant, the following conditions were in place: four sets of capacitor banks with the specification of each 2.4 $MVAr$, 20 kV, double star (Y-Y) arrangement and isolated neutral point, two power transformers with the rated capacity of 240MVA and impedance of % 13.3, two earthing /auxiliary transformers, and the approximate power catering of the substation at the incident instant was 16 MW. Also, the consumption load of the mentioned substation was fed from one side (from the upstream 230 kV transmission substation). The main contributions are as follow:

- Analyze and Reinforcement of Insulation in the studied power grid
- Impact of Neutral Point Grounding as a Cost-Free and Simple Solution
- Evaluation of NGR Equipment and replacing in the neutral point of capacitor bank and transformed to RC Filter (Snubber) in a real power grid

In this paper, based on an incident report, we examine surge voltages caused by an evolving close-in fault. Through four different scenarios and with a focus on SCBs, we analyze the effectiveness of various overvoltage mitigation and suppression methods. Simulations of the studied substation demonstrate different levels of success in reducing overvoltages. The structure of this paper is as follows: Part 2 outlines the problem statement, Part 3 presents simulation results, and Part 4 discusses the proposed solutions for overvoltage reduction.

2. PROBLEM STATEMENT

The incidents happened in 2020 and 2021 (11/24/2020, 23/01/2021), and the SOE of the latter incident is as follows: first with the emergence of insulation weakness and defectiveness which led to rupture and explosion of the cable termination in one-phase (in a 20 kV outgoing feeder), a single-phase to ground fault occurred. During the detection of the fault by the relays and due to the ionizing of the air around the faulty phase, the event evolved to double line to ground fault. Along with the three-phase trip of the outgoing CB, the transient overvoltage appeared due to the clearing of the fault, and in this state, it caused the three-phase fault to occur at the 20 kV busbar. With the occurrence of this type of evolving fault, and by overcurrent protection relay of the coupling feeder (OC/ time delay relay) and the incoming feeder of the power transformer (OC/ time delay relay), the 20 kV busbar outage happened. It should be added that all 20 kV circuit breakers of the substation are conventional circuit breakers (without ZCS module). In the following, a detailed description of the fault happened on 23/01/2021 at 7:38 is discussed. First, with the beginning of the fault in phase C which had the SC current (IKSS) of 1.84 kA, after 47 ms the fault spread to phase A. Then after 108 ms, the instantaneous earth fault protection function operated and the feeder was automatically switched off. Due to the failure of the outgoing cable termination, and with the strong possibility that the ionization of the air around it led to the spreading of contamination to the busbar (carbonization), a three-phase (triple) fault occurred. With the operation of the overcurrent relay, the coupler CB and then the incoming CB opened. Based on the provided settings, the current setting for the coupling feeder is equal to 1250 A and its TMS is 0.12, which is in accordance with the standard characteristic curve (normal/NI) for the short-circuit current. The maximum recorded current was 4230 A, (short circuit currents in the three-phases were 4.17, 4.19 and 4.23 kA), and the operation time was about 700 ms, but the total operation time was 806 ms due to the circuit delays (tripping command by the over current relay, trip signal delay in intermediate circuits, operation time of the trip relay, operation time of the trip coil of the breaker and the opening time of the CB contacts). Also, the current setting of the incoming feeder is equal to 1350 A and its TMS is 0.2, with the maximum recorded current of 5680 A (short-circuit currents in the three phases were 5.68, 5.55 and 5.61 kA). For better explanation, the records of the relay for incoming current are shown in Fig. 2. The calculated operation time was 960 ms, but the recorded operation time by ER was 1168 ms. The sequence of operation of the protective system was correct and the reason for spreading of the incident was due to the existence of defects in the design of the insulating clearances in the cubicle (busbar compartment), which is mentioned in the following part. The amount of SC currents captured by the relay recorder is in good agreement with the results obtained from the power system simulation file (Deck) and short-circuit calculations. During the investigations carried out to find other causes and factors that lead to overvoltage and deterioration of insulation in the studied substation, power quality indices were analyzed for all feeders. One reason for occurrence of the overvoltage is the

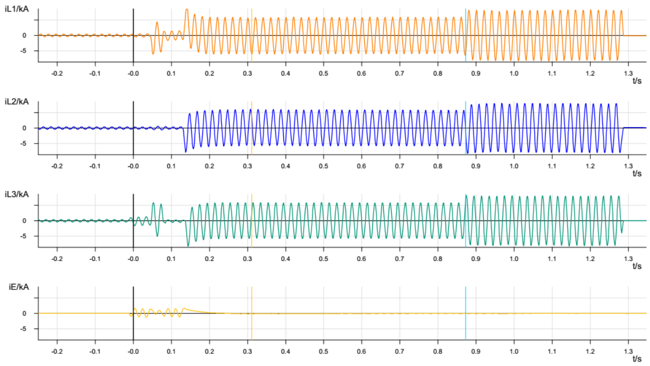

Fig. 2. The recorded waveforms of the incoming feeder relay (SIP4 7SJ647)

harmonic resonance. The condition of the 20 kV incoming feeder is acceptable from the point of view of power quality indices (PQI), but due to the presence of some consumers with harmonic disturbance levels (HDL) beyond the standard limits (electric arc furnace, steel mill, foundry and melting industry), the capacitor bank feeder had an unfavorable situation and played the role of a harmonic trap. During the power quality test period, the current harmonic magnitude (H11 and H13) of the capacitor bank feeder was 4 times the standard limit and they were recorded by the PQA (which has fine characteristics of: Waveform capture up to 1024 samples/cycle; Harmonics: magnitude, phase and inter-harmonics to the 40th). It should be mentioned that the percentage of total demand distortion (TDD) of the capacitor feeder was more than twice the limit approved by the standard. In other words, the existing capacitor bank plays the role of a harmonic absorption filter and reduces the number of current harmonics transferred to 63 kV. Of course, this issue can lead to overheating and consequently reducing useful lifetime of capacitor bank cells in the mentioned substation. By extracting the driving point impedance spectrum (frequency characteristics of equivalent impedance and frequency sweep analysis) for various operating scenarios of the 20 kV busbar at the substation, we observed the potential for harmonic resonance at the 5th and 7th order harmonics. This analysis was performed using spectroscopy with the frequency scanning feature in PowerFactory software. Despite this potential, due to the low levels of individual harmonic current distortion (HD5 and HD7), these modes did not reach a threshold that would cause dangerous over voltages in steady-state conditions. However, it is important to note that under asymmetric or transient conditions, the equivalent impedance vs. frequency characteristics of the busbar can differ significantly from those in steady, symmetrical states. In such cases, these harmonic modes may contribute to the excitation of disturbances. Notably, the overvoltage resulting from resonance is proportional to the quality factor (Q index) of the circuit and the reactance-to-resistance ratio at the time of occurrence. Based on the harmonic analyses conducted for this incident, the likelihood of overvoltage occurrence due to harmonic resonance remains low.

For investigating the cause of the spreading of the incident, the insulation condition and the necessary checks regarding the dimensions and insulation distances in the interior space of the 20 kV cubicle (which is installed in the altitude of 1500 m) were carried out. It was observed that the distances of the busbars from each other and from the ground (zero potential) are less than the standard limit (Fig. 3). According to VDE and IEC standards, the minimum distance of phase-to-ground and phase-to-phase insulation clearance for the voltage level of 20 kV is determined based on the lightning impulse wave (BIL). The minimum distance stated in the [2] standard tables for the standard impulse of 1.2/50 μs with the peak of 125 kV is 220 mm, and for the impulse with characteristics of 1.2/50 μs and peak of 95 kV is 160 mm, and also the minimum distance stated in the German standard [12] for the impulse of 1.2/50 μs with the peak of 125 kV is 220 mm. In this case, as shown in Fig. 3, the measured phase to phase distance is less than 110 mm, and the phase (busbar) to ground (cubicle enclosure) distance is less than 140 mm. In order to have the necessary insulation withstand in the voltage class of 24 $kV(Um)$ against a single impulse (single polarity) with a peak of 95 kV, a minimum air distance of 160 mm must be provided. Referring to the air insulation endurance curves in the special schematic (needle-plate) for the impulse voltage at the altitude of 1500 m, the maximum intensity of the electric field must not exceed 6 kV/cm. For the 20 kV busbar of the mentioned substation, the minimum insulation distance for impulse is equal to

Fig. 3. Measured Phase to phase clearance (11 cm; Note that the Raychem strip insulator was wrapped on some parts of the busbar before the incident and did not have thickness more than 0.5 cm)

$$L_{\min} > 92[kV]/6[kV/cm] = 15.33[cm] \quad (1)$$

In order to prevent similar events in the future, the defect of insufficient clearance was compensated by wrapping insulator (Raychem strip) on all parts of busbars. It is reminded that the insulator was partly wrapped on the busbars after the first incident in 2020. It should be noted that after the second incident, in spite of recent incidents of cable termination failure, there has not been any evolving phenomenon like above. This shows that the cause for the evolving fault was correctly found[16-18].

3. RESULTS OF THE SIMULATION

The fault was simulated in DIgSILENT PowerFactory to enable comparison with the relay records. The simulated current and voltage waveforms are shown in Fig. 4 and Fig. 5. Notably, from a system perspective, the 20 kV busbar at the substation was ineffectively grounded, with its grounding achieved via the HV

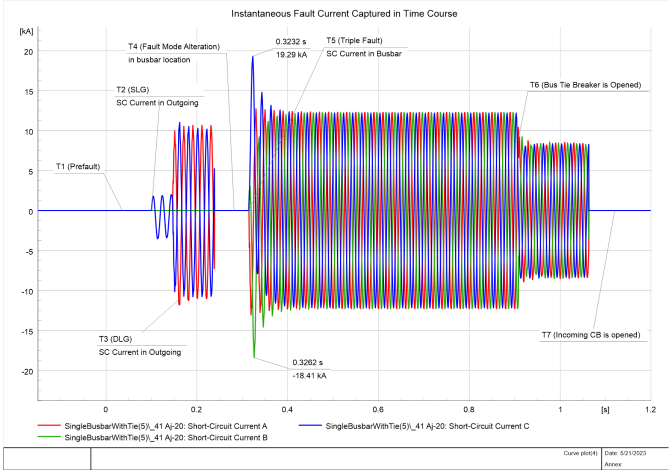

Fig. 4. Simulated fault current at 20 kV busbar (which is in compliance with COMTRADE File Format of relays)

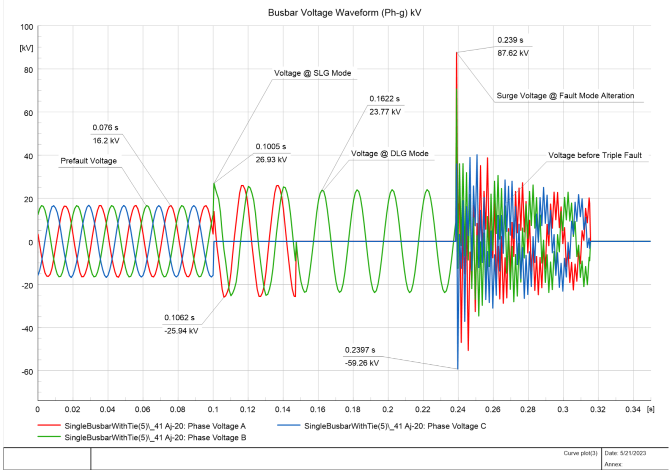

Fig. 5. Voltage transient waveform of the 20 kV busbar at the fault presence (surge voltage (peak) 88 kV- 5.4 pu)

Zigzag winding's neutral of auxiliary transformers (250 kVA) limited to a neutral current of 1200 A, and zero impedance of 31 $Ohms$. Additionally, at the moment of fault, the 4-set shunt capacitor bank (SCB) was operational, with its neutral point isolated.

As shown in Fig. 4 and Fig. 5, the SOE is as follows:

- T_1: Pre fault
- T_2: Single line to ground fault (SLG) in the outgoing feeder
- T_3: Double line to ground fault (DLG) in the outgoing feeder (fault mode alteration from SLG to DLG)
- T_4: Fault mode alteration from DLG to triple fault (process of ionization of air and air breakdown)
- T_5: Triple fault in the 20 kV busbar
- T_6: Bus tie breaker is opened
- T_7: Incoming CB is opened

Fig. 6 illustrates impedance spectrum (impedance frequency sweep) for the studied substation. According to this spectrum, the possibility of the harmonic resonance can be observed in the 5th and 7th order harmonics, but due to the small amount of individual current distortion (HD5 and HD7), the mentioned modes did not reach the threshold of dangerous overvoltage in the steady state.

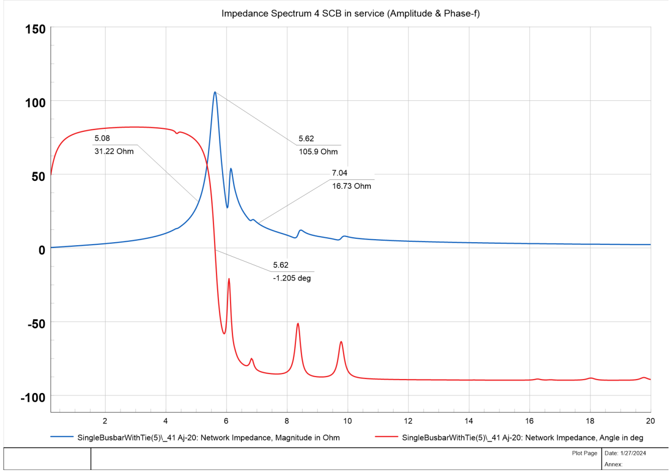

Fig. 6. 6. 20 kV busbar Equal Impedance spectrum of the studied substation ($Amplitude\&Phase - f$)

It should be mentioned that the overvoltage and surge (breaker tripping surge/opening surge) are caused by the state alteration during the opening of the contacts of the breaker. Traveling wave [13],[14] is created by fault current amplitude and circuit equivalent characteristic impedance. The equivalent circuit causing surge which is made by state alterations during the transient state of opening of contacts of the CB is shown in Fig. 7. Determining equivalent characteristic impedance for this problem needs accurate information of the stray capacitors and equivalent inductances. For this purpose, the Electro Geometry Characteristics (E-GM) of all equipment including busbars, auxiliary transformers, PT, stray capacitors should be taken into account (which is not in hand at this time)[15]. Due to the nature of the close-in fault, transient recovery voltage (TRV) with dangerous rate of rise can be seen at breaker contacts, which can cause failure of the breaker[19,21] .

4. SUGGESTED SOLUTIONS

For mitigation of the surge overvoltage, different scenarios are simulated and scrutinized as follows:

A. First of all, there is a need to cast light on the role of SCBs on surge overvoltages. It might be questionable if presence of SCBs could lead to intensification of surge overvoltages. For this purpose, the incident is simulated in the presence of SCBs and the results are shown in Fig.8 and Fig. 9. It can be seen that presence of 4-set capacitor banks (Fig. 5) is more effective compared to 2-set capacitor banks in mitigation of surge voltage (Fig. 8). It is also obvious that the presence of 4 sets of the capacitor bank can reduce the overvoltage dramatically compared to the condition in which no capacitor bank is connected (Fig. 9). Hence, it can be concluded that SCBs can be fruitful in mitigation of surge overvoltage.

B. It is suggested to ground the neutral point of the capacitor banks in order to mitigate the transient overvoltage peak caused by a fault near the busbar, and this will adjust the overvoltage well. Grounding the neutral point of the capacitor banks has

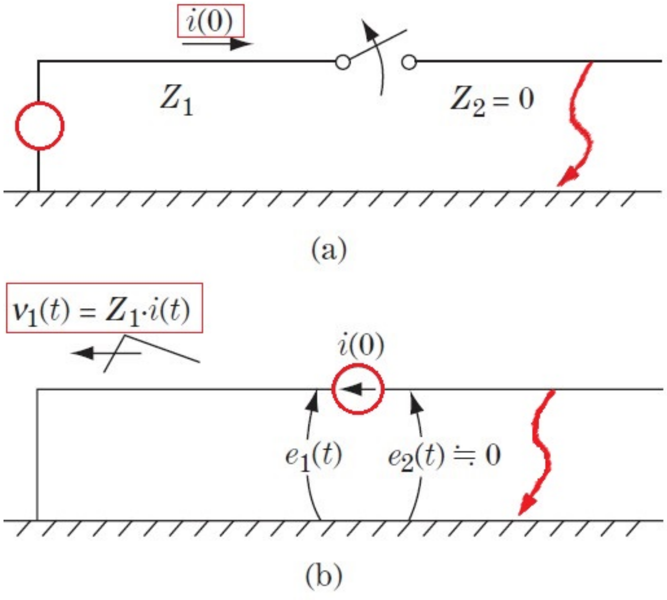

Fig. 7. Equivalent circuit causing surge which is made by state alterations during opening of CB contacts

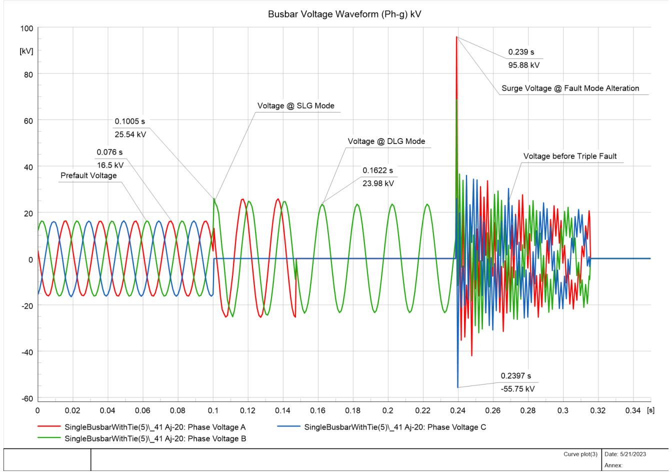

Fig. 8. Fault voltage waveform of the 20 kV busbar considering 2 sets of capacitor banks (peak of transient voltage 96 kV-5.8 pu)

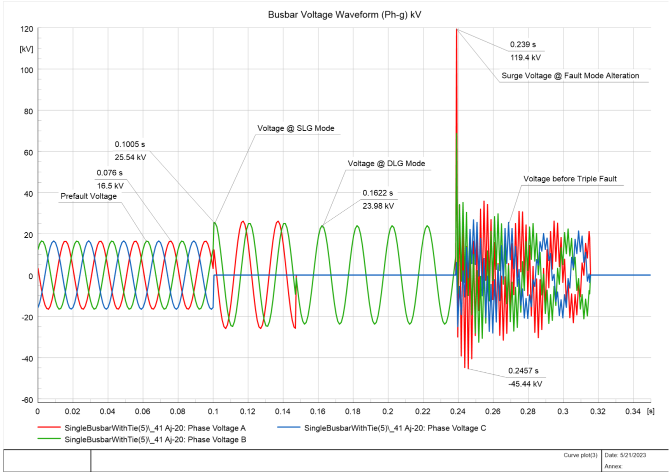

Fig. 9. Fault voltage waveform of the 20 kV busbar without considering capacitor bank (peak of transient voltage 119.4 kV-7.23 pu)

other consequences, which from the point of view of the power quality, the third-order current harmonics (triplen/homopolar) with closing path through the capacitor bank can cause heating of the cells to some extent and decreasing their lifetimes. Moreover, it can create some audible noises in telephone circuits. In this case, the leakage and homopolar currents passing through the earth system increase to some extent. It should be mentioned that in this situation, protective considerations should be taken into account regarding the protection of capacitor banks and asymmetric fault currents with zero component passing through capacitor banks. According to Fig. 10, 4-set capacitor bank with a grounded neutral point can reduce the amount of overvoltage peak by 47 kV compared to the state of isolated neutral point. It is also shown that grounding one set of the capacitor banks can reduce the overvoltage to 54.4 kV (Fig. 11).

C. Neutral point of capacitor banks can be connected to the substation's earthing/grounding system through a single-phase power resistor (according to [26]). Adding NGR solid metallic resistance (damper resistor) at the neutral point can reduce the mentioned circuit quality factor (Q index) to below 0.5 and increase the damping factor of the circuit. This method can dampen similar surge peaks well. By studying and simulating the transient states, it is possible to calculate the suitable and optimal resistance size. In fact, capacitor banks become snubber filters and damper circuit. A power resistor -with specification of: 10 ohm, 14 kV (24/3 kV) withstand voltage, maximum duration time of 5 seconds and current rating of 200 A- can have a good damping influence, and also plays an effective role in mitigation of the overvoltages caused by the stimulation of resonance ferro-resonance condition. The presence of the resistance reduced the amount of single-phase short-circuit current by 35% in the busbar. It should also be noted that the single-phase resistor connected to the neutral point of the three-phase capacitor bank can reduce and limit the TRV appearing at both ends of the 20 kV CB contact. This is an effective surge suppressing technique which has been utilized in the industry, and in this case, it has decreased the surge overvoltage to 41.8 kV (see Fig. 12).

D. The other suggestion for limiting transient overvoltages is the use of breakers with the ability to clear the fault at zero current point (ZCS). As shown in Fig. 13, this method can re-

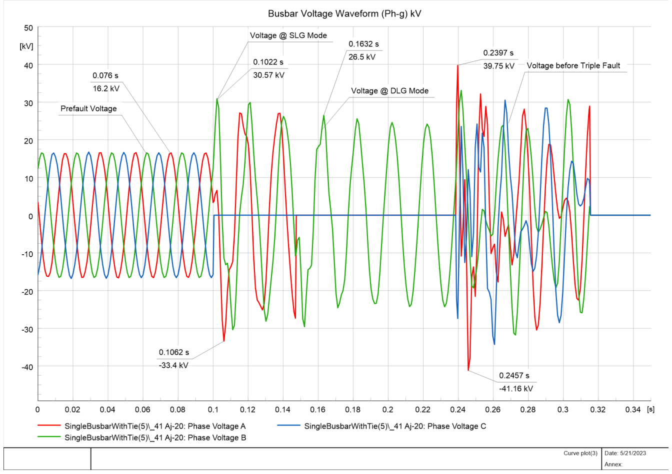

Fig. 10. The busbar fault voltage with 4 sets of grounded capacitor banks (with peak voltage of 41.2 kV-2.54 pu)

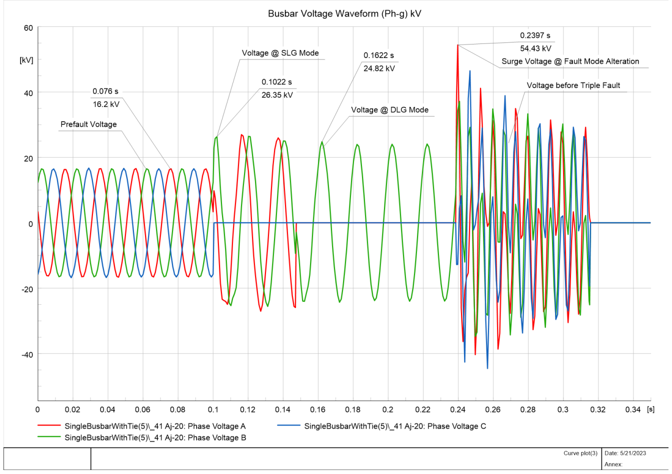

Fig. 11. Busbar fault voltage considering 1 set grounded and 3 sets with isolated neutral capacitor bank (with peak of 54.43 kV-3.35 pu)

duce the surge overvoltage to 28.46 kV which is the lowest value compared to other solutions. A summary of the results of different scenarios are presented in Table 1. It is worth mentioning that in MiCOM P127 (Overcurrent and earth fault protection relay) with two setting group, for confronting the evolving fault phenomenon, the DMT characteristic can be enabled instead of IDMT to fast clear the single-phase short circuit. It can be suggested that in designing cubicles from insulating point of view, in addition to considering single polarity surge like lightning impulse, the role of double polarity surges should be taken into account.

5. CONCLUSION

This article investigates the overvoltage caused by a close-in fault occurring on a 20 kV busbar with an operational capacitor bank. The fault demonstrated an evolving nature, beginning as a single-line-to-ground (SLG) fault, then progressing to a double-line-to-ground (DLG) fault, and ultimately becoming a three-phase fault. The primary cause of this evolution was identified as inadequate insulation clearance in the cubicle, which

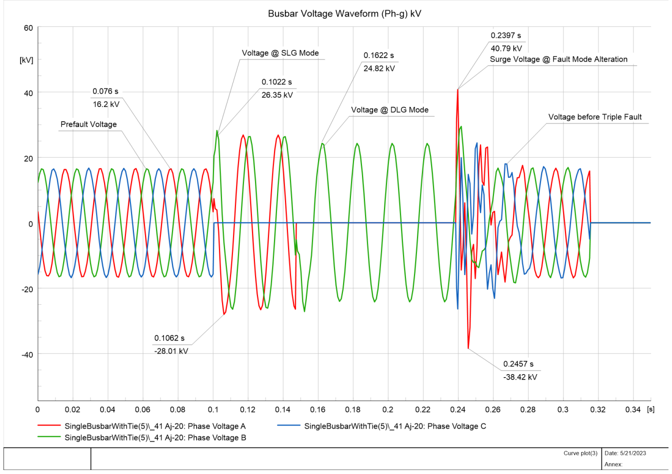

Fig. 12. Busbar fault voltage considering grounded neutral through 10-ohm resistor capacitor bank (with peak of 40.8 kV-2.51 pu)

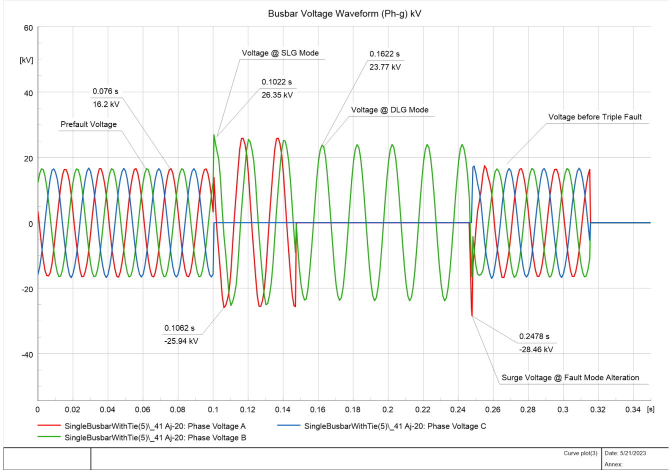

Fig. 13. Busbar fault voltage considering 4-set capacitor bank with isolated neutral, and CB equipped with zero current switching function (with peak of 28.46 kV-1.75 pu)

Table 1. Peak of The Surge Voltage for Different Scenarios for SCB

	Scenarios	Surge Voltage Peak (kV)	Cost
Scen. 1	Without capacitor bank	119.4	No infrastructure cost
Scen. 2	Two sets with isolated Neutral	96	No infrastructure cost
Scen. 3	Four sets with isolated Neutral	88	No infrastructure cost
Scen. 4	Four sets with grounded Neutral	41.2	No infrastructure cost
Scen. 5	One set grounded Neutral and 3 sets isolated Neutral	54.43	No infrastructure cost
Scen. 6	Four-set grounded neutral through 10-ohm NGR (Power Resistor)	40.8	4*2942 $
Scen. 7	Four sets with isolated neutral and CB equipped with CBM (zero current switching function- ZCS)	28.46	4*6000$

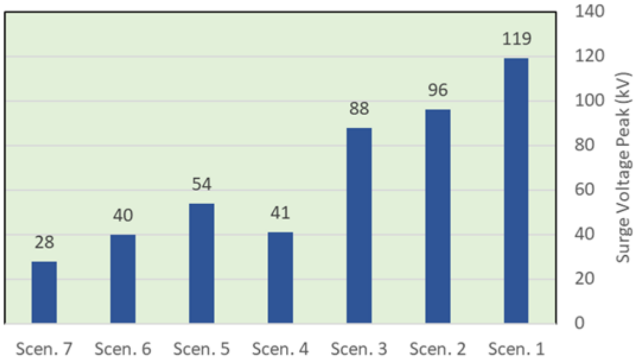

Fig. 14. The comparison of surge voltage peak in different scenarios

was insufficient for the installation altitude. Effective surge voltage mitigation methods were then examined, revealing that the presence of a capacitor bank contributed positively to reducing overvoltage. Additionally, the grounding method of the capacitor banks—whether direct or through a grounding resistor—proved to significantly influence surge voltage mitigation. Finally, it was determined that circuit breakers (CBs) with zero-current switching capability are the most effective solution for further reducing overvoltage levels.

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