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Application of Controlled Switching to Reduce Switching Over-voltages on EHV Transmission Lines

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ABSTRACT

This study investigates the effectiveness of controlled switching techniques in reducing switching over voltages on EHV transmission lines. The case study is the Sudanese 500 kV transmission line connecting generation at Merawi to the load centre at Khartoum (Sudan). The method used is modeling and simulation the line using MATLAB/SIMULINK. The results show that the phase-controlled switching technique is far superior to the Pre-insertion Resistor (PIR) method. It is also found that switching over-voltages are very much reduced when Metal-Oxide Surge Arresters (MOSA) are installed at the line ends and also when the transmission line is compensated.

1. INTRODUCTION

Operation of any electrical system necessarily involves switching operations. These switching operations produce high undesirable over voltages, which propagate as surges through the system and if not controlled could cause considerable damages. Transmission systems are not exception, since they have inductances and capacitances, so that switching operations performed on transmission lines produce transient surges known as switching over-voltage surges (SOV)[1]. SOVs are oscillatory in nature and are characterized by their transient period of oscillations [2].

The switching operations which are usually conducted on transmission lines are:

i. Line energization (CB making).
ii. Line de-energization (CB breaking).
iii. Line Reclosing (CB making and breaking simultaneously).

The controlled switching techniques, which are used in electrical power systems to reduce switching over voltages on transmission lines, are Pre-Insertion Resistance Method (PIR) and Phase-Controlled Switching [3].

1.1. Pre-Insertion Resistance Method (PIR)

Refer to the Figure 1, the idea is very simple; a high-voltage resistor "R" is connected across the CB contacts through a switch. When CB is to be operated, close the switch (i.e. connect the resistor) and when the switching operation is completed open the switch (i.e. remove the resistors). The function of resistor R is to reduce the magnitude of the switching surges produced during switching.

This technique is suitable for low and medium voltage but for EHV, high voltage resistors, which are very difficult to manufacture are required [4-7].

1.2. Phase-Controlled Switching

The magnitude of switching overvoltage or overcurrent depends on the voltage at the instant of switching [8].

In the Figure 2, if switching is performed at instant t_1 on the system voltage waveform when the magnitude of the system voltage or current is V_1 or I_1, the switching over voltage or current is extremely high. While if the switching is performed at instant t_2 when the system voltage or current approaches zero, the switching over voltage or over current are very small. An electronic control circuit (controller) monitors the voltage waveform in case of opening (de-energization) or current waveform in case of line (energization) and operates the CB at the required instant is needed. In both cases over voltage and over current are of much reduced magnitudes [9–12].

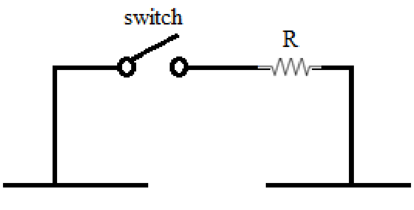

Figure 1: PIR method

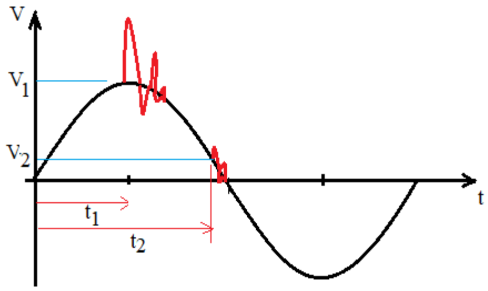

Figure 2: phase - control method

2. SYSTEM SIMULATION AND RESULTS

Figure 3 illustrates the single-line diagram of the 500 kV Merowe-Al-Markhiat double-circuit transmission line, the test system for this study.. This line connects Merowe generating power plant and Al-Markhiat substation. The test system data is illustrated in Table 1. This line uses the highest transmission voltage in Sudan, thus, the highest SOVs are expected. In this study, different switching operations are performed on the simulated line with different scenarios. The test system is modeled in MATLAB/SIMULINK as shown in Figure 4 with the proposed switching control time sequences codes for opening and closing switches.

The voltage source represents Merowe generating power plant with generation voltage of 11 kV stepped up to 500 kV using step-up transformers. The voltage source is simulated using an equivalent source in MATLAB/SIMULINK consisting of three sinusoidal AC voltage sources with a peak value of $\left(\frac{500}{\sqrt{3}}\right)*\sqrt{2}$ = 408.2482905 kV (phase-to-ground) with a 120° phase shift angle between the three phases. The generators and transformers are represented by their equivalent impedances. Transmission lines are modeled by distributed parameters model, which best fits transient simulation. In all scenarios, phase-controlled switching is investigated for the zero-crossing instants on the voltage waveform.

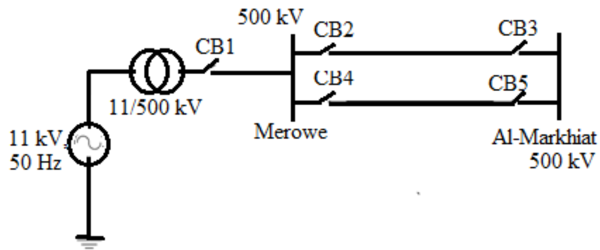

Figure 3: Single line diagram of Merowe-Al-Markhiat

Table 1: case study data

Element	Value
Voltage Source	500 kV (Line-to-Line RMS)
System Frequency	50 Hz
Source Impedance	0.81+j.00826 ohm
Line Length	346 km
Line positive sequence Impedance	0.028+ j0.276 ohm/km
Line zero sequence Impedance	0.3445+ j0.981 ohm/km
Shunt Compensation	125 Mvar
Surge Arrester	3-stage, 420 kV_{rms} , at line ends

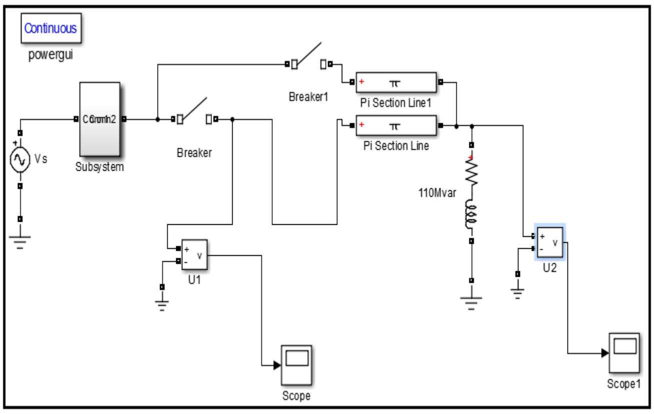

Figure 4: The test system modelled in MATLAB/SIMULINK

2.1. Random Energization and Re-closing

The results of this simulation are used as reference for case study system energization and re-closing scenarios.

1. Random Energization:

In this simulation the line is energized randomly without using any mitigation method. The closing command is issued randomly, so that the switching times of the three phases are assumed to be t_A=t_B=t_C =75 ms. The simulation result of voltages at the receiving end is given in Figure 5.

2. Random Re-closing

This simulation assumed that a sudden de-energization of the three phases occurred at t_A= 50 ms, t_B= 70 ms, and t_C= 80 ms, and then re-closing at t_A= 317 ms,t_B= 319 ms, and t_C= 321 ms. The simulation result of voltages at the receiving end for three phases are shown in Figure 6.

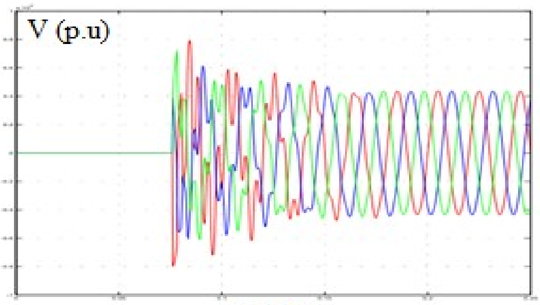

Figure 5: SOVs at the receiving end due to Random energization

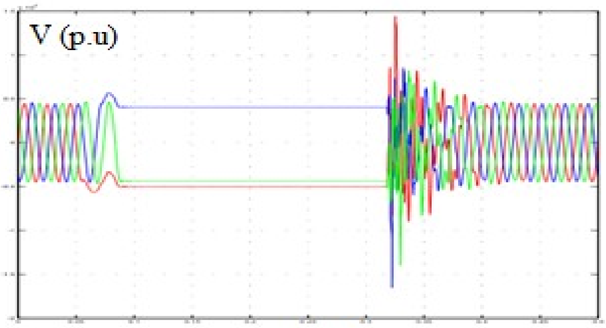

Figure 6: SOVs at the receiving end due to random re-closing

2.2. Simulation with Pre-insertion Resistors

1. Energization

In this scenario the closing command is issued randomly, so that the switching times of the three phases are assumed to be t_A=t_B=t_C =75 ms, using a PIR with resistance of 400 ohms in series with each CB pole, then removing them after 8 msec. The simulation result of voltages at the receiving end are given in Figures 7.

2. Re-closing

This simulation assumed that a sudden de-energization, using PIR, of the three phases occurred at t_A= 50 ms,t_B= 70 ms, and t_C= 80 ms, and then re-closing at t_A= 317 ms,t_B= 319 ms, and t_C= 321 ms. The simulation result of voltages at the receiving end for single and three phases are shown in Figure 8.

Three-phase re-closing is simulated with a sudden de-energization of the three phases at t_A= 50 ms,t_B= 70 ms, and t_C= 80 ms, and then re-closing at t_A= 315 ms,t_B= 330 ms, and t_C= 335 ms. The simulation result of voltages are shown in Figure 10.

2.3. Observations

The summary of the above simulation results for the highest SOVs in pu at the receiving end in case of 3-phase energization and re-closing with random switching and different PIR and phase controlled mitigation methods for the test system is given in Table 2

From the SOVs simulation results given in Table 2, for different switching operation scenarios, it can be noticed that; the application of phase controlled for energization of the line reduced the random SOVs by 22.96% and 64.53% for reclosing, while PIR reduced the SOVs by 7.65% for the case of energization and by 61.58% for re-closing.

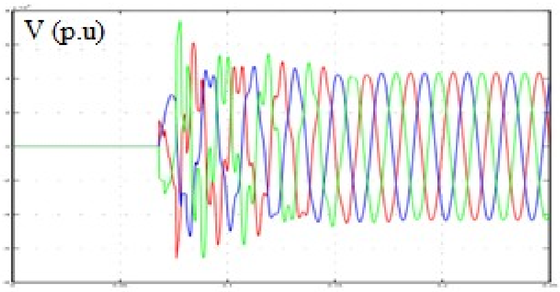

Figure 7: SOVs at the receiving end due to energization with PIR installed

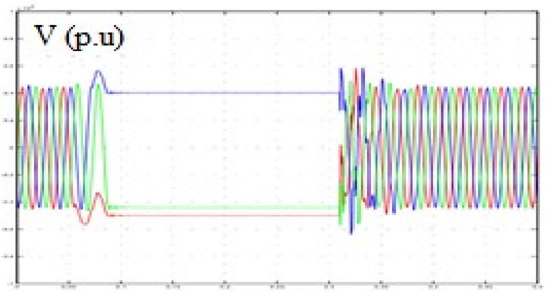

Figure 8: SOVs at the receiving end due to re-closing with PIR of the 3-ph

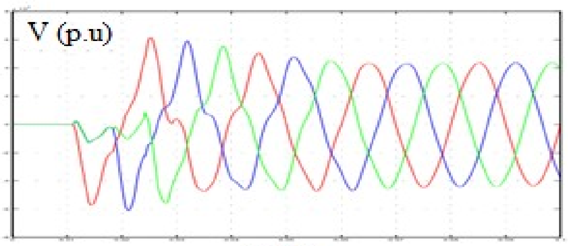

Figure 9: SOVs at the receiving end due to Phase-controlled energization

Comparing controlled switching with PIR mitigation method, it is observed that phase controlled gives the best results and reduced the SOVs in the range 1.44 – 1.51 p.u, while PIR method limit the SOVs in the range 1.28 – 1.81 p.u.

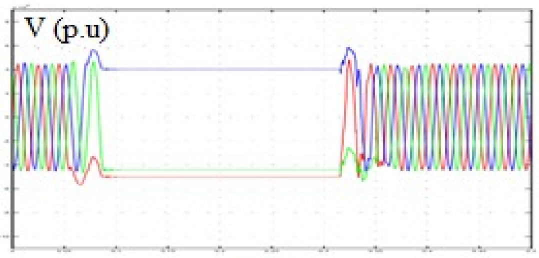

Figure 10: SOVs at the receiving end due to Phase-controlled 3-ph re-closing

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Table 2: The highest SOVs for 3-phase switching with different mitigation methods

Switching method	Highest Switching Over-voltage (pu)	
	Line energization	Line re-closing
Random	1.96	4.06
PIR	1.81	1.56
Ph-control.	1.51	1.44

3. EFFECTS OF SURGE ARRESTER (MOSA) AND LINE OMPENSATION

3,1. Energization with Line compensation

1. Energization without phase controlled

In this case, the line is compensated by 125 MVars shunt reactors. The closing command is issued randomly, so that the switching times of the three phases are assumed as t_A=t_B=t_C =75 ms.

The simulation result of voltages at the receiving end for uncontrolled energization with line compensation is given in Figure 11.

2. Line Energization with phase controlled:

In this scenario the phase controlled switching technique is applied to a compensated line. The closing instant of each phase is set equal to the zero crossing instant with respect to the source voltage. The switching times of the three phase are taken as: t_A= 10 ms,t_B= 17 ms, and t_C= 23 ms. The result of voltages at the receiving end, with line compensation, are shown in Figure 12.

3.2. Re-closing with Line compensation

1. Without phase controlled

This simulation assumed that a sudden de-energization of the three phases compensated line occurred at t_A= 50 ms,t_B= 70 ms, and t_C= 80 ms, and then re-closing at t_A= 317 ms,t_B= 319 ms, and t_C= 321 ms. The simulation result of voltages at the receiving end for single and three phases are shown in Figure 13.

2. Controlled Re-closing with CS

In this simulation, a sudden three-phase re-closing compensating line is simulated with a sudden de-energization of the three phases at t_A= 50 ms,t_B= 70 ms, and t_C= 80 ms, and then re-closing at t_A= 315 ms,t_B= 330 ms, and t_C= 335 ms. The simulation result of voltages are shown in Figure 14.

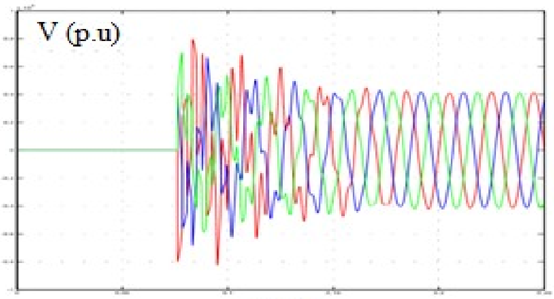

Figure 11: SOVs at the receiving end due to uncontrolled energization with compensation

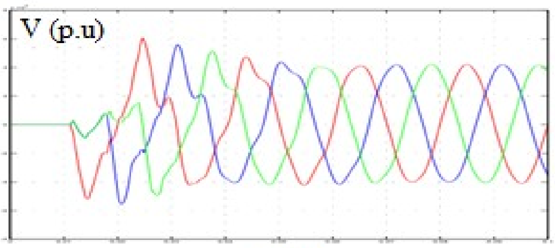

Figure 12: SOVs at the receiving end due to Phase -controlled energization with compensation

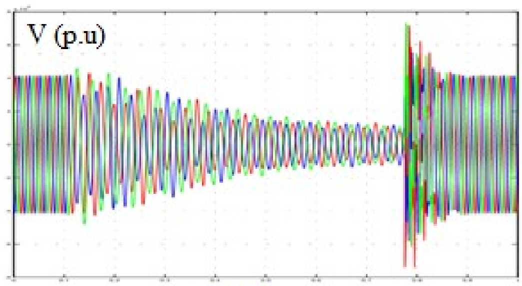

Figure 13: SOVs at the receiving end due to uncontrolled 3-ph re-closing with compensation

3.3. System with surge arrester (MOSA)

1. Energization without CS

The simulation of energization operations are performed with MOSA at the terminals of the transmission lines without phase-controlled switching, the resulting voltages at the receiving end is as shown in Figure 15.

2. Controlled Re-closing with MOSA

A simulation of the energization operation is performed with MOSA at the terminals of the transmission lines. The resulting voltages obtained at the receiving end is shown in Figure 16.

3.4. System with PIR and MOSA

In this scenario, the same energizing and re-closing operations described in part (A & B) are simulated but in this case, PIR and MOSA are used together. The voltages at the receiving end are shown in Figure 17 (a and b).

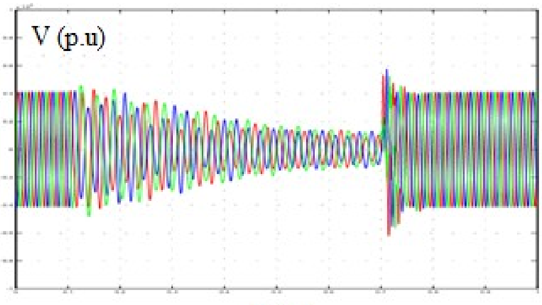

Figure 14: SOVs at the receiving end due to phase-controlled 3-ph re-closing with compensation

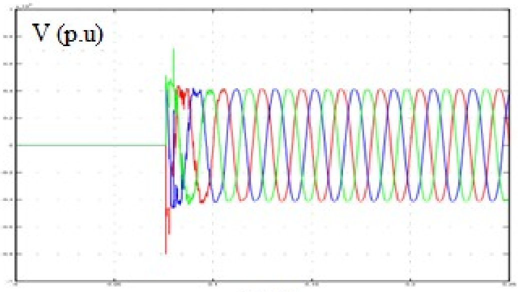

Figure 15: SOVs at the receiving end due to uncontrolled energization with MOSA

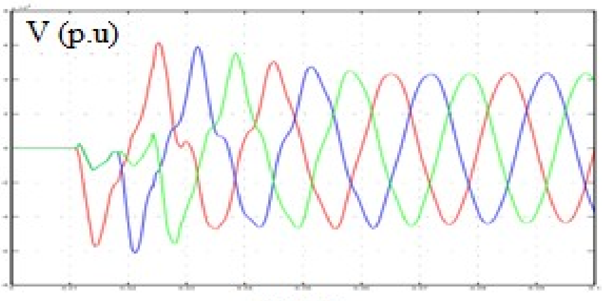

Figure 16: SOVs at the receiving end due to Phase-ontrolled energization with MOSA

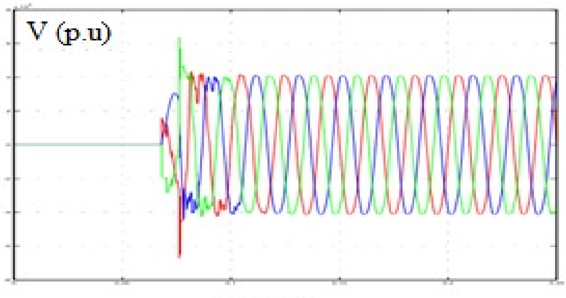

Figure 17a: SOVs at the receiving end due to uncontrolled energization with PIR & MOSA

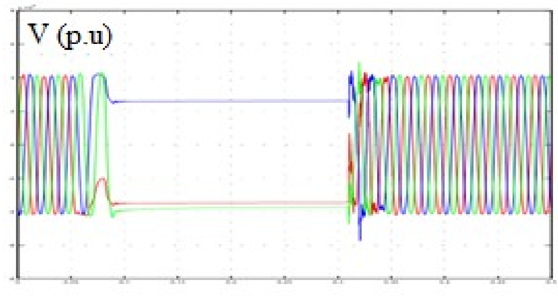

Figure 17b: SOVs at the receiving end due to uncontrolled re-closing with PIR & MOSA

4. DISCUSSION

Table 3 gives the summary of the simulation results for all switching scenarios of section II and III. The results shows the highest SOVs in pu at the receiving end in case of 3-phase energization and re-closing for random switching and different mitigation methods for the test system.

From the SOVs simulation results given in Table 3, comparing the effects of compensation on controlled switching with other mitigation methods, it can be noticed that; controlled energization of the transmission line has reduced the maximum SOV from 2.02 pu to 1.49 pu in case of compensated line, and from 1.96 pu to 1.51 pu in case of uncompensated line.

The application of MOSA reduced the SOVs in the range 1.9 – 2.08 pu. The combination of controlled switching together with MOSA has resulted in the lowest range of SOVs compared to other methods. The combination of phase controlled & MOSA has limited the SOVs to the range 1.11 – 1.23 pu. Though, the use of PIR together with MOSA has given slightly better results in case of 3-phase re-closing on compensated line, this due to the fact that the resistors dissipated the trapped charge in form of heat before the re-closing operation. However, suitable MOSA must be used at the line terminals to give better results.

5. CONCLUSION

Controlled switching techniques used to reduce switching over-voltages on EHV lines have been described and implemented on the Sudanese 500KV Merawi-Khartoum double circuit line.

The methodology of the study is modelling and simulation using MATLAB/Simulink. The simulation results show that random switching operations on the line result in over-voltages of very high magnitudes. For example, in the case of a 3-phase auto-reclosing of an uncompensated line, the switching surge magnitude may reach 4.06 p.u. This high value of the switching surge may be much higher than the impulse with stand insulation level of the transmission system and may cause considerable damage. The controlled switching techniques considered, namely the Pre-Inserted Resistor (PIR) and Phase-Controlled techniques were found to be very effective in reducing the switching over-voltages. However, Phase-Controlled switching is far superior than the PIR technique. Surge arresters which are essentially installed at the ends of the line to protect transmission equipment from all kinds of surges, are found to lead to further reduction in the magnitudes of the switching surges. Also line-compensation, a technique essentially used to increase the line loading capacity, also participates in the reduction of switching over-voltages. Finally, it may be concluded that using Phase-Controlled switching in the presence of surge arresters, which are invariably installed in any decent EHV system, gives the best results in reducing switching over-voltages.

Table 3: The effects of line compensation and MOSA on SOVs for 3-phase energization and re-closing

Switching method	Highest Switching Over-voltage (pu)					
	Line energization			Three phase re-closing		
	Without comp & MOSA	With Comp.	With MOSA	Without comp & MOSA	With Comp.	With MOSA
Random	1.96	2.02	1.96	4.06	1.95	1.90
PIR	1.81	1.50	1.65	1.56	1.28	1.21
Phase -control	1.51	1.49	1.10	1.44	1.47	1.23

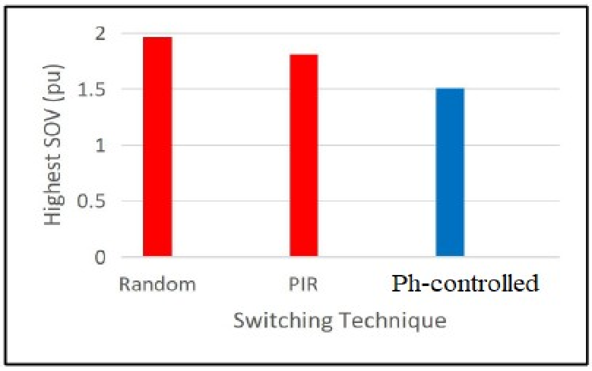

Figure 18: Highest SOVs at the receiving end due to Transmission line energization without compensation for different switching techniques

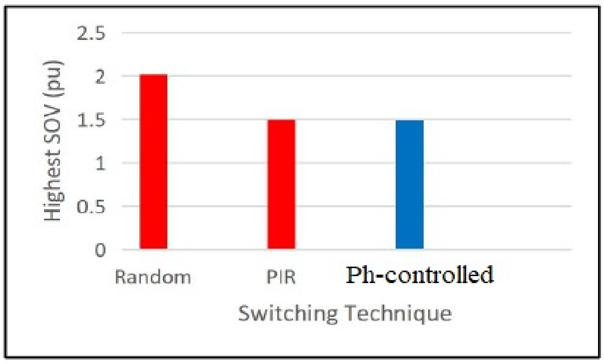

Figure 19: Highest SOVs at the receiving end due to Transmission line energization with compensation for different switching techniques

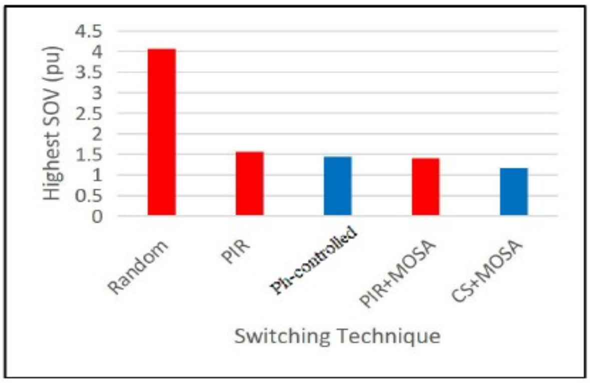

Figure 20: Highest SOVs at the receiving end due to 3-phase re-closing without compensation for different switching techniques

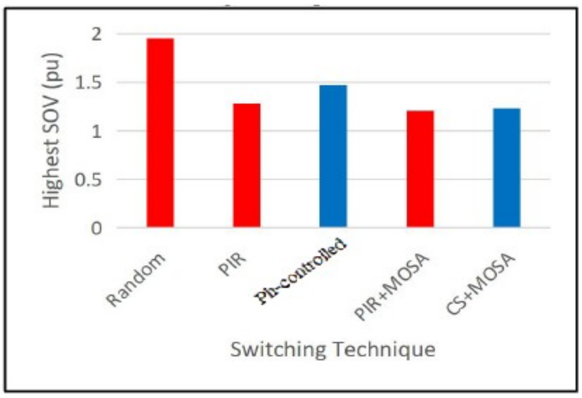

Figure 21: Highest SOVs at the receiving end due to 3-phase re-closing with compensation for different switching techniques

REFERENCES

[1]. Naidu M. S., Kamaraju V., "High Voltage Engineering", McGraw-Hill, second edition, 1995.

[2]. VelimirLackovic Char. Eng., "Introduction to Switching Transients Analysis Fundamentals", Continuing Education and Development, Inc., 2006.

[3]. Victor F. Hemosillo, "Overall Benefits of Controlled Switching", WG 13.07, CIGRE, 2007.

[4]. CIGRE 13.07, "Controlled Switching of HVAC Circuit Breakers - Guide for Applications - Part 1", Electra No. 183, pp. 43-73, April 1999

[5]. International Electrotechnical Commission, IEC 60071-2, "Insulation Co-ordination – Part 2: Application guide", edition 3, 1996.

[6]. Cigre T.F. 13.00.1, "Controlled Switching-A-State-Of-The-Art- Part 1": Electra No. 162, Pp. 65-96, Part 2: Electra No. 164, , pp. 39-61, October 1995.

[7]. Arafat, E. and Ghassemi, M., 2024, April. Switching Overvoltage Analysis in Conventional and Unconventional Transmission Lines. In 2024 IEEE Kansas Power and Energy Conference (KPEC) (pp. 1-4). IEEE.

[8]. Reddy, S. A., & Kumari, M. S. (2024). A review of switching overvoltage modeling in UHV AC transmission lines. Electric Power Systems Research, 236, 110902.

[9]. R. Rudenberg, "Transient Performance of Power Systems", McGraw Hill, 1950. (MIT Press 1969).

[10]. CIGRE WG 13.05, "The Calculation of Switching Surges in Transmission Line Presentation for energization and re-energization studies with complex feeding networks", Electra no. 62, pp. 45-78, 1979.

[11]. H. W. Dommel, " Digital Computer Solution of Electromagnetic Transients in Single and Multiphase Networks", IEEE Trans. Power Appar. Syst., vol. PAS-88, no. 4, pp. 388-399, 1969.

[12]. C. Woodford, C. Philips, "Numerical Methods with Worked Examples: Matlab Edition", springer, second edition, p. 1, 2011.