Application of Controlled Switching for Limitation of Switching Overvoltages on 400 kV Transmission Line

B. Filipović-Grčić, I. Uglešić, S. Bojić, A. Župan

Abstract--**This paper deals with the application of controlled switching technique for limitation of switching overvoltages (SOVs) and transient currents on the 400 kV transmission line with capacitive voltage transformers installed at both ends. Switching off unloaded transmission line and line reclosing was analysed by using EMTP-RV software. The simulation results show that the controlled switching significantly reduces SOVs, current transients and energy stress of station surge arresters.**

***Keywords*: controlled switching, EMTP-RV, switching overvoltages, 400 kV transmission line.**

I. Introduction

SWITCHING overvoltages (SOVs) are of a concern in transmission networks with rated voltages of 400 kV and above, especially regarding long transmission lines. In these high voltage networks the switching impulse withstand voltage of the equipment is about 2-3 p.u., so SOVs must be kept under control [1]. The amplitudes of SOVs during the closing or reclosing of the transmission line depend on the difference between the supply voltage and the line voltage at the instant of energizing, and are related to traveling wave phenomena on the line. For long transmission lines, the severe SOVs may occur in the case of reclosing with trapped charge on the line, usually after clearing of a single-phase fault on the line. Therefore, reclosing occurs with more or less trapped charge corresponding to DC voltage on the healthy phases. Such trapped charge may normally be neglected in cases with inductive voltage transformers connected to the line ends, while in cases with capacitive voltage transformers, the trapped charge may remain on the line for a considerable time, up to several seconds [2]. SOVs caused by reclosing can endanger the external insulation because it has the lowest breakdown strength under overvoltages with front time in the range 50-500 μs, which is typical for SOVs. Therefore, all the equipment designed for operating voltages above 300 kV should be tested under laboratory simulated switching surges [3].

The most used techniques for reducing SOVs are the installation of circuit breakers equipped with closing resistors, controlled switching and application of surge arresters [4-6]. In recent years, several large utilities have experienced problems with the long term mechanical reliability of closing resistor mechanisms (especially in older circuit breakers) with adverse impact on the overall system reliability and have begun to examine alternative approaches to SOV control. The controlled switching is a method for eliminating harmful transients via time controlled switching operations. Closing or opening commands to the circuit breaker are delayed in such a way that switching occurs at the optimum time instant related to the voltage phase angle. The controlled switching has become an economical substitute for a closing resistor and is commonly used to reduce SOVs. The number of installations using controlled switching has increased rapidly due to satisfactory service performance since the late 1990s. Currently, the controlled switching is often specified for shunt capacitor and shunt reactor banks because it can provide several economic benefits such as the elimination of closing resistors and the extension of a circuit breaker nozzle and contact maintenance interval. It also provides various technical benefits such as improved power quality and the suppression of transients in transmission and distribution systems. The controlled switching is also used for switching of unloaded power transformers and it is also gaining acceptance for switching of high voltage transmission lines. The effectiveness of the controlled switching depends on several factors, the most important of which is the circuit breaker operating time consistency. The breakers with a deviation in operating times of less than ±1 ms and with steep rate of decay of dielectric strength are best suited for controlled switching applications [7].

This paper deals with transients caused by switching of uncompensated 400 kV transmission line with capacitive voltage transformers installed at both line ends. The following transients were analysed by using EMTP-RV software: switching off and re-energization of unloaded transmission line. The effect of the controlled switching on reduction of SOVs and transient currents was investigated.

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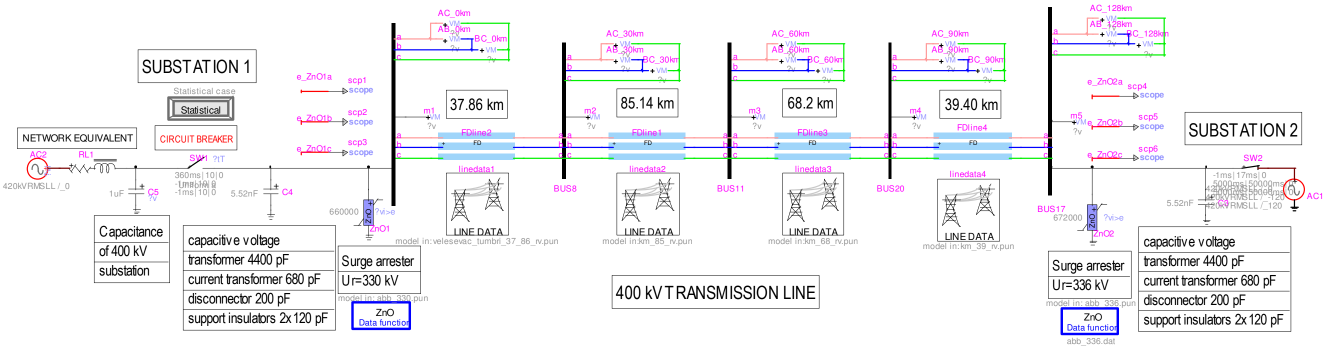

Fig. 1. Model of 400 kV transmission line and substations in EMTP-RV

II. Model in EMTP-RV

EMTP-RV software was used for the simulation of SOVs. Model of 400 kV transmission line and substations in EMTP-RV is shown in Fig. 1. The line considered is a single circuit 231 km long 400 kV line equipped with a two shield wires. Phase conductors are bundled and consist of 2 sub-conductors separated by a distance of 0.4 m. The position of conductors at tower and their average heights above ground are shown in Fig. 2. Characteristics of conductors are given in Table I.

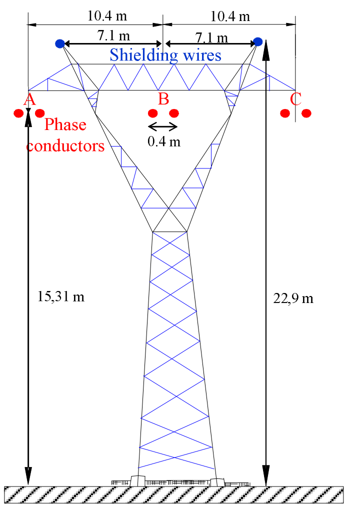

Fig. 2. Conductor arrangement at tower and average heights above the ground

TABLE I
Characteristics of Conductors

Conductors	Phase conductors	Shield wire
Type	Aluminium Conductor Steel Reinforced (ACSR)	Alloy AlMgSi 0.5/Aluminium Clad Steel Conductor (ACSC)
Cross section (mm^2)	490/65	120/70
External diameter (mm)	30.6	18.0
DC resistance (Ω/km)	0.059	0.270

The transmission line was modelled by a frequency dependent model in EMTP-RV software. This model represents the true nature of a transmission line by considering the line parameters as distributed and frequency dependent. The line resistance and inductance are evaluated as functions of frequency, as determined by skin effect and ground return conditions. For soils with a relatively low ground resistivity, in the considered case 100 Ωm, the frequency dependence of soil parameters was not considered since it has only a reduced effect [8]. The insulator flashover was not observed and therefore the frequency dependency of the grounding was not modelled. The phase transpositions of the transmission line have been taken into account. Capacitive voltage transformers are connected at both line ends. The equipment in high voltage substation was represented by surge capacitances obtained from manufacturer's data and from reference [9]. Station surge arresters at both line ends were modelled according to the nonlinear *U–I* characteristics shown in Table II.

TABLE II
Nonlinear U-I Characteristics of Surge Arresters

I (A)	U_r=330 kV (beginning of the line)	U_r=336 kV (end of the line)
	U (kV)	
100	593	604
500	627	639
1000	644	656
2000	667	679
3000	684	696

The equivalent 400 kV network was modelled by a voltage source behind Thevenin equivalent impedance. The parameters of the equivalent network, determined from short circuit currents at 400 kV level, are shown in Table III.

TABLE III
Parameters of the Equivalent Network

Source voltage (line voltage)	420 kV
Positive sequence resistance	0.81 Ω
Zero sequence resistance	2.09 Ω
Positive sequence inductance	30.99 mH
Zero sequence inductance	47.65 mH

III. Energization of Unloaded Transmission Line

A. *Uncontrolled energization of unloaded transmission line*

The international standard [1] gives the typical values of $U_{2\%}$ SOVs, i.e. the values of the phase-to-ground overvoltages having a 2% probability of being exceeded. Switching operations such as line energization and re-closure or circuit breaker opening due to a phase-to-ground fault are considered to be producing a large magnitude of SOVs. In order to obtain $U_{2\%}$ overvoltage profiles along the line length, the statistical calculation of SOVs was performed. The circuit breaker mechanism closes the contacts at high speed and mechanical tolerances give a spread of closing times between three phases. The line was energized through the statistic switches of EMTP-RV software and 500 switching operations were performed in substation 1. The closing time of a statistic switch is randomly selected according to a uniform probability distribution, with mean closing time 10 ms and the standard deviation σ=2 ms. Phase-to-ground and phase-to-phase SOVs were calculated at the line ends and at three points along the line (Figs. 3 and 4). Figs. 5 and 6 show SOVs at both line ends in case of maximum phase-to-ground overvoltage 2.198 p.u. along the transmission line length.

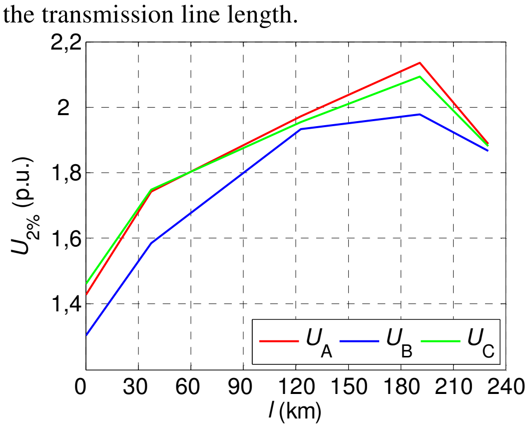

Fig. 3. $U_{2\%}$ phase-to-ground SOV profiles along the transmission line length (uncontrolled energization)

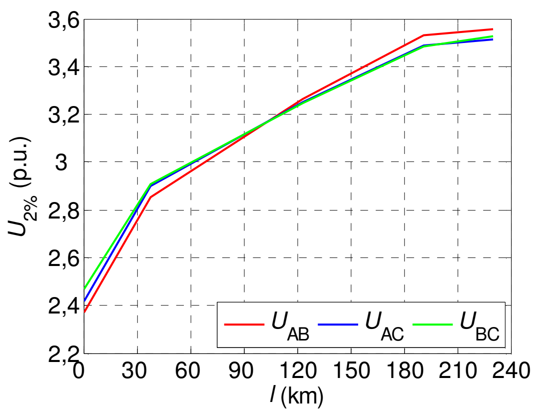

Fig. 4. $U_{2\%}$ phase-to-phase SOV profiles along the transmission line length (uncontrolled energization)

Voltages at the open end of the line shown in Fig. 6 have higher values in steady state compared to voltages at the beginning of the line shown in Fig. 5, due to Ferranti effect. In transient state, SOVs are higher at the open-end of the line due to reflection of travelling voltage waves and they are limited by surge arresters. Energy stress of station surge arresters at the end of the transmission line are shown in Fig. 7. Maximum energy stress is equal to 311 kJ.

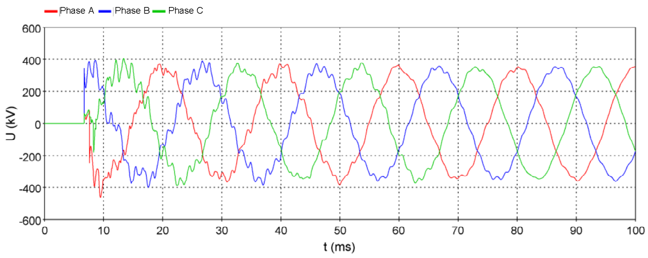

Fig. 5. SOVs at the beginning of the line (uncontrolled energization)

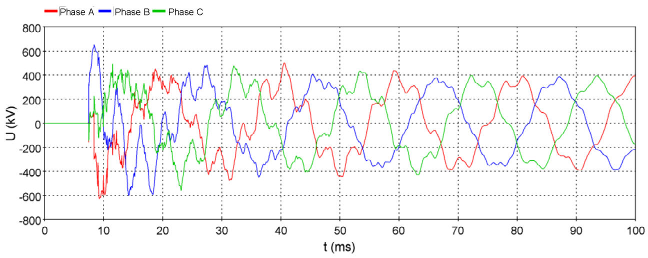

Fig. 6. SOVs at the end of the line (uncontrolled energization)

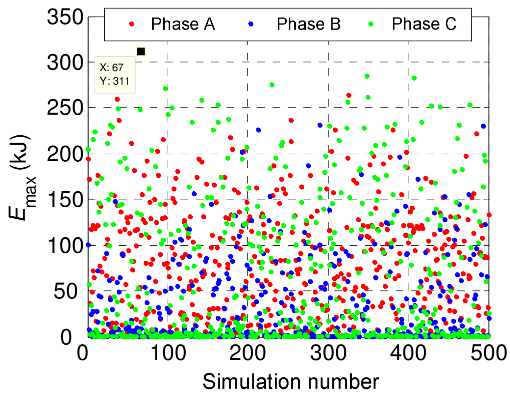

Fig. 7. Energy stress of station surge arresters at the end of transmission line (uncontrolled energization)

The energization of an unloaded transmission line produces high frequency transients which may have substantial current amplitudes. The energization at unfavourable time instant corresponding to peak voltage value was simulated. Fig. 8 shows currents when energizing unloaded transmission line.

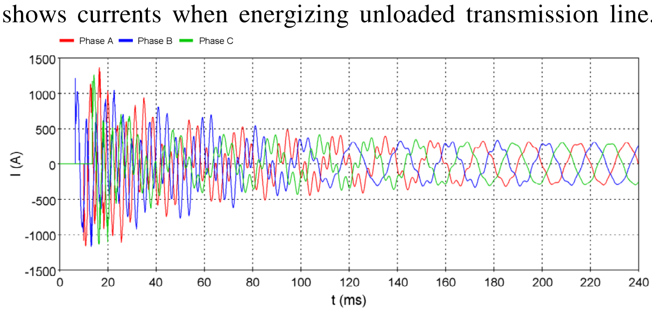

Fig. 8. Currents caused by uncontrolled energization of transmission line (I_{maxA}=1365.9 A, I_{maxB}=1213.8 A, I_{maxC}=1263.5 A)

B. *Controlled energization of unloaded transmission line*

The controlled energization at optimum instants of circuit breaker poles closing at voltage zero-crossing was simulated. The closing time of a statistic switch is randomly selected according to a uniform probability distribution, with closing times t_A=5 ms, t_B=11.7 ms, t_C=8.3 ms and the standard deviation σ=0.3 ms.

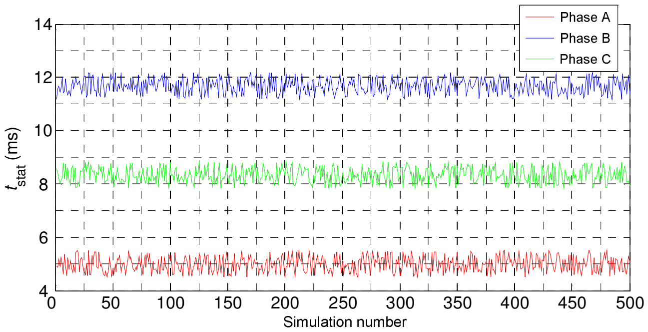

Fig. 9. Closing time of a circuit breaker contacts for 500 switching operations

Phase-to-ground and phase-to-phase SOV profiles along the transmission line length are shown in Figs. 10 and 11.

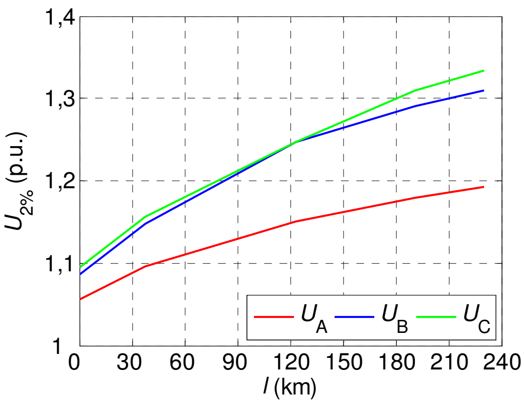

Fig. 10. $U_{2\%}$ phase-to-ground SOV profiles along the transmission line length (controlled energization)

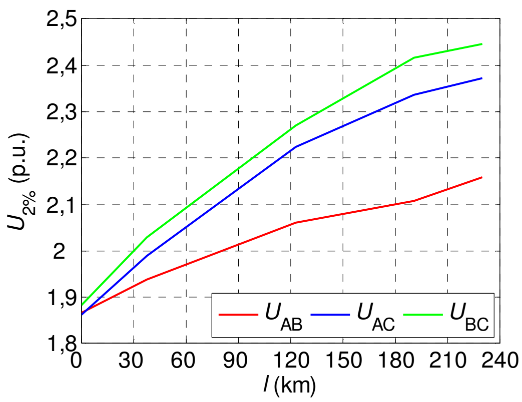

Fig. 11. $U_{2\%}$ phase-to-phase SOV profiles along the transmission line length (controlled energization)

Figs. 12 and 13 show SOVs at both line ends in case of maximum phase-to-ground overvoltage 1.36 p.u. along the transmission line length. The maximum energy stress of station surge arresters at the end of the line is reduced from 311 kJ in case of uncontrolled switching (Fig. 7) to 31 J in case of controlled switching (Fig. 14). The significant reduction of energy stress is the consequence of controlled switching which effectively reduces SOVs at the line end.

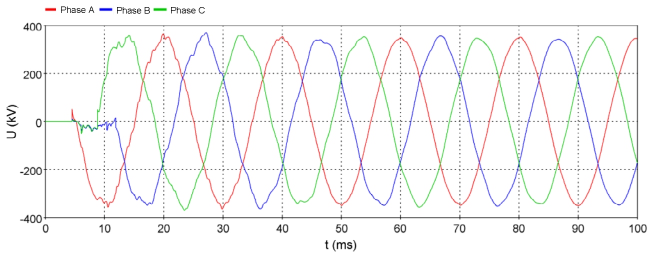

Fig. 12. SOVs at the beginning of the line (controlled energization)

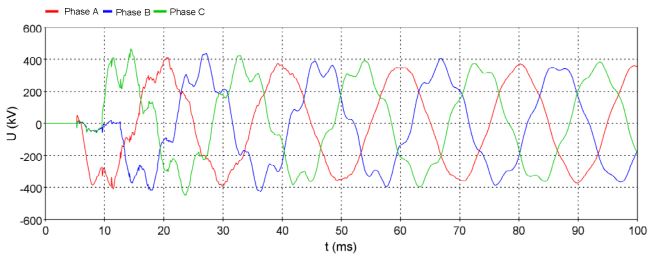

Fig. 13. SOVs at the end of the line (controlled energization)

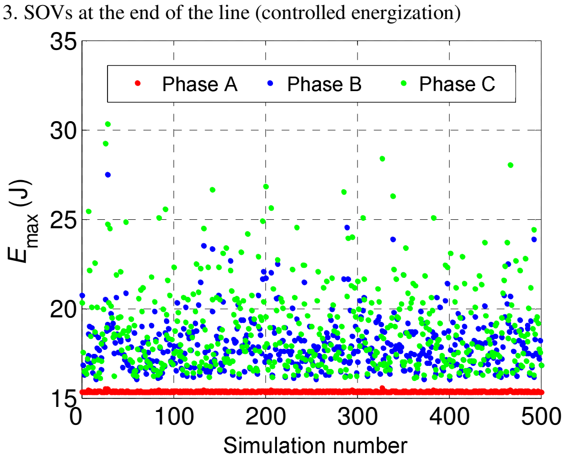

Fig. 14. Energy stress of station surge arresters at the end of transmission line (controlled energization)

Fig. 15 shows currents when energizing unloaded transmission line at optimum instants of circuit breaker poles closing at voltage zero-crossing. Table IV shows a comparison between controlled and uncontrolled energization of the unloaded transmission line with respect to current amplitudes.

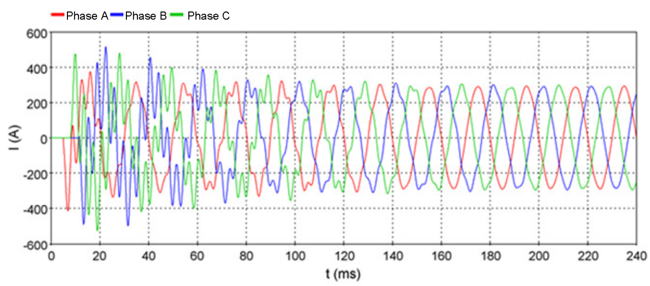

Fig. 15. Currents caused by controlled energization of transmission line (I_{maxA}=-415.5 A, I_{maxB}=-513.7 A, I_{maxC}=-528.2 A)

TABLE IV
CURRENT AMPLITUDES CAUSED BY ENERGIZATION OF UNLOADED TRANSMISSION LINE

	I_A	I_B	I_C
Uncontrolled energization	1365.9 A	1213.8 A	1263.5 A
Controlled energization	-415.5 A	-513.7 A	-528.2 A

IV. SINGLE-PHASE AUTORECLOSURE OF TRANSMISSION LINE

A. *Uncontrolled single-phase autoreclosure*

In the case of the transmission line with a capacitive voltage transformers connected at both ends, no leakage path exists for the trapped charge. Fig. 16 shows voltages at substation 2 (end of transmission line) in case of uncontrolled reclosing in phase A from the substation 1 (beginning of the line). After switching off phase A at *t*=20 ms a trapped charge of positive polarity remains on the line. Contact closing occurs at voltage peak on the source side of the opposite polarity to the trapped charge (*t*=350 ms). This represents the most severe case of uncontrolled autoreclosure.

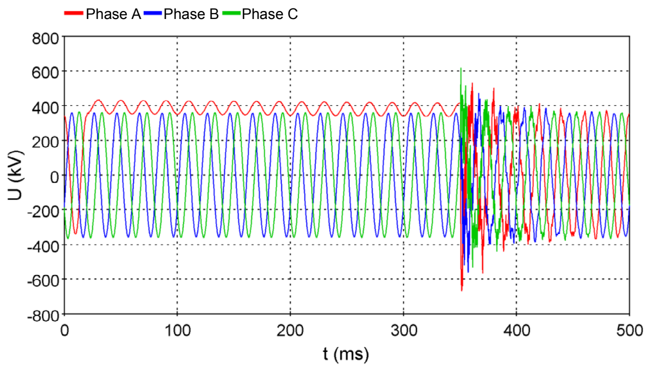

Fig. 16. Voltages at the end of transmission line in case of uncontrolled reclosing in phase A from the beginning of the line

Fig. 17 shows energy stress of surge arresters at the end of the line for the case shown in Fig 16.

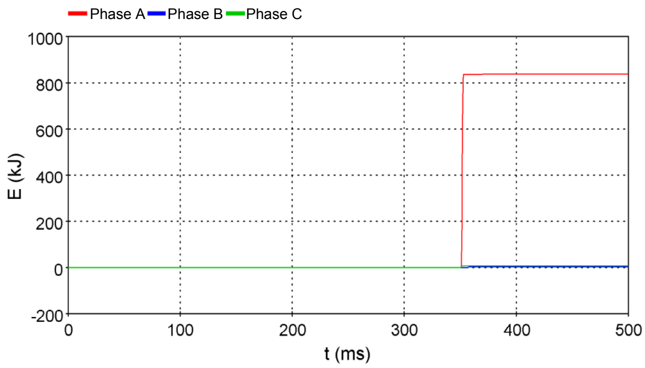

Fig. 17. Energy stress of station surge arresters at the end of transmission line

The reclosing time is randomly selected according to a uniform probability distribution, with mean closing time 350 ms and the standard deviation σ=2 ms. 500 reclosing operations were simulated. Phase-to-ground and phase-to-phase SOV profiles along the transmission line length are shown in Figs. 18 and 19. Energy stress of station surge arresters at the end of the transmission line are shown in Fig. 20.

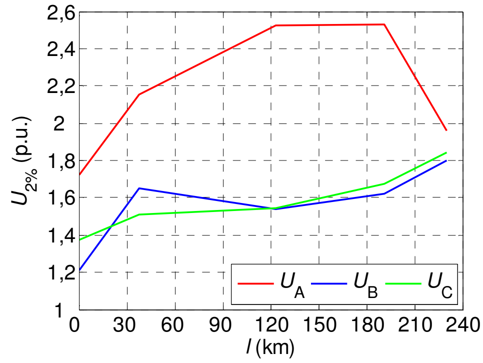

Fig. 18. $U_{2\%}$ phase-to-ground SOV profiles along the transmission line length (uncontrolled reclosing)

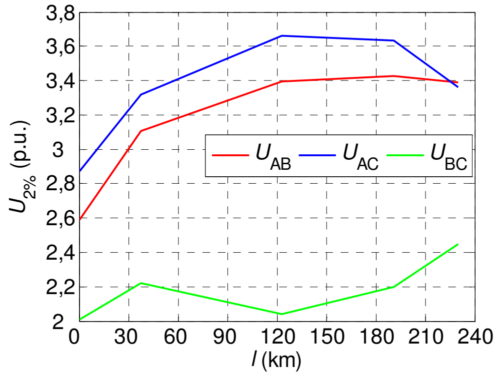

Fig. 19. $U_{2\%}$ phase-to-phase SOV profiles along the transmission line length (uncontrolled reclosing)

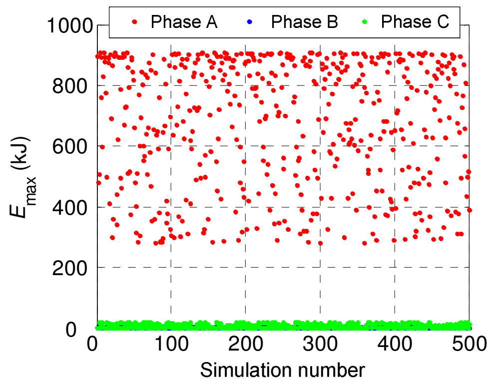

Fig. 20. Energy stress of station surge arresters at the end of transmission line (uncontrolled reclosing)

B. *Controlled single-phase autoreclosure*

The optimum instant of circuit breaker switching is the voltage peak on the source side of the same polarity as the trapped charge (*t*=360 ms). Fig. 21 shows voltages at the end of the transmission line in case of controlled reclosing in phase A from the beginning of the line. Fig. 22 shows energy stress of surge arresters at the end of the line for the case shown in Fig 21. The maximum energy stress of station surge arresters at the end of the line is reduced from 950 kJ in case of uncontrolled reclosing (Fig. 20) to 270 J in case of controlled reclosing (Fig. 22). The significant reduction of energy stress is the consequence of controlled reclosing which effectively reduces SOVs at the line end.

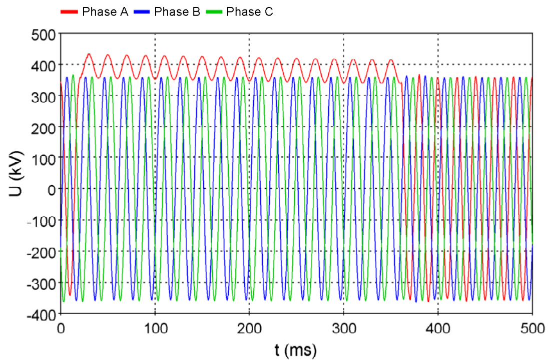

Fig. 21. Voltages at the end of transmission line in case of controlled reclosing in phase A from the beginning of the line

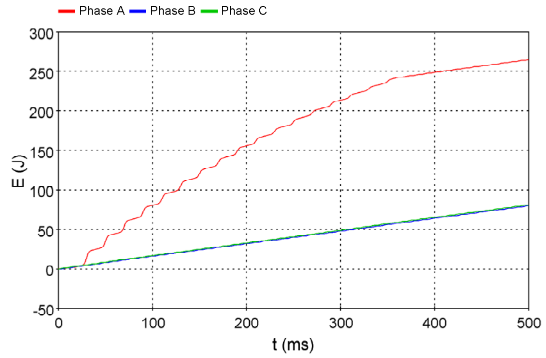

Fig. 22. Energy stress of station surge arresters at the end of transmission line

V. Reliability of the Controlled Switching

A crucial aspect of circuit breaker performance in the application of controlled switching is the level of predictability in its arcing contact closing and opening operating times. A circuit breaker with a high consistency in its operating times, within a reasonable range of operating conditions, is preferable for controlled switching applications as such performance greatly simplifies the implementation of controlled switching. Statistical variations in the electrical characteristics of a circuit breaker will exist even in the absence of mechanical operating time variations. However, mechanical operation "scatter" inherently affects electrical characteristics and hence is a fundamentally important characteristic in the application of a circuit breaker for controlled switching. Reference [10] summarizes the factors that can influence circuit breaker operating time, including: type of stored energy (i.e. spring, pressurized fluid), control voltages, ambient temperature, accumulated number of operations, ageing effects and intervals between successive operations. Maximum scatter of breaker operating times is used in the simulations to consider the worst case regarding SOVs.

VI. Conclusions

This paper deals with the effect of controlled switching on the reduction of SOVs and currents on uncompensated 400 kV transmission line with capacitive voltage transformers installed at both line ends. The energization and autoreclosure of unloaded line were analysed using EMTP-RV software.

The simulation results showed that controlled energization of the unloaded transmission line reduces $U_{2\%}$ phase-to-ground SOV profiles along the line length in the range 0.2183 p.u. – 0.9552 p.u. in relation to uncontrolled energization. $U_{2\%}$ phase-to-phase SOV profiles are reduced along the line length in the range 0.5019 p.u. – 1.4217 p.u. The maximum energy stress of station surge arresters at the end of the line is reduced from 311 kJ in case of uncontrolled switching to 31 J in case of controlled switching. The energization of an unloaded transmission line produces high frequency transients which have substantial current amplitudes. The controlled energization reduces current amplitudes up to 70%.

The controlled single-phase autoreclosure of transmission line reduces $U_{2\%}$ phase-to-ground SOV profiles at the end of the line in the range 0.6952 p.u. – 1.2650 p.u. in relation to uncontrolled autoreclosure. $U_{2\%}$ phase-to-ground SOV profiles at the end of the line are reduced in the range 0.6323 p.u. – 1.2419 p.u. The significant reduction of energy stress of station surge arresters is the consequence of controlled reclosing which effectively reduces SOVs at the line end.

The simulation results showed that the controlled switching significantly reduces both SOVs, current transients and energy stress of station surge arresters in case of the transmission line energization and autoreclosure. Consequently, the controlled switching reduces the mechanical and electromagnetic stresses of the high voltage equipment and also prevents the unwanted operation of relay protection.

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