Electric Power Systems Research 140 (2016) 830–835

Contents lists available at ScienceDirect

Electric Power Systems Research

journal homepage: www.elsevier.com/locate/epsr

Application of line surge arresters for voltage uprating and compacting of overhead transmission lines

Božidar Filipović-Grčić*, Ivo Uglešić, Ivica Pavić

Faculty of Electrical Engineering and Computing, University of Zagreb, 10000 Zagreb, Croatia

ARTICLE INFO

Article history:
Received 16 January 2016
Received in revised form 17 March 2016
Accepted 27 April 2016
Available online 11 May 2016

Keywords:
Switching overvoltages
Uprated transmission line
Line surge arrester
EMTP-RV
Risk of flashover
Compacting transmission lines

ABSTRACT

This paper discusses the possibility of using line surge arresters (LSAs) for the reduction of switching overvoltages (SOVs) on voltage uprated transmission lines. The method for the selection of LSA energy class and determination of optimum installation locations was proposed. The method was applied in case of improving the overvoltage protection of the transmission line uprated from 220 kV to 400 kV.

The possibility of compacting a 400 kV transmission line by installing LSAs was considered. Since a risk of flashover increases due to the reduction of insulation clearances, an algorithm that estimates the risk of flashover was developed and applied in case of compacting a 400 kV transmission line.

1. Introduction

In recent years, with the increase of power demand, the need for transmitting large amounts of power over long distances has also increased. The uprating of existing overhead transmission lines has become a popular option for electric utilities to address the increasing demand for power [1,2]. Uprating the transmission lines by increasing voltage allows a considerable increase in power transfer capability, but consequently it increases switching overvoltages (SOVs) which makes them one of the main factors in the insulation coordination of high voltage transmission lines and substations.

SOVs are of a concern in transmission networks with rated voltages of 420 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 have to be kept under control [3]. The amplitudes of SOVs during the closing or re-closing 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 most severe SOVs occur in the case of three-phase reclosing with trapped charge on the line. Three-phase reclosing normally occurs after the clearing of a single-phase or three-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 [4]. SOVs 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 equipment designed for operating voltages above 300 kV should be tested under laboratory simulated switching surges [5].

The most used techniques for reducing SOVs are the installation of circuit breakers equipped with closing resistors, controlled switching and application of surge arresters [6,7]. 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 effectiveness of controlled switching depends on several factors, the most important of which is the circuit breaker operating time consistency [8]. 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 [9].

This paper presents the method of uprating and compacting overhead transmission lines by installing LSAs. The method consists of two parts: (1) selection of LSA energy class and determination of optimum installation locations for controlling SOVs and

* Corresponding author. Tel.: +385 1 6129 714; fax: +385 1 6129 890.
E-mail addresses: bozidar.filipovic-grcic@fer.hr (B. Filipović-Grčić), ivo.uglesic@fer.hr (I. Uglešić), ivica.pavic@fer.hr (I. Pavić).

http://dx.doi.org/10.1016/j.epsr.2016.04.023

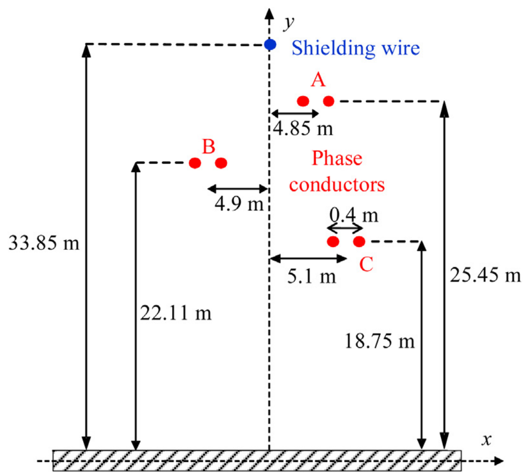

Fig. 1. Conductor arrangement at tower and average heights above the ground.

(2) estimation of risk of insulation flashover when reducing the insulation clearances. The method was applied in case of uprating the existing 220 kV transmission line to 400 kV and in case of compacting the 400 kV transmission line.

2. Description of model in EMTP-RV software

2.1. Transmission line

EMTP-RV software was used for the simulation of SOVs. The line considered is a single circuit 220 kV line equipped with a single shield wire, uprated to 400 kV without major modifications of the design of the towers. Phase conductors are bundled and consist of 2 sub-conductors separated by a distance of 0.4 m. The line is 350 km long. The position of conductors at tower and their average heights above ground are shown in Fig. 1. Characteristics of conductors are given in Table 1. The transmission line has an average span length 250 m, average sag length 11.5 m and measured switching impulse withstand voltage of the glass insulator strings 790 kV.

The transmission line was modeled 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 taken into account since it has only a reduced effect. The insulator flashover was not observed and therefore the frequency dependency of the grounding was not modeled. Capacitive voltage transformers are connected at line ends. In this case, the level of SOVs in some cases may exceed the switching withstand voltage of the insulator strings.

Table 1
Characteristics of conductors.

Conductors	Phase conductors	Shield wire
Type	Aluminum Conductor Steel Reinforced (ACSR)	Alloy AlMgSi 0.5/Aluminum Clad Steel Conductor (ACSC)
Cross section (mm^2)	490/65	95/55
External diameter (mm)	30.6	16.0
DC resistance (Ω/km)	0.059	0.3412

Table 2
Parameters of the equivalent network.

Source voltage (line voltage)	420 kV
Positive sequence resistance	2.71 Ω
Zero sequence resistance	6.17 Ω
Positive sequence inductance	89.55 mH
Zero sequence inductance	127.93 mH

Table 3
Nonlinear U–I characteristics of surge arresters.

I (A)	U (kV)	
	Energy class 4	Energy class 3
100	593	605
300	616	629
500	627	634
700	635	648
900	642	653
1000	644	654
2000	667	680
3000	684	706

2.2. Equivalent network and surge arresters

The equivalent 400 kV network was modeled 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 2.

Surge arresters were modeled according to the nonlinear U–I characteristics shown in Table 3.

Surge arresters with rated voltage U_r = 330 kV and energy classes 3 (7.8 kJ/kV) and 4 (12 kJ/kV) were considered in simulations.

2.3. Computations of switching overvoltages in EMTP-RV

The international standard [3] gives the typical values of $U_{2\%}$ SOVs, i.e. the values of the phase-to-earth overvoltages having a 2% probability of being exceeded. Switching operations such as line energization and re-closure or circuit breaker opening due to a line-to-ground fault are considered to be producing a large magnitude of SOVs. The most severe SOVs will occur in case of three-phase reclosing with trapped charge present on the line. Therefore, this case was considered in the statistical overvoltage analysis.

In order to obtain $U_{2\%}$ overvoltage profiles along the line length, the statistical calculation of SOVs was performed. The circuit for simulation of three-phase reclosing with trapped charge is shown in Fig. 2.

Voltage sources at the end of the line with amplitude of 1 p.u., corresponding to the maximum system AC voltage of 420 kV, are switched off by CB 2 at t = 20 ms. The maximum trapped charge of 1.18 p.u. remains in the phase A which is firstly switched-off due to the electromagnetic coupling of the other phases and due to the Ferranti effect. The voltages at the end of the line during the three-phase reclosing with trapped charge and without surge arresters are shown in Fig. 3.

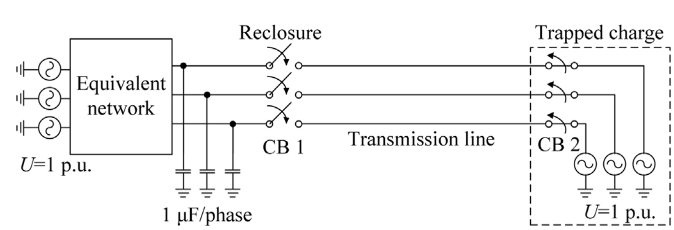

Fig. 2. Equivalent circuit for the simulation of three-phase reclosing with trapped charge.

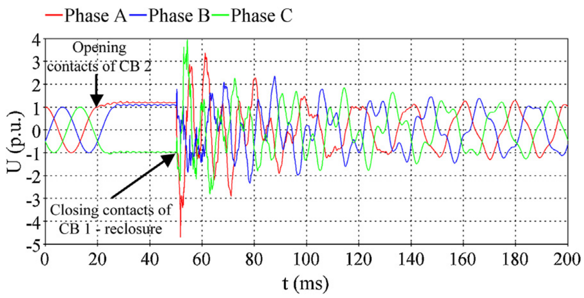

Fig. 3. Voltages at the end of the line during three-phase reclosing with trapped charge present on the line.

The values of trapped charge magnitudes were varied from −1.18 p.u. to 1.18 p.u. in all phases, and in each case, the overvoltage amplitudes were determined. When the trapped charge values were set as 1.18 p.u., 1.05 p.u. and −1 p.u. in phases A, B and C, respectively, a maximum SOV amplitude 4.7 p.u. occurred if line is reclosed at t = 50 ms, which corresponds to −1 p.u. voltage in phase A. Hence, this case was considered in the calculations since it represents the worst case regarding SOVs.

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 each considered case. The closing time of a statistic switch is randomly selected according to a uniform probability distribution, with mean closing time 50 ms and the standard deviation σ = 1.4 ms. SOVs were calculated at 35 points along the line (each 10 km), including the line ends.

The $U_{2\%}$ overvoltage profiles along the line were determined for the following cases:

(a) without surge arresters;
(b) surge arresters at line ends only;
(c) surge arresters at line ends and up to five LSAs at optimally determined locations.

3. Method for selection of surge arrester energy class and determination of optimum installation locations

The use of LSAs is an effective technique in controlling SOVs [10,11]. Fig. 4 shows SOV profile along the transmission line length in case when surge arresters are installed at line ends and at 240 km.

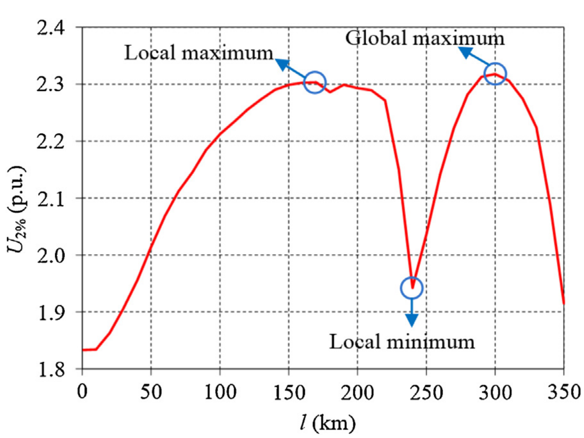

Fig. 4. $U_{2\%}$ switching overvoltage profile along the transmission line length in case when surge arresters are installed at three locations.

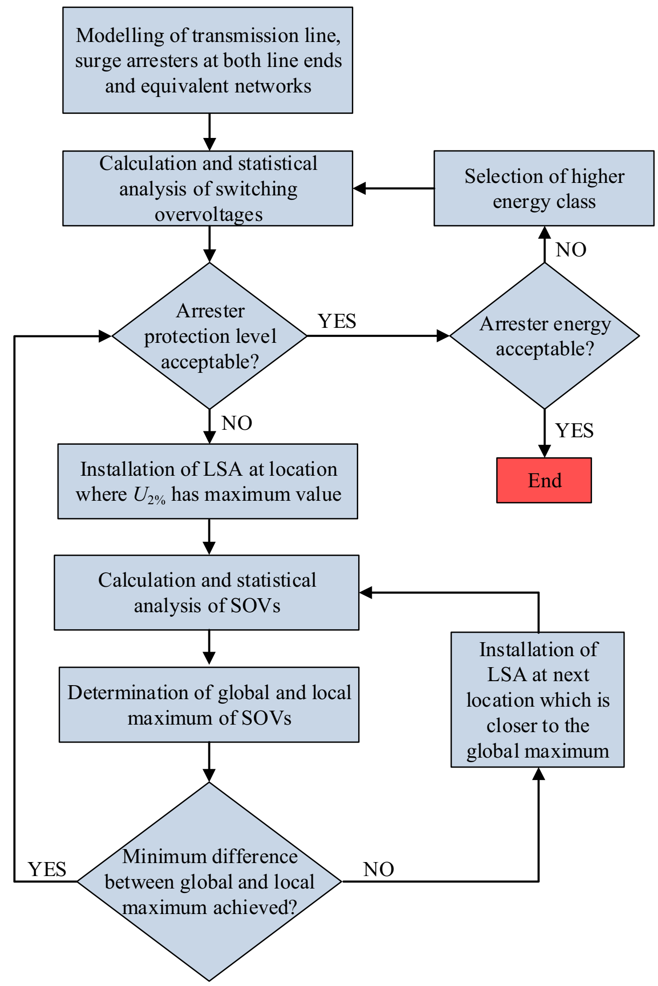

Fig. 5. Flowchart of the method for the selection of surge arrester energy class and optimum installation locations due to SOVs.

The local minimum of SOVs along the transmission line length appears at the location of LSA installation, while the maximums appear at both sides of the local minimum (Fig. 4). One is the global maximum and the other one is the local maximum. The optimum location for LSA installation is obtained when the global maximum reaches its minimum value, i.e. when the global and local maximums are almost equal. Fig. 5 shows the flowchart of the proposed method for the selection of surge arrester energy class and the determination of optimum installation locations with respect to SOVs.

Matlab software (M-file) was used for running multiple EMTP-RV simulations of SOVs, the selection of surge arrester energy class and optimum installation locations according to Fig. 5.

4. Calculation results

Figs. 6 and 7 show the calculated phase-to-ground and phase-to-phase overvoltage profiles for seven different cases of surge arrester installation.

The calculation results show that high SOVs occur in case of the three-phase reclosing of the transmission line. By installing the LSAs at five optimum locations on the transmission line the maximum $U_{2\%}$ phase-to-earth SOVs decreased by 236 kV and the maximum $U_{2\%}$ phase-to-phase SOVs decreased by 212 kV. Fig. 8 shows the reduction of SOVs along the transmission line length after the installation of five LSAs in relation to case when surge arresters are installed only at both line ends.

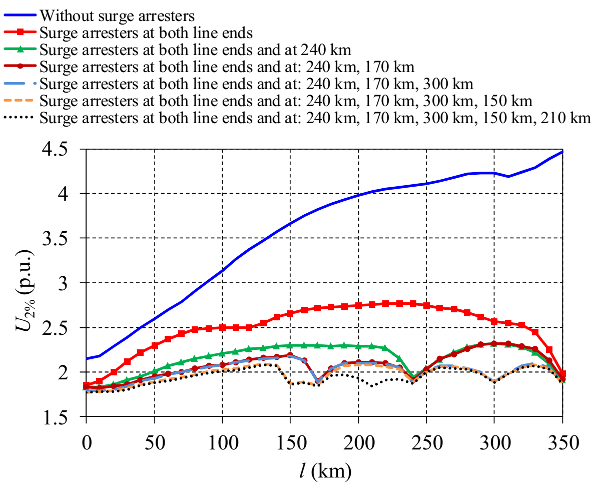

Fig. 6. Calculated phase-to-ground SOV profiles.

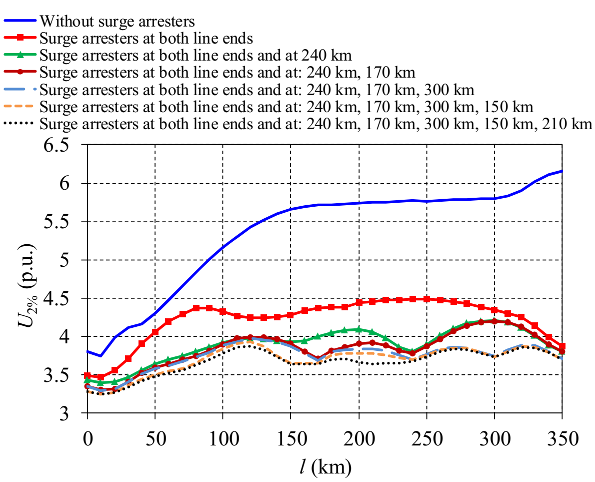

Fig. 7. Calculated phase-to-phase SOV profiles.

The insulation clearance requirements for the uprated line must be fulfilled for power frequency, lightning and switching overvoltages. The clearance requirements for each operating voltage level are specified in [12]. It should be noted that for the operating voltage levels higher than 245 kV, the amplitude of SOVs is the dominant factor in specifying the clearance requirements [13]. In most of the cases, the clearance requirements for SOVs are either equal or more than the clearance requirements for corresponding

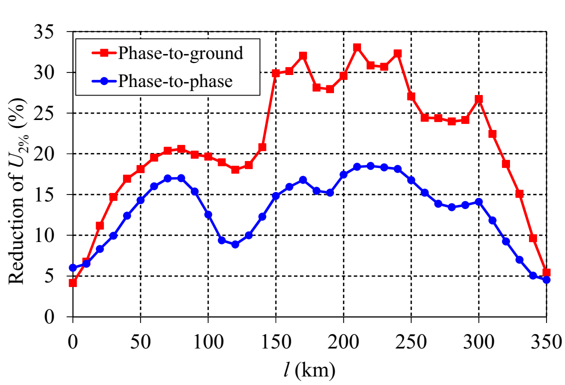

Fig. 8. Percent reduction of $U_{2\%}$ after installation of five LSAs in relation to case when surge arresters are installed only at both line ends.

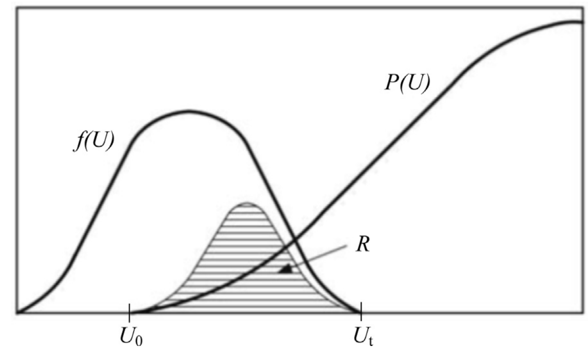

Fig. 9. Evaluation of the risk of failure [3].

lightning overvoltages. Hence, a reduction in SOV level would lead to a noticeable reduction in clearance requirements.

The switching impulse withstand voltage of insulator strings on the existing 220 kV transmission line is equal to 790 kV and this value was obtained from the wet switching impulse voltage test performed in a high voltage laboratory. The calculation results showed that if surge arresters are installed at both line ends and LSAs at only three locations phase-to-ground SOVs reduced to 748 kV, which is lower than the switching withstand voltage 790 kV of the insulator strings. The amplitude of phase-to-phase SOVs reduced to 1362 kV and this is significantly lower than the phase-to-phase switching withstand voltage of the line.

The calculation results showed that the energy stress of station surge arresters reduces with installation of LSAs. Therefore, the following energy classes could be selected in the following scenarios of surge arrester installation:

- surge arresters at both line ends: energy class 4;
- surge arresters at both line ends (energy class 3) and at two locations on the transmission line (energy class 2);
- surge arresters at both line ends (energy class 2) and at three or more locations on the transmission line (energy class 2).

4.1. Risk of insulation flashover due to SOVs

The insulation level and the cost of the transmission lines and other equipment depend on the magnitudes of SOVs. Therefore, the calculation of SOVs and estimation of risk of insulation failure is fundamental for an appropriate insulation design. Once the frequency distribution of the overvoltages and the corresponding breakdown probability distribution of the insulation are determined, the risk of failure of the insulation can be calculated as follows [3]:

$$R = \int_0^{\infty} f(U) \cdot P(U) dU, \tag{1}$$

where $f(U)$ is the probability density of SOVs and $P(U)$ is the probability of flashover of the insulation under a switching impulse of value U. The evaluation of the risk of failure is shown in Fig. 9 [3].

U_t represents the truncation value of the overvoltage probability distribution and U_0 the truncation value of the discharge probability distribution, which can be determined by:

$$U_0 = U_{50} - 3 \cdot \sigma, \tag{2}$$

where U_{50} represents the value of the 50% discharge voltage of self-restoring insulation and σ represents the conventional deviation which shows the scatter of flashover voltages. For tower insulation, a 5% conventional deviation was assumed according to [14,15]. The statistical withstand voltage of the insulation U_{10}, which represents

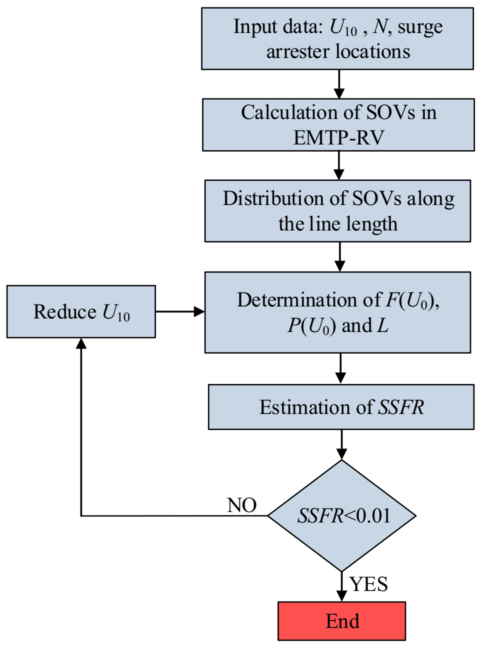

Fig. 10. Flowchart of the algorithm for estimation of SSFR.

the value of the 10% discharge voltage of self-restoring insulation, can be determined from:

$$U_{10} = U_{50} - 1,3 \cdot \sigma. \quad (3)$$

Since the risk of insulator flashover increases with the reduction of insulation clearances, an algorithm that estimates the switching surge flashover rate (SSFR) was developed according to [3,14]. SSFR can be estimated by using the following expression:

$$\text{SSFR} = F(U_0) \cdot P(U_0) \cdot L \cdot N, \quad (4)$$

where $F(U_0)$ represents the cumulative distribution of maximum SOVs above U_0 obtained from EMTP simulations; $P(U_0)$ represents the breakdown voltage distribution of the insulation for voltages less or equal to U_0; L represents the length of the line where the voltage is above U_0; N represents the number of towers per kilometer of line length.

Fig. 10 shows the flowchart of the algorithm for the estimation of SSFR.

The algorithm from Fig. 10 was applied in case of compacting the previously described 400 kV transmission line. The aim was to reduce the insulation clearances e.g. lower the withstand voltage U_{10} of the transmission line insulators as much as possible, while keeping SSFR within the acceptable limits. Acceptable SSFR for overhead transmission lines lies in the range 0.01–0.001 per circuit breaker operation [3]. For each case of the optimally determined surge arrester locations by using the previously proposed method (Fig. 5), the lowest U_{10} of the insulator strings was determined while keeping SSFR within the acceptable limits. Fig. 11 shows the distribution of the maximum phase-to-ground SOVs in the case with surge arresters installed only at both line ends.

The lowest withstand voltage U_{10} = 3.05 p.u. (U_0 = 2.81 p.u., U_{50} = 3.3 p.u., σ = 0.165) was determined with acceptable SSFR.

Fig. 12 shows the cumulative frequency distribution of the maximum phase-to-ground SOVs above U_0 at 260 km (Fig. 11).

Fig. 13 shows the breakdown voltage distribution $P(U)$ of the insulator string with U_{50} = 3.3 p.u. and the corresponding probability density of breakdown voltage $p(U)$.

Finally, SSFR = 0.0045 was determined for the case with surge arresters installed only at both line ends. The same procedure was applied for different cases of surge arrester installation. Fig. 14 shows the estimated risk of flashover per breaker operation as a function of U_{10} for a different number of surge arresters installed at optimally determined locations along the line to control SOVs.

It can be seen that SSFR increases with the reduction of withstand voltage U_{10}. In the case of arresters installed only at line ends, the minimum required withstand voltage is 3.05 p.u. (1046 kV), with acceptable risk of flashover. With five additional LSAs along the line, the necessary withstand voltage decreases to 2.25 p.u. (772 kV). Therefore, by installing LSAs it is possible to reduce the required switching impulse withstand voltage of the insulator

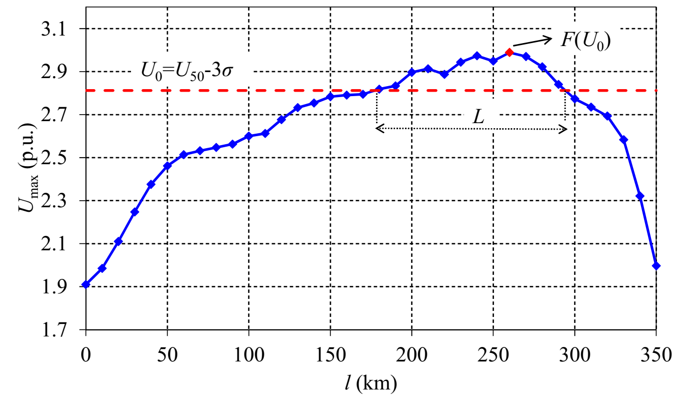

Fig. 11. Maximum phase-to-ground SOVs along the line length in the case with surge arresters installed only at both line ends.

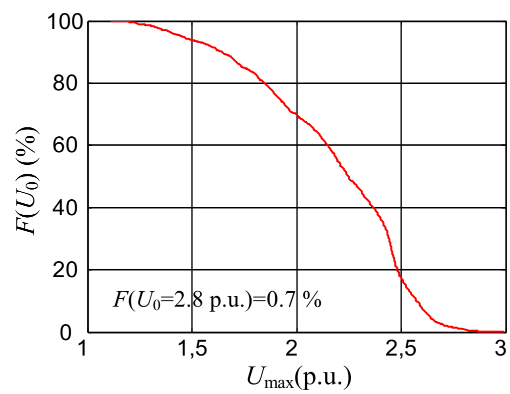

Fig. 12. Cumulative distribution of maximum phase-to-ground SOVs above U_0 (at 260 km).

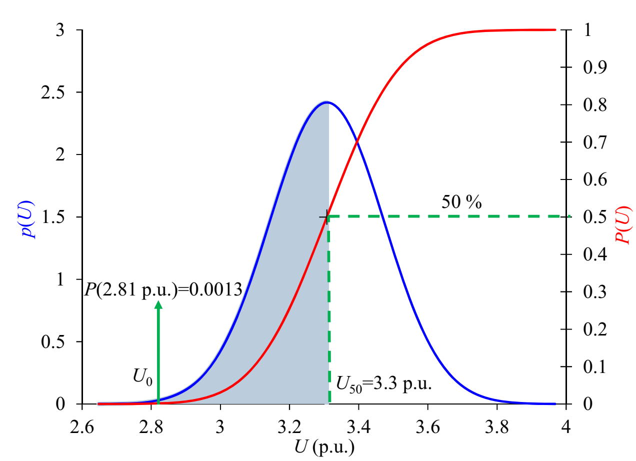

Fig. 13. Breakdown voltage distribution $P(U)$ of the insulator string with U_{50} = 3.3 p.u.

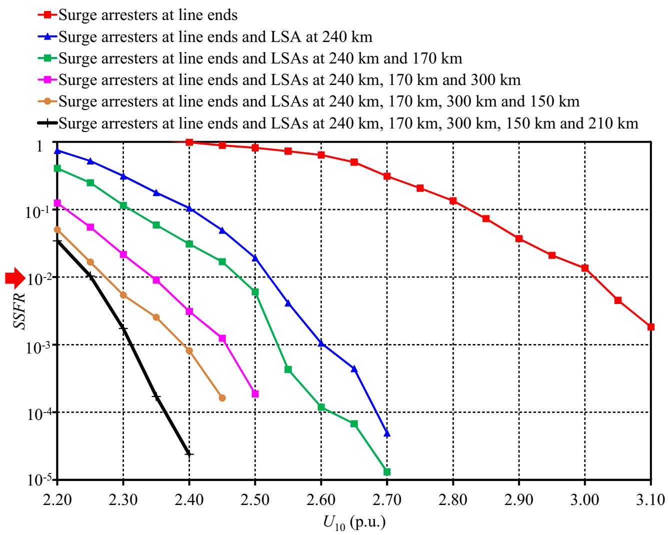

Fig. 14. Estimated risk of flashover as a function of U_{10}.

strings on 400 kV transmission line, with an acceptable level of risk of flashover. However, the expected switching impulse performance of insulators is not the sole criterion for reducing the insulation clearances of an uprated line, since insulators should be dimensioned for an acceptable level of flashover performance based on the creepage distance requirements, depending on pollution level. Also, there are many other items to consider besides SOVs, such as lightning overvoltages, before a real uprating of transmission line may take place. However, SOVs are of major concern in 400 kV networks and the method proposed in this paper solves efficiently this problem for both uprated and compact transmission lines. After installing LSAs and reducing SOVs to an acceptable level, lightning overvoltages should be considered. The amplitudes of lightning overvoltages depend on many parameters such as tower footing resistance, tower configuration, shielding wires and lightning activity around the transmission line, which are specific for each transmission line. Lightning overvoltages can be efficiently reduced by installing LSAs on critical towers based on the information about the tower footing resistance and lightning activity recorded by the lightning location system.

5. Conclusion

The paper describes the method for selection of surge arrester energy class and optimum installation locations due to SOVs. The method was applied in the case of uprating 350 km long transmission line from 220 kV to 400 kV. The calculation results showed that the transmission line could be uprated if surge arresters are installed at both line ends and at three optimally determined locations along the line. With the installation of additional LSAs the energy stresses of station surge arresters reduced and thus the lower energy class can be selected.

An algorithm that estimates the risk of flashover due to SOVs was developed and applied in case of compacting the 400 kV transmission line. The calculation results showed that the switching impulse withstand voltage of insulator strings could be reduced with an acceptable level of risk of flashover. By LSAs at five optimally determined locations, the maximum phase-to-earth SOVs decreased by 236 kV and the maximum phase-to-phase SOVs decreased by 212 kV. The statistical switching withstand voltage of the transmission line insulators decreased by 274 kV with an acceptable risk of flashover.

The advantage of the proposed method is that it enables the voltage uprating and compacting of overhead transmission lines with high SOVs, by installing a minimum number of LSAs, while keeping the risk of flashover within acceptable limits.

Acknowledgements

This work has been supported in part by the Croatian Science Foundation under the project "Development of advanced high voltage systems by application of new information and communication technologies" (DAHVAT).

References

[1] S. Venkatesan, A. Haddad, H. Griffiths, N. Harid, M. Albano, Reducing air clearance requirements for voltage uprating of overhead line by use of line surge arresters, in: IEEE Conference on Electrical Insulation and Dielectric Phenomena, VA, USA, 2009, pp. 224–229.
[2] R. Bhattarai, A. Haddad, H. Griffiths, N. Harid, Voltage uprating of overhead transmission lines, in: 45th International Universities Power Engineering Conference (UPEC), Cardiff, United Kingdom, 2010, pp. 1–6.
[3] International Electrotechnical Commission, IEC 60071-2, Insulation Co-Ordination – Part 2: Application Guide, 3rd ed., 1996.
[4] B. Filipović-Grčić, I. Uglešić, S. Bojić, Analysis of transient recovery voltage on SF6 circuit breakers when switching unloaded 400 kV transmission lines, in: The 12th International Symposium on High-Voltage Technique "Höfler's Days", Portorož, Slovenia, November 2015, 2015.
[5] E. Kuffel, W.S. Zaengl, J. Kuffel, High Voltage Engineering: Fundamentals, 2nd ed., Newnes, Great Britain, 2000, August.
[6] P. Mestas, M.C. Tavares, Comparative analysis of techniques for control of switching overvoltages during transmission lines energization, Electr. Power Syst. Res. 80 (January (1)) (2010) 115–120.
[7] I. Uglešić, B. Filipović-Grčić, S. Bojić, Transients caused by uncontrolled and controlled switching of circuit breakers, in: The International Symposium on High-Voltage Technique "Höfler's Days", Portorož, Slovenia, November 2013, 2013, pp. 1–7.
[8] B. Filipović-Grčić, A. Župan, I. Uglešić, D. Mihalic, D. Filipović-Grčić, Transients caused by switching of 420 kV three-phase variable shunt reactor, in: International Conference on Power Systems Transients (IPST), Cavtat, Croatia, June 2015, 2015.
[9] D. Goldsworthy, T. Roseburg, D. Tziouvaras, J. Pope, Controlled switching of HVAC circuit breakers: application examples and benefits, in: 61st Annual Conference for Protective Relay Engineers, TX, USA, April 2008, 2008, pp. 520–535.
[10] L. Stenström, M. Mobedjina, Limitation of switching overvoltages by use of transmission line surge arresters, in: CIGRE SC 33 International conference, Zagreb, Croatia, 1998.
[11] H. Seyedi, M. Sanaye-Pasand, M.R. Dadashzadeh, Application of transmission line surge arresters to reduce switching overvoltages, in: International Conference on Power Systems Transients, Montreal, Canada, 2005.
[12] International Electrotechnical Commission, IEC 60071-1, Insulation Co-Ordination – Part 1: Definitions, Principles and Rules, 2011, March.
[13] S. Venkatesan, R. Rashedin, R. Bhattarai, A. Haddad, N. Harid, H. Griffiths, Significance of switching impulse breakdown voltage characteristics in voltage uprating, in: XVII International Conference on Gas Discharges and Their Applications, vol. I, Cardiff, United Kingdom, 2008, pp. 353–356.
[14] J.R. Ribeiro, M.E. McCallum, An application of metal oxide surge arresters in the elimination of need for closing resistors in EHV breakers, IEEE Trans. Power Deliv. 4 (January (1)) (1989).
[15] A.R. Hileman, Insulation Coordination for Power Systems, CRC Press, Boca Raton, FL, 1999.