International Electrical Engineering Journal (IEEJ)
Vol. 7 (2016) No.3, pp. 2196-2203
ISSN 2078-2365
http://www.ieejournal.com/

Analysis and Mitigation Techniques of Switching Overvoltages for A 500 kV Transmission Line

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Abstract— **When an overhead Transmission line is energized, transients overvoltages are generated in the electrical networks including the line and the supply network that can be dangerous and may lead to insulation failure. Therefore, it would be of great importance to study these overvoltages and the different factors affecting on it and the different methods and techniques used to reduce these overvoltages and its undesirable effects. In this paper, the overvoltages due to energization of a typical Egyptian 500kV single line from A_Mousa to Taba are investigated. The effects of the various parameters on the switching overvoltages are analyzed. The power system under study and its components are simulated using ATP/EMTP software package. The statistical distributions of the switching overvoltages for the different cases under study are derived. The techniques of mitigation for the switching overvoltages by shunt reactors, pre-insertion resistor, surge arrestors and point on wave controlled switching are demonstrated.**

Index Terms— Switching Overvoltages, Energization, Transmission Line, Mitigation Techniques, Controlled Switching.

I. INTRODUCTION

Switching surges are considered as the most severe type of overvoltage originated on the EHV and UHV transmission lines. They are known to have front durations of a few hundred microseconds, through which transmission lines insulation usually shows a minimum strength [1, 2]. Furthermore, switching surge magnitudes are proportional to the normal operating transmission voltage. Because of these facts, the transient switching surges have become the dominant factor in the design process of the transmission systems insulation [3]. The main Switching surges on the transmission line are generated by, the initial closing of a circuit breaker to energize a transmission line, by the opening of a circuit breaker and by the reclosing of a circuit breaker to re-energize a transmission line. Voltage surges can also be a result of the initiation of a fault on a transmission line[4, 5]. The magnitude of switching surges is affected by several factors such are:

- The circuit breaker performance.
- The source network.
- Line parameters including dimensions, earth resistivity, trapped charges, terminating network and coupled energized circuits.

Many techniques have been developed to reduce the peak value of switching transients [5 - 10]. These techniques are widely used to economically optimize the design process of the higher voltage systems (400 kV and above). The main used techniques are:

- Switching resistors.
- Shunt reactors.
- Controlled synchronized closing of circuit breakers.
- Protective devices, such as surge arresters.

The current work focuses on the overvoltages occurring upon the energization of no loaded transmission lines since these are considered to be the most dangerous case [11]. The statistical distributions of switching overvoltages for a typical 500kV single line in Egypt extended from A_Mousa to Taba were derived. The statistical analysis is based on the results of 100 cases of line switching with statistical (random) switching using alternate transient program (ATP/EMTP). The statistical distributions and its key values, such as mean value, standard deviation, and 2% statistical overvoltages values have been recorded. The effect of the line length, degree of shunt compensation and the mean closing times of the circuit breaker poles are tackled. Also the different mitigation techniques applied to the transmission line energization are analyzed and compared to present the most suitable and economical technique for reducing the switching overvoltages.

II. SYSTEM UNDER STUDY

Figure 1 shows the analyzed system based on typical transmission system 500kV transmission line in Egypt extended from High–Dam to Taba. The study is focused on the final line section, which corresponds to a 244-km-long line from A_Mousa Bus to Taba Bus. The line was switched using the circuit breaker CB1. The transient analysis and power system modeling were carried out through simulations by using ATP/EMTP software package. The time step used for all simulations is 1µs. The rated voltage of the system is 500 kV, and the base value is the maximum phase to ground voltage 449 kV. Overhead transmission lines are modeled using JMARTI model which is a frequency dependent model and thus suitable for switching transients studies. The basic parameters of the transmission system used are shown in Table I. Phase conductors are assumed to be transposed ideally and there are two ground wires with directly tower grounding. The soil resistivity is 100 Ω.m. The tower shape and dimensions are shown in figure 2. The three phase voltages are assumed to have cosine waveform as shown in figure 3 with maximum voltage of phase A at zero time and with power frequency 50 Hz.

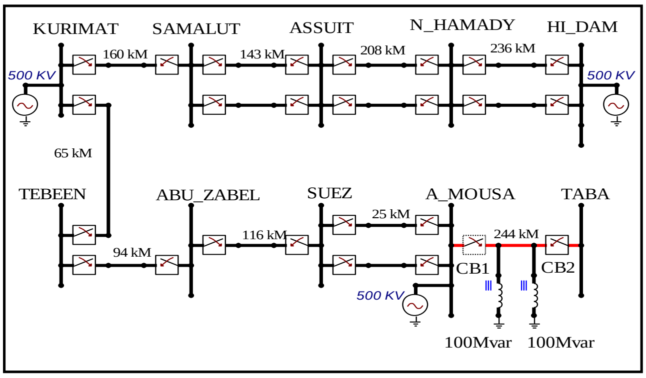

Fig.1: The transmission system under study

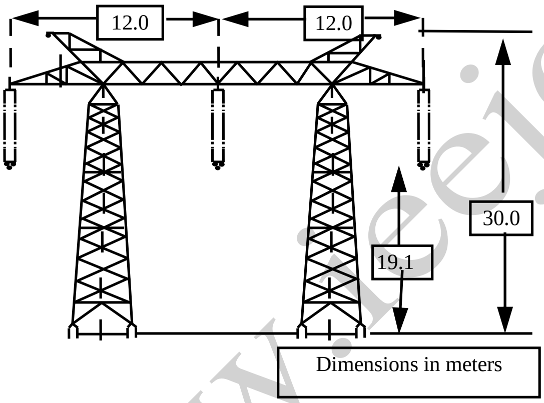

Fig. 2: The 500kv transmission line towers

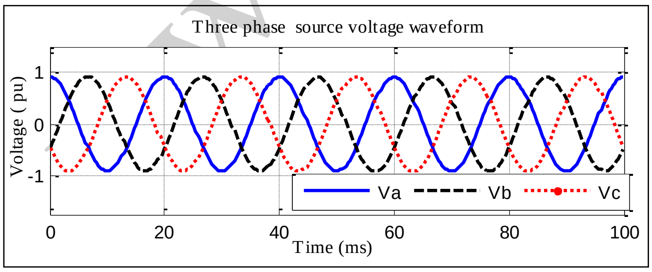

Fig.3: Source voltages waveforms for the three phases

Table 1: Data of the Transmission System under Study

Voltage level	500 kV
Number of circuits	2
Number of bundle conductors	3
Diameter of a single conductor	30.6 mm
Spacing between bundle conductors	47 cm
Number of sky wires	2
Diameter of sky wire	11.2 mm
Number of circuits per tower	1
Span	400 m

III SYSTEMATIC STUDY FOR ENERGIZATION OVERVOLTAGES

In this part, the effect of circuit breaker closing time is demonstrated using a systematic circuit breaker. Figure 4 shows the simulated network for the systematic study of energization overvoltages when three-pole switching is performed at A_Mousa substation. At the end of the line in Taba, the line circuit breaker is open.

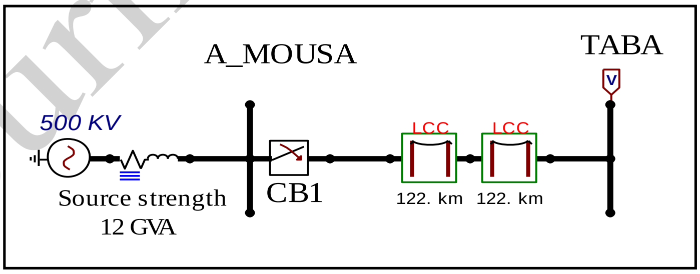

Fig.4: The simulated network using ATP/EMTP for systematic study of energization overvoltages

The three poles of the circuit breaker are closed simultaneously. The simulated circuit breaker closing times are considered from 20ms corresponding to source phase angle 0° to 40ms corresponding to source phase angle 360° in steps of 1.667ms or 30°. The obtained voltage waveforms at the receiving end for each step are shown in figures 5-7. Table 2 summarizes the peak values (+ve) and (-ve) for the three phases voltages obtained at Taba substation for each case. It is clear that the highest peak (-ve) overvoltage of (-2.14 pu) occurs when switching of the circuit breaker occurs at the time of the maximum of the source phase voltage (20ms for phase A , 26.67ms for phase B and 33.33ms for phase C) as shown in Figure 5. The highest peak positive overvoltage of (+2.14 pu) occurs when switching of the circuit breaker occurs at the time of the minimum of the source phase voltage (30ms for phase A , 36.67ms for phase B and 23.33ms for phase C) as shown in Figure 6.

International Electrical Engineering Journal

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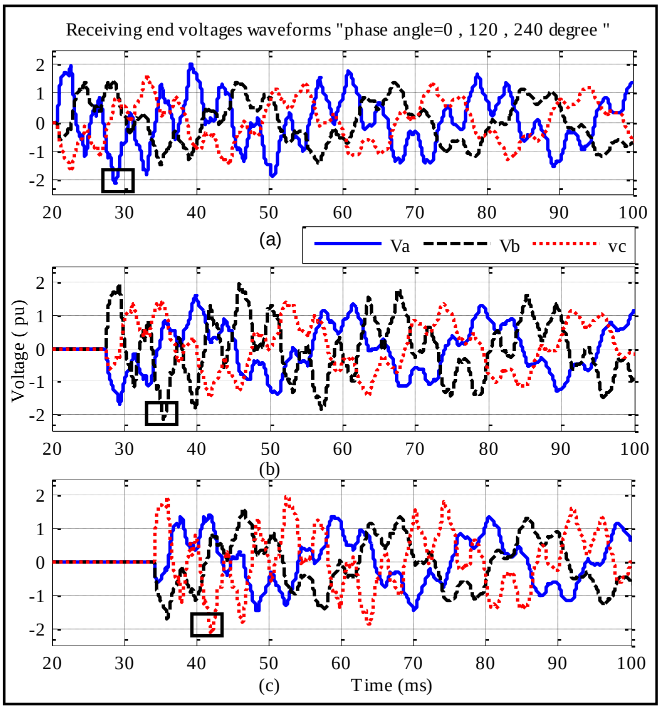

Fig.5: Voltage waveforms at the receiving end for (a) 20ms, (b) 26.67ms and (c) 33.33ms switching times

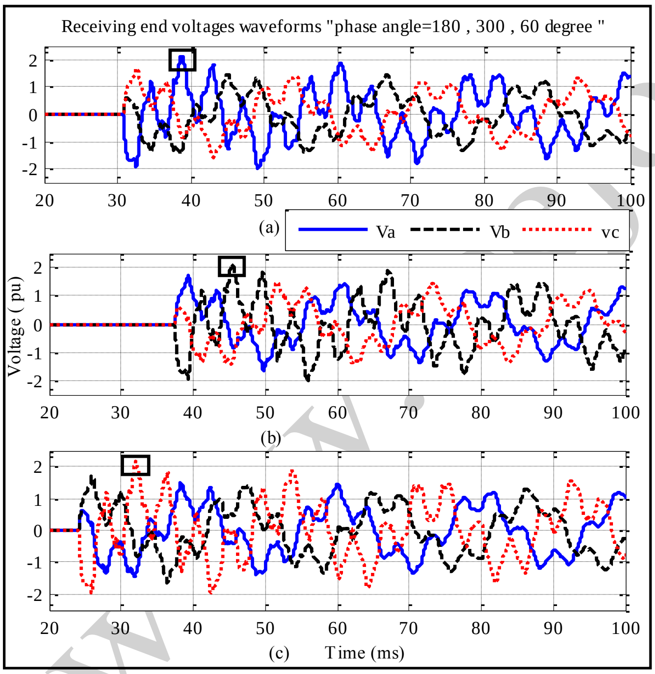

Fig.6: Voltage waveforms at the receiving end for (a) 30ms, (b) 36.67ms and (c) 23.33ms switching times.

The lowest peak positive and negative overvoltages of 1.15 pu and -1.15 pu occurs when switching of the circuit breaker occurs at the time of the zero crossing of the source phase voltage (25 ms and 35 ms for phase A, 21.67 ms and 31.67 ms for phase B and 28.33 ms and 38.33 ms for phase C) as shown in Figure7.

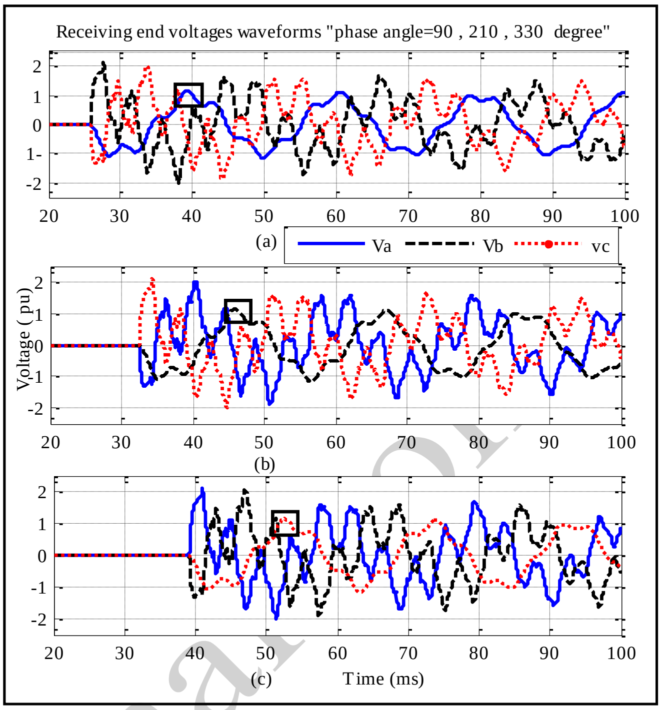

Fig.7: Voltage waveforms at the receiving end for (a) 25ms, (b) 31.67ms and (c) 38.33ms switching times.

Table2: Peak Values Of Overvoltages Obtained For Each Phase For Different Switching Times

Switching time(ms)	*phase A*		*phase B*		*phase C*	
	Max	*Min*	*Max*	*Min*	*Max*	*Min*
20.00	1.98	-2.14	1.42	-1.50	1.63	-1.71
21.67	1.90	-2.04	1.17	-1.15	1.99	-2.11
23.33	1.51	-1.42	1.71	-1.63	2.14	-1.98
25.00	1.15	-1.17	2.11	-1.99	2.04	-1.90
26.67	1.63	-1.71	1.98	-2.14	1.42	-1.50
28.33	1.99	-2.11	1.90	-2.04	1.17	-1.15
30.00	2.14	-1.98	1.50	-1.42	1.71	-1.63
31.67	2.04	-1.90	1.15	-1.17	2.11	-1.99
33.33	1.42	-1.51	1.63	-1.71	1.98	-2.14
35.00	1.17	-1.15	1.99	-2.11	1.90	-2.04
36.67	1.71	-1.63	2.14	-1.98	1.50	-1.42
38.33	2.11	-1.99	2.04	-1.90	1.15	-1.17
40.00	1.98	-2.14	1.42	-1.50	1.63	-1.71

IV STATISTICAL STUDY FOR ENERGIZATION OVERVOLTAGES

The statistical behavior of the overvoltages is caused by the randomness in which each pole of the CB connects the line to the voltage source. The closing speed of CB poles is subject to variations determined by the temperature, pressure, and other factors [6]. The statistical studies are performed in ATP/EMTP using statistical switches. The statistical distributions and its key values, (mean values, 2% statistical over voltages, standard deviations, and coefficient of variation) of overvoltages have been derived from the results of 100 cases of energization with statistical (random) switching for the different cases of study. In the statistical switching, two kinds of statistical variations were considered. The first statistical variation is the phase angle (point-of-wave) when the line circuit breakers receive the command to close. A uniform distribution from 0 to 360 degrees is assumed for this variation. The second statistical variation is the difference in closing time between the three phases. A normal distribution with standard deviation of 1 ms is assumed for this variation. Then the derived distribution is best fitted to a normal Gaussian distribution curve. Figure 8 shows the simulated network using ATP for the statistical study of energization overvoltages.

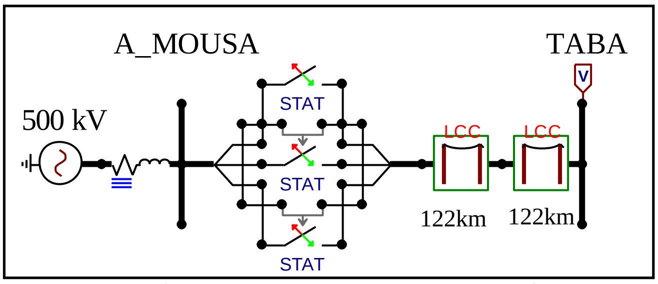

Fig.8: Diagram of the simulated network using ATP/EMTP for statistical study of energization overvoltages

For each switching case, breakers are randomly switched throughout their pole closing span and the switching overvoltages are obtained. The data are collected and analyzed by two methods which are widely used for purpose of insulation coordination and risk of failure calculations [3].

1- Case Peak Method: For each switching operation, the overvoltages for the three phases are collected. Only the voltage with the largest crest value, either positive or negative polarity, is used. This voltage is treated as positive since, if it is negative, the opposite breaker switching sequence would produce an opposite polarity voltage.

2- Phase Peak Method: The phase peak method consists of using the overvoltages for each phase individually and each of these is assumed as positive polarity.

Figure 9 shows the statistical distribution and the best fitted normal probability density functions of the overvoltages at receiving end for the three phases V_A, V_B and V_C (phase peak method) and the summary of them V_S which represents the case peak method. The mean closing times for circuit breaker are 10ms for the three phases with standard deviation of 1ms. Figure 10 shows the cumulative probability distribution and the best fitted cumulative Gaussian distribution functions for the energization overvoltages. Table 3 summarizes the overvoltages distribution parameters (mean value, standard deviation, 2%SOV "statistical overvoltages" and coefficient of variation C_V which equals the standard deviation divided by the mean value of the overvoltages) for different mean closing times of the three poles of the circuit breaker.

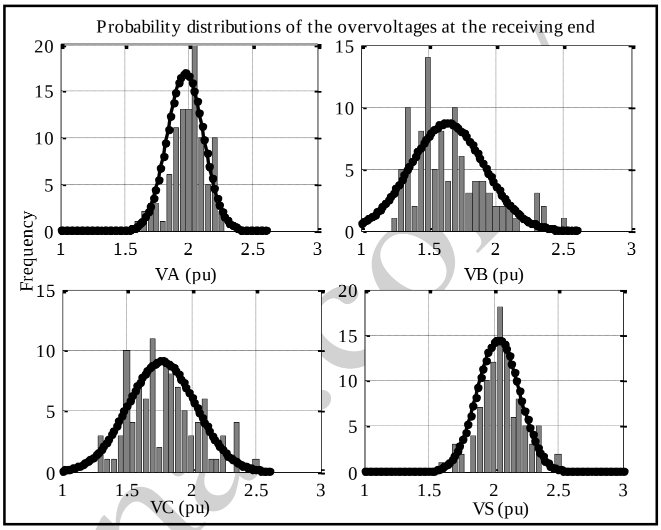

Fig.9: Statistical distributions of energization overvoltages at Taba.

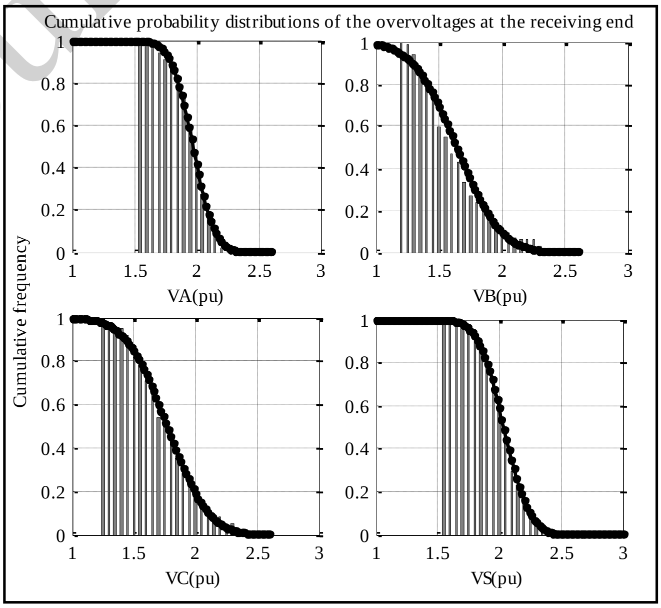

Fig.10: Cumulative probability distribution of energization overvoltages at Taba.

It is clear that the overvoltage distribution parameters for each phase change with the change of the mean closing time of the circuit breaker while it is approximately the same for any closing mean time for the summary using case peak method. It is also clear that the maximum overvoltage which represents here by the (2% SOV) is high and reaches to 2.35pu because no control method is used and the switching occurs for a no loaded transmission line. Because the case peak method appears to be a superior approximation, the development in the remaining study uses only the case peak method.

Table 3: Effect of The Circuit Breaker Mean Closing Times

Mean closing time (ms)	Phase Voltage (Mean Value)			Case Voltage			
	V_A	V_B	V_C	*V_meann*	*Std*	*2% SOV*	C_V
10	1.98	1.63	1.80	2.04	0.15	2.35	0.08
11.67	1.83	1.61	1.97	2.04	0.16	2.36	0.08
13.33	1.66	1.85	1.96	2.06	0.15	2.37	0.07
15	1.59	1.97	1.83	2.05	0.16	2.37	0.08
16.67	1.79	1.97	1.62	2.04	0.15	2.36	0.08
18.33	1.99	1.83	1.59	2.05	0.14	2.34	0.07
20	1.97	1.69	1.84	2.06	0.16	2.38	0.08

V EFFECT OF LINE LENGTH

As the line length increases the total line shunt capacitance increases so the peak overvoltages reach to higher values. Figure 11 shows the cumulative distribution functions and the best fitted Gaussian cumulative probability distribution of the overvoltages at receiving end for line lengths of 244 km, 488 km(the length is assumed to be doubled) and 122 km (the length is assumed to be halved) without any control method.

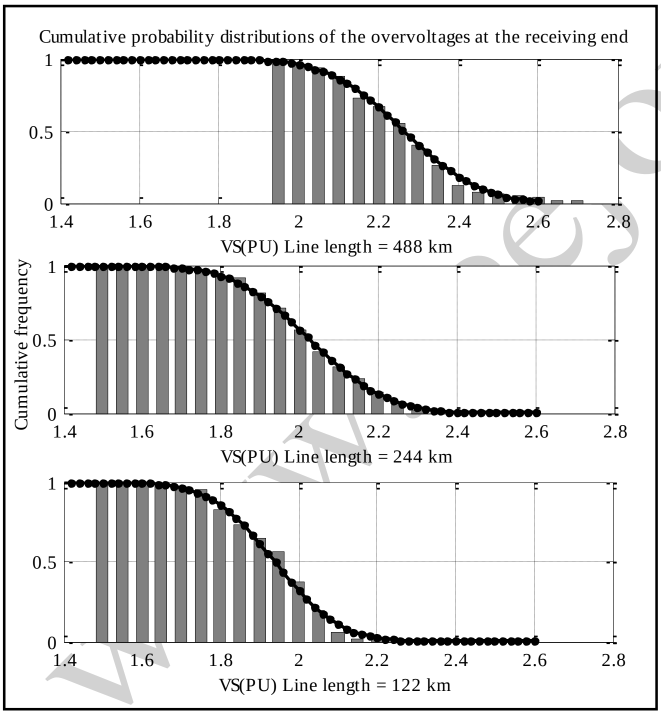

Fig.11: Cumulative probability distribution of energization overvoltages at Taba bus for different line lengths.

It can be observed that as line length increases, peak overvoltages increases. Table 4 summarizes the overvoltages distribution parameters for the different line lengths considered.

Table 4: The Overvoltages Distribution For Different Line Lengths

Line length	*V_mean*	*Variance*	*Std*	*2% SOV*	C_V
488km	2.26	0.02	0.15	2.58	0.07
244 km	2.03	0.02	0.15	2.34	0.08
122 km	1.94	0.02	0.13	2.21	0.07

VI OVERVOLTAGES MITIGATION TECHNIQUES

It is obvious from the previous results that the maximum overvoltages are high and may lead to insulation failure with higher probability, so the overvoltages must be reduced to reduce the risk of insulation failure. The overvoltages mitigation techniques analyzed in this study are:

A. Use of shunt reactor.

B. Use of surge arrestor.

C. Use of pre-insertion resistor.

D. Circuit breaker controlled switching.

A. Effect of Shunt Reactor

Figure 12 shows the cumulative distribution and the best fitted normal cumulative distribution function of the overvoltages at receiving end when the transmission line is energized in the presence of the shunt reactors of 100 MVAR 200 MVAR respectively. The effect of shunt reactor values and locations on the energization overvoltages are studied and summarized in Table 5. It is clear that it is better to locate the shunt reactor at the receiving end than locating it at the sending end , the shunt compensation at both ends of transmission line with 200 MVAR will reduce the magnitude of the 2% SOV to 2.09pu compared to 2.25pu for shunt compensation of 100 MVAR at the both ends , while the 2% SOV without shunt compensation is 2.35 pu .thus as the degree of shunt compensation increase the peak values of the switching overvoltages are reduced but they still have high values and the risk of insulation failure is still has high values.

Table 5: The Overvoltages Distribution For Different Shunt Reactors

shunt reactor	*location*	*V_mean*	*Variance*	*Std*	*2% SOV*	C_V
100 MVAR	A_Mousa	2.03	0.02	0.14	2.32	0.07
	Taba	1.98	0.02	0.14	2.27	0.07
	Both	1.96	0.02	0.14	2.25	0.07
200 MVAR	A_Mousa	1.98	0.02	0.14	2.27	0.07
	Taba	1.88	0.01	0.12	2.12	0.06
	Both	1.85	0.01	0.12	2.09	0.06

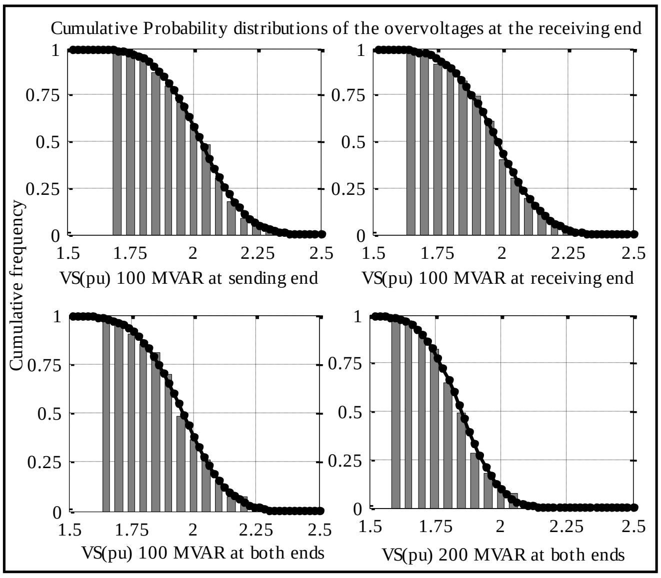

Fig.12: Cumulative probability distribution of energization overvoltages at Taba bus for different shunt reactors

B. Effect Of Surge Arrestor

The surge arresters normally specified for Egyptian 500-kV transmission lines are the metal–oxide type. These arresters are appropriately modeled according to its V-I characteristic curve as shown in figure 13. The effects of surge arresters locations on the energization overvoltages distributions for both ends are summarized in table 6. Figure 14 shows the cumulative distribution and the best fitted normal cumulative distribution function of the overvoltages at receiving end when the transmission line is energized in the presence of the surge arrester. When one surge arrester is located at Taba or two surge arresters are located on the both ends of the transmission line, the 2%SOVs for Taba bus are approximately the same and reach 1.8 pu, while the 2%SOV is 2.31 pu when one surge arrester is located only at A_Mousa bus. The 2%SOVs for A_Mousa are 1.49 pu when one surge arrester is located only at any one end or two arresters are located at the both ends.

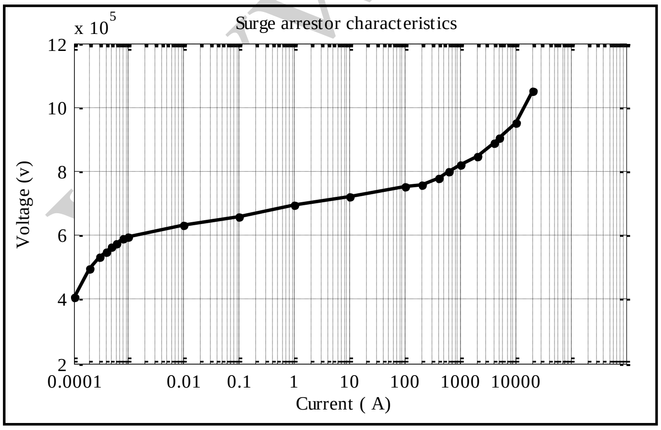

Fig.13: Surge arresters V-I characteristics

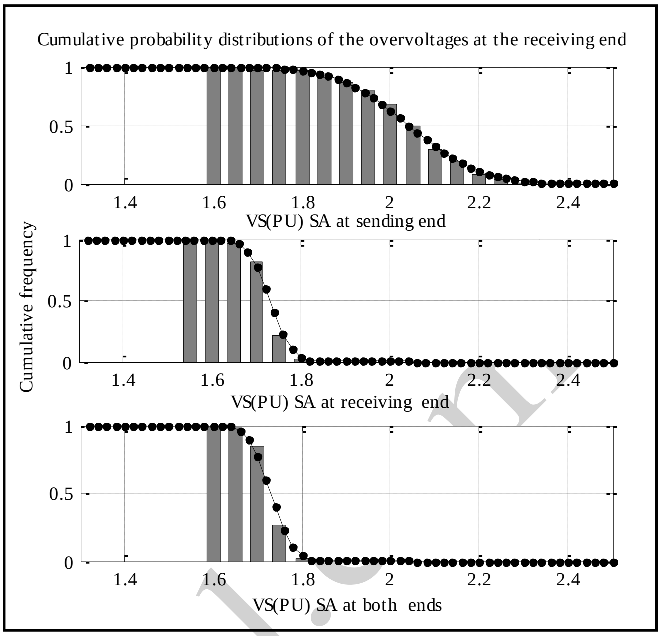

Fig.14: Cumulative probability distribution of energization overvoltages at Taba bus with surge arresters

Table 6: The Overvoltages Distribution For Different Surge Arrester locations

OV_Dist.	*SA_location*	*V_mean*	*Variance*	*Std*	*2% SOV*	C_V
Receiving end	A_Mousa	2.04	0.018	0.13	2.31	0.07
	Taba	1.73	0.002	0.04	1.80	0.02
	Both	1.73	0.001	0.04	1.81	0.02
Sending end	A_Mousa	1.33	0.006	0.08	1.49	0.06
	Taba	1.32	0.007	0.08	1.49	0.06
	Both	1.31	0.008	0.09	1.49	0.07

Table 7 tabulates the overvoltages distributions at different distances from the sending end when two arresters are located on the both ends of the transmission line.

Table 7: The overvoltages distribution with surge arrestor

Distance %	*V_mean*	*Variance*	*Std*	*2% SOV*	C_V
0%	1.34	0.009	0.09	1.53	0.07
10%	1.46	0.011	0.11	1.68	0.07
20%	1.57	0.016	0.12	1.82	0.08
30%	1.67	0.012	0.11	1.89	0.06
40%	1.69	0.012	0.11	1.92	0.07
50%	1.70	0.012	0.11	1.93	0.06
60%	1.75	0.010	0.10	1.95	0.06
70%	1.78	0.006	0.08	1.94	0.04
80%	1.78	0.005	0.07	1.92	0.04
90%	1.77	0.004	0.06	1.89	0.03
100%	1.73	0.001	0.04	1.81	0.02

The peak value of the 2%S0Vs is 1.95 pu at a distance equal 60% of the total length of the transmission line. Figure 15 shows the mean and the maximum values of the overvoltages profile along the transmission line for different distances from the sending end.

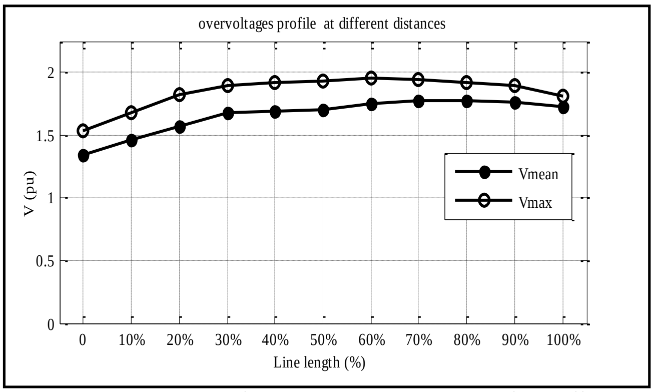

Fig.15: Overvoltages profile along the transmission line for a different distances from the sending end in the presence of surge arrester

B. Effect of pre-insertion resistor

The closing resistors are inserted in series with the load circuit, acting as a voltage divider, before closing the main contacts, thereby damping the switching transient overvoltages. These resistors are switched off after a given time, in this study, the mean insertion time of the resistor is 8 ms. Figure 16 shows the cumulative distribution and the best fitted normal cumulative distribution function of the overvoltages at receiving end when the transmission line is energized in the presence of pre-insertion resistor of 250 ohms in parallel with the main circuit breaker before switching occurs.

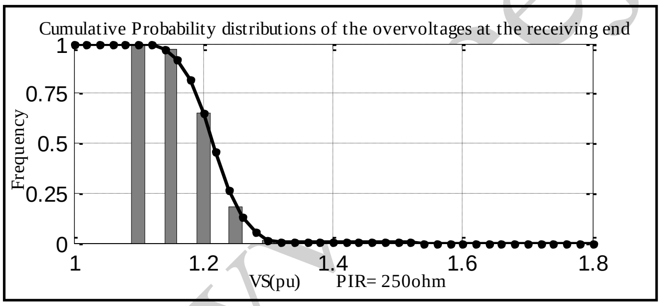

Fig.16: Cumulative probability distribution of energization overvoltages at Taba bus with PIR of 250Ω

Table 8 tabulates the overvoltages distributions for different values of the pre-insertion resistors. It is clear that the mean values and the 2% SOVs at the receiving end are much reduced. The minimum value for the 2% SOVs equal 1.3 pu is obtained when the resistor value is 250 ohm which equals the surge impedance of the transmission line. Thus using circuit breakers with pre-insertion resistor is a very effective technique to reduce the peak values of the switching overvoltages but they have disadvantages related to economic and technical considerations because its implementation and maintenance costs are very high and they have higher failure rates.

Table 8: The Overvoltages Distribution For Different Values Of Pre-Insertion Resistor

PIR (ohm)	*v_mean*	*variance*	*Std*	*2% Sov*	*Cv*
100	1.43	0.020	0.14	1.72	0.10
200	1.22	0.005	0.07	1.36	0.06
250	1.21	0.002	0.04	1.30	0.03
300	1.27	0.002	0.04	1.35	0.03
400	1.36	0.004	0.06	1.48	0.04
500	1.45	0.004	0.07	1.59	0.05

D. Circuit Breaker Controlled Switching

The controlled switching involves the individual closing of each phase in the CB at the optimal point of wave to reduce switching overvoltage and the closing commands of the circuit breaker poles are delayed in such a way that switching will occur very close to the voltage across CB zero crossing [8, 12]. For transmission line energization, the line is considered to have no trapped charges. It means that the phase's voltages at the line side of the circuit breaker are zero. So that the optimal instant of switching for each phase is the zero, crossing instant of the voltage wave of the phase source voltage. Figure 17 shows the mean closing instants for each pole (T_{oA} equals 15ms, T_{oC} equals 18.33ms and T_{oB} equals 21.67ms). The sequence starts closing the phase A at zero crossing, followed by the phase C and, finally, by phase B with 60^{o} delay between them. The values dt_A, dt_B and dt_C represent the time deviation (circuit breaker standard deviation) of the actual mechanical contact of poles 1, 2, and 3, respectively and follow normal distribution.

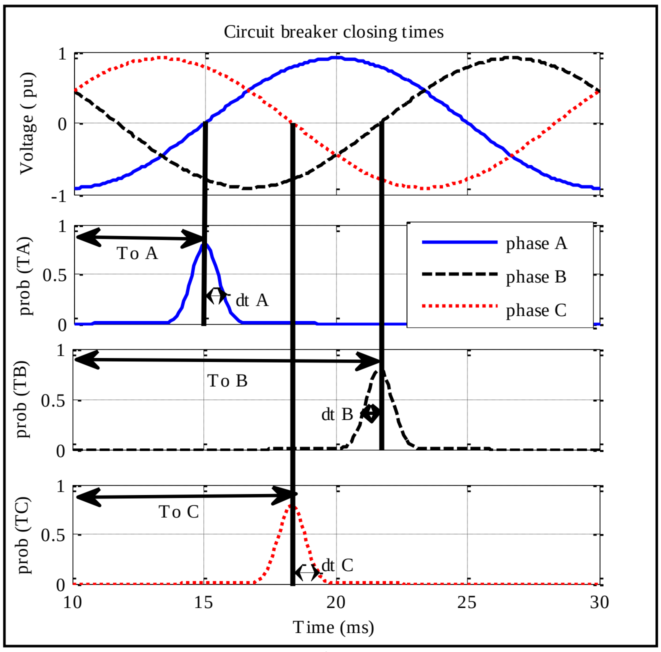

Fig.17: The mean closing instants of each pole with controlled switching

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Vol. 7 (2016) No.3, pp. 2196-2203
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Figure 18 shows the cumulative distribution and the best fitted normal cumulative distribution function of the overvoltages at receiving end when the transmission line is energized via circuit breaker controlled switching with standard deviation of 0.5ms.

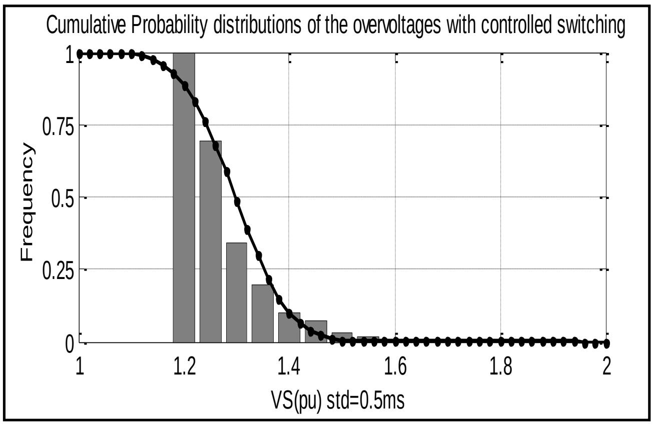

Fig.18: Cumulative probability distribution of energization overvoltages at Taba bus with circuit breaker controlled switching

Table 9 tabulates the overvoltages distributions for different values of the circuit breaker standard deviations. The mean value and the 2% SOV at the receiving end are much reduced when using controlled switching with low value of circuit breaker standard deviation. The minimum value of the 2%SOV of 1.26 pu is obtained when the standard deviation of the circuit breaker closing times is 0.2ms. Thus using circuit breakers with controlled switching with small standard deviation can eliminate the need of using pre-insertion resistors in parallel with the circuit breaker during energization of the transmission lines.

Table 9 : The Overvoltages Distribution With Controlled Switching

C.B Std (ms)	*v_mean*	*variance*	*Std*	*2% Sov*	*Cv*
2.00	1.76	0.056	0.24	2.25	0.13
1.00	1.48	0.034	0.18	1.86	0.12
0.50	1.30	0.006	0.08	1.46	0.06
0.20	1.23	0.0003	0.02	1.26	0.01

VII. CONCLUSIONS

The statistical distributions of overvoltages occurring upon the energization of a no loaded transmission lines are demonstrated. The effect of line length, degree of shunt compensation and the mean closing time of the circuit breakers on the energization overvoltages are analyzed. Moreover, the statistical analysis of mitigation methods applied to the transmission line energization is studied as well. The pre-insertion resistor method has better performance to reduce the 2%SOVs obtained at Taba bus to 1.3 pu. However, the results for controlled switching methods are just slightly higher but if the circuit breaker standard deviations are small enough, the 2%SOVs are much reduced and reach 1.26 pu for circuit breaker have standard deviations of 0.2ms. It is suggested then that the controlled switching method should be used for mitigating transmission line energization overvoltages instead of the pre-insertion resistor due to the drawbacks of the latter method, such as higher implementation and maintenance costs.

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