Transmission Lines Energization: Relevant Factors on Statistical Evaluation of Transient Overvoltages

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***Abstract*-- This paper aims to evaluate important factors that affect switching transients overvoltages during transmission line energization. These factors include the number of repetitions to ensure the statistical characteristic of the study, the variation range of the mean closing time of the circuit breaker contacts, the model used for the representation of the transmission line and the influence of transposition. The shunt compensation degree is considered as an independent parameter. Digital simulations were performed with PSCAD/EMTDC software.**

***Keywords*: Transient overvoltages, Transmission Line Energization, Controlled Switching, Surge Arresters, Pre-insertion Resistor, PSCAD.**

I. INTRODUCTION

THE studies of overvoltages have acquired greater importance in recent years because transmission systems have reached higher voltage levels, which makes necessary power systems increasingly reliable and economical. The importance of these studies lies in providing information necessary for the insulation coordination of transmission lines and substations as well as for the equipments specification.

For the overvoltages evaluation, statistical studies should be performed taking into account the randomness of the closing instant, and the pole-spread or time interval between closing of the first and final poles. For this purpose, the circuit breakers must be represented including the randomness of poles closing instants. These features are achieved representing the circuit breaker through a statistical switch.

An important aspect in this type of study is to determine the minimum number of repetitions required to ensure its statistical significance. For statistical switches the closing instant can be distributed uniformly throughout 1 or ½ cycle of the fundamental frequency. It is important to verify whether these intervals produce results statistically different.

Likewise, related to the transmission lines model, it is important to verify if to use constant parameter line model or frequency dependent line model generates results significantly dissimilar. Another important verification is if representing the actual transposition scheme of transmission line compared to a supposed ideally transposed line has influence on the overvoltage magnitude.

In this context, this study aims to evaluate statistically the influence of various factors that affect the overvoltages generated during transmission lines energization. These factors include: the number of repetitions to ensure the statistical characteristic of the study, the variation range of the average closing time of the circuit breaker contacts, the model used for the transmission line representation and the influence of transposition.

II. ANALYZED SYSTEM

Fig. 1 shows the analyzed system based on an actual transmission system of 500 kV and 1052 km. The study is focused on the final segment of the line, which corresponds to a length of 252 km in the direction of B4 to B5. The line was switched using the CB7 circuit breaker. The compensation scheme is composed of three single-phase reactors banks, existing in field, with quality factor of 400, grounded through a neutral reactor with quality factor of 40.

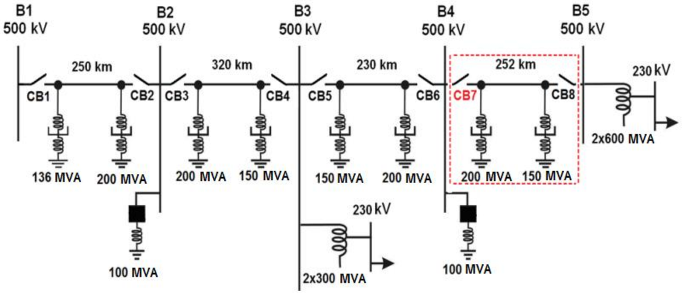

Fig. 1. 500 kV transmission system

The line parameters for the fundamental frequency (60 Hz) are shown in Table 1.

TABLE I
BASIC LINE UNITARY PARAMETERS – 60 HZ

Components	Longitudinal (Ω/km)	Transversal (µS/km)
Non homopolar	0.0161 + j 0.2734	j 6.0458
Homopolar	0.4352 + j 1.4423	j 3.5237

III. STATISTICAL TREATMENT OF OVERVOLTAGES

In electromagnetic transients generated by closing of circuit breakers the statistical nature of the overvoltages is caused by the spread in which each pole of the circuit breaker connects the line to the voltage source. Thus, the mechanical poles spread, the instant in the fundamental frequency cycle at which the command of the operation is done, and the electric arc established between the contacts before its closing

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determine the effective circuit breaker's closing.

The non-simultaneity of the mechanical closing of the circuit-breaker contacts, can be simulated by *statistical* switches [1]. In this case, the closing instants are characterized by Gaussian curves for the three phases with a mean time and a standard deviation associated. Additionally, the variation of the mean time over a given time period is characterized by an uniform distribution [2, 3].

The maximum pole spread of circuit breaker is an information normally provided in the circuit breakers' manufacturers specifications, then it is necessary to link it to the standard deviation of the normal curve modeled. This can be done by truncating the gaussian curve [1,3].

In the present study the standard deviation is limited to +/- 2σ, which means that 95% of the values is distant from the mean lower twice the standard deviation value.

The statistical switch used in the simulations was modeled according to [4]. Based in the same reference, a high speed circuit breaker with a closing time of 13 ms at each pole was selected. However an additional analysis was performed for higher values of closing times. Was verified that this fact does not influence the results whereas the closing time is lower than two cycles.

The closing speed of the circuit breaker contacts is subject to variations determined by the temperature, the wear and other factors. The circuit breaker model accommodates these variations in the closing speed of the contacts according to a normal distribution with a standard deviation.

The electric arc occurs when, during the contacts approximation, the potential difference between them exceeds the decreasing voltage of the dielectric supportability. The electric arc is another random parameter in the generation of the transient; nevertheless, in [4] it is showed that its effect is minimal in high speed circuit breakers. Otherwise, its effect can be easily included in the analysis, by increasing the maximum mechanical dispersion between circuit breaker poles.

The statistical analysis was performed using the software OriginPro 8 [5].

IV. STATISTICAL EVALUATION

The overvoltage magnitudes generated during line energization follow a normal distribution (verified by Kolmogorov–Smirnov test). Therefore, the analysis of variance (ANOVA) can be used for the statistical evaluation of overvoltages magnitude [6].

ANOVA is essentially an inferential analysis procedure for testing the statistical significance among different groups of data for homogeneity. It is a robust test, because it is not limited to comparing the means of only two groups [6].

F-test is part of ANOVA process. It is used to assess whether the expected values of a quantitative variable within several pre-defined groups differ from each other.

The following aspects were evaluated:

- Minimum number of energizations to ensure the statistical significance of the study.
- The range variation of the mean closing time of circuit breaker contacts.
- Model used to represent the frequency dependence of line longitudinal parameters.
- Influence of the line transposition scheme.

The shunt compensation degree was taken as an independent parameter.

A. Minimum number of energization

In this study the cases of line energization were simulated using a Multiple Run feature available in PSCAD program. A random number generator, also available in the program, allows a new selection of closing instant of circuit breaker contacts for each execution.

The closing of the circuit breaker is randomly initiated over the period of a fundamental frequency cycle (in this case, over the 16.67 ms), and each pole closes in an interval defined by a normal distribution with a mean value and a standard deviation of 1 ms.

The line was considered ideally transposed and the frequency dependence of the longitudinal parameters was modeled using the Frequency-Dependent (Phase) model of transmission lines [8]. The existent surge arresters of line ends were not represented so that the worst overvoltages were not limited by such devices.

With the purpose of determining the minimum number of energizations necessary to ensure statistical representation of the study a comparison among 100, 200, 300, 400 and 500 shots was conducted.

The maneuvers were performed at the final segment of the transmission line (Figure 1). The segment of the line was analyzed for 90, 70 and 50 % of shunt reactive compensation.

Table 2 presents a summary of the maximum, mean, standard deviation, and coefficient of variation (CV) obtained for the overvoltages at the open end of transmission line.

TABLE II

TRANSIENT OVERVOLTAGES AT LINE REMOTE TERMINAL. ANALYSIS OF MINIMUM NUMBER OF ENERGIZATIONS

Comp. degree (%)	Number of runs	Overvoltages at line end (p.u)			
		Max.	Mean	Standard deviation	CV (%)
90	100	1.660	1.589	0.0343	2.476
	200	1.671	1.596	0.0397	
	300	1.671	1.593	0.0372	
	400	1.673	1.592	0.0404	
	500	1.676	1.594	0.0408	
70	100	1.810	1.746	0.0347	2.232
	200	1.826	1.754	0.0396	
	300	1.825	1.752	0.0373	
	400	1.829	1.751	0.0399	
	500	1.829	1.753	0.0401	1.997
50	100	2.057	1.989	0.0350	
	200	2.068	1.998	0.0414	
	300	2.073	1.997	0.0376	
	400	2.075	1.996	0.0402	
	500	2.073	1.997	0.0412	

Comparing the results obtained for the mentioned quantities of energizations, it is possible to observe that there is a similarity between the results. Therefore, a one-way ANOVA test was applied to establish if there exist statistically significant differences between groups of energizations, as shown in Table 3.

With these results it can be stated that no statistical significance between the numbers of shots is observed. That means that the number of energizations of 100 or 500 will result in similar overvoltage profiles.

Since the shot number results in similar overvoltages, either option can be used for simulations. Due to processing speed of current computers, for this work was selected a central value, in this case 300 runs.

TABLE III
ANALYSIS OF VARIANCE OF MAXIMUM OVERVOLTAGES AT LINE REMOTE TERMINAL. MINIMUM NUMBER OF ENERGIZATIONS

Comp. degree (%)	Source	Degrees of freedom	Sum of Squares	Mean Squares	F	F Crit.
90	BG	4	0.00442	0.00110	0.7089	3.3317**
	WG	1495	2.32845	0.00156	-	-
	Total	1499	2.33287	-	-	-
70	BG	4	0.00635	0.00159	1.0392	3.3317**
	WG	1495	2.28473	0.00153	-	-
	Total	1499	2.29108	-	-	-
50	BG	4	0.00551	0.0014	0.8672	3.3317**
	WG	1495	2.37624	0.0016	-	-
	Total	1499	2.38176	-	-	-

** Significance level of 1%.
BG: Between group
WG: Within group

B. Variation range of the mean closing time of circuit breaker contacts

The statistical switches are characterized by Gaussian curves for the three phases with a mean time and a standard deviation associated. In turn, the variation of the mean time is characterized by a uniform distribution.

This analysis aims to determine if the uniform distribution of the mean time of the contacts operation over 1 or ½ cycle of the fundamental frequency influences the resulting overvoltages.

For this analysis, for a second time, the line was considered as ideally transposed and the frequency dependence of the line longitudinal parameters was modeled using the Frequency-Dependent (Phase) model.

For each variation range of mean closing time (01 cycle or ½ cycle) 300 simulations were performed. The analysis was done for 90, 70 and 50 % of shunt compensation.

Comparing the results for both ranges of mean times, the Table 4 shows a similarity between the results.

Through F-test of ANOVA shown in Table 5 it can be concluded that the fact of adopting 1 or ½ cycle of the fundamental frequency as the variation range of the mean closing time does not alter the results concerning to the maximum transient overvoltages at the end of the transmission line.

From the results it is proposed that for statistical studies of transmission lines energization, the closing instants can be distributed uniformly over 1 cycle of the fundamental frequency.

TABLE IV
TRANSIENT OVERVOLTAGES AT LINE REMOTE TERMINAL. ANALYSIS OF MEAN TIME VARIATION.

Comp. degree (%)	Range of mean time variation	Overvoltages at line end (p.u)			
		Max.	Mean	Standard deviation	CV (%)
90	1 cycle	1.671	1.593	0.0372	2.434
	½ cycle	1.672	1.592	0.0403	
70	1 cycle	1.825	1.752	0.0374	2.203
	½ cycle	1.829	1.752	0.0399	
50	1 cycle	2.073	1.997	0.0376	1.928
	½ cycle	2.068	1.994	0.0393	

TABLE V
ANALYSIS OF VARIANCE OF MAXIMUM OVERVOLTAGES AT LINE REMOTE TERMINAL. MEAN TIME VARIATION.

Comp. degree (%)	Source	Degrees of freedom	Sum of Squares	Mean Squares	F	F Crit.
90	BG	1	0.00016	0.00016	0.1050	6.677**
	WG	598	0.90002	0.00151	-	-
	Total	599	0.90018	-	-	-
70	BG	1	0.00001	0.00001	0.0039	6.677**
	WG	598	0.89200	0.00149	-	-
	Total	599	0.89201	-	-	-
50	BG	1	0.00126	0.00126	0.8525	6.677**
	WG	598	0.88522	0.00148	-	-
	Total	599	0.88648	-	-	-

****** Significance level of 1%.

C. Model used to represent the transmission line

The goal of this evaluation is to verify if differences can be found in studies of line energization depending on the model used to represent the transmission line.

For this purpose were analyzed the following models of transmission lines, available in PSCAD program:

- Line model with frequency constant parameters or *Bergeron Model* [7].
- Line model with frequency dependence of the longitudinal parameters or *Phase Model* [8].

For each type of transmission line 300 simulations were performed. One cycle of the fundamental frequency was considered for the variation range of the mean closing time. The analysis was performed for 90, 70 and 50 % of shunt compensation. The surge arresters at the line ends were not represented.

In Table 6, comparing the results obtained with the *Bergeron Model* and the *Phase Model*, for the three compensation levels, was verified higher overvoltages when the line is modeled through *Bergeron Model*.

From the F-test of ANOVA shown in Table 7, for a significance level of 1%, statistically significant differences between treatments regarding to the transmission line model were found.

TABLE VI
Transient overvoltages at line remote terminal. Analysis of Transmission Line Model Influence

Comp. degree (%)	Transmission Lines Models	Overvoltages at line end (p.u)			
		Max.	Mean	Standard deviation	CV (%)
90	Bergeron	1.749	1.653	0.0264	2.718
	Phases	1.671	1.593	0.0372	
70	Bergeron	1.865	1.811	0.0230	6.646
	Phases	1.825	1.752	0.0374	
50	Bergeron	2.157	2.042	0.0356	2.130
	Phases	2.073	1.997	0.0376	

TABLE VII
Analysis of variance of maximum overvoltages at line remote terminal. Transmission line model influence

Comp. degree (%)	Source	Degrees of freedom	Sum of Squares	Mean Squares	F	F Crit.
90	BG	1	0.54308	0.54308	521.626	6.677**
	WG	598	0.62260	0.00104	-	-
	Total	599	1.16568	-	-	-
70	BG	1	0.51226	0.51226	532.367	6.677**
	WG	598	0.57542	0.00096	-	-
	Total	599	1.08768	-	-	-
50	BG	1	0.30501	0.30501	227.176	6.677**
	WG	598	0.80289	0.00134	-	-
	Total	599	1.10790	-	-	-

** Significance level of 1%.

The results are consistent because the resistive part of line series impedance increases with frequency, resulting in a greater attenuation of the transients. Consequently, when the line is represented with constant longitudinal parameters, the overvoltages resulting from the maneuver will not be so attenuated, having higher values. However, these higher results will not be observed in field.

For these reason, Bergeron Model should not be used for transient studies. In contrast, the Phase Model will give more accurate representation for a wide range of frequencies contained in the transient phenomena, compared to the constant parameter line model.

D. Influence of transposition on the overvoltages level.

Transmission lines employ the concept of phase transposition in order to minimize system imbalance. In a practical sense, this is achieved by periodically rotating the phase positions in the circuit. In general, in Brazil is commonly used the transposition scheme which uses three towers such that the lines are divided into four parts, respectively with 1/6, 1/3, 1/3 and 1/6 of its length.

Ideal transposition is a mathematical average of the unbalanced line. This is equivalent to visualizing an infinite number of transposition cycles, where the line segment length approaches zero. The result is a series impedance matrix and a shunt admittance matrix that are perfectly symmetrical and balanced.

Usually, the line energization is evaluated representing the line with ideal transposition. However, the real lines are not ideally transposed, i.e. have an actual transposition scheme. In order to determine the influence of the transposition scheme, the transmission line was modeled for the following cases:

- Transmission line ideally transposed (IT).
- Transmission line with real transposition scheme (RT) (transposition scheme 1/6-1/3-1/3-1/6).

For each transposition scheme, 300 simulations were performed. The transmission line was represented by *Phases Model* and one cycle of the fundamental frequency was considered for the variation range of the mean closing time. The analysis was performed for 90, 70 and 50 % of shunt compensation. The surge arresters at the line ends were not represented.

Table 8 shows that the representation of the line as ideally transposed or with actual transposition scheme was decisive for the results. In all cases analyzed higher overvoltages were obtained when the line is modeled with actual transposition scheme.

TABLE VIII
Transient overvoltages at line remote terminal. Influence of line transposition

Comp. degree (%)	Line Transposition Scheme	Overvoltages at line end (p.u)			
		Max.	Mean	Standard deviation	CV (%)
90	IT	1.671	1.593	0.0372	3.920
	RT	1.817	1.662	0.0664	
70	IT	1.825	1.752	0.0374	7.978
	RT	2.006	1.841	0.0731	
50	IT	2.073	1.997	0.0376	4.735
	RT	2.344	2.139	0.0872	

Table 9 shows the results of ANOVA. In this case the F-test shows statistically significant differences between treatments, depending on the line simulation with or without real transposition scheme.

TABLE IX
Analysis of variance of maximum overvoltages at line remote terminal. Influence of line transposition

Comp. degree (%)	Source	Degrees of freedom	Sum of Squares	Mean Squares	F	F Crit.
90	BG	1	0.70462	0.70462	243.072	6.677**
	WG	598	1.73348	0.00290	-	-
	Total	599	2.43810	-	-	-
70	BG	1	1.19188	1.19188	354.087	6.677**
	WG	598	2.01290	0.00337	-	-
	Total	599	3.20477	-	-	-
50	BG	1	3.03983	3.03983	672.289	6.677**
	WG	598	2.70392	0.00452	-	-
	Total	599	5.74375	-	-	-

The results are coherent because when the transposition is represented the travelling wave reaches a terminal in a much shorter time, and a new wave travels backwards to the sending end and another wave continues to the next transposition tower. The process is repeated until the transient disappears, resulting in sharper waveforms that will also have higher maximum values.

From the obtained results it is recommended that the transmission lines should be represented with the field existing transposition cycles and not through ideally transposed line models.

V. CONCLUSIONS

In the present study a statistical analysis of relevant factors that affect the transients overvoltages associated with transmission lines energization was performed.

From the results obtained for 100, 200, 300, 400 and 500 simulations, it is concluded that the number of repetitions does not alter significantly the results regarding the maximum transient overvoltage on the transmission line terminal under analysis. Therefore, any group can be used for simulations depending of the processing speed of computers.

Regarding the variation range of the mean closing time of circuit breaker contacts it can be concluded that the fact of adopting 1 or ½ cycle of the fundamental frequency as the variation range of the mean closing time does not alter the results concerning to the maximum transient overvoltages at the end of the transmission line. It is suggested that 1 cycle should be used in line energization statistical study.

About the modeling of the transmission line, comparing results obtained using the Bergeron Model and the Phase Model higher overvoltages were obtained when the Bergeron Model is used. It is therefore strongly recommended that a model that properly represent longitudinal line frequency dependence parameters like the Phase Model is used in electromagnetic transient studies, such as transmission line energization.

The representation of the line ideally transposed or with the actual transposition scheme was decisive for the results. In all cases analyzed higher overvoltages were obtained when the line is modeled with the transposition scheme 1/6-1/3-1/3-1/6. For this reason, it is recommended that the transmission lines should be represented with the field-existing transposition cycles and not through ideally transposed line models.

VI. REFERENCES

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