A Knowledge Base for Switching Surge Transients

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Abstract--This paper presents a knowledge base for switching transients overvoltages, and more specifically, for transmission line switching. A practical case of line energization is also presented in this paper as a base case. The objective is to provide practical rules and modeling suggestions to evaluate switching transients simulations. These rules will be extracted by studying the switching transient phenomena in more detail. CIGRE Working Groups [2,3,4] and an IEEE Working Group [5] provided background information for the development of this knowledge base.

Keywords: EMTP, Knowledge Base, Switching Overvoltages, Line Energization, Modeling Suggestions.

I. Introduction

ELECTROMAGNETIC transients programs such as EMTP are extensively used for simulating fast transient effects in electric power systems. However, these programs are not easy to use for the following two reasons:

1. All of them require a high level of technical expertise to apply them properly.
2. Some of them are not user friendly.

This paper presents the development of a knowledge base for switching transient overvoltages. From this knowledge base, we can derive some practical rules for switching surge transients. These practical rules will be used in the proposed EMTP intelligent support system [1]. The objective of this work is to give simple and approximate rules for the support system. These rules will be extracted by studying the switching transient phenomena in more detail. These extracted rules will provide the beginning EMTP user and practicing engineer with a simple scheme based on the experience of knowledgeable EMTP users.

The knowledge base for switching surge studies solves the problem of selecting the proper models for representing power system components in the EMTP. It helps in checking the validity of the data used to represent the simulated transient phenomena, and gives some suggestions to the user to correct his case data before simulation. It also helps in the evaluation of the results, using the knowledge of the phenomena being simulated.

A. Switching Surge Transients-Background

With the increasing operating voltage of transmission systems, switching surge overvoltages determine the insulation design rather than lightning overvoltages. The insulation level required to withstand the switching surge overvoltages can have a significant influence on the cost of transmission systems. Therefore, an accurate estimation of the switching overvoltages under various conditions of operation is an important factor for the design of transmission systems [2] [3] [4]. Switching overvoltages result from the operation of switching devices, either during normal conditions or as a result of fault clearings. These transients have durations from tens to thousands of microseconds. They belong to the category of slow front transients. The main operations that can produce switching overvoltages are line energization and re-energization, capacitor and reactor switching, occurrences of faults and breaker openings.

B. Source and Characteristics of Switching Overvoltages

In general, a switching operation in a power system changes the status of the system from those conditions existing before the switching to those existing after the operation. This will produce transient phenomena. The power frequency voltage before and after the switching operation may be of a different value due to the change in the state of the system. This means that the total amplitude of the overvoltage due to switching may be considered in two parts, namely a transient component which is superimposed on a power frequency component [3].

Switching transients usually show complex waveforms with frequencies in the range of 100 Hz to 1000 Hz superimposed on the power frequency.

C. Parameters Influencing Switching Overvoltages

There are a number of parameters of the system and of the operating elements that influence overvoltages. CIGRE Working Group 13.02 [3] summarized these parameters, based on an evaluation of a large amount of collected data on closing and reclosing overvoltages. This data is based on Transient Network Analyzer (TNA), computer and field test results. The evaluation shows the relative influence of the large number of parameters on overvoltages. The most important influencing parameters are explained below.

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In long transmission lines, the most important factors which affect the power frequency voltages on the line during normal operation, and the increase in voltages during a fault, are the length of the line and the degree of shunt compensation. Both parameters have a major indirect influence on the transient phenomena connected with the initiation or clearing of a fault, as well as with normal switching operations. Even the connection of a transformer at the end of a line can affect the overvoltages. Although one might think that the saturation of the transformer limits the increase in power frequency voltage, that is not so. Instead, the harmonics created by saturation and superimposed on the power frequency typically cause an increase in voltage.

Circuit breakers are less often the direct cause of high overvoltages in power systems than is generally assumed. Their operation is similar to that of an ideal circuit breaker, even when switching high short-circuit currents, switching capacitive current, and to a lesser extent in the case of low inductive currents. They interrupt the current mostly at its natural zero crossing point. Overvoltages are, on the other hand, caused by the switching process itself, the characteristic of the system and operation elements, as well as by switching operations and faults immediately prior to it. The circuit breaker itself, together with its closing resistance (the optimum value of which depends on the system characteristic) has a damping effect on switching surges.

There are two characteristics of the system itself which have a major influence on the increase in power frequency voltage and transient phenomena. One of them is the short-circuit power and the other is the system configuration. Low short-circuit power and feeding via a transformer only (inductive source), which occurs in the initial stages of setting up a system, cause much higher switching overvoltages than a high short-circuit power and feeding via transformers and transmission lines (complex system).

D. Switching Overvoltages in Closing and Reclosing Operations

Many measurements, TNA and computer calculations of voltage surges occurring during closing and re-closing of transmission lines were compiled in [2] [3] [4]. The following parameters were varied:

- Closing or reclosing
- Circuit breaker with or without closing resistors
- Complex or inductive feeding systems
- Shunt compensation greater or less than 50%. In most of the cases for >50%, the degree of compensation was approximately 70%, while for the cases of <50% mostly no compensation was employed [3].

As per this CIGRE Working Group Report, it can be clearly seen that the highest overvoltages occur during reclosing without closing resistors, when the system consists of a feeding transformer only and no shunt compensation for the transmission line was provided. On the other hand, a simple charging of the line via closing resistors from a complex system, and with shunt compensation of the line, results in the lowest value of overvoltage.

It was also indicated in this report that switching overvoltages are a function of various parameters of the system and the operating elements. At EHV levels, they are limited by shunt compensation, closing resistors, surge arresters and other measures taken during system operation. The overvoltages occurring at a particular location in the system must be known in order to decide on the use of a particular equipment and its insulation [3].

In conclusion, faults and switching surges are daily occurrences in a system. The switching surges that they cause should not result in further faults or failure of the necessary switching operation. Overvoltages caused by switching on and off of lines, transformers, reactors and other equipment can be effectively reduced by shunt compensation, closing resistors, and surge arresters. Overvoltages which occur at the moment of fault initiation and fault clearing are, on the other hand, a function of the system configuration, the short-circuit power and the method of neutral grounding, and can be controlled or influenced only to a limited extent. Although switching surges are unavoidable, we can nevertheless reduce their frequency of occurrence and magnitude [5].

II. Switching Surge During Energization (Case Study)

This section introduces a switching surge case study of a transmission line energization to be used as the base case for studying the transient phenomena. The network configuration for this case study is shown in Figure 1. The data comes from tests on the Jaguara-Taquaril line, which were conducted by the Brazilian utility company CEMIG. Field test data was made available for these tests [7] [8]. The details of this case study are presented in [9].

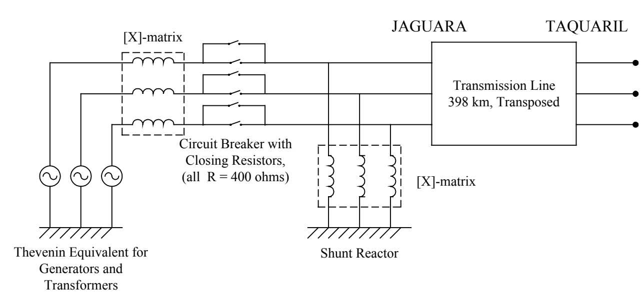

Fig. 1. Network configuration for switching surge case.

III. ModelLing Suggestions

This section presents some modelling suggestions for the simulation of line energizations. These suggestions will provide some practical rules which are based on some of the parameters presented in this section. These modelling suggestions will help the EMTP user to select the proper model and to understand the simulation results better.

A. Step Size

When using the EMTP, the selection of the step size Δt is of importance. On the basis of the highest expected frequency, and assuming that ten points would define one period of this frequency f_{max} with sufficient accuracy, Δt is given by [5]:

$$\Delta t \leq \frac{1}{10 \times f_{\max}} \quad (1)$$

For the line energization case study, the maximum frequency f_{max} is expected to be less than 2 kHz. A step size for this case study of 50 μs is therefore a reasonable choice. For Δt <50 μs, the results are practically identical with those for Δt = 50 μs. When the step size Δt is increased to 100 μs, the results are still accurate. However for 200 μs, the deviations become noticeable and the results are less accurate [5].

1) The maximum frequency rule:

"If the maximum frequency in the system is f_{max}, then use the simulation step size of $\frac{1}{10 \times f_{\max}}$ ".

The travel times for the transmission line are calculated as follows:

$$\tau_1 = l\sqrt{L_1^{'}.C_1^{'}} \quad (2)$$

$$\tau_0 = l\sqrt{L_0^{'}.C_0^{'}} \quad (3)$$

where τ_1 is the positive sequence travel time and τ_0 is the zero sequence travel time. In this case, τ_1 = 1.36328 ms and τ_0 = 2.06432 ms.

For the existing distributed parameter line model in the EMTP, the step size Δt must be less than the travel time of the shortest line in the network. In the case here, the step size Δt is less than the travel times τ_1 and τ_0.

2) The step size constraint rule:

"If the step size Δt is larger than the travel time τ of the shortest line in the network, then a new line model [11] should be used for lines with $\tau \langle \Delta t$ ".

All line models have some discretization errors, except the lossless line if its travel time is an integer multiple of the step size. If this is not the case, then linear interpolation is used in the EMTP. Linear interpolation is believed to be a reasonable approximation for most cases, since the curves are usually smooth rather than discontinuous. If discontinuities or very sharp peaks do exist, then rounding τ to the nearest integer multiple of Δt may be more sensible than interpolation [5].

One simple rule that can be applied for checking whether the step size is suitable is to check if no further accuracy can be obtained if the step size is divided by two [5].

3) Step size accuracy rule:

"If you want to check the accuracy of the simulation, then divide the used step size by 2 and run the simulation".

B. Transmission Line Models [6]

The Jaguara-Taquaril case has been simulated using the constant parameter line model as shown in Figure 2, and good results were obtained. This is because there is very little zero sequence current in the results. For comparison purposes, the transmission line was also represented with frequency-dependent parameters and simulation results are shown in Figure 3.

From the results of Figures 2 and 3 we can observe that the voltages at the receiving end are almost identical, except for a 10% difference in the peak, which is caused by a less damped high frequency oscillation in the constant parameter line model. This is because the zero sequence current flowing in the network is small compared to the phase currents. The currents for the three phases A, B and C are shown in Figure 4.

If the zero sequence current is relatively high, then the constant parameter line model will not give accurate results as compared to the frequency dependent line model.

The frequency dependent model includes information about the variation of the parameters with frequency. This is an important consideration when the ground return mode (zero sequence) is involved. In these cases, the frequency dependent line model will give more accurate representation for a wide range of frequencies contained in the transient phenomena, as compared to the constant parameter line model.

1) The zero sequence current rules:

"If the zero sequence current is small, then use the constant parameter line model".

"If the zero sequence current is high and contains high non-power frequencies, then the frequency dependent line model should be used".

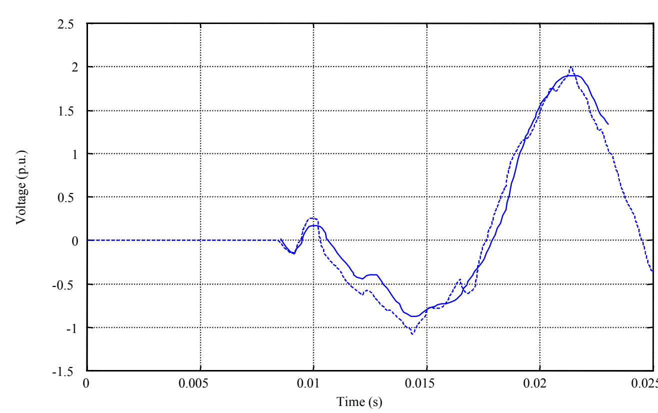

Fig. 2. Comparison between field test (solid) and constant parameter line model (dashed) in phase A

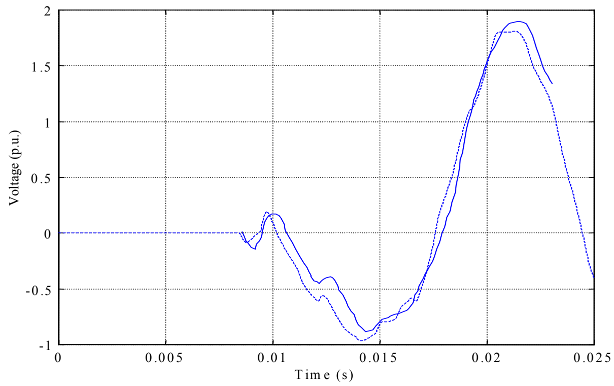

Fig. 3. Comparison between field test (solid) and frequency dependent line model (dashed) in phase A

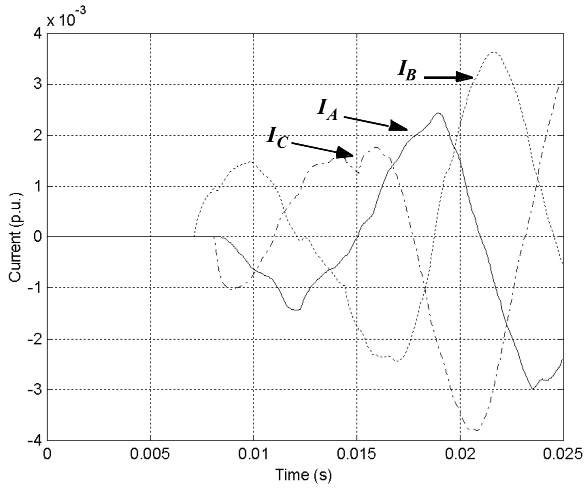

Fig. 4. Currents in the three phases for Jaguara case study

C. Shunt Compensation

Shunt reactors are usually modelled as a simple lumped inductance with a series resistance. A parallel resistance may be added for more realistic high frequency damping [5].

The main purpose of shunt compensation in EHV systems is to limit the power frequency overvoltages. Since the total overvoltage factors on closing and reclosing depend approximately linearly on the power frequency overvoltages, shunt compensation also has an important effect on the magnitude of the total overvoltages.

For 100% compensation, we need a shunt reactor at both ends of the line with a positive sequence value of $\frac{1}{X_{pos}} = \frac{1}{2}\omega C'_{pos} l$. In this case, the voltages at both ends would be identical under no-load condition. In practice, 100% compensation is avoided because of the danger of resonance. Typical degrees of compensation are 50% to 70%. In that case, $\frac{1}{X_{pos}} = \frac{1}{2}\omega C'_{pos} l \times \frac{k}{100}$ where k is the percentage of compensation.

1) The shunt compensation rule:

"If you want to have k% shunt compensation for the line, then place a shunt reactor with a positive sequence value of $\frac{1}{X_{pos}} = \frac{1}{2}\omega C'_{pos} l \times \frac{k}{100}$ *at both ends of the line".*

D. Trapped Charges

In switching surge studies, one must also simulate cases where it is assumed that the line to be energized has trapped charges on it, while the feeding network behind the circuit breaker will be in normal ac steady-state condition. This produces the highest overvoltages in the network. This applies to lines without shunt reactors only, because shunt reactors connected to the line (or inductive potential transformers) would drain off the trapped charges. The severity of the overvoltages in cases with trapped charges depends on the polarity of the trapped charges and the inserting instants of the breaker poles. There are two ways of simulating trapped charges in the EMTP:

1. Use the override "initial conditions" feature of the EMTP.
2. Let the circuit breaker opening action of switches trap a charge, before the circuit breakers are closed again.

1) The trapped charges rule:

"If you want to simulate trapped charges in the EMTP, then use the override "initial conditions" feature of the EMTP, or let the circuit breaker opening action of switches trap a charge before the circuit breakers are closed again".

E. Feeding Network

In most switching transient studies, the generators are modelled as voltage sources behind subtransient reactances, the non-switched lines with constant parameter models, and the transformers with their short-circuit impedances. How extensive the feeding network has to be modelled depends on the particular case. CIGRE Working Group 13.05 [2] recommends for normal switching operations "that the detailed model of the system in general must comprehend the part of network up to the second substations behind that of the operating circuit breaker. For line energization and re-energization exact representation only up to the first substations is sufficient in most cases".

Often, a network equivalent which approximately represents the frequency response characteristic of the entire feeding network is used to simplify its representation.

1) The feeding network rules:

"If you want to model the feeding network for normal switching operations, then the detailed model of the system must include the part of the network up to the second substations behind that of the operating circuit breaker".

"If you want to model the feeding network for line energization and re-energization then line models only up to the first substations are sufficient in most cases".

"If the feeding network is complex, then the resulting overvoltages are typically 10% to 15% less than those with an inductive source".

F. Closing Resistors

Circuit breakers are often equipped with closing resistors, which are inserted in series with the circuit for a short period of time before the main breaker contacts close. The closing resistors are one of the most effective ways to reduce the switching overvoltages [9]. When shunt compensation is present, the effect is more assured.

The selection of the optimum pre-insertion resistor value depends on the line shunt compensation, the short circuit power of the feeding network and the length of the line. For example, shorter lines have higher optimum pre-insertion resistors.

1) The closing resistors rule:

"If the circuit breaker has one-step closing resistors, then model each pole with two switches, one for the auxiliary contacts with the resistor and one for the main contact".

G. Line Length

The total overvoltages are strongly affected by the line length. The increase in the total overvoltages with the increasing line length is primarily due to the increase of the power frequency voltage, which is further a function of the shunt compensation and the short-circuit power of the feeding network. The transient overvoltage shows no clear dependence on the length of the switched line, but is influenced by closing resistors [3]. The given line energization case is simulated with a shorter line length of 125 miles and compared with the original simulation results.

As we can observe, the overvoltages for the longer line are higher than those for the shorter one. This is because of the Ferranti rise effect phenomenon [10]. The rise in the receiving end voltage due to the Ferranti effect can be explained with a voltage divider equation, using the series impedance $R'l + j\omega L'l$ of the π-circuit and the shunt impedance $\frac{1}{\frac{1}{2}j\omega C'l}$ at the receiving end of the π -circuit. Since $R' \langle\langle \omega L'$ on high voltage lines, we can ignore the resistance and get:

$$\frac{V_2}{V_1} = \frac{\frac{1}{\frac{1}{2}j\omega C'l}}{\frac{1}{\frac{1}{2}j\omega C'l} + j\omega L'l} = \frac{1}{1 - \frac{\omega^2 L'C'l^2}{2}} \quad (4)$$

or

$$\frac{V_1 - V_2}{V_2} = \frac{\Delta V_2}{V_2} = -\frac{1}{2}\omega^2 L'C'l^2 \quad (5)$$

This shows that the relative voltage drop $\frac{\Delta V_2}{V_2}$ is negative, which means a voltage rise, and that this relative voltage rise is proportional to the square of the line length.

H. Closing Angle and Pole Span

The closing angles of the three breaker poles are the phase angles of the source side voltages at the instant of electrical closure of the contacts. These angles have a strong influence on the line closing and reclosing overvoltages as they determine the initial conditions for the transients. For transients, when they are not controlled, undesired closing instants of the three poles may occur, but only within the limits of the breaker's pole span. The pole span is the time between the first and the last pole to close. When all the three breaker poles close simultaneously, the overvoltages are smaller than those of random closing. When closing resistors are used, the resistor insertion time should exceed the pole span of the breaker [3].

I. Statistical Switching

Transient voltage and current magnitudes depend upon the instant on the voltage waveform at which the circuit breaker contacts close electrically. A statistical switching case study typically consists of 100 or more separate simulations, each using a different set of circuit breaker closing times. Statistical methods can then be used to process the peak overvoltages from all the simulations.

The switching overvoltages that occur in any specific system arrangement follow a statistical distribution. The distribution function of the amplitude of the switching overvoltages does not behave according to a normal Gausssian distribution. There exists a minimum and a maximum overvoltage magnitude that cannot be exceeded due to technical reasons.

The procedure for assessing the statistical distribution of overvoltages can be presented as follows:

- Generate the input data file.
- Run the case many times with different closing times to get a large enough random sample for the phase voltages.
- Apply statistical methods to the phase voltages to get their statistical distribution.
- Determine the protective level of the system considering both reliability and economy.

An extensive statistical analysis for the Jaguara-Taquaril case has been done in [9].

1) Statistical switching rule:

"To design the insulation of the line, run 100 cases or more, with statistical variation of the closing angles and pole spans. Normally, the 2% value on the cumulative frequency distribution curve is used to design overvoltages".

IV. Derived Practical Rules from the Knowledge Base

From the knowledge base presented in the previous sections, several practical rules can be obtained. These rules could be included in the proposed rule-based systems.

Also, from the information presented in [2] [3] [4] [5], we can derive various rules for the results evaluation process. These rules can be formulated based on the average values, as well as the maximum and minimum values for the overvoltages. For example, if the overvoltages occur during reclosing without closing resistors, when the system consists of a complex feeding network and no shunt compensation of the transmission line is used, then the maximum overvoltage should not exceed 3.5 p.u. The same scenario can be repeated for different system conditions.

V. Conclusions

The following topics have been covered in this paper: an overview of switching transient overvoltages, the parameters that influence the switching overvoltages, a practical case study of transmission line energization, and modelling suggestions for the simulation of line energizations based on the parameters that influence the switching overvoltages.

Using the knowledge presented in this paper as a starting point should increase the knowledge of EMTP users about transients phenomena, and how to apply this knowledge to the use of the EMTP for more complex studies. An understanding of power system transient phenomena is needed before sufficient expertise can be claimed; there is no other alternative for understanding the fundamentals of transient phenomena and what their effects are expected to be, and this is what this paper is partially trying to answer.

VI. Acknowledgment

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VIII. Biographies

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Hermann W. Dommel: was born in Germany in 1933. He received the Dipl.-Ing. and Dr.-Ing. degrees in Electrical Engineering from the Technical University Munich, Germany, in 1959 and 1962, respectively. From 1959 to 1966 he was with the Technical University Munich, and from 1966 to 1973 with Bonneville Power Administration, Portland, Oregon. Since July 1973 he has been with the University of British Columbia in Vancouver, Canada. Dr. Dommel is a Fellow of IEEE and a registered professional engineer in British Columbia, Canada.