

Analysis of the Occurrence of a Three-Phase Short-Circuit Due to Lightning on CEMIG Extra-High Voltage System

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Abstract - The operative experience has shown that three-phase short-circuits caused by lightning on extra-high voltage transmission lines are rare occurrences in power systems since adequate insulation, shielding effectiveness and low tower-footing resistance are considered in their designs. This paper describes the occurrence of a three-phase fault on a 500 kV transmission line, part of Companhia Energética de Minas Gerais-CEMIG transmission system, which led the Company to start a serie of investigations with the purpose of determining its cause, evaluating the probability of its occurrence and, if required, implementing measures in order to prevent it.

Keywords: Lightning, 500kV Transmission Line Three-phase Short-Circuit, Transient and Protection analysis, Real-Time Monitoring, Power Quality.

I. INTRODUCTION

Companhia Energética de Minas Gerais – CEMIG is the electrical power utility of the State of Minas Gerais, with an installed capacity of 5514MW and an extra-high voltage transmission system comprising 30 substations and 4817 km of transmission lines at voltages ranging from 230kV to 500 kV. CEMIG supplies electricity to 96% of the State of Minas Gerais, which is located in the Southeastern region of Brazil. The area supplied is 560 thousand square kilometers and is equivalent to a country the size of France.

This electrical system is installed in regions having high soil resistivity and high keraunic levels, which can negatively affect the performance of the installations due to lightning discharges. Such adverse environmental conditions of the State of Minas Gerais have led CEMIG to invest resources in new technologies and lightning research with the purpose of minimizing the impact of such conditions on the power quality supplied to its consumers.

In the specific case of transmission lines, international statistics point to lightning discharges as the major cause for unscheduled interruptions. These interruptions, most of the times, are caused by single phase short-circuits due to backflashovers and are concentrated on lines with voltages below 230 kV. Thus, the occurrence of a three-phase short-circuit on transmission line 500kV Jaguara-Nova Ponte of CEMIG transmission system, during a thunderstorm, gave rise to a series of detailed analysis of the disturbance, considering its important impact on the quality of the

system operation, such as the disconnection of major transmission consumers.

The 500kV Jaguara – Nova Ponte transmission line is part of the brazilian interconnected transmission system responsible for the power flow produced by the main hydroelectric generating plants of the southeastern region of the country. This line links Jaguara Hydroelectric Power Plant (448 MVA) to Nova Ponte Hydroelectric Power Plant (537 MVA) and plays a decisive role in the power exchanges among the generating regions of the Brazilian electrical system. Fig. 1 shows CEMIG’s main generation and transmission system in the State of Minas Gerais.

From the standpoint of ground flash densities, the 500kV Transmission Line Jaguara-Nova Ponte crosses one of the regions with the highest ground flash densities in the State of Minas Gerais, reaching 8 flashes/km²/year, near Jaguara substation.

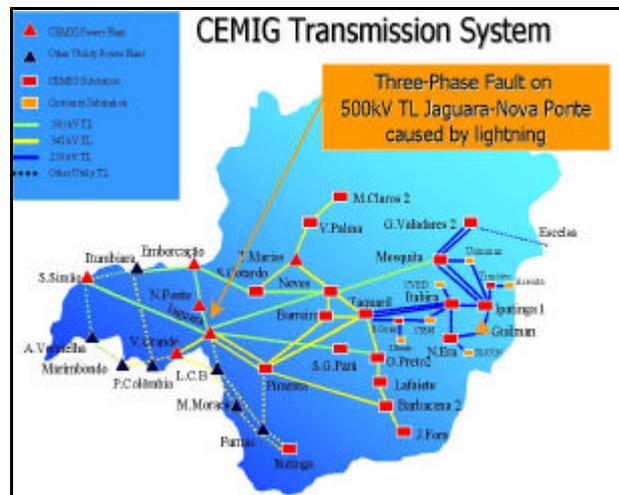


Fig. 1. CEMIG Transmission System – 230kV and above

This paper presents the evaluations performed for the disturbance involving this 500kV transmission line, including the analysis of the protection operation, the analysis of the meteorological conditions at the time of the fault and its effects, the transient simulations performed and field measurements.

II. DISTURBANCE ANALYSIS

A. Protection Analysis

In order to properly monitor its large transmission system and to provide resources to help the analysis of disturbances, CEMIG installed an Oscillography Network (SAPNET), comprising a set of integrated hardware and software, which allows an adequate processing of the data generated by Digital Fault Recorders, Digital Relays and Local Supervisory and Control System. One important feature of this system is the transmission line fault location software which through specific algorithm determines the fault site on the line with an accepted deviation. SAPNET enables us to find out the type of fault, its duration, location and its effect on the other buses of the interconnected system as well. Presently, this system has 50 Digital Fault Recorders (DFR) installed at the main substations of CEMIG transmission and subtransmission systems [1].

Three-phase faults on 500 kV transmission line are very rare events and the few cases that had already occurred in CEMIG's transmission system have not been registered, so they could not be confirmed and analyzed thoroughly.

The three-phase short-circuit on the 500kV Jaguara-Nova Ponte transmission line occurred on March 8, 1999, at 4:40 PM. Fig. 2 presents the waveform of the three-phase fault, obtained through the DFR at Nova Ponte substation. The short-circuit lasted for approximately 45 ms and the voltage reached 40% of its rated value at this substation. By means of simulations with the Aspen Onliner® short-circuit program [2], such values were confirmed and extrapolated to the other buses of the system. Fig. 3 presents the results given by the fault location system. The fault location range was the first three kilometers from Jaguara substation. This was the first time an occurrence of this type was recorded in such detail.

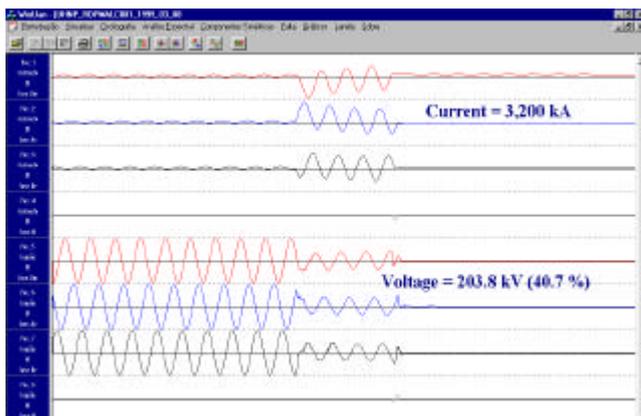


Fig. 2. Waveform of the three-phase fault

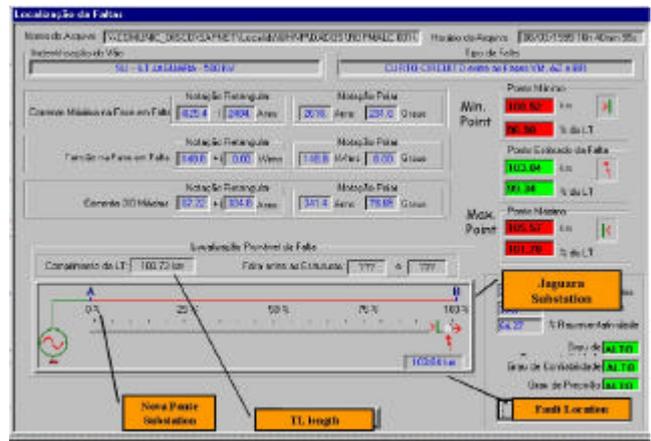


Fig. 3. Fault location range

The analysis of this occurrence was facilitated due to the fact that the DFR was synchronized by Global Positioning System (GPS) with CEMIG Lightning Location System (SLT), providing the identification of the discharge location and its intensity. The integration of these two systems shall be described in the next item.

B. Lightning Stroke Analysis

The confirmation of lightning as the most probable cause for the transmission line three-phase short-circuit was possible utilizing CEMIG Lightning Location System (SLT) technology. This system combines information from the Fault Locator and Analysis System (FALLS) with the transmission line routes digitized and converted into a geoprocessing platform using GPS [3]. The matching of such information with that obtained from the SAPNET line fault location software allowed the identification of the probable stroke causing the fault, providing input for the analysis of the disturbance.

CEMIG Lightning Location System (SLT) was first installed in 1988 and was upgraded in 1997 with the purpose of enhancing the rates of detection and reducing discharge location errors to less than 500 meters. The utilization of such resources in the analysis of the occurrence involving the Transmission Line 500kV Jaguara-Nova Ponte is shown in Fig. 4.

A high number of discharges, summarized in the table of Fig. 4, was observed striking the line at the site where the fault was located and in the period when it occurred (intervals of seconds). As the short-circuit was recorded at 16:40:55 hours by the oscillographic network, the stroke number 7 (38kA) was, most probably, the one that caused the fault. It is interesting to notice that this value is close to the 50% lightning current value around 42kA, observed by CEMIG research programs [4].

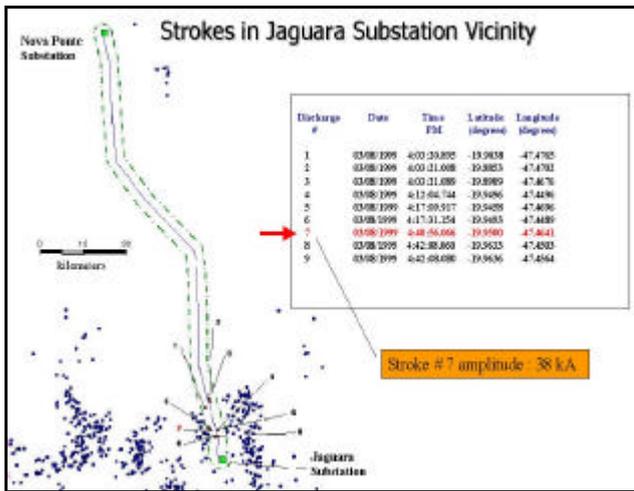


Fig. 4. Strokes in Jaguarua Substation Vicinity

C. Power Quality Analysis

Nowadays, industrial consumers are investing more and more in the modernization of their industrial plants, by means of equipment provided with electronic processing such as Programmable Logical Controllers (PLC) and variable speed drives. Such equipment is extremely sensitive to voltage variations, especially those involving more than one phase. Such voltage sags are presently the major cause of production loss at industrial consumers.

During the occurrence of March 8, 1999, there was a loss of load of 270 MW in CEMIG system. Such loss is justified by the values of three-phase voltage in the order of 70% the rated value, due to the short-circuit, on some of the major industrial consumers buses.

D. Transient Analysis

The transient simulations were performed with the Alternative Transient Program (ATP) and had the main purpose of reproducing the three-phase short - circuit, using as reference the information registered by the SAPNET and SLT systems during the disturbance.

The models used for the system components being analyzed are summarized below. A detailed description of these models are found in [5] and [6].

• Transmission line modelling

Seventeen spans of Transmission Line 500kV Jaguarua – Nova Ponte were simulated, starting from the Jaguarua Substation, in accordance with the line fault location results. Each span was represented, as an untransposed line, by a model transformation matrix (phase-mode transformation) calculated by the line constant routine of ATP at 100kHz. This matrix was an input to the JMarti line model which determines the characteristic impedance and propagation factor functions which represent the line over a frequency range. After the last span, the line surge

impedance in phase domain, calculated by ATP Line Constant routine, was introduced. This procedure was adopted for the other 500kV transmission lines connected to the Jaguarua Substation.

It is known that the presence of corona, which is significant at the 500kV voltage level, will have an effect on the insulator overvoltages as it increases the conductor capacitances, changing their coefficient couplings. This effect was not taken into account in the simulations due to a lack of an available model in the ATP to reproduce it.

The towers were modelled as distributed-parameter elements with surge impedances equal to 150 ohms, and travel time calculated as a function of their heights of the tower, according to equation $\tau = \text{tower height} / 300\text{m} / \mu\text{s}$. The crossarm region was simulated in the same way, considering the length of its parts. The grounding impedance was modelled as a concentrated resistance, varying its value from 30 ohms (maximum value considered in the line project) to 400 ohms.

• Sources

A senoidal voltage source ATP type 14, connected to the Jaguarua Substation, was used to represent the 60Hz system voltages.

The lightning discharges were represented by optimum current sources ATP type 13, slope ramp $2.6/65\mu\text{s}$. The amplitude of the lightning current was varied from 38 (value registered by the SLT) to 80kA, taking into account some inaccuracy in current estimation by the SLT.

• Insulators

The insulators were modelled as switched resistances, ATP type 99, having as reference the insulator critical flashover voltage U50 for lightning discharges (voltage with 50% flashover probability), considered equal to 1904kV for negative impulse.

Initially, the simulations were performed for some combinations of stroke amplitudes and tower foot resistances, without considering the presence of the 60Hz voltage source. It was assumed a stroke hitting one of the shielding wires, next to phase C, of a tower located approximately 2 km from the Jaguarua Substation, within the region detected by the fault location system. Fig. 5 represents a sketch of the tower with the relative position between the phases and the stroke.

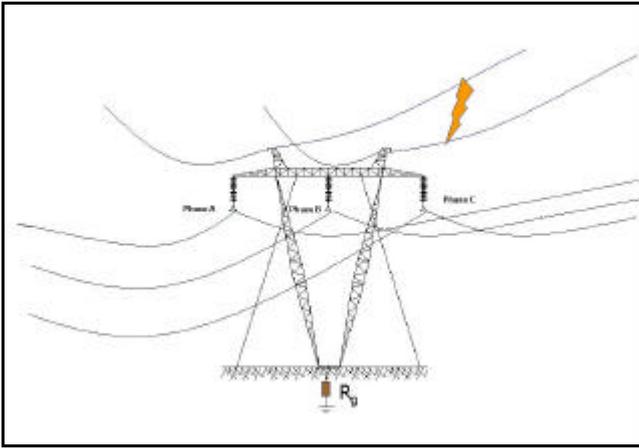


Fig. 5. 500kV Transmission Line tower sketch

For the cases studied, without the 60Hz voltage sources, no simultaneous flashovers occurred on the three-phases, a necessary condition for the three-phase short – circuit, even when considering values lesser than 1904 kV (minimum 3% standard deviation considered) for the insulator strength. On most cases simulated, flashover occurred only on phases A and C. This could be explained by the fact that phase B has a larger coupling with the shielding wires, which tends to reduce phase B insulator voltage.

As an example, Fig. 6 presents the three-phases insulator voltages for a stroke with amplitude of $IS=38$ kA, which was the value registered by the SLT near the time of the occurrence, and a tower foot resistance $R_g = 400$ ohms. Flashover occurred only on phases A and C, even for the value considered for the tower foot resistance in this case, significantly higher than the line’s average.

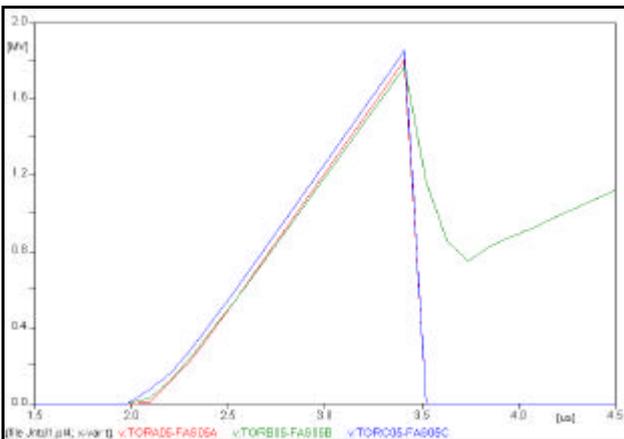


Fig. 6. Phase A and C Insulator Flashovers
 $IS = 38$ kA and $R_g = 400 \Omega$

Fig. 7 also shows the behavior of the insulator voltages, this time for an amplitude of 80kA, almost double the one recorded by the SLT, and 30 ohms tower foot resistance (the maximum value considered for the transmission line). In this case, flashover took place only on phase C insulator, considered the nearest to the stroke, which

caused an instantaneous decrease of the tower voltage, preventing the insulator flashovers on the other phases.

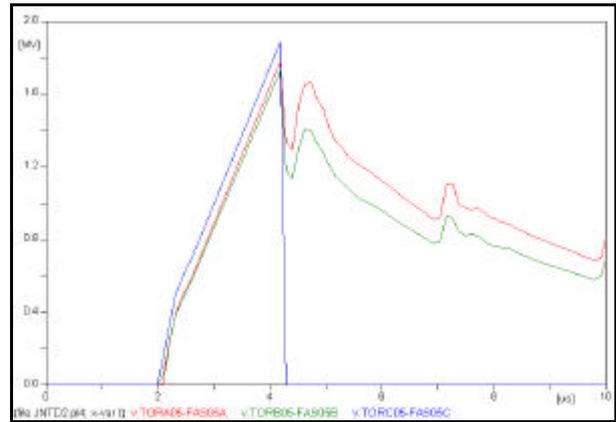


Fig. 7. Phase C Insulator Flashover
 $IS = 80$ kA and $R_g = 30 \Omega$

These results confirmed the importance of considering the influence of the 60 Hz voltage in the analysis of the insulator behavior, concerning lightning discharges for Extra-High-Voltage systems. For the 500kV system, the peak value of the line to ground 60Hz voltage is significant compared with the insulator strength (around 20%) which can be determining as far as flashovers are concerned.

Therefore, the next step was the evaluation of the necessary conditions to have the flashover of the insulators on the three-phases, taking into account the operation of 60Hz voltages sources. The following methodology was considered in the simulations:

- The stroke was considered hitting phase C shielding wire as in the previous simulations (Fig.5).
- Since the 60Hz voltages may either increase or decrease the insulator voltages, the amplitudes and polarities of 60Hz voltage waves were varied with the purpose of determining the range that would be more favorable for the occurrence of the flashovers of insulators on the three-phases, This analysis was made considering, as reference, the 38kA registered by the SLT during the instant of the disturbance and 400 ohms tower foot resistance.
- The tower foot resistances were calculated by the ATP for a given value of lightning current amplitude and the favorable region of the 60Hz voltage wave. The resistance values found were later confirmed by means of field measurements, which will be discussed in the following item of this work.

Among the simulated cases, the flashover of the insulators on the three phases occurred for phase C with positive 60Hz voltage, condition that minimizes the value of the insulator voltage, causing a delay in its flashover. Also, for such flashover to occur, it was necessary to consider a

lower value for the insulator strength of that phase, which introduced a compensation for the positive polarity.

For phases A and B, flashover took place at the 60Hz voltages with negative polarities, a condition which tends to increase the insulator voltages of such phases. The 60Hz voltage of phase B also had to be more negative than that of phase A, compensating for a larger coupling of phase B with the shielding wires.

Fig. 8 shows the regions of the 60Hz voltages for which the three-phase insulators flashovers were achieved, for the conditions evaluated.

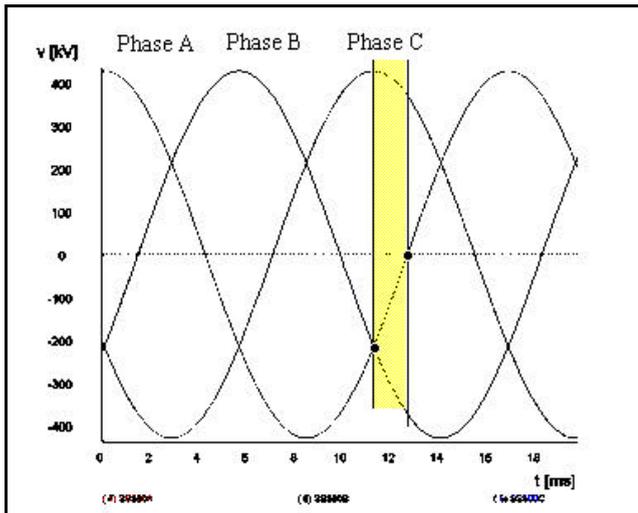


Fig. 8 .60Hz Voltage range to produce a flashover on the three phases

Fig. 9 shows the result of one of the simulations, 40kA lightning current and 400 ohms tower foot resistance, showing flashover of the insulators on the three-phases.

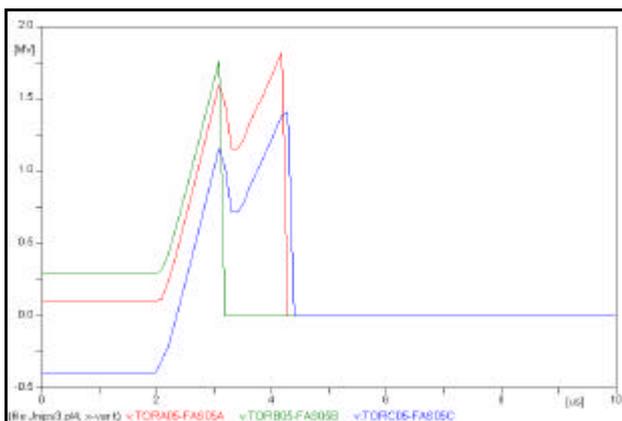


Fig. 9. Three Phase Insulator Flashovers

Table 1 presents the minimum grounding resistance required for the occurrence of flashover on the three-phases as a function of the stroke current, with 60Hz voltages within the range indicated in Fig. 8.

Table 1. Stroke Current x Tower Foot Resistance Three-Phase Insulator Flashover

IS (kA)	Rg (Ω)
40	400
60	200
80	90

The simulations confirmed that very specific conditions are needed in order to enable the occurrence of three-phase short-circuits, due to atmospheric discharges on extra-high-voltage transmission lines, such as: high amplitude stroke, high tower grounding resistance and specific values for the 60Hz instantaneous voltage. The need to have the simultaneous occurrence of all these factors explains the rarity of this type of event in the operation of the transmission system.

III. FIELD MEASUREMENTS

With the purpose of validating the results of the simulations which pointed to the need of having high grounding resistance at Transmission Line 500kV Jaguarua-Nova Ponte to enable the three-phase short-circuit to occur, tower foot resistance measurements were performed on six line structures located in the section indicated by the line fault location system (first kilometers from Jaguarua Substation).

The soil of Jaguarua region is dry and very rocky, having high resistivity. A summary of the results achieved is shown in Table 2 and confirms such features. It is also observed that measurements at structure 691, due to its unfavorable location and worse soil sample, has shown the highest value of grounding resistance, 383 ohms.

Table 2. Tower Foot Resistances Field Measurement Results

Tower (#)	Distance from Jaguarua (%)	Resistance (Ω)
691	5.0	383
701	1.5	111
698	2.5	28

Such value is near the one found for the tower foot resistance in the simulation for a 40kA discharge current (Fig. 4, Table 1). The coherence between the results given by the ATP simulations, the SLT records, the fault location region detected by SAPNET and the tower foot resistance field measurements allowed to reach a safe conclusion about the cause of the occurrence, helping to evaluate the need of possible corrective action regarding the line.

CEMIG is implementing actions with the purpose of evaluating the grounding resistance of its EHV lines in order to prevent occurrences of this nature to repeat. Also, studies are being carried out to analyze the feasibility of the installation of line surge arresters on the 230kV system,

which feeds a significant number of industrial transmission system consumers. CEMIG has already applied this technology at other voltage levels with great success.

IV. CONCLUSION

This paper presented the analysis carried out by CEMIG of the occurrence of a three-phase short-circuit on the 500kV Jaguara-Nova Ponte transmission line, which is part of its transmission system. Such event, which is considered a rare one, had an important effect on the operation of the system, causing the interruption of important industrial consumers.

The analysis of the available information from CEMIG oscillographic network with the fault location system and CEMIG Lightning Location System was essential for the characterization of the fault. Such fact stresses the importance of investing in new technologies for a better knowledge of the disturbances in the electrical system, with consequent improvement of the quality of the energy supply to the consumers.

Another important conclusion of this study emphasizes the usage of ATP as an effective complementary tool for analysis of electrical system occurrences. In this specific case, the transient simulations not only corroborated the possibility that a lightning stroke was the cause of the fault, but also demonstrated the reasons of its low probability, contributing for a deeper knowledge of such type of event on extra-high-voltage systems.

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