STUDIES OF ELECTRICAL DISTRIBUTION RADIAL FEEDERS PARALLELISM

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***Abstract* – This paper shows the preliminary results of a study of voltages and currents transients related to parallelism between two distribution lines derived from different transformers belonging to the same substation or to different substations. The main subject of this work is the development of a mathematical model of the system and the development of a software to simulate the dynamic behavior of the system during the opening and closing of the switch responsible for the parallelism. The preoccupations emerging with this parallelism are that referred to the overvoltages and overcurrents on the transformers and on the switch responsible for this parallelism. The software developed can help the operators involved in the electrical system studies and security.**

***Keywords* - Parallelism of distribution lines, parallelism of transformers, voltages and currents transients.**

I. INTRODUCTION

This study has the objective of studying the dynamic modeling of transformers and distribution lines and the developing software able of simulating voltage and current transient effects of the parallelism between two transformers of the same substation of different substations. The effects on the circuit breaker, on the paralleled transformers operation and on the network are analyzed.

The simulation results using the software developed in this work, based on real data of part of the electrical system of the Guarujá city in Brazil are compared with results obtained by using the ATP (Alternative Transients Program) and SimPowerSystems software of the Matlab/Simulink.

II. ELEKTRO SYSTEM IN GUARUJÁ

The Guarujá Elektro regional system is situated in a touristic coast region of São Paulo State, in Brazil, with about 3.7 thousand km of primary network serving 203.8 thousand consumers with a typical residential load.

The studied system is made up of GUT40 and GUT47 feeders, both located in the Guarujá Substation 3. With the parameters of the system in the ELEKTRO data base (length of the feeders, type of conductors, loads and the transformers data) the system model in SimPowerSystems was implemented as in Figure 1.

In this work the effect of saturation in the transformers and the existence of nonlinear load in the system was not considered.

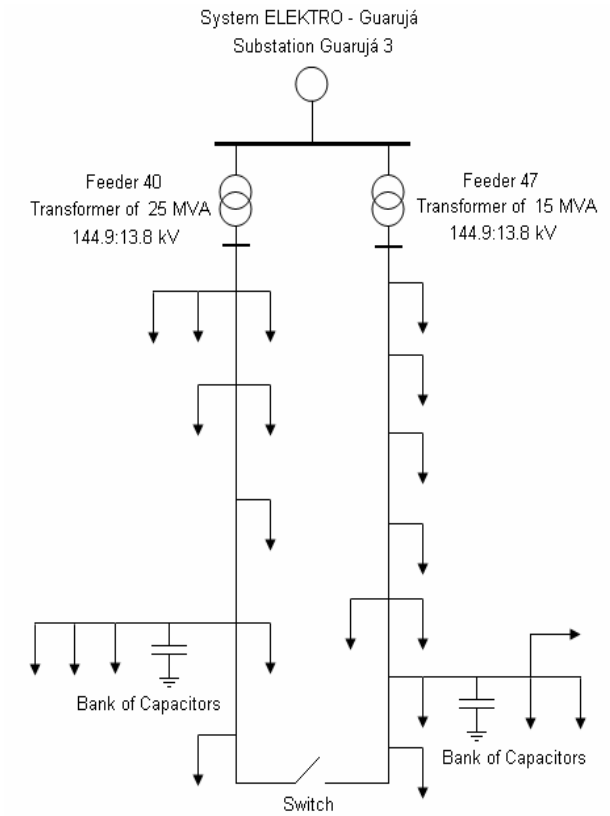


Fig. 1. Feeders Model GUT40 and GUT47

III. MATHEMATICAL MODELING

Due to complexity of the system a program of reduction of circuits was used to reduce the original system to a equivalent model. However, the GUT40 and GUT47 feeders have present a characteristic that showed to be very important in the transitory voltage and current analysis, and that is the presence bank of capacitors close to the switch, Figure 1.

When the Guarujá system was reduced to the equivalent, the simulation analysis demonstrated that the bank of capacitors cannot be included in the circuit reduction, that is, the point where the bank of capacitors must be preserved, because in the equivalent calculations the inductance and capacitance values go to zero that annul the bank capacitor effect on the switch. So, a reduction system having a bank of capacitors is smaller than that without one.

Therefore, equivalents of parts of the circuit in study were constructed keeping the points where the 1.2 MVAr banks of capacitors are.

The resultant equivalent model is presented in Figure 2.

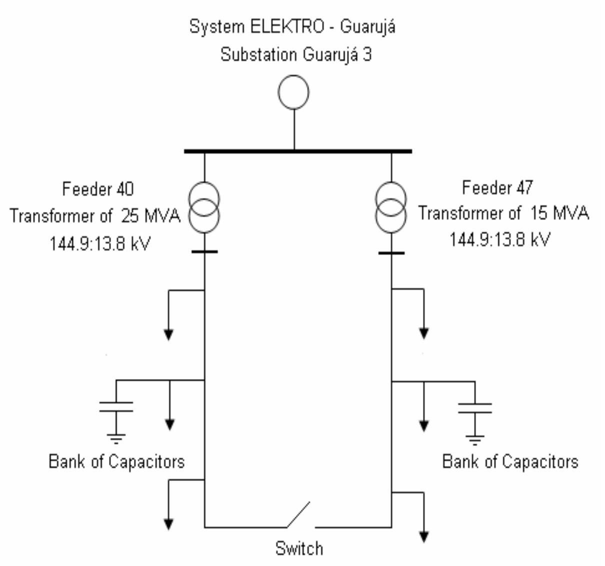
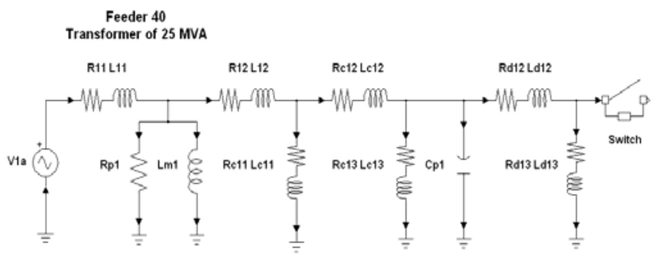


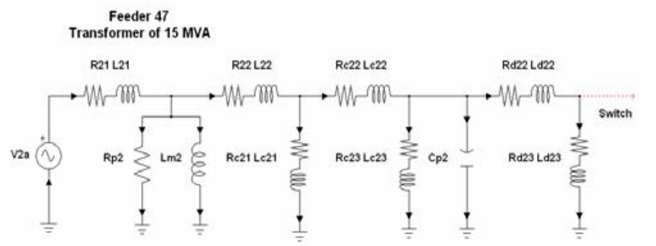
Fig. 2. Equivalent model

After, simulations showed that the equivalent model in Figure 2 correctly represented the system in study. The equations of the system using differential equations were calculated (1).

In Figure 3 presents the unifilar diagram of the equivalent model which was used to validate the equations model.



(a)



(b)

Fig. 3. Unifilar diagram of the equivalent model: a) circuit left side of the switch, b) circuit right side of the switch

Considering that the diagram of the Figure 3 represents the A phase of the electrical distribution system and the meshes are numbered 1 to 13 (from left to right, and the same direction for the mesh current), starting the circuit analysis from the voltage source (V_{1a}) one has the mesh currents from 1 to 6 (i_1A_1 ... i_1A_6), Figure 3a.

The number 7 mesh is the one that has the switch and its electric current is called i_{ch}. In the sequence from the mesh of the switch, one has the meshes from 8 to 13 (i_2A_6 ... i_2A_1) up to the voltage source (V_{2a}), Figure 3b.

Calculating the equation for the Figure 3 circuit, with the adopted direction from left to right from mesh 1 up to 13, one has:

$$
\begin{aligned}
& L_{11}p\dot{i}_1A_1 = -(R_{11}+R_{p1})i_1A_1 + R_{p1}i_1A_2 + V_{1A} \\
& L_{m1}p\dot{i}_1A_2 - L_{m1}p\dot{i}_1A_3 = R_{p1}i_1A_1 - R_{p1}i_1A_2 \\
& -L_{m1}p\dot{i}_1A_2 + (L_{m1}+L_{12}+L_{c11})p\dot{i}_1A_3 - L_{c11}p\dot{i}_1A_4 = \\
& \quad -(R_{12}+R_{c11})i_1A_3 + R_{c11}i_1A_4 \\
& -L_{c11}p\dot{i}_1A_3 + (L_{c11}+L_{c12}+L_{c13})p\dot{i}_1A_4 - L_{c13}p\dot{i}_1A_5 = \\
& \quad R_{c11}i_1A_3 - (R_{c12}+R_{c11}+R_{c13})i_1A_4 + R_{c13}i_1A_5 \\
& -L_{c13}p\dot{i}_1A_4 + L_{c13}p\dot{i}_1A_5 = R_{c13}i_1A_4 - R_{c13}i_1A_5 - V_{cp1} \\
& C_{p1}p\dot{V}_{cp1} = i_1A_5 - i_1A_6 \qquad (1) \\
& (L_{d12}+L_{d13})p\dot{i}_1A_6 - L_{d13}p\dot{i}_{ch} = -(R_{d12}+R_{d13})i_1A_6 + R_{d13}i_{ch} + V_{cp1} \\
& -L_{d13}p\dot{i}_1A_6 + (L_{d13}+L_{d23})p\dot{i}_{ch} - L_{d23}p\dot{i}_2A_6 = R_{d13}i_1A_6 \\
& \quad -(R_{d13}+R_{ch}+R_{d23})i_{ch} + R_{d23}i_2A_6 \\
& -L_{d23}p\dot{i}_{ch} + (L_{d23}+L_{d22})p\dot{i}_2A_6 = R_{d23}i_{ch} - (R_{d23}+R_{d22})i_2A_6 - V_{cp2} \\
& L_{c23}p\dot{i}_2A_5 - L_{c23}p\dot{i}_2A_4 = -R_{c23}i_2A_5 + R_{c23}i_2A_4 + V_{cp2} \\
& C_{p2}p\dot{V}_{cp2} = i_2A_6 - i_2A_5 \\
& -L_{c23}p\dot{i}_2A_5 + (L_{c23}+L_{c22}+L_{c21})p\dot{i}_2A_4 - L_{c21}p\dot{i}_2A_3 = R_{c23}i_2A_5 \\
& \quad -(R_{c23}+R_{c22}+R_{c21})i_2A_4 + R_{c21}i_2A_3 \\
& -L_{c21}p\dot{i}_2A_4 + (L_{c21}+L_{22}+L_{m2})p\dot{i}_2A_3 - L_{m2}p\dot{i}_2A_2 = R_{c21}i_2A_4 \\
& \quad -(R_{c21}+R_{22})i_2A_3 \\
& -L_{m2}p\dot{i}_2A_3 + L_{m2}p\dot{i}_2A_2 = -R_{p2}i_2A_2 + R_{p2}i_2A_1 \\
& L_{21}p\dot{i}_2A_1 = -(R_{21}+R_{p2})i_2A_1 + R_{p2}i_2A_2 + V_{2A}
\end{aligned}
$$

where:
R_{11}, L_{11} winding primary transformer 1 resistance and inductance, referred to secondary; R_{12}, L_{12} winding secondary transformer 1 resistance and inductance; R_{p1}, L_{m1} leakage primary transformer 1 resistance and inductance; R_{c11}, L_{c11} equivalent feeder 40 parallel resistance; R_{c12}, L_{c12} equivalent feeder 40 serial resistance; R_{c13}, L_{c13} equivalent 40 feeder parallel resistance; C_{p1} capacitor of feeder 40 bank of capacitors; R_{d12}, L_{d12} equivalent feeder 40 serial resistance; R_{d13}, L_{d13} equivalent feeder 40 parallel resistance; R_{ch} switch resistance;
R_{21}, L_{21} winding primary transformer 2 resistance and inductance, referred to secondary; R_{22}, L_{22} winding secondary transformer 2 resistance and inductance; R_{p2}, L_{m2} leakage primary transformer 2 resistance and inductance;

R_{c21}, L_{c21} equivalent feeder 47 parallel resistance; R_{c22}, L_{c22} equivalent feeder 47 serial resistance; R_{c23}, L_{c23} equivalent 47 feeder parallel resistance; C_{p2} capacitor of feeder 47 bank of capacitors; R_{d22}, L_{d22} equivalent feeder 47 serial resistance; R_{d23}, L_{d23} equivalent 47 feeder parallel resistance.

It is observed that beyond the mesh equations, two branch equations related to the bank of capacitors. The variable system state is, then, the electric currents of each mesh together with the ground voltage in each bank of capacitors. In this form, the general state equations (1) can be written in a compact way as shown in (2), normally used when it is desirable to find the solutions of differential equations by simulation on a digital computer.

The state equations for the system being studied follow directly from equation (1), where:

$$\begin{aligned} \dot{x} &= Ax + Bu \\ y &= Cx + Du \end{aligned} \tag{2}$$

$$\begin{aligned} x &= [i_1 A_1, i_1 A_2, ..., i_2 A_1, V_{cp1,} V_{cp2}] \\ u &= [V_{1A}, 0, 0, ..., V_{2A}, 0, 0] \end{aligned} \tag{3}$$

The trapezoidal method was used to solve the state equations:

$$\begin{cases} \bar{x}_{k+1} = \left(I - \frac{T}{2}A\right)^{-1}\left(I + \frac{T}{2}A\right)\bar{x}_k + \frac{T}{2}\left(I - \frac{T}{2}A\right)^{-1} B\left(\bar{u}_{k+1} + \bar{u}_k\right) \\ \bar{y}_{k+1} = C\bar{x}_{k+1} + D\bar{u}_{k+1} \end{cases} \tag{4}$$

It is important to point out that both the transformers and the distribution lines had been modelled without taking into account their capacitances.

IV. SOFTWARE

The software was written in Matlab 6.5, mainly for it being a straightforward language, with pre-defined operations, for example, inverse matrices, that simplify the programming. It also has excellent graphical resources.

To validate the mathematical modeling (1) used in software the following simulations had been carried out: 1) Voltage in the 25 MVA (GUT40) transformer secondary terminal, Figure 4; 2) Current in the 25 MVA (GUT40) transformer secondary terminal, Figure 5; 3) Switch current, Figure 6; 4) Switch voltage, Figure 7; 5) Voltage in the 15 MVA (GUT47) transformer secondary terminal, Figure 8; 6) Current in the 15 MVA (GUT47) transformer secondary terminal, Figure 9.

The simulation parameters were: simulation time 0.5s; initially the switch is open, after 0.2s it is closed, and after 0.4s it is opened again.

The developed software used 10^{-3} as the step simulation and the SimPowerSystems used 10^{-5}.

Figures 4 to 9 present comparative results between the developed software and the SimPowerSystems.

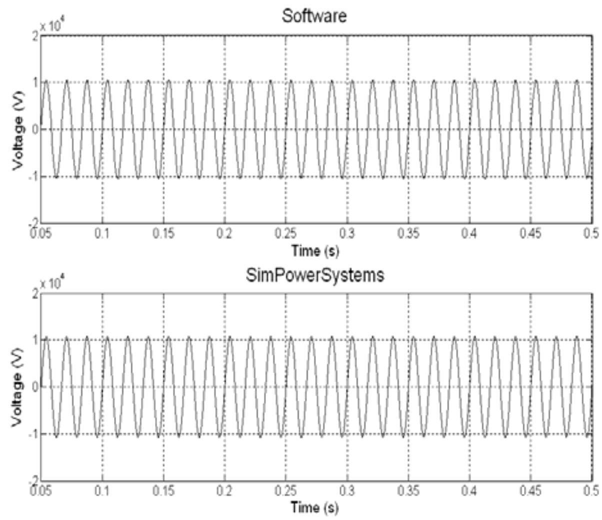


Fig. 4. Voltage in the 25 MVA transformer secondary terminal

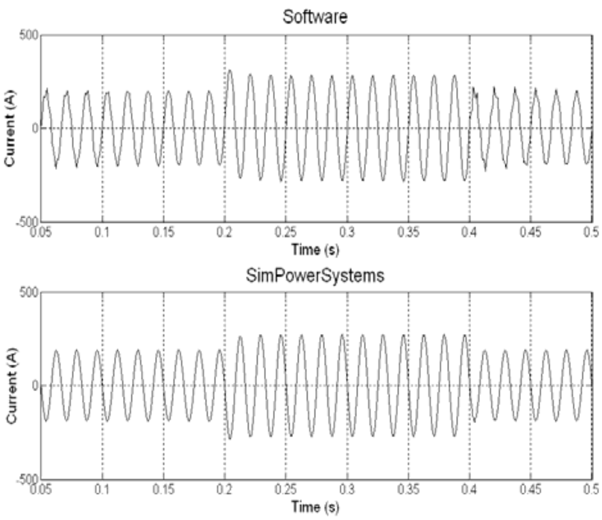


Fig. 5. Current in the 25 MVA transformer secondary terminal

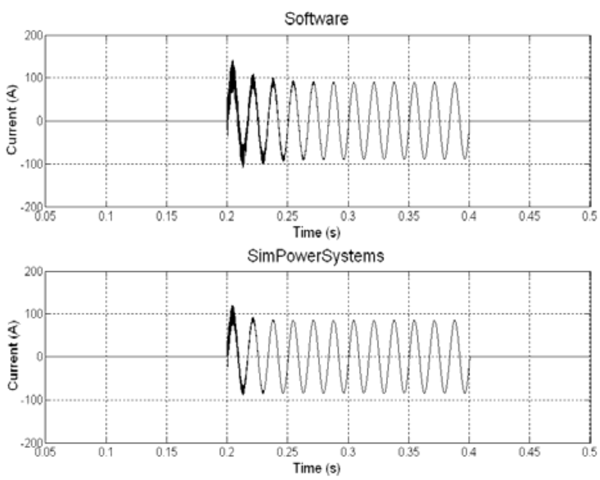


Fig. 6. Switch current

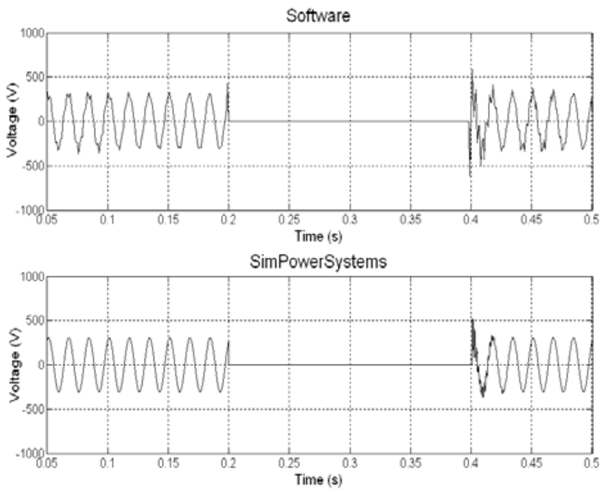


Fig. 7. Switch voltage

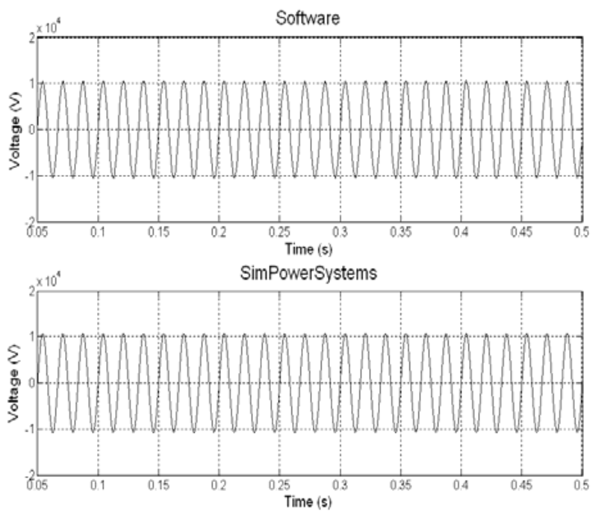


Fig. 8. Voltage in the 15 MVA transformer secondary terminal

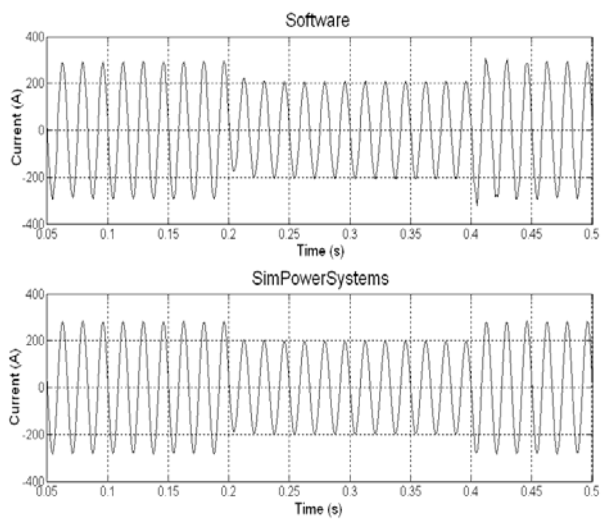


Fig. 9. Current in the 15 MVA transformer secondary terminal

V. MEASUREMENTS

To validate the model of the system implemented in the SimPowerSystems and the mathematical model of the developed software, switching and measurements at the parallelism point were carried out, as presented in Figure 10.

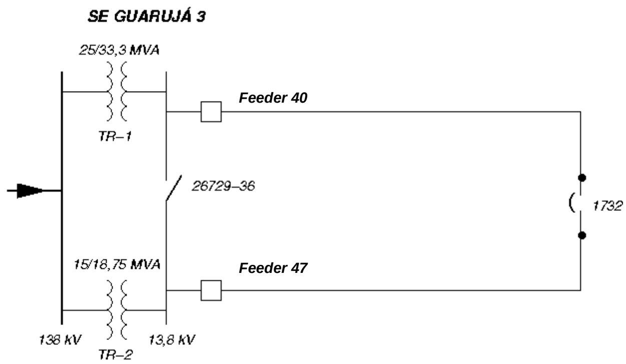


Fig. 10. Unifilar simplified ring diagram

At the beginning it was believed that TPs on both sides of the 1732 switch existed. However, the existence of TPs (V connection) was verified only at the feeder 40 arrival side. The inclusion of TPs at the feeder 47 side turned out to be impracticable, due to the lack of space in the poles. It was decided that the measurement at the side of feeder 47 would be carried out in the distribution transformer secondary (Dy-1 connection).

It must be pointed out that, as shown in Figure 11, the secondary voltages registered by the oscillograph come from equipment with different characteristics, i.e., at the side of feeder 40 the voltage comes from a TP, while at the side of feeder 47 it comes from a usual voltage transformer.

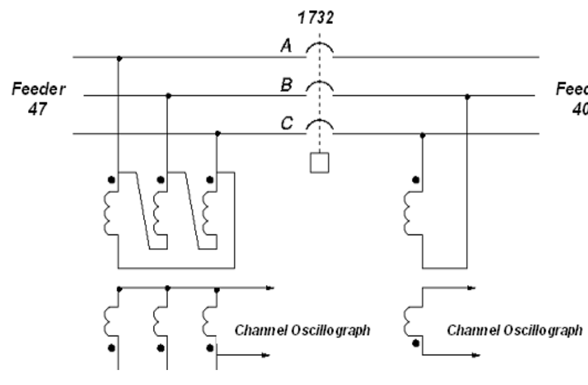


Fig. 11. Oscillograph voltage measurements

The registering of switching and measurements register were carried out in the following sequence: 1) Closing of the 1732 switch with the 13.8 kV busbars closed by the 26729-36 switch, Figure 12; 2) Opening of the 1732 switch with the 13.8 kV busbars closed by the 26729-36 switch, Figure 13; 3) Closing of the 1732 switch with the 13.8 kV busbars separated, Figure 14; 4) Opening of the 1732 switch with the 13.8 kV busbars separated, Figure 15.

In Figures 12 to 15 the results obtained in the field measurements and in the simulations with the SimPowerSystems are compared.

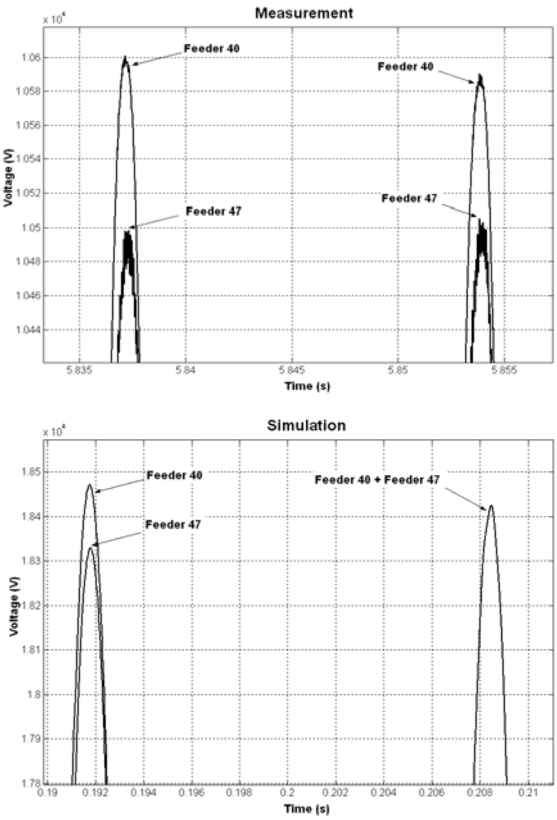


Fig. 12. Closing of the 1732 switch with the 13.8 kV busbars closed

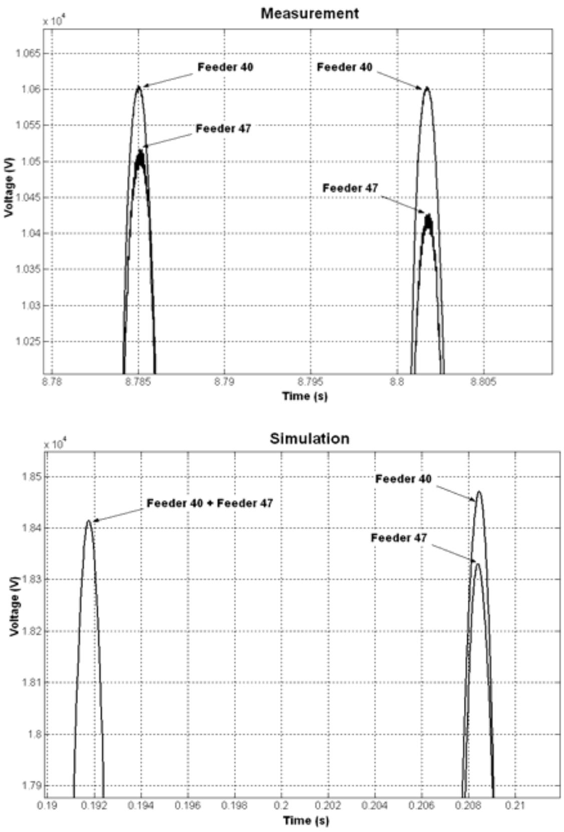


Fig. 13. Opening of the 1732 switch with the 13.8 kV busbars closed

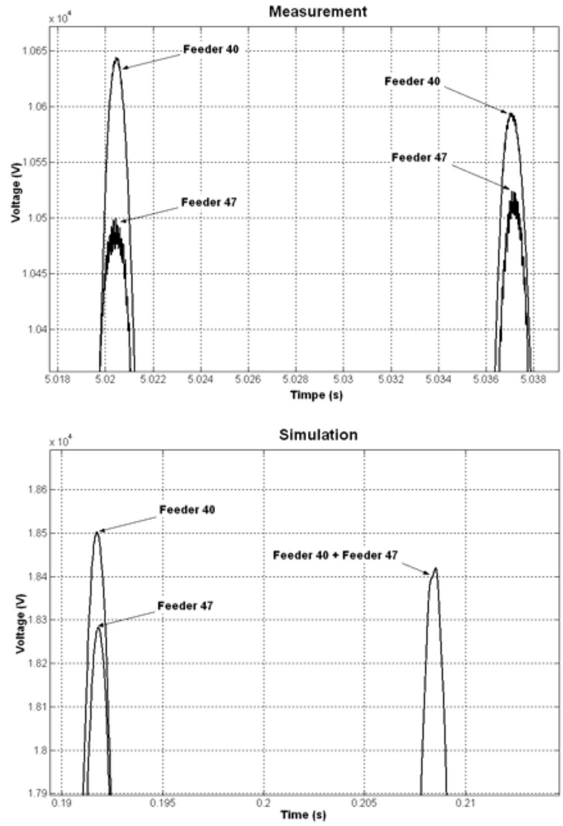


Fig. 14. Closing of the 1732 switch with the 13.8 kV busbars separated

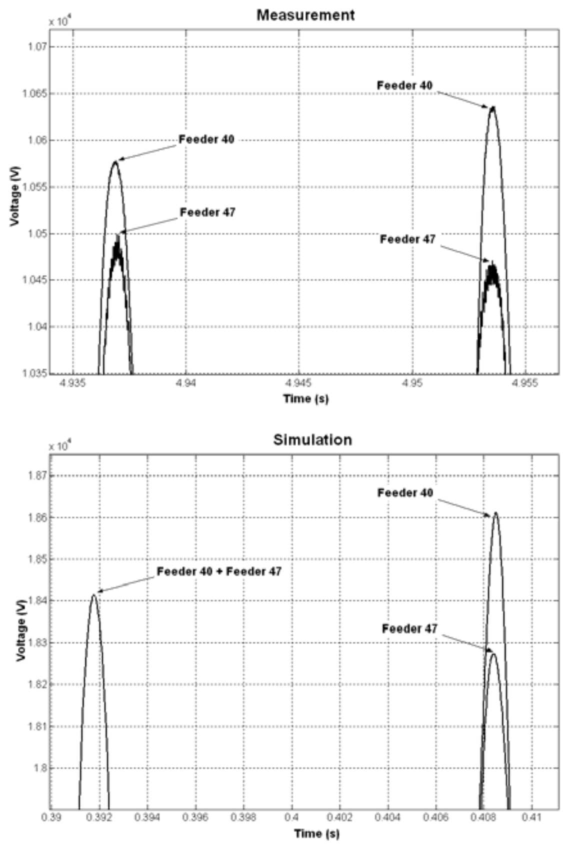


Fig. 15. Opening of the 1732 switch with the 13.8 kV busbars separated

In the resulting measurement figures the following considerations must be made: 1) Oscillations in the voltage peak value region at the feeder 47 side can be explained by the fact that the voltage at the feeder 47 side comes from a distribution transformer and not from a TP, which is the case at the feeder 40 side. The TP is appropriate equipment for measurement, which is not the case for the common voltage transformer; 2) There are voltages differences at both sides of the switch after its closing. It can be affirmed that the primary voltages at both sides of the switch will be the same after its closing, and thus, to explain this difference, it must be considered that the transformation relations of the TP and the voltage transformer are different, which can reproduce the different secondary values; 3) The voltage scales in the resulting measurement curves were considered in the phase voltage. To be consistent with the resulting simulation curves it is enough to multiply by 1.7321.

VI. CONCLUSION

The analysis of the measurement results showed that the implemented mathematical model in the SimPowerSystems and the developed software present similar behavior to those found in the real system showed by field measurements, which validates the adopted mathematical modelling of the distribution primary network components.

The voltages do not show different variations, neither with the ring closing or opening nor with closed or opened substation 13.8 kV busbars. In the measurements and in the simulations relevant transient changes in the voltages at the exact time of the switch closing or opening were not observed.

The results show that the ring closing with two feeders proceeding from the same substation can be executed without any risk and certainly it can bring some benefit, in the case of being incorporated in the Electrical System Operation Procedures.

The next step will be to close the ring closing with feeders connected to different substations. The obtained simulation results using Matlab may conclude that the system behavior in the case of feeders connected to different substations will be not very different of the studied cases.

ACKNOWLEDGEMENTS

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