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Voltage Sag Studies in Electric Systems of Industrial Plants due to Disturbances in the Interconnected Power System

Sylvio Cayres, Marcos J. P. Leme Souza, and Eudifran C. Caetano

***Abstract* — This technical paper shows a feature that can be implemented in short circuit programs for power quality studies. The voltage behavior in areas nearby an industrial substation is determined for disturbances in the interconnected power system.**

The studies were initiated a few years ago as a subsidy to the analysis of voltage sags in an oil refinery in the Northeast of Brazil. There was a need for specific features to do this type of study using short circuit programs to make possible the implementation of a large number of faults, however with simple and effective ways of analyzing the results.

***Index Terms* — Protection Relay Undervoltage Setting, Short Circuit Simulation, Voltage Sag**

I. Introduction

Nowadays, due to the extremely complex meshed grid, large industrial plants directly connected to transmission or subtransmission systems of electric utility companies are facing problems regarding the impact that short circuits somewhere in the network may cause to their processes. So, dedicated protection schemes are installed in order to preserve the most important industrial activities, by disconnecting the equipment from the external source and using internal generation systems instead, whenever necessary.

It happens that a short circuit in the transmission system may reduce the voltage level at the plant main substation and in its internal network, disturbing the industrial processes and also allowing undervoltage and voltage-controlled overcurrent relays to trip. Therefore, short circuit studies all over the network around the plant must be carried on, what demands many thousands simulations for only one single system configuration. If contingencies are to be taking into account, the quantity of faults to be applied will increase.

The intention of this paper is not to study the industrial area protection system, but to show how faults in the transmission network around it can influence the industrial network, highlighting the boundary of such interference.

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The power system database is normally obtained from the system regional operator, in this specific case, the Brazilian System National Operator (ONS). So, it is a database already existing and duly updated according to the network evolution. However, the protective relay data is also needed. It is a hard task to put together all information about the different devices used by the local utility and the ones interconnected to it in the area of interest. In this work, three different electric energy utilities share the area that surrounds the industrial plant.

The very first works on voltage sag analysis, some years ago, revealed that the power system database should be treated with special care due to the large quantity of mistakes found in the network models. So, additional time was spent in the present work for checking the database components.

A specific tool was developed for a short circuit program used for the studies in order to run all kind of faults that could produce voltage sags within a certain area previously set, checking the resulting voltage drop values and the actual fault clearance times. The feature has been improved, with a greater automation of controls allowed, and its latest version was used in these recent studies for an industrial area in the Southeast.

This paper covers basically the network modeling, the method for the short circuit simulation and the special features developed for the voltage sag analysis.

II. Network Modeling

As any other short circuit and power flow studies, the work described in this paper depends on the network equipment models used for the simulations. This information is normally arranged in structured database. Software of several vendors can organize the format and data storage differently for easier and faster search, retrieval and manipulation. However, the database of a certain network is frequently the same or, at least, has the same origin. Either through a complete migration from another database system and, many times, from another computer platform, or just converted from an old format to a newer one of similar applications, the data parameters can be essentially the same. And these parameters may have been unchanged for years.

So, a first task is to check possible anomalies in the whole database, concentrating efforts to fix the errors and mistakes in the network in the area under analysis.

The mistakes found and fixed in the database network elements were mostly related to:

- omission of generator and transformer resistances;
- very simple models for transmission lines;
- nonobservance of direction in mutual coupling between transmission circuits;
- incorrect phasing of power transformers;
- inaccurate model of magnetizing impedance of three-phase transformers;
- incorrect zero-sequence parameters of wye-wye-delta transformers;
- incorrect grounding transformer sequence connection;
- incorrect model of shunt reactors;
- omission of loads.

A. *Omission of generator and transformer resistances*

Many engineers model generators and transformers with a resistance equal to zero and a reactance equal to the value of the impedance given by the test sheet. This method is quite practical and has been used because the effect of the resistance on the resulting short circuit currents seems to be negligible. However, it is not strictly correct. In fact, the resistance of some power transformers can be as high as 5% to 10% of the reactance. The short circuit currents are usually not affected significantly by the zero resistance, but the assumption of zero resistance can lead to unrealistic X/R ratios. Developers of short circuit programs have strongly recommended that the correct transformer resistance and reactance be entered in the database if the engineer plans to use the X/R ratios for breaker or CT rating studies. Otherwise the equipment can be treated as overstressed, in an extremely conservative evaluation, when it could be still submitted to some overcurrent.

For transformers, the short circuit program used for the simulations in this work recommends the use of the IEEE Standard Test Code for Dry-Type Distribution and Power Transformers, ANSI/IEEE C57.12.91, based on which one can break down the impedance into its resistance and reactance components using the transformer load-loss data, which are also given on test sheets. The formulas can be entered into some kind of script that runs together with the short circuit program, as the one of the example of Fig. 1.

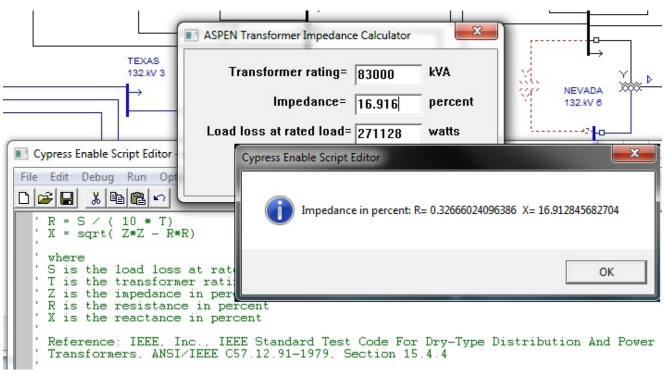

Fig. 1. Script for transformer resistance in a short circuit program using ANSI/IEEE C57.12.91 formulas.

Indeed, any study that demands the analysis of the shape of the current wave and, then, depends on the decay of the wave along the circuits, should have a more accurate representation of the impedance, including the resistance of the elements besides their reactance.

And another good reason to take resistances into account is directly related to this work: the checking of the instantaneous settings of overcurrent relays. When the relay is sensitive to DC offset, the DC component of the fault current must be considered, in order to make sure that the instantaneous unit will not trip for faults outside the protected zone. The current multiplier is a function of the X/R ratio. If the resistances of some network elements considered in the X/R calculation are set to zero, the multiplier will result too high and the instantaneous unit operation will not correspond to the real case. A typical case is shown in the Fig. 2, where the dialog box on the left shows that the program used for the short circuit simulations has the option for the computation of the X/R ratio based on the network elements when the overcurrent relay instantaneous setting is checked.

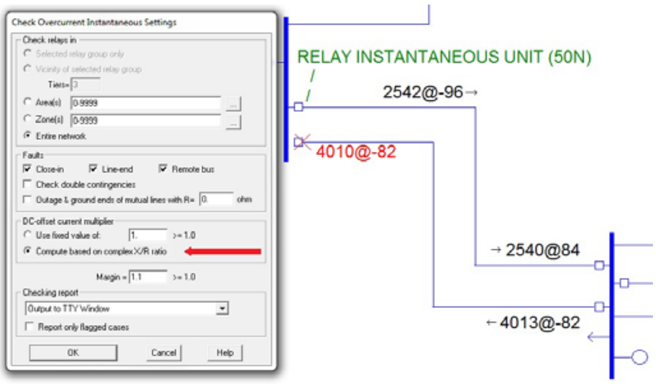

Fig. 2. Checking of overcurrent relay instantaneous setting taking into account the X/R ratio and a typical case of influence of mutual coupling.

B. *Very simple models for transmission lines*

The fact is that most of the transmission lines in databases are modeled as series lumped impedances only. However, such simplification is not a good solution for some applications. The shunt admittances are directly related to the line length and should be represented whenever the line is not said to be short. Thus, transmission lines in general should have a π model, normally called nominal π. When no line shunt admittance is available, we have used a very small capacitive shunt at the two ends of the transmission line in order to emulate the effect of natural line capacitances. The short circuit program used for the simulations did it automatically, selecting a certain level empirically, large enough to avoid mathematical singularity and, at the same time, small enough to have an insignificant effect on short circuit solutions, with the assumption that no value is to be entered.

C. *Nonobservance of direction in mutual coupling between transmission circuits*

The absence of zero sequence mutual coupling of the transmission lines in the short-circuit database can make protection studies more difficult to be carried out. In the past, the inclusion of a great quantity of mutuals was sometimes treated with some special care due to the need of many fictitious nodes that could reach the bus limit of the application software. Today many programs allow mutual coupling without such additional nodes. The mutuals are geographically included, covering the exact percent of real coupling of lines in the same right-of-way.

We have been suggesting the use of construction editors of line constant programs to take into account transmission line mutual coupling accurately. The effect of the mutuals on the setting of ground overcurrent and distance relays is well known. This typical influence is shown in Fig. 2, where is checked if the relay instantaneous unit trips for remote line-end faults on parallel lines.

D. *Incorrect phasing of power transformers*

Two- and three-winding power transformers with incorrect phase shift must be checked in the database. Typical wrong phasing refers to wye-delta transformers in parallel, one with the delta leading and the other with the delta lagging. However, phasing errors in practice are rarely this obvious. The system may have hundreds or even thousands of transformers in a complex meshed network. Then, the short-circuit program logic must be capable of finding the mistake by checking the transformers that are in the same contiguous network.

Due to a lack of a consistent check of anomalies in large networks, some impossible transformer connections are sometimes found in the database. Whenever such mistakes are found or foreseen as a possible reason for strange results, until they are definitely fixed in the database, we have suggested the use of options to ignore phase shift and to use "flat voltage" as the pre-fault voltage profile when simulating faults, if the short-circuit program has such flexibility.

E. *Inaccurate model of magnetizing impedance of three-phase transformers*

Three-phase transformers are normally modeled with the same impedance for the zero sequence as for the positive and negative sequence networks. It is so assumed because the magnetizing impedance of most transformers is very large, generally greater than 50 per unit, and can be ignored in short-circuit studies. This is true for three-phase transformer banks consisting of separate three single-phase units.

But this is not the case of transformers where the core is shared by the three phases. The magnetizing impedance of a transformer is the apparent impedance measured at a terminal with the other terminals open-circuited. In the existing designs of core-type three-phase transformers, the shunt branch that corresponds to the excitation can be omitted for the positive and negative sequence networks, since the resulting phasor sum of the flux of each phase is confined in the iron paths. For the zero sequence network all the fluxes are in phase and the sum is not zero. The magnetizing impedance of these core-type transformers is still very large if it is of shell-form, as shown in Fig. 3 (b), while the magnetic circuit is not saturated. In this case, it can be ignored as well in short-circuit studies.

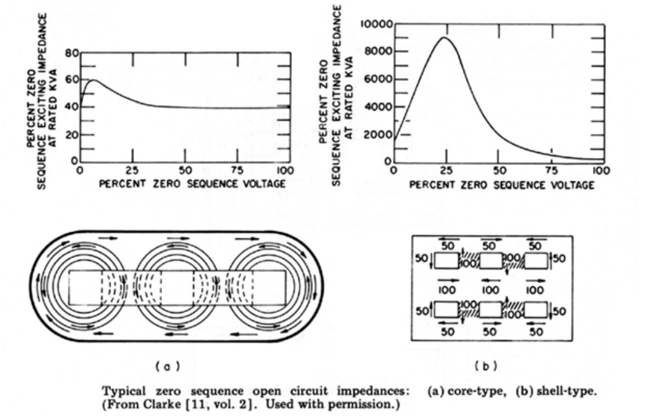

Fig. 3. Typical zero sequence open circuit impedance for core-type and shell-type transformers.

The zero-sequence magnetizing impedance of three-leg-core transformers of Fig. 3 (a) is a notable exception. This low impedance, as shown in the figure, is a direct result of the core construction. When a set of three-phase windings is excited by zero-sequence current, the three fluxes are forced out of the iron core to return through the air or oil where the magnetic permeability is much smaller than that of iron. For this reason the transformer tank can be treated as a fictitious tertiary winding connected in delta. We have said that the engineer should consider the modeling of zero-sequence magnetizing impedance of three-leg-core transformers if high accuracy is desired. Some programs, as the one used in this work, provide a field for this parameter as a part of the model, as the "B" and mainly "B0" indicated in Fig. 4.

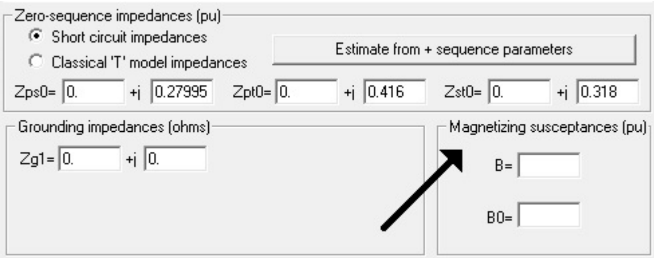

Fig. 4. Transformer model with a field for the magnetizing susceptances indicated in a dialog box of the short circuit program used for the simulations.

F. *Incorrect zero-sequence parameters of wye-wye-delta transformers*

We use to call it "three-winding transformers with questionable parameters". The wye-wye-delta transformers in most databases have dubious zero-sequence short-circuit impedances. The data normally come from the classical T-model impedances. Short-circuit impedances from the primary side to the secondary side are derived from tests where the voltage is applied to the one side with the other side short-circuited. Then, Zps0 cannot be greater or even equal to the positive-sequence Zps, since the delta tertiary side is connected to the reference, i.e., it is also short-circuited, creating the parallel impedance shown in Fig. 5. We have recommended the checking of anomalies available in some short circuit programs, as the one indicated in Fig. 6.

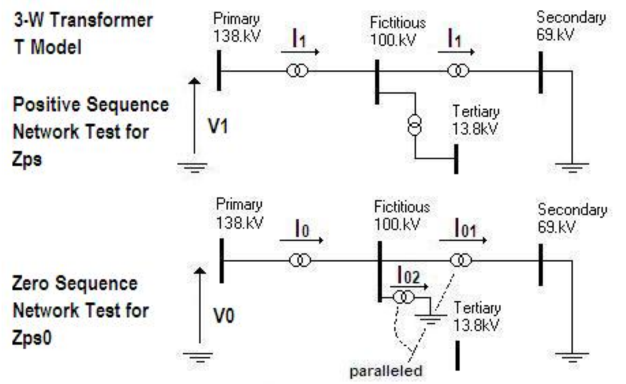

Fig. 5. Test for Zps0 in wye-wye-delta transformers.

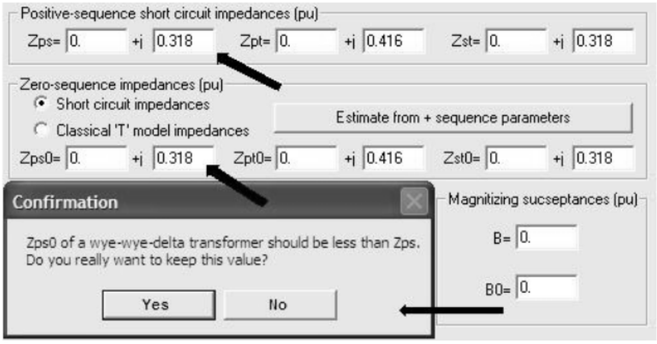

Fig. 6. Transformer model dialog box of the program used for the simulations with checking of Zps0 in wye-wye-delta transformers indicating possible anomaly.

G. Incorrect grounding transformer sequence connection

A source of mistakes in short-circuit database refers to grounding transformers. Zigzag and wye-delta transformers are used for such purpose. These transformers have their windings connected so that only the zero-sequence impedance is present in the sequence networks. The fact that the positive sequence is open-circuited is often forgotten by the personnel in charge for the database. The wrong modeling of these elements in the short-circuit database can lead to incorrect ground current calculation. This will affect protective relay setting and substation grounding mat design, among other studies. To avoid this problem, grounding transformer manufacturers use to highlight the zero sequence reactance in their data sheets.

H. Incorrect model of shunt reactors

The incorrect model of shunt reactors is also related mainly to the sequence network connection. Engineers responsible for short-circuit studies must pay attention to the configuration of the reactors. Some are solidly grounded while others are grounded through impedances (transformers, reactors or resistors). However, the three sequence components must be present in the network. The zero sequence impedance must be added in accordance with the real connection in the field. We have already seen considerable differences in the total zero-sequence currents due to wrong models used for the reactors.

I. Omission of loads

Today short-circuit and power flow programs tend to share the same database and the immediate application is the starting of a short-circuit case with the pre-fault determined by the power flow case. Especially for protection engineers this has been of great help. But many old databases are still separated. We have been encouraging people to include load in their short-circuit database, which already has parameters of positive, negative and zero sequences and, in many cases, information on equipment voltage, power limits and control features. Significant differences are observed between with and without loads. Even though we do not consider that the omission of loads is to be seen as a common mistake, we have noticed that it is a practice not to include them. Then, we have recommended the modeling of loads in the database for protective relay studies. If the short-circuit program also does relay setting and coordination studies, the protection engineer will be happy for having the chance to consider the load.

On the contrary, a common mistake may occur when the addition of loads is not a practice. Sometimes a large, concentrated load is added at a single location, e.g., on a bus that represents a large substation of the area under analysis, for a specific study. If it is behind or in front of relays, it may be left there after the study and cause incorrect operation in future simulations, like the ones based on stepped event logics. Although the misoperation may be obvious for some relays, it may be more difficult to be found if the network has distance relays that under- or overreaches according to the load direction.

Still considering the loads, we have seen that big induction motors have been omitted in the short circuit simulations, while generators of same size are in the database. Additional motors produce current sources that must be included since their sum to the fault current may be of interest. These rotating machine contributions typically decrease in 8 cycles at a maximum. Synchronous motors may still produce some lower currents while asynchronous motors currents will practically reduce to zero. So, they should be computed in the subtransient and initial part of transient periods.

III. Relay Modeling

The protective systems surrounding the area under analysis were entered into the short circuit program database. Such hard task could be done directly on the program one-line diagram. The program used for the simulations has also an interesting feature that allowed the importation of digital relay settings, which is essential for those with a large number of parameters. Overcurrent and distance relays were modeled in the program, including the time delay curves and distance characteristics. Telecommunication assisted protection schemes were also included in the program protection systems.

IV. Simulation Method

A. Voltages sag simulation

The program starts the process by applying all types of fault connections – three-phase, phase-to-phase, phase-to-phase-to-ground and phase-to-ground short circuits at the bus to be monitored, user-defined, and automatically at the buses around

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it, also including intermediate faults on the transmission lines connected to these buses. The program simulates all relay tripping events, sequentially, in accordance with their actual settings. Thus, outages of lines, transformers and other elements of the network during the disturbance are taken into account in the process.

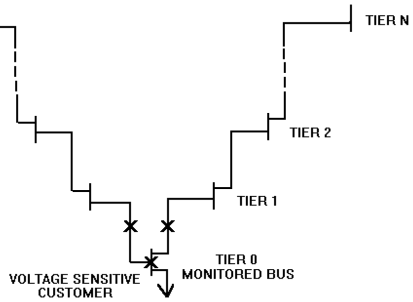

Fig. 7. Voltage sag process with faults applied tiers around the monitored bus – bus faults and transmission line intermediate faults.

The position of each fault point on the relay overcurrent curves, including those of electromechanical relay induction disc types, is tracked. So electromechanical device reset time is considered in the tracking process. Distance relay zone timers are also modeled. The timing of communication assisted relay schemes for transmission lines (teleprotection systems) is also computed.

The program will continue simulating faults until it finishes faulting buses at a certain number of tiers away and has found that the voltage magnitude at the monitored bus stays above the voltage threshold when faults are applied to all the buses within that tier. So, this feature has an automatic stopping criterion that ends the simulations when the monitored voltage is above this threshold for all the faults at a certain distance away. The threshold used in the studies was the voltage setting of the industrial plant undervoltage relays and voltage-controlled over current relays. The value of 0.75 pu was used for the simulations.

B. Pre-fault voltage profile

As faults are applied all over the system without previous control from the user, it may happen that they are on buses with shunts or loads, or across a some phase shifted equipment, such as delta-wye transformers. So, it is important to avoid the use of flat bus voltage methods for the pre-fault voltages. Instead, a pre-fault voltage profile based on a linear network solution or on a complete non-linear network solution through a power flow program must be simulated prior to the fault application for the accuracy of the simulations.

C. Output report and voltage-sag diagram

For analysis of the results a worksheet is created, showing the phase voltages at the monitored substation and indicating which phases reach the limit previously set, the protection clearance time for each fault applied, the total number of sequential events related to the relay operations and the confirmation of the fault clearance by detecting the current contribution values updated at every sequential event, until they come to zero. The program output shows voltage and current in polar format so that reactive power compensation studies are made possible to be easily developed. Since loads and shunts are modeled and a power flow solution used for the pre-fault voltage profile, then capacitor shunts can be distributed all over the industrial plant buses for a better voltage control. In the areas where the use of switched reactive power compensation proves to be helpful to mitigate the effects of the voltage sag, other power quality studies can be performed, e.g., flicker checking.

Monitored Bus: 16 BUS 16 13.8kV													
Fault Impedance Z=0+j0 Ohm													
Tier	Flt	Bus No.1	Bus Name	kV	Bus No.2	Bus Name	Perc	Va (pu)	Va (deg)	Vb (pu)	Vb (deg)	Vc (pu)	Vc (ang)
0	3LG	16	BUS 16	13,8				0	0	0	0	0	0
0	2LG	16	BUS 16	13,8				1,38572	-29,9814	0	0	0	0
0	1LG	16	BUS 16	13,8				0	0	1,45907	-172,063	1,39841	113,783
0	L-L	16	BUS 16	13,8				0,995014	-30,7494	0,497507	149,251	0,497507	149,251
1	3LG	0	BUS0	33				0,071485	-30	0,071485	-150	0,071485	90
1	2LG	0	BUS0	33				0,50223	0,956074	0,508471	-170,963	0,071485	90
1	1LG	0	BUS0	33				0,522268	-62,6486	0,588221	-115,471	0,995014	89,2506
1	L-L	0	BUS0	33				0,862915	-3,1231	0,861981	-178,373	0,071485	90
2	3LG	17	BUS 17	33				0,093324	-36,2912	0,093324	-156,291	0,093324	83,7088
2	2LG	17	BUS 17	33				0,62182	-4,99814	0,630863	-176,493	0,093324	83,7088
2	1LG	17	BUS 17	33				0,618776	-54,5699	0,61563	-127,143	0,995014	89,2506
2	L-L	17	BUS 17	33				0,858458	-3,85071	0,867458	-177,68	0,093324	83,7088
2	3LG	17	BUS 17	33	0	BUS0	50	0,082384	-33,6414	0,082384	-153,641	0,082384	86,3586
2	2LG	17	BUS 17	33	0	BUS0	50	0,575388	-3,2716	0,581782	-175,131	0,082384	86,3586
2	1LG	17	BUS 17	33	0	BUS0	50	0,576972	-57,8064	0,599478	-122,309	0,995014	89,2506
2	L-L	17	BUS 17	33	0	BUS0	50	0,860613	-3,48934	0,864765	-178,023	0,082384	86,3586
3	3LG	18	BUS 18	33				0,104785	-38,3939	0,104785	-158,394	0,104785	81,6061
3	2LG	18	BUS 18	33				0,652339	-6,00765	0,664995	-176,95	0,104785	81,6061
3	1LG	18	BUS 18	33				0,651639	-52,3092	0,631644	-130,644	0,995014	89,2506

Fig. 8. Voltage sag output table with the voltage level at the monitored bus when bus faults and transmission line intermediate faults are applied around it.

A one-line diagram is also created to show, at a glance, which areas of the interconnected system would lead to a higher percentage of voltage sags at the industrial substation under a short circuit condition. So, the program paints a colored halo around each bus to help to visualize the fault effect on the monitored bus. The more severe the voltage sag at the monitored bus caused by a fault, the darker is the halo painted around the faulted bus.

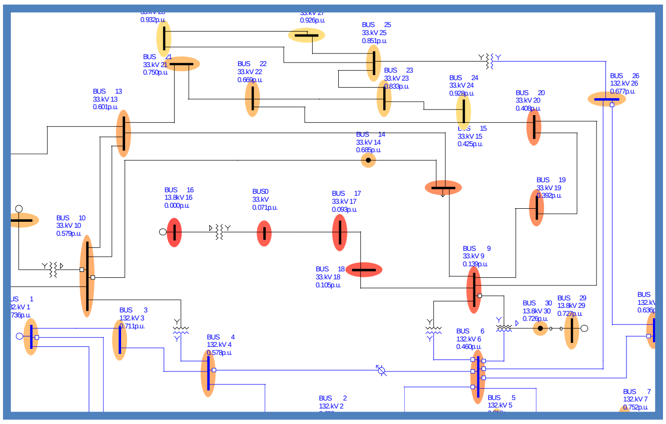

Fig. 9. Voltage sag output on a one-line diagram with the voltage level at the monitored bus indicated on the faulted buses.

D. Industrial plant and interconnected system configurations

Several industrial plant internal load, reactive compensation and generation scenarios are covered, as well as contingencies in the configuration of the interconnected system.

The following scenarios were analyzed and the voltage sag simulations repeated for each one:

- industrial plant with normal, minimum and maximum generation;
- nearby generation plant with normal, minimum and

maximum number of units;
- transmission network with outages of one line;
- combination of the above configurations.

V. Results

The completion of the studies allows obtaining the values of voltages and currents at the industrial substation buses and internal circuits against several faults applied, making possible the analysis of the network configuration and its protective relay behavior and studies for changes in the network and relay settings, if necessary, for specific external disturbances that cause significant sags.

When the main substation bus of the industrial plant (138 kV) is the monitored bus, the total of faults applied for each scenario ranged from 2096 to 4568 simulations. For some cases, 656 protective relay operation times were computed in the sequential events that followed the fault application.

When an internal bus (of 13.8 kV) is to be monitored, the most critical simulations reached a total of 25392 faults and a maximum of 9650 relay operation times duly computed.

VI. Conclusions

Voltage levels below the threshold of 0.75 pu were found at the main substation bus (high voltage side of 138 kV) of the industrial plant and in its internal network (13.8 kV) for several simulations.

Cases of voltage sag below this limit of 0.75 pu were also found for faults apparently distant from industrial plant, what reveals the difficulties of doing the necessary simulations without a practical tool to make them easier and faster.

Without the time-saver tool used in the present work, simulations with the respective results, which took some minutes, would have taken many hours of hard work.

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