Voltage Sag Index Calculation Using an Electromagnetic Transients Program

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Abstract – **This paper presents a Monte Carlo based method for prediction of voltage sags in distribution networks using a time-domain simulation tool. The approach applied in this work assumes that the load is characterized by a daily demand variation curve and has a voltage dependent behavior. The main goal is to analyze the influence that this load model can have on a voltage sag index based on the average lost energy during sags.**

Keywords – Voltage Sags, Voltage Sag Index, Voltage Sag Prediction, Monte Carlo Method, ATP.

I. Introduction

A voltage sag is a sudden short duration drop of the rms voltage, followed by a recovery within 1 minute. The most severe voltage sags are generally caused by short-circuits. Although voltage sags are less severe than interruptions, they are more frequent; in addition, their consequences for sensitive equipment, such computers, adjustable speed drives or control equipment [1], [2], can be as important as those by an interruption. Given the diversity of their causes and the difficulty of preventing all these causes, voltage sags are one of the main and most frequent power quality disturbances.

Digital simulation can be a powerful mean to predict the voltage sag performance of a power network. Several methods have been proposed to predict the number of voltage sags caused in power networks, the approach presented in this paper is based on the application of the Monte Carlo method [3], and assumes that voltage sags are caused only by faults [4].

This paper presents the stochastic prediction of voltage sags and the calculation of voltage sag indices in power networks using the ATP (Alternative Transients Program) version of the EMTP (ElectroMagnetic Transients Program) [5]. The present work has been based on the development and implementation of new ATP capabilities created for this specific application, see [4] for more details.

Voltage sag indices can be useful to reflect the behavior of a system and to assess the effect of mitigation techniques. Indices proposed to date can characterize either a site or a full system, using a single event, or a group of events [6]. These indices are based on the frequency of rms variations or the concept of voltage sag energy. An index based on rms variations can be easily deduced from simulation results if it is clearly defined. An index based on energy can present some limitations. One of them comes from the fact that sags and swells, and even interruptions, can be simultaneously caused by the same fault. On the other hand, the energy supplied during a transient process is very depending on the assumed load representation. A final drawback is the random nature of voltage sags. Energy calculations cannot be then based on a deterministic value of the load demand.

The main goal of this paper is to analyze the influence of the load model on a voltage sag index based on the lost energy. For this purpose a load model presenting voltage dependency, random behavior and sag sensitivity has been developed.

All test studies presented in the paper are based on a distribution network of small size. They show the results to be expected from a time domain tool, what factors affect the severity of voltage sags and what influence they have on a voltage sag index based on the lost energy. A discussion about the limitations of the procedure and the indices analyzed in this paper is also included.

II. Load Model Analysis

A realistic model of a power demand has to include a random variation, diversity between demands at different nodes and voltage dependency, and a dynamic behavior.

The load model used in this work does not include any dynamics; this aspect has been analyzed in [7]. In other words, the model will have a static performance and the waveshape of sags caused by faults will present the so-called rectangular form.

The goal of the following subsections is to analyze the behavior of the load model mentioned above. First, the analysis will be focused on the voltage dependency, next, on the random daily variation curve.

A. Steady State Analysis of a Voltage Dependent Load

A power demand that incorporates voltage dependency can be expressed as follows

$$S_i = P_{irat} \sum_{k=0}^{np} a_{ik} V_i^{\,k} + jQ_{irat} \sum_{k=0}^{nq} b_{ik} V_i^{\,k} \qquad (1)$$

where P_{irat} and Q_{irat} are the rated real and reactive power at nominal voltage, and V_i the p.u. voltage. On the other hand

$$\sum_{k=0}^{np} a_{ik} = 1 \quad ; \quad \sum_{k=0}^{nq} b_{ik} = 1 \qquad (2)$$

The maximum degree for n_p and n_q is not higher than 4 [8].

The above equations assume that there could be a part of a power demand that is voltage-independent. In fact, this is the approach implemented in most load flow programs. No matter what voltage results after the load flow solution, the power demand remains the same. This is not a realistic model for voltage sag calculation, as it would mean that even for very low retained voltages, the demand will be the same that prior to the sag. Only models presenting V^1 and V^2 dependency are analyzed in this work.

A V^1 dependency means that the load behaves as a constant current source, while a V^2 dependency means that a load behaves as a constant impedance, whose per-phase value can be calculated according to the following expression

$$Z = \frac{V^2}{S^*} \qquad (3)$$

being V and S the rated values of the line voltage and the three-phase apparent power, respectively.

Fig. 1 shows the scheme of a very simple system used to test the performance of these models. The two plots included in this figure illustrate its behavior. It can be easily deduced that the per unit energy lost during a voltage sag will be greater than the per unit voltage drop.

As a conclusion, an accurate calculation, not only for steady state analysis, but also for voltage sag calculations should be based on an accurate knowledge of the actual demand performance, since any of the models mentioned above would be a very crude representation for most loads.

B. Steady State Analysis of a Probabilistic Load Model

The daily demand variation will be based on the following information: two curves for the mean value of the apparent power and the power factor, and a normal probability density function for each concept. Fig. 2 shows the curve of the mean value of the apparent power and the normal probability density function for a given period. Similar information is to be considered for the power factor.

Fig. 3a depicts the scheme of a two-feeder test system that will be used to analyze the steady state performance of this probabilistic load model. Both feeders have the same parameters, and the same demand curve at the two load nodes, see Fig. 2. An advantage of using the same demand curve for both load nodes is that the resulting voltage and the actual power demand at both nodes must be the same once the convergence of the probabilistic calculations is achieved.

The determination of the real and reactive power at a given node for every period will be therefore based on the random generation of two values. The steady state solution will be determined using the Monte Carlo method

- for each period of the demand curve, two random numbers are generated according to a normal distribution to obtain the final values of both apparent power and power factor
- after the above quantities are generated the network is solved, using the load model presented above.

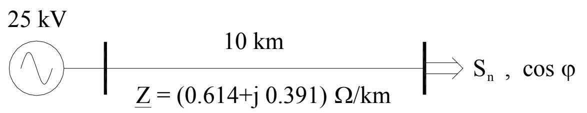
Fig. 3b shows the distribution of active power demand at Node 1 from 17 to 24 hours. The resulting voltage distribution is shown in Fig. 3c. Similar voltage and power results were obtained at Node 2.

III. VOLTAGE SAG PREDICTION

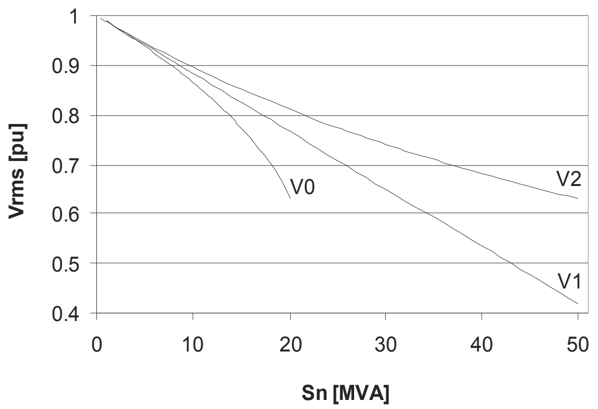
The approach presented in this paper is based on the random generation of disturbances, and assumes that sags are due only to faults caused within the distribution network. As mentioned above, the load model does not incorporate a dynamic behavior; voltage sags will be rectangular, and characterized by the retained voltage and the duration [1].

The test system is simulated as many times as required to achieve the convergence of the Monte Carlo method. Every time the system is run, fault characteristics are randomly generated using the following parameters:

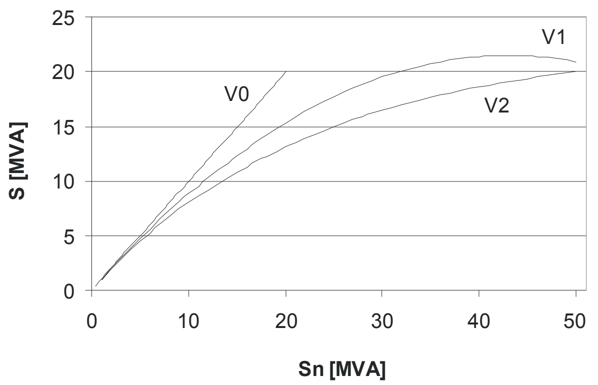
- The fault location, which can be any point of the system, and is selected by generating a uniform random number.
- The fault resistance, which has a normal distribution, being the mean value 10 Ω and the standard deviation 1 Ω.



a) Scheme of a single-feeder distribution system

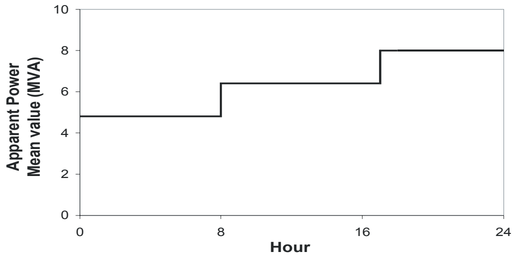


b) Voltage at the load node

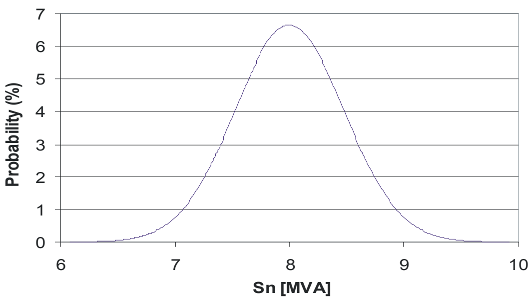


c) Power demand at the load node

Fig. 1. Steady-state analysis of voltage-dependent load models (Power factor = 0.8 lagging).

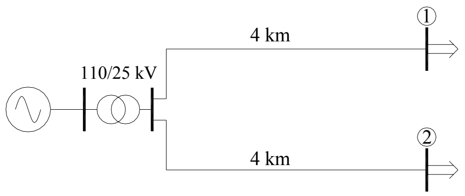


a) Mean value of the power demand



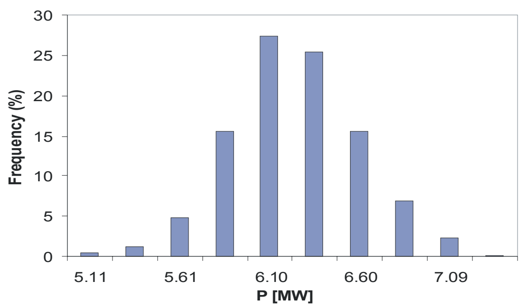
b) Probability density function of the power demand (from 17 to 24 h)

Fig. 2. Daily demand variation curve - Node 1.

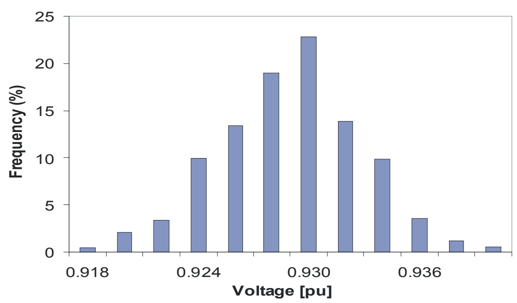


HV equivalent : 110 kV, 1500 MVA, X/R = 10
Substation transformer: 110/25 kV, 20 MVA, 8%, Yd
Lines : $Z_{1/2} = 0.61 + j0.39$, $Z_0 = 0.76 + j1.56$ Ω/km

a) Diagram of a two-feeder distribution test system



b) Real power demand at Node 1 – From 17 to 24 h



c) Voltage at Node 1– From 17 to 24 h

Fig. 3. Probabilistic load model behavior – Model V2.

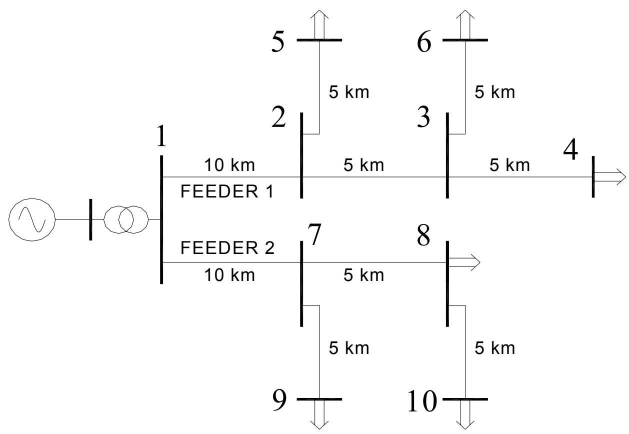
- Two random time values, the first one is needed to determine the hour of the day and then to obtain the power demand at any node, the second value is required to fix the voltage phase at the instant the fault is caused. Both values are uniformly distributed
  - ♦ the hour can vary between 1 and 24
  - ♦ the fault time can vary between 0.10 and 0.12 s.
- The duration of the fault, which has a normal distribution, being the mean value 0.06 s and the standard deviation 0.012 s.
- The probabilities of each type of fault are as follows: LG = 80%, 2LG = 17%, 3LG = 0%, LL = 2%, 3L = 1%.

Since many of the characteristics shown above are not based on monitoring, some results could be non-realistic. The advantage of a prediction based on simulation is that these characteristics can be easily varied and the simulation can be useful to determine what parameters can have a strong influence of the system behavior.

The method has been applied to the system depicted in Fig. 4, by assuming a constant impedance representation of the load at all load nodes. The system is a small size distribution network with two radial feeders. The lower voltage side of the substation transformer is grounded by means of a zig-zag reactor of 75 Ω per phase.

Fig. 5 shows the sag density function at Node 4 derived without the operation of any protective device. These results were obtained after 1000 iterations. A previous work did show that this number of iterations could be good enough even for networks larger than that used in this work [9]. If it is assumed that 12 short-circuits are generated by year and 100 km of overhead lines; as the network has 55 km, then the simulation equals the performance of the network during 152 years.

Voltage sag severity depends on the location and the duration of the fault. It is usually assumed that, depending on the distribution voltage level and the substation grounding system, only those faults caused not far from the substation terminals will produce severe voltage sags. Fig. 6 shows the severity of voltage sags seen at some nodes of the test system as a consequence of faults caused at Node 8, located 15 km from the substation terminals.



HV equivalent : 110 kV, 1500 MVA, X/R = 10
Substation transformer: 110/25 kV, 10 MVA, 8%, Yd
Lines : $Z_{1/2} = 0.61 + j0.39$, $Z_0 = 0.76 + j1.56$ Ω/km

Fig. 4. Diagram of the test system.

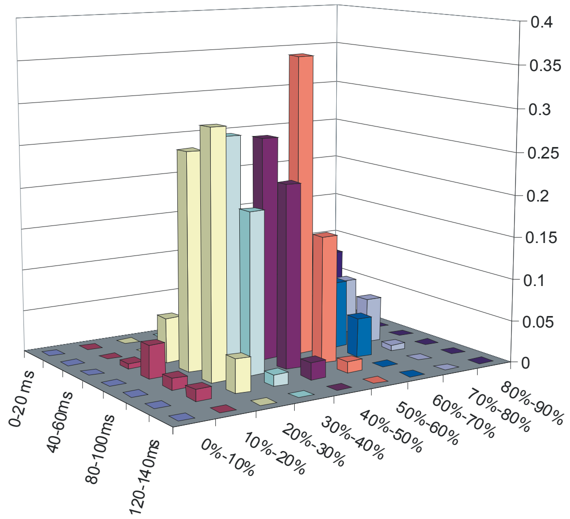


Fig. 5. Number of sags per year – Node 4, Phase "a".

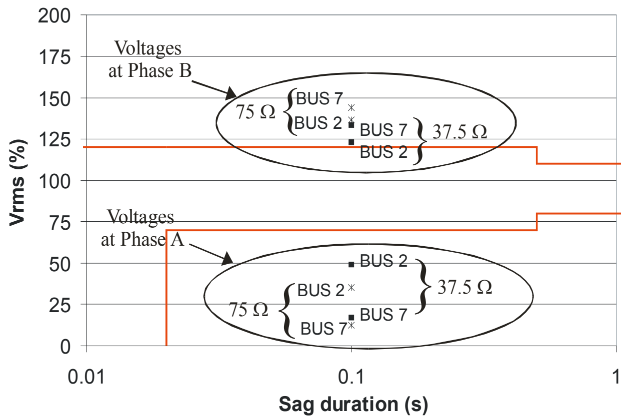


Fig. 6. Voltage sag severity for different grounding impedance values - Faults at Node 8.

IV. Voltage Sag Index Calculation

A. Introduction

Voltage sag indices can be useful to reflect the behavior of a system and to assess the effect of mitigation techniques. Indices proposed to date can characterize either a site or a full system, using a single event, or a group of events [6], [10]. These indices are based on the frequency of rms variations or the concept of voltage sag energy. Since the lost energy during a sag depends on the voltage dependency of the load, an index covering every type of dependency is proposed in this paper. The lost energy during a voltage sag will be calculated as follows

$$W = \int (P_{pre-sag} - P_{sag})dt \tag{4}$$

being $P_{pre\text{-}sag}$ and P_{sag} the real power prior to the sag and during the sag, respectively. This concept is similar to one of those proposed in [6].

The Average Voltage Sag Energy Index (AVSEI) will be then

$$AVSEI = \frac{1}{N}\sum_{k=1}^{N} W_k \tag{5}$$

being W_k the lost energy during the sag event k, and N the number of events.

It is worth noting that the calculation of this index will be made taking into account only voltage sags, and considering only those cases for which the voltage drops below 90% of the rated voltage. Given the characteristics of the test system, many faults will cause sags and swells at the same time, see Fig. 7. The subsequent figure shows how the load models behave. The case corresponds to a single-phase-to-ground fault; although the voltage drops about 70% at the faulted phase, the power demand at this phase drops the same percentage with model V^1 and more than 90% with model V^2.

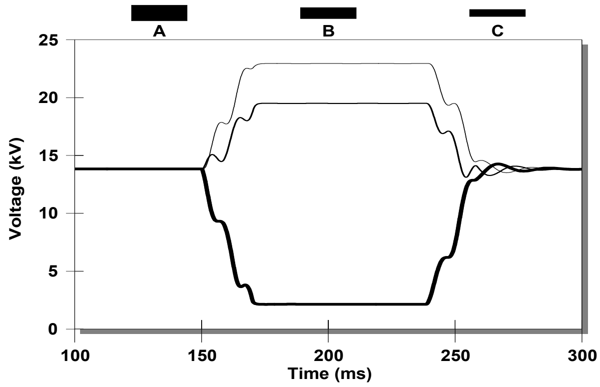
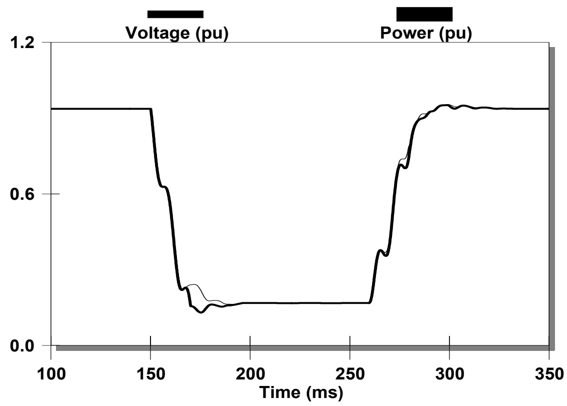
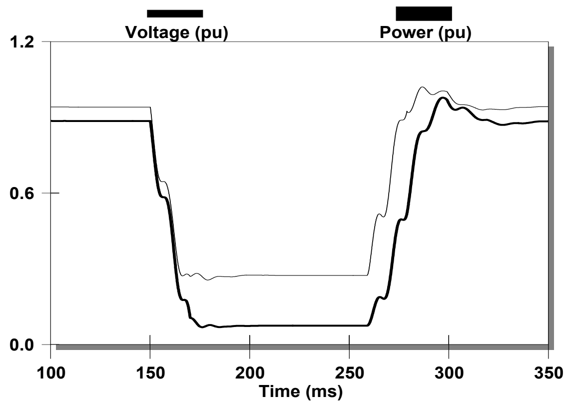


Fig. 7. Voltage sag simulation.



a) Model V^1



b) Model V^2

Fig. 8. Voltage and active power demand calculation.

B. Test Cases and Results

The calculation of the voltage sag index will be made taking into account voltage dependency of the load and diversity between loads. The diversity factor can be defined as the ratio of the sum of individual maximum demands to the maximum demand of the whole system [11]

$$F_{div} = \frac{\sum_{i=1}^{n} P_{\max,i}}{P_{\max,total}} \qquad (6)$$

In a similar way, a coincidence factor could be also defined. In fact, it would be the reciprocal of the diversity factor [11].

Table I shows the different load curves considered for this study. They present the daily variation of the mean apparent power at a given load node. According to the load model detailed above, another curve is required for the power factor, and a probability density function, as that shown in Fig. 2b, for both the apparent power and the power factor.

Table II shows the test cases; note that up to four diversity factors have been analyzed.

The grounding impedance at the distribution side of the substation transformer is an important factor in the performance of the distribution system, as deduced from the plot depicted in Fig. 6. Four different values of this grounding impedance have been considered for every diversity factor shown in Table II.

In addition, the two voltage dependent models, V^1 (constant current source) and V^2 (constant impedance), have been assumed for every combination of load curves and grounding impedance.

One can easily predict the trend of the voltage sag index, as defined above, from the results presented in Sections II and III

- the higher the grounding impedance value, the greater the lost energy during voltage sags
- the lost energy will be greater with constant impedance models than with constant current source models
- the lost energy index, with a given load model and a given grounding impedance value, will not depend on the diversity factor, since the energy under every load curve shown in Table I is the same and the probability of the fault hour is uniform during the 24-hour period.

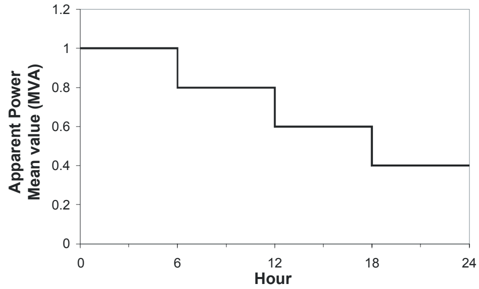
Fig. 9 shows the AVSEI values obtained for all the simulated cases. It is easy to confirm that the tendency is that summarized above: the voltage sag index does not depend on the diversity factor, decreases with the grounding impedance value and is greater for a constant impedance model.

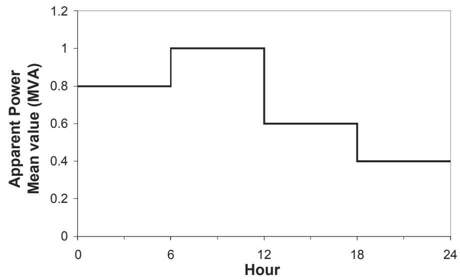
C. Discussion

The index presented above can be a good indicator of the voltage sag performance, but there are several aspects related to energy calculations that should not be neglected.

- Even more important than the lost energy during voltage sags is the energy non-supplied to equipment that trips as a consequence of a voltage sag. This energy

Table I – Load curves

1


2


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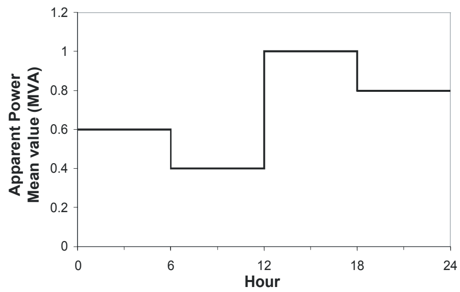

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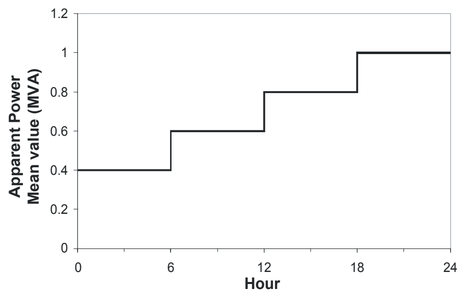
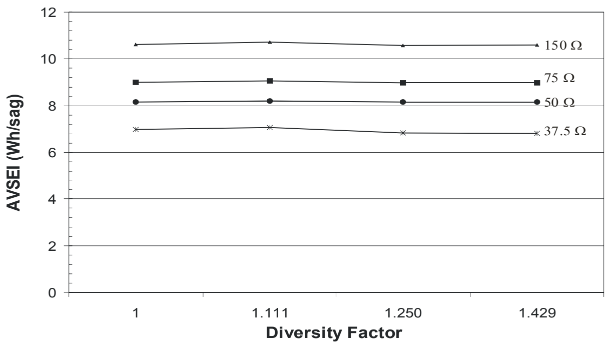
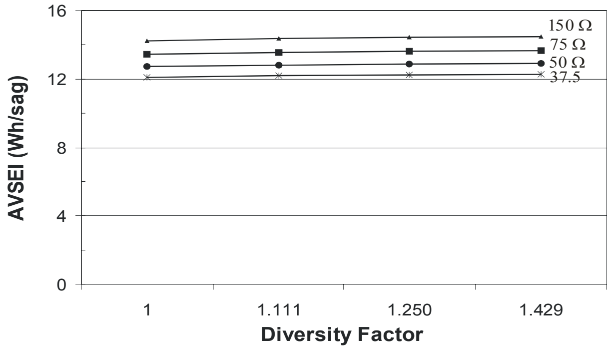


Table II – Test cases

	Case 1	**Case 2**	**Case 3**	**Case 4**
Node 4	Curve 1	Curve 1	Curve 1	Curve 1
Node 5	Curve 1	Curve 1	Curve 2	Curve 1
Node 6	Curve 1	Curve 2	Curve 3	Curve 4
Node 8	Curve 1	Curve 1	Curve 1	Curve 4
Node 9	Curve 1	Curve 2	Curve 2	Curve 4
Node 10	Curve 1	Curve 2	Curve 3	Curve 1
Diversity Factor	1.0	1.111	1.250	1.429
Coincidence Factor	1.0	0.9	0.8	0.7



a) Model V[1] – Constant current source



b) Model V[2] – Constant impedance

Fig. 9. AVSEI calculations

could be either considered as the basis of a different index or incorporated to the index presented above. In any case, this energy could be another useful indicator of the network performance.

- It has been shown above that sags and swells can be caused at the same time and at the same node. In general, swells are not of concern for utilities, but they can also produce equipment trip, as one can easily deduce from the cases shown in Fig. 6.

Therefore swells might be taken into account in voltage sag studies, and the non-supplied energy during equipment trip could also be calculated and incorporated into a voltage sag index.

Fig. 10 depicts the average net energy supplied by the system during a short circuit, including the effects of both sags and swells. The plot shows the effect of the grounding impedance at the substation and the load model. It is obvious from this figure that for the network analyzed in this paper, the average energy passes from negative to positive, its value is greater with model V^2, and increases with the value of the grounding impedance.

A consequence of the performance shown in Fig. 7 is that dynamic restoration of voltage sags can be achieved during single-phase-to-ground faults using the extra energy supplied by the system to the unfaulted phases. However, it is important to keep in mind that the studies have been performed by assuming that the loads are seen from the medium voltage side, they are symmetrical and present impedances only for positive sequence, which is not always true. In fact, the severity of the sags can be modified by distribution transformers, so the effect at the low voltage side can be very different from that derived above.

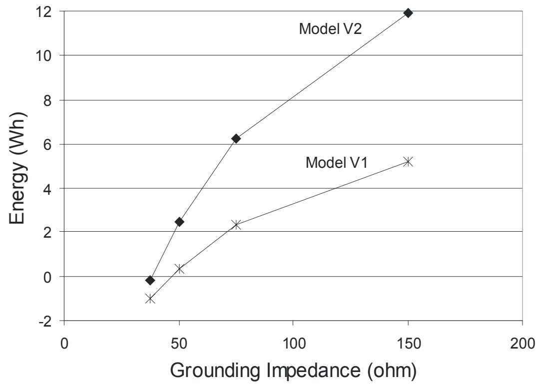


Fig. 10. Average energy supplied during a short-circuit.

V. CONCLUSIONS

Digital simulation is a very efficient mean for predicting the performance of a network and for testing devices and techniques which could mitigate voltage sag effects. A tool based on a time-domain has many advantages, but some of its limitations are also obvious, as full simulations can be time consuming.

Load representation is an important subject in which capabilities of a tool like ATP have several advantages. The document has presented a rather complex load model and the influence that this model can have on voltage sag indices based on the non-supplied energy.

One of the main goals of a voltage sag prediction is to deduce the number of sensitive equipment trips. Therefore, the representation of equipment sensitivity is also required. Future work will be dedicated to this aspect. Several approaches can be considered, since ATP capabilities can be used to include very detailed models.

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