Voltage Sag Estimation of Real Transmission Systems for Faults Along the Lines

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***Abstract*— In this paper, we dealt with the problem of the voltage sags due to faults along the lines using the Fault Position Method (FPM). The objective of the study was to demonstrate that for actual transmission systems the FPM can be used in a very effective way to solve real problems with acceptable accuracy and reduced computational times. A very simple procedure for adding further fault positions along the lines, if needed, is proposed. Numerical applications provide evidence of the proposed method. The results obtained were based on a portion of the Italian transmission system and the quantities we used were obtained from the data of the TSO.**

***Index Terms*-- Power quality, Voltage Sag, Power Transmission**

I. Introduction

The prediction of the system's performance in terms of voltage sags assessable at its nodes is of great interest. The frequency of voltage-sag is very low so that the theoretical analyses represent the most useful way to predict the voltage sags in electrical power systems. For this objective, two main methods are available in the literature, the Critical Distances method (CDM) and the Fault Position method (FPM) [1]-[4].

Certainly, the FPM represents the most powerful method for obtaining a global vision of the large-scale system's response to faults. The FPM, in particular, provides information about amplitudes and frequency of the voltage sags for all nodes, the amplitude and the frequency of voltage sags caused by each fault position, the position in which the faults are critical due to the voltage sags they cause at other nodes and the ones in which loads could experience the largest number of voltage sags.

Last but not least, the FPM delivers useful information on the propagation of the voltage sags around the network in a very compact way, especially if additional tools are realised using the results of the FPM. The graphic visualization of the matrix of the during fault voltages by means of a proper colour grade scale [2], [3] is a clear example of the great potentiality of the FPM.

If we are interested to the voltage sags due to faults along the lines, the FPM requires the introduction of additional fictitious nodes that represent the positions of the faults along the lines. The CDM, with proper simplifications, allows the analytical evaluation of the distance along a line that causes in a node a pre-assigned voltage sag. However, the CDM is prohibitive to apply to large-scale system characterized by complicated meshed networks. Further analytical methods were proposed in the literature for balanced [5] and unbalanced faults [6]. The most attractive feature in respect to FPM is that the analytical methods are based on models that include the fault position along the line as a variable. Consequently these methods do not require any additional fictitious node for the estimation of the voltage sags due to the faults along the lines.

The method proposed in [5] provides the probability density function of the voltage sags for the random variations of the fault position along the lines and for the variations in generating patterns. The method proposed in [6] extends the analytical models to unbalanced faults. Further, the study estimates the errors of the FPM in respect to the analytical proposed method. The errors are in terms of the expected number of voltage sags within a given range of amplitude for different number of fault positions along each line of the IEEE 24-bus test system.

Recently, the interest of estimating the voltage sags for faults along the lines received a revived interest; in particular [7] presented a systematic hybrid method for determining the area of vulnerability (AOV) to the voltage sags induced by the faults along the lines. The concept of the AOV is analogous to the concept of the Exposed Area (EA) [1-4, 6]; both of them ascertain the part of the system that caused in a defined node the voltage sags not greater than a pre-assigned value. Fig. 1 shows the examples of AOV reported in the

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IEEE Standards [4]. Fig.1 also evidences in red colour the boundary points of the AOV's named critical points. The EA, or the AOV, of a node can be found after that the voltage sags at that node were computed. Typically, the EA, or the AOV, is determined for assigned level of voltage sag amplitude linked to the sensitivity of vulnerable loads fed by that node; for example the EA-70, or the AOV-70, of a given node of a system is the region that encloses nodes and line segments where the occurrence of faults led to voltage sags in that node with amplitude not greater than 70%.

The novelty of the formulation in [7] consists in proposing a systematic procedure that encloses numerical method for determining the AOV directly from its boundary points (see the red points in the Fig.1). The proposals are based on the characteristics of the plot of the during fault voltage at a node versus the length of a loop line. This plot has a maximum that can be used to ascertain the AOV of a given node. The systematic procedure of [7] was proposed to overcome the drawbacks and the limitations they found using other numerical hybrid methods that they proposed in [8],[9].

As previously mentioned, the main advantage of the methods based on the analytical formulation of the during fault voltages is that they do not require the pre-assignation of the fault positions in spite of the FPM.

In this paper, we dealt with the problem of the voltage sags due to faults along the lines using FPM. The objective of the study was to demonstrate that for actual transmission systems the FPM can be still used in a very effective way to solve real problems with acceptable accuracy and reduced computational times. We proposed in this paper a very simple procedure for adding further fault positions along the lines, if needed. The main advantage of the proposal was that the great potentialities of the FPM are not lost also when the objective of a study is more focused on the voltage sags due to the faults along the lines.

The paper firstly analysed the relevant studies of the literature addressing the analytical methods for computing the voltage sags due to the faults along the lines. Then, we described the proposed procedure based on the FPM to

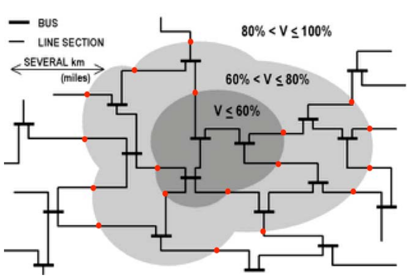

Fig.1- Example of areas of vulnerability (AOVs) of a transmission network [4] with the critical points in red colour.

overcome the main drawbacks of the method that have practical values. Finally, the results obtained on a portion of a real transmission system were presented.

II. Existing Studies for Estimating the Voltage Sags due to the Faults along the Lines

The voltage sags in the nodes of a large-scale electric systems can originate from the faults occurred at the busses and along the lines.

The available methods to compute the voltage sags due to the faults along the lines are mainly the FMP, the CDM, the analytical methods, and hybrid methods. FPM and CDM are well known and largely described in the literature. The analytical and hybrid methods are briefly recalled in the following.

The analytical methods are based on the expressions of the transfer and driving bus impedance of a location along a line to the transfer and driving impedances of buses at the ends of that line and to the line impedance [6].

The first analytical method was proposed in [5] for balanced faults. The core of the method is the analytical expression of the during fault voltage V_m, at the node m, due to a fault position p on the line k-j:

$$V_m = 1 - \frac{(1-\lambda)Z_{mk} + \lambda Z_{mj}}{(1-\lambda)^2 Z_{kk} + \lambda^2 Z_{jj} + 2\lambda(1-\lambda)Z_{kj} + \lambda(1-\lambda)Z_{kj}} \qquad (1)$$

where Z_{mk} is the transfer impedance corresponding to busbar m and k; Z_{mj} is the transfer impedance corresponding to bus m and j; Z_{kj} is the transfer impedance corresponding to bus k and j; Z_{kk} is driving impedance corresponding to bus k; Z_{jj} is driving impedance corresponding to bus j; and z_{kj} is the impedance of trasmission line k-j;

Note that equation (1) is expressed in terms of variable λ, which defines the fault position:

$$\lambda = \frac{L_{kp}}{L_{kj}} \qquad 0 \le \lambda \le 1 \qquad (2)$$

where L_{kp} is the distance between node k and position p; and L_{kj} is the length of transmission line k-j. Parameter λ moves from 0 to 1 as the point p moves from busbar k to busbar j.

Starting from the equation (1), the authors in [5] obtained in closed form the probability density function of V_m, $f(V_m)$, for random distribution of the fault position p along the line k-j.

The probability density function of V_m due to all possible faults on the lines of the transmission system is calculated as the weighted average of the conditional probability density function, $f(V_m|b)$, of the voltage sags at node m caused by faults on each line b at node m , given that the fault occurs on line b:

$$f(V_m) = \sum_b f(V_m|b)P(b) \qquad (3)$$

In (3), the weighting factor $P(b)$ is the probability of symmetrical faults occurring on the corresponding line b.

Successive studies [6] extended the analytical models to unbalanced faults appearing in balanced networks using the sequence components, positive, negative and zero. The voltage at the node m when a balanced or unbalanced fault occurs at a position p along the line k-j is given in terms of sequence components by:

$$\begin{bmatrix} V_m^{0pf} \\ V_m^{1pf} \\ V_m^{2pf} \end{bmatrix} = \begin{bmatrix} V_m^{0} \\ V_m^{1} \\ V_m^{2} \end{bmatrix} + \begin{bmatrix} Z_{mi}^{0} & 0 & 0 \\ 0 & Z_{mi}^{1} & 0 \\ 0 & 0 & Z_{mi}^{2} \end{bmatrix} I_p^{012} \quad (4)$$

where the terms V_m^0, V_m^1 and V_m^2 are zero, positive, and negative sequence voltage phasors at m, respectivley, the terms V_m^{0pf}, V_m^{1pf} and V_m^{2pf} are zero, positive, and negative sequence prefault voltage phasors, respectivley, Z_{mi}^k (with $k=0,1,2$) are the transfer bus complex impedance between busbar m and i in the Z-bus bus matrix; the currents I_p^{012} of (4) were calculated for any type of fault (three-phase fault, single-line to ground fault, line-to-line fault, double-line to ground fault). In [6] the complete expressions of the transfer impedances Z_{mi}^k (with $k=0, 1, 2$), and of the currents I_p^{012} can be found.

The statistics of the voltage sags at the node m is computed in terms of probability of occurrence within a selected range of sag magnitude, rather than as probability density function as in [5]. In particular, if p_1 is the position along a line corresponding to the sag magnitude V_1, and p_2 is the position along the same line that corresponds to the sag magnitude V_2, the probability of a voltage sag of magnitude between V_1 and V_2, $P(V_1 \leq V \leq V_2)$, is computed from the probability of a fault to occur between positions p_1 and p_2, $P(p_1 \leq p \leq p_2)$ given by:

$$P(p_1 \leq p \leq p_2) = \int_{p_1}^{p_2} g(p)dp \quad (5)$$

where $g(p)$ is the probability distribution function associated with the faults distribution along the line considered.

Finally, the voltage sag estimation is performed for all the system lines; the final number of voltage sags at phase a of bus m can be calculated by adding up the number of voltage sags estimated for each line of the system:

$$N_m(V_1 \leq |V_m^a| \leq V_2) = \sum_q N_q^a(V_1 \leq |V_m^a| \leq V_2) \quad (6)$$

where $N_m(V_1 \leq |V_m^a| \leq V_2)$ is the number of voltage sags/year at bus m due to faults at all system lines.

The hybrid methods [7]-[9] have the objective to know the fault positions leading to sag magnitudes equal to a given threshold in a given node starting from the voltage equations given by (4) in the case of balanced and unbalanced faults. The searched fault positions are the critical points of the AOV that represent the borders of an AOV (see Fig.1 for example). These methods are named hybrid since they include a numerical procedure for finding the solution of the analytical expressions of the during fault voltages directly in the unknown variable p along a line.

Focusing the attention on the loop lines, the during fault voltage equations are higher than the fourth degree with the variable p. For the solution of such equations in [7], the golden section search is proposed as the numerical technique that finds a maximum sag magnitude and the point p corresponding to such a maximum. Based on the maximum magnitude and point, it is possible identify the number of critical points on a line and detect line parts inside the searched AOV. The authors proposed such numerical technical procedure to overcome the drawbacks and the limitations they found using other numerical techniques that they proposed in [8], [9].

It is important to evidence that in [7], for determining the critical points of the AOV's, the authors proposed a systematic procedure that includes a preliminary solution of the FPM with the fault positions placed in the nodes of the system for the detection of nodes and lines that belong to a searched AOV's.

III. Estimation the Voltage sags Due to Faults also along the Lines based on FPM

The analytical methods are proposed to overcome the pre-assignation of the positions of the faults in the FPM to achieve an acceptable error, considered the most relevant drawback of the method.

In [6] the authors compare the results obtained by the analytical method with those obtained by the FPM using different numbers of fault positions in very simple 5-bus test system and in the IEEE 24-bus reliability test system.

The number of fault positions along each line required by the FPM to achieve an error on the expected number of faults lower than 10%, 5%, and 3% at all system buses of the IEEE 24-bus reliability test system is computed. From the obtained results, they conclude that a high number of fault simulations (up to 100 for every line) is necessary if precise accuracy is demanded. This conclusion is also presented as a general rule for any system in proposing the hybrid methods in [7].

The high number of simulations by FPM needed to obtain a pre-assigned precision provided in [5] for two well defined test systems is computed directly on the expected number of sag in every node in two test systems. This implies that the fault rates of the lines and of the busses are used. However, these values can be characterized in real systems by an error greater than the pre-assigned total error on the final estimation of the expected number of sags. Moreover, the contribution to the total fault rate of the line can be really lower than the contribution of the nodes.

Finally, the error is computed with reference to all the possible values of the amplitude of the voltage sags with steps of 5% or 10%. Even if this analysis provides a valuable benchmark, the effected computations seem to be unrealistic on actual systems if real problems have to be faced.

In real systems, two main problems can be relevant.

The first problem refers to the estimation of the performance in some busses where sensitive loads are fed.

Typically, a defined value of the amplitude of the voltage sag is known as the critical value equal to the maximum value below which the sensitive loads do not operate correctly.

The second problem refers to the estimation of the expected number of voltage sags in defined ranges of amplitude and duration provided by the existing standards or by the regulatory schemes. Actually, the most used tables of the ranges (amplitude, duration) are those reported in [10] for Class I and Class II equipment's. In particular, the amplitudes are organised in ranges of values that are different from those considered in [5].

Starting from the previous considerations, for real systems we proposed to estimate the expected number of the voltage sags with the FPM that represent a method largely used by the system operators, and recognised as a robust tool also by the Standard [4].

The first step of the analysis consisted in applying the FPM with the fault positions coincident with the network buses. Once obtained the During Fault Voltage (DFV) matrix, we extracted only the rows of the DFV matrix that correspond to the nodes where the sensitive loads are fed; this extraction can use the graphical colour visualization of the DFV [3].

The second step was to ascertain the nodes that correspond to the EA of each sensitive nodes; they constitute the critical sections of each considered nodes (see as an example Fig. 2).

Once detected the critical sections of each sensitive node, the following procedure was applied.

1. For every line that connects every node of the critical section to the network, apply the FPM for faults along the line considering fault positions in a pre-fixed points of the line (as usual in 0, ¼ L; ½ L, ¾ L, L) and obtain the V_{df} along the line (see the example of a plot shown in Fig. 3).
2. Detect the sub-sections, ΔL_i, of every critical feeder L_i, that correspond to the V_{df} close to pre-fixed values. These values can be:
   a. the maximum acceptable voltage sags of the sensitive loads (for example 0,7 in Fig.3);
   b. the susceptibility limits indicated by the standards like the limits for Class I and for Class II equipment's [10].
3. Make a deeper analysis only in the sub-sections detected in step 2 for a more accurate calculation of the length of the lines that falls in the EA. The deeper analysis is conducted applying again the FPM for faults along the sub-sections of critical feeder identified by points in which V_{df} assumes values equal to ±5% of the threshold.

The additional number of the fault positions was not so large. In fact, if the total number of fault positions on the line of length L_i was 50 or 100, as indicated in [6], the resulting number of fault position for every critical sub-section, was $50*\Delta L_i / L_i$ or $100*\Delta L_i / L_i$, in case of 50 or 100 total fault positions, respectively.

With the assumption that the faults were uniformly distributed along the lines, we computed the probability of a fault to occur only within the line sub-sections detected in the previous steps; it was obtained by multiplying the line fault rate for the length of the sub-sections ΔL_i.

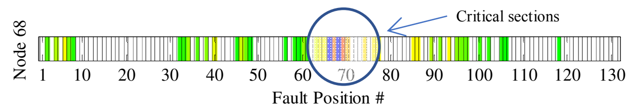

Fig. 2. Graphical representation of row of the DFV matrix corresponding to the node where a sensitive load is connected with the indication of its critical sections.

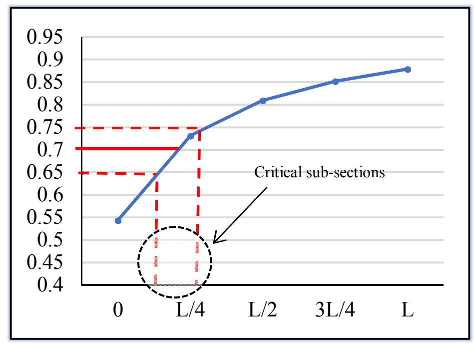

Fig. 3 - During-fault voltage of a sensitive node for faults along a radial feeder

For improving the accuracy of the resulting expected numbers of voltage sags due to faults along the lines of a system, the proposed procedure provided the increase of the resolution of the fault positions only where required.

It is important to evidence that this procedure covers also the case of line loop. In fact, a line loop in a system is realized by means of more feeders that connect the nodes each other. In a real transmission system, for example, a typical line loop is the line that connects a section of sub-transmission. Typically, a number of substations is fed at each node by a line loop to the low voltage side of the transformers of a transmission station. These nodes are always considered as fault positions in the FPM and, consequently, are included in the DFV matrix. If they belong to critical sections, the previous procedure can be applied.

The following section shows the results of the procedure applied to radial feeders separately from those obtained in the case of loop lines.

IV. Numerical Results on a Real Transmission System

The voltage sag performance for faults along the lines was estimated for a portion of the Italian transmission system whose simplified scheme is shown in Fig. 4; the main characteristics are reported in [11].

Two cases of radial and loop lines are reported in the following.

Radial line

A real 380 kV overhead radial line with total length of L=113.97 km connects node #6 to node #45. The nodes #68 and #119 (highlighted in Fig. 4 with blue circles) were selected as observation nodes, due to the high vulnerability to voltage sags. The limit of vulnerability for the loads ($V_{critical}$) is 0.7 (node #68) and 0.4 p.u. (node #119).

The expected number of sags at bus #68 and #119 was computed using real failure rate of lines and nodes obtained from the operating data of the transmission system. In particular, the Monitoring and Business Intelligence (MBI) [11] provided the statistical data.

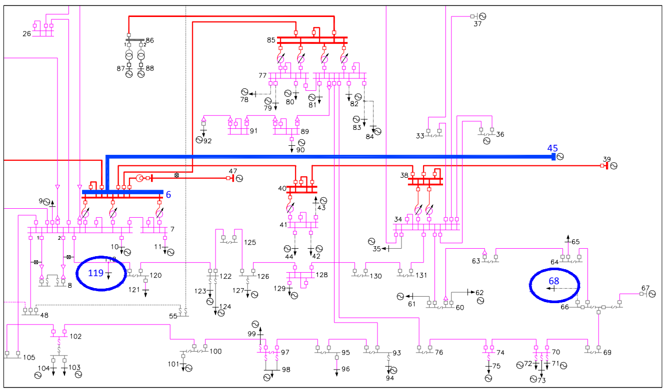

Fig. 4 - A portion of the Italian transmission system

The proposed procedure has been firstly applied for ascertaining the critical subsections of the line for the node #68 and #119. The during-fault voltages for both observation nodes has been obtained by moving the fictitious node in the five equidistant fault positions of the line of L length and applying FPM.

Fig. 5 shows the during-fault voltages along the line 6-45 in the discrete points corresponding to ¼ *L*; ½ *L*, ¾ *L*, as well as to the node 6 and 45. Fig. 5 reports the linearized plots of the voltage at the node #68 (red line) and at the node #119 (yellow line). The critical subsection of the node #68 corresponds to the range [0.65, 0.75] p.u.; that of the node #119 corresponds to [0.35, 0.45] p.u..

To obtain a reference for the comparison of the results, the during-fault voltage at node #68 and at node #119 was computed also for faults on line 6-45 calculated in 100 points equally distributed along the line (blue line in Fig. 5).

The average error of the during-fault voltage along all the line 6-45 obtained in the two cases (5 points and 100 points) is 0.58% for node #68 and 0.98% for node #119 with a maximum error equal to about 2.5 % for node #68 and 4.2 % for node #119.

The expected number of voltage sags at the considered nodes for the critical subsections around the critical value was computed following the procedure described in the Sec. III;

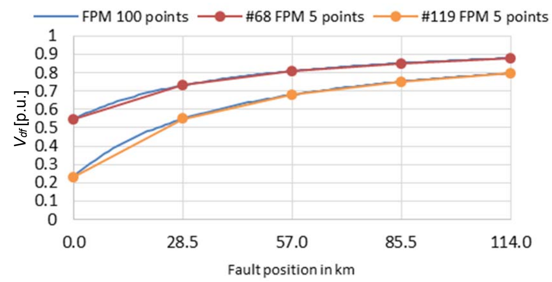

Fig. 5 - Voltage magnitude at node #68 and #119 for faults on line 6-45 obtained with 5 and 100 points equally distributed along the line

the number of fault positions is equal to 20, for the node #68, and 12 for the node #119.

The results are organized in the following cases:

Case 1: 5 points equally distributed along the line;

Case 2: 100 points equally distributed along the line;

Case 3: applying the procedure of the Section III for the critical subsections around the critical value, with an additional number of points as previously indicated and obtained considering a distance between two successive faults equal to *L*/100.

Table I clearly shows that the results obtained in the Case 2 and the Case 3 are practically coincident. Even in the Case 1, the maximum error is 0.5%.

TABLE I - VOLTAGE SAG/YEAR AT THE BUSES #68 AND #119, WITH AMPLITUDE NOT GREATER THAN A CRITICAL VALUE ($V_{CRITICAL}$) DUE TO FAULT POSITIONS ALONG THE LINE 6-45.

Number of voltage sag per year					
Bus #68			Bus #119		
$V_{critical}$ = 0.7 p.u.			$V_{critical}$ = 0.4 p.u.		
Case 1	***Case 2***	***Case 3***	***Case 1***	***Case 2***	***Case 3***
0.448	0.446	0.446	0.442	0.440	0.439

Finally, the procedure was applied considering the expected number of sags per year at buses #68 and #119 in case of faults along the line 6-45 considering the ranges of V_{df} of the Class I table of IEC 61000-4-11 (Table II). The total number of additional fault position is 60 for the bus #68 and 40 for the bus #119.

Table II shows that the results obtained in Case 2 and Case 3 are practically coincident.

TABLE II - VOLTAGE SAG/YEAR OF THE BUSES #68 AND #119 DUE TO FAULT POSITIONS ALONG THE RADIAL LINE 6-45.

V_{df} range [%]	**Number of Sag per year**					
	Bus #68			**Bus #119**		
	Case 1	***Case 2***	***Case 3***	***Case 1***	***Case 2***	***Case 3***
$80< V_{df} \leq 90$	0.042	0.043	0.043	0	0	0
$70< V_{df} \leq 80$	0.022	0.022	0.022	0.034	0.035	0.035
$40< V_{df} \leq 70$	0.448	0.446	0.446	0.035	0.037	0.038
$5< V_{df} \leq 40$	0	0	0	0.442	0.440	0.439
$V_{df} < 5$	0	0	0	0	0	0

Loop line

The 150 kV loop line of the real portion of the Italian transmission system shown in blue color in Fig. 6 was considered.

Fig. 7 shows with orange line the magnitude of the during-fault voltage at the bus #26 obtained linearizing the results of the FPM applied to the fault positions (discrete orange points) corresponding to existing nodes of the loop. The bus #26 of the loop supplies a sensitive load whose critical voltage sag is 0.3 p.u..

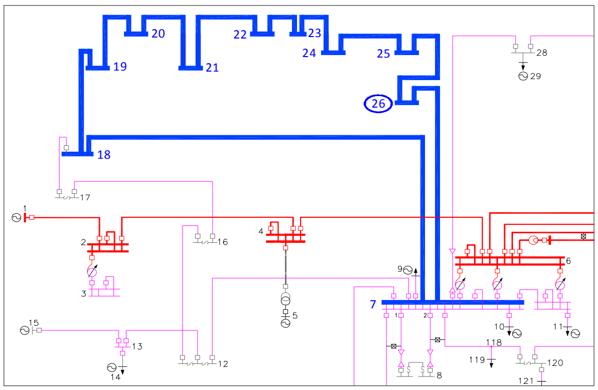

Fig. 6 - Loop system at 150 kV

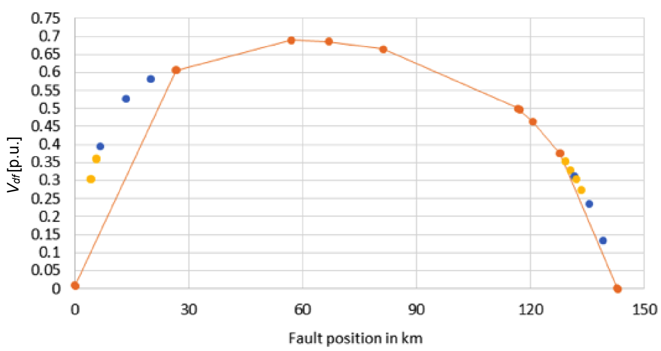

Fig. 7 - Loop system at 150 kV

It is evident from Fig.7 that the considered critical voltage intercepts two critical sub-sections each on a different line composing the loop. In fact, following the procedure of the Section III, we considered the range [0.25, 0.35] p.u.. For such a range, the lines that can cause voltage sags not greater than 0.25 when a fault occurs on them are only the line between the nodes #7 and #18, and that between the nodes #25 and #26. The FPM was applied also to 100 points equally distributed along the loop line for obtaining a reference case. The results are organized (Table III) in the following cases:

Case 1: 5 points equally distributed along the lines (7, 18) and (25, 26).

Case 2: 100 points equally distributed along the loop line;

Case 3: for the critical subsections of each line around the critical value, additional two fault positions points (yellow points in Fig. 7) for the line (7, 18) and four for the line (25, 26).

Table III shows that the results of the Case 3 are practically coincident with those of Case 2. The maximum value of the error is 2%.

TABLE III - VOLTAGE SAG/YEAR AT THE BUSES 26, WITH AMPLITUDE NOT GREATER THAN THE CRITICAL VALUE EQUAL TO 0.3 P.U. DUE TO FAULT POSITIONS ALONG THE LINE LOOP OF FIG. 6.

Number of voltage sag per year					
Line (7,18) $V_{critical} = 0.3$ p.u.			Line (25, 26) $V_{critical} = 0.3$ p.u.		
Case 1	***Case 2***	***Case 3***	***Case 1***	***Case 2***	***Case 3***
1.240	1.240	1.240	0.247	0.252	0.247

V. CONCLUSIONS

We analyzed the problem of performance of an electrical transmission system against voltage sags due to faults along the lines. In particular, it has been demonstrated that for actual transmission systems the FPM can be still used in a very effective way to solve real problems with acceptable accuracy and reduced computational times. A very simple procedure for adding further fault positions along the lines, if needed, is proposed. An important feature of this paper is that the system we considered is an actual portion of the Italian transmission system, and all of the quantities we used were obtained from the data of the TSO.

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