VULNERABILITY ARIA TO DISTURBANCE IN ELECTRICITY NETWORK

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Această lucrare îşi propune să pună în evidenţă necesitatea cunoaşterii ariei de vulnerabilitate la apariţia, în reţeaua electrică, a unor perturbaţii determinate de defecte*. Este prezentată o metodă de evaluare a ariilor de vulnerabilitate pentru cazul perturbaţiilor sub formă de goluri de tensiune, determinate de scurtcircuitele din reţeaua electrică. Studiul de caz se referă la o reţea electrică de medie tensiune care alimentează utilizatori importanţi care necesită un nivel ridicat al calităţii energiei electrice. Rezultatele obţinute pot fi utilizate pentru elaborarea unor studii pentru îmbunătăţirea nivelului calităţii energiei electrice în zonă.*

The objective of this paper is to reflect the importance of knowing the vulnerability area, in the electrical network, after the appearance of some disturbances determined by faults. In this sense, it is presented a method to evaluate the vulnerability areas as a result of voltage sags determined by short-circuits in the electrical network. The case study refers to a distribution electric network supplying important consumers, requesting electrical power with high quality level. The results obtained can be used to elaborate studies to improve the electrical power quality level in the area.

Keywords: vulnerability area, short-circuit, medium voltage network

1. Introduction

Short-circuits in electrical networks lead to the appearance of voltage dips and short-term interruptions affecting the quality of electricity supplied to users [1]. In this respect, the knowledge of the events characteristics and the affected area (vulnerability area) present special interest when assessing the quality of the electrical power supplying service.

Duration of voltage dips or short interruptions is determined by the protection time response. The incidents occurred in distribution networks are eliminated by the protection of the affected equipments. Meanwhile, in a large area of distribution networks, the voltage of the affected phase (phases) decreases to values between 1 and 0 p.u., according to the “electrical distance” from the place where the incident took place. The resulted voltage dip is transferred to all

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the connected networks. A similar situation is found in distribution networks of users, but the resulted voltage dip, usually affects short areas of related networks [2].

Vulnerability area is considered the zone of a distribution network in which short-circuit causes a voltage dip, with the specified value, or an interruption of short duration. Vulnerability area is defined depending of voltage dip amplitude [3][13].

A short-circuit close to the analyzed network node, causes short interruptions, while the voltage dip amplitude, after removing the short-circuit, depends on the "electric distance" between the examined node and the point where the incident occurred.

Determining the vulnerability area is the starting point for the estimation of the voltage dips caused by faults in distribution networks, and their propagation. Estimated frequency of voltage dips, combined with statistics on the annual number of events/km of network, is used to assess measures to be taken in order to enhance power quality in the area.

2. Method of calculation

Determining the vulnerability area of an electrical network in the case of a short-circuit disturbance is based on matrix methods for short-circuit currents calculation. In general, for short-circuit currents calculation, depending on the pursued purpose, can be used two types of methods [4]:

– complete method, in which it can be used a more precise representation of the electrical network elements and its operating system for the period before the defect occurrence;

– simplified method, in which there are allowed some simplifying assumptions over the complete method, the results having an error up to 10% over complete method.

The complete method used to calculate short-circuit currents is based on several general assumptions:

– electric network is considered symmetrical and the loading is balanced;

– electrical network elements have linear characteristics;

– synchronous and asynchronous machines of large rated power are represented through constant electromotive forces;

– generator swings are neglected.

In order to simplify calculations, by using the simplified method there are allowed additional assumptions[5]:

– steady-state regime before the defect is ignored; the electrical network is considered in no-load regime;

– electrical network elements' characteristics for the negative sequence are considered identical for the positive sequence (including those representing the synchronous generators);

– arc resistances are not taken into account.

Generally, short-circuits represent unsymmetrical operating regimes (except three-phase short-circuits). For the calculation of such operating mode in three-phase balanced electrical networks, it can be used the symmetrical component method. A three-phase voltage system, represented by three phasors $\underline{V}_a$, $\underline{V}_b$ and $\underline{V}_c$ may be replaced with three symmetrical systems of phasors: positive, negative and zero sequence. The relationship between two groups is expressed through a linear equations system:

$$\begin{cases} \underline{V}_a = \underline{V}^+ + \underline{V}^- + \underline{V}^0 \\ \underline{V}_b = \underline{a}^2\underline{V}^+ + \underline{a}\underline{V}^- + \underline{V}^0 \\ \underline{V}_c = \underline{a}\underline{V}^+ + \underline{a}^2\underline{V}^- + \underline{V}^0 \end{cases} \tag{1}$$

where $\underline{V}^+$, $\underline{V}^-$ and $\underline{V}^0$ are symmetrical voltages of positive, negative and respectively zero sequence, and $\underline{a}$ is a rotating phasor of unit magnitude that causes a rotation of $2\pi/3$ in the counterclockwise direction.

Based on the general and additional assumptions mentioned above, for modeling a short-circuit in the *k* node of an electrical network having *n* nodes, three systems of *n* equations can be written:

$$\begin{cases} \left[\underline{\mathbf{V}}^+\right] = \left[\underline{\mathbf{V}}_\mathrm{n}\right] - j\left[\mathbf{X}_\mathrm{nn}^+\right]\left[\underline{\mathbf{I}}^+\right] \\ \left[\underline{\mathbf{V}}^-\right] = j\left[\mathbf{X}_\mathrm{nn}^-\right]\left[\underline{\mathbf{I}}^-\right] \\ \left[\underline{\mathbf{V}}^0\right] = j\left[\mathbf{X}_\mathrm{nn}^0\right]\left[\underline{\mathbf{I}}^0\right] \end{cases} \tag{2}$$

where $\left[\underline{\mathbf{V}}_\mathrm{n}\right]$ is the column matrix of phase-to-neutral nodal voltages of the electrical network of no-load regime before the short-circuit;

$\left[\underline{\mathbf{V}}^+\right]$, $\left[\underline{\mathbf{V}}^-\right]$, $\left[\underline{\mathbf{V}}^0\right]$ – column matrices of nodal phase-to-neutral voltages of positive, negative and zero sequence networks;

$\left[\underline{\mathbf{I}}^{+}\right], \left[\underline{\mathbf{I}}^{-}\right], \left[\underline{\mathbf{I}}^{0}\right]$ – column matrices of short-circuit currents injected into the network nodes of positive, negative and zero sequence;

$\left[\mathbf{X}_{\text{nn}}^{+}\right], \left[\mathbf{X}_{\text{nn}}^{-}\right], \left[\mathbf{X}_{\text{nn}}^{0}\right]$ – square matrices of nodal reactances of positive, negative and zero sequence.

The values of short-circuit currents at the fault point depend on the short-circuit type [6]. Ecuations for calculating these values are presented in Table 1.

Table 1

Calculation of short-circuit currents at fault point

Short-circuit type	Positive sequence	Negative sequence	Zero sequence
Three-phase short-circuit	$\underline{I}_k^{+} = \dfrac{\underline{V}_k}{jX_{kk}^{+}}$	$\underline{I}_k^{-} = 0$	$\underline{I}_k^{0} = 0$
Phase-to-phase short-circuit clear of earth	$\underline{I}_k^{+} = \dfrac{\underline{V}_k}{j\left(X_{kk}^{+} + X_{kk}^{-}\right)}$	$\underline{I}_k^{-} = -\underline{I}_k^{+}$	$\underline{I}_k^{0} = 0$
Phase-to-phase-to-earth short-circuit	$\underline{I}_k^{+} = \dfrac{\underline{V}_k}{j\left(X_{kk}^{+} + \dfrac{X_{kk}^{-} X_{kk}^{0}}{X_{kk}^{-} + X_{kk}^{0}}\right)}$	$\underline{I}_k^{-} = -\dfrac{X_{kk}^{0}}{X_{kk}^{-} + X_{kk}^{0}} \underline{I}_k^{+}$	$\underline{I}_k^{0} = -\dfrac{X_{kk}^{-}}{X_{kk}^{-} + X_{kk}^{0}} \underline{I}_k^{+}$
Phase-earth short circuit	$\underline{I}_k^{+} = \dfrac{\underline{V}_k}{j\left(X_{kk}^{+} + X_{kk}^{-} + X_{kk}^{0}\right)}$	$\underline{I}_k^{-} = \underline{I}_k^{+}$	$\underline{I}_k^{0} = \underline{I}_k^{+}$

The element $\underline{V}_k$ from Table 1 represents the phase-to-neutral voltage of k node before fault occurrence and is equal to the voltage of equivalent voltage source at the short-circuit location:

$$\underline{V}_k = \frac{cU_n}{\sqrt{3}} \tag{3}$$

where U_n is the nominal phase-to-phase voltage of electrical network fault place and c is the voltage factor, whose values are defined according to the nominal voltage of the network and the pursued regime (maximum or minimum) [6].

The calculation algorithm to determine the residual voltages in electrical network nodes by using the simplified method to compute the short-circuit currents, includes the following calculation steps:

1. Initialization of calculation process:
   1.1. Determination of the branches (electrical lines and transformers) and generators (synchronous and asynchronous) reactance of positive and zero sequence;
   1.2. Calculation of nodal reactance matrices corresponding to the positive and zero sequence schemes $\left[\mathbf{B}_{\mathrm{nn}}^{+}\right]$ and $\left[\mathbf{B}_{\mathrm{nn}}^{0}\right]$;
   1.3. Reversing the reactance matrices corresponding to the positive and zero sequence schemes to obtain the matrices $\left[\mathbf{X}_{\mathrm{nn}}^{+}\right]$ and $\left[\mathbf{X}_{\mathrm{nn}}^{0}\right]$;
   1.4. Defining values of nodal phase-to-neutral voltages $\left[\mathbf{V}_{\mathrm{n}}\right]$ corresponding to electrical network nodes;
2. Defining the *k* node in which the short-circuit occurs;
3. Calculation of short-circuit current at fault location $\underline{I}_k^{+}$, $\underline{I}_k^{-}$ and $\underline{I}_k^{0}$;
4. Setting the short-circuit type and calculation of the network nodes residual voltage.

In order to simulate a fault on an electrical line it was considered an additional node, obtained by dividing the electrical line in two sections whose reactance equivalent was considered proportional to length.

In the case of unbalanced short-circuits, the imbalance occurs on the *A* phase.

3. Case study

The purpose of the electrical network analysis is to provide the necessary information for understanding the nodes characteristics, in terms of power quality and information based on which decisions can be taken on network maintenance, also what investment is necessary to increase power quality level. In order to evaluate the vulnerability areas related to the voltage sags

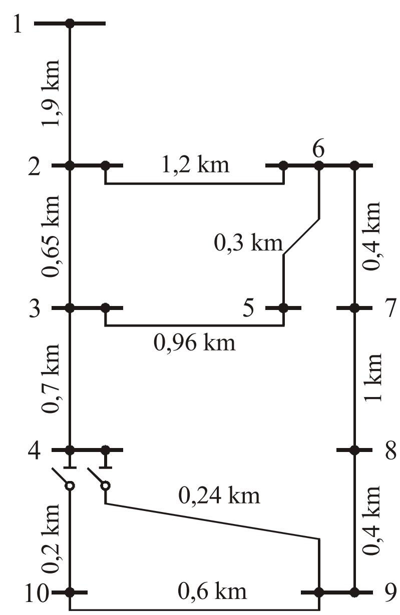

Fig. 1. *TEST* electrical network.

disturbances, the *TEST* distribution electric network, shown in Figure 1, was considered. This is a 20 kV distribution network with 10 nodes and 12 branches. All branches are cable electric lines type, which per unit length values are $0.116\,\Omega/\text{km}\,\text{phase}$ for positive sequence reactance and $0.406\,\Omega/\text{km}\,\text{phase}$ for zero sequence reactance.

For this network the node 1 is considered as being supplying node, which short-circuit power S_{SC} is 250 MVA. Concerning the ratio between zero sequence reactance and positive sequence reactance of supplying node, the following value was considered: $\frac{X_1^0}{X_1^+} = 2$.

To determine the vulnerability area in *TEST* electric network, by calculations, a short-circuit simulations software was used. The software was developed in T.D.E.E. laboratory of Power Engineering Faculty - University “POLITEHNICA” of Bucharest - using the VisualC++ 6.0 programming language, witch is capable to calculate both nodes voltage and current flows through the branches of the electric networks.

The calculations were performed for two types of faults on 7-8 electric line: a three-phase short-circuit and a phase-to-phase-to-earth short-circuit. Regarding the fault location of short-circuits, four places were considered: at 0.2 km, 0.4 km, 0.6 km and respectively 0.8 km for the 7 node.

Figure 2 shows voltage variation for a three-phase sort-circuit. The voltage variation for a phase-to-phase-to-earth short-circuit is shown in Figures 3 and 4. The Figure 3 shows the nodal voltages on the unaffected phase, while in the Figure 4 the nodal voltages on faulted phases are shown.

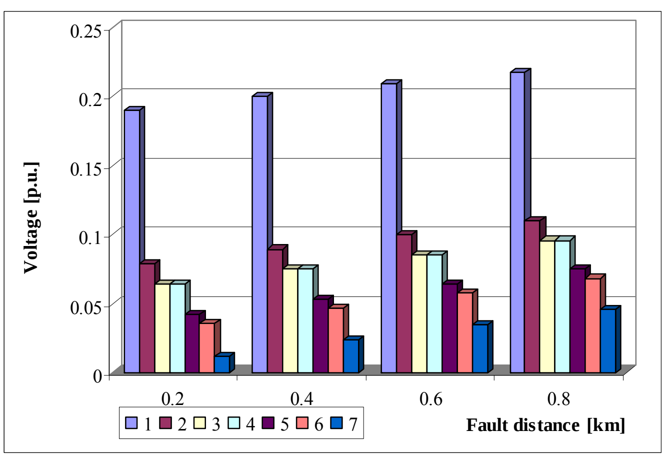

Fig. 2. Voltage variation of nodes in case of three-phase short-circuit for S_{SC} = 250 MVA.

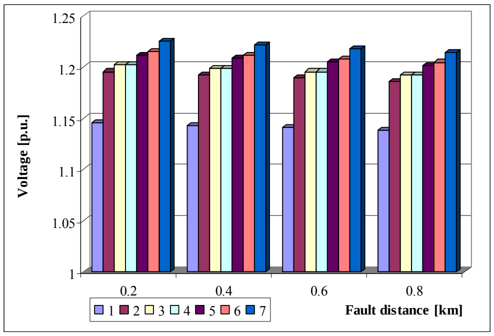

Fig. 3. Voltage variation of nodes on the unaffected phase in case of phase-to-phase-to-earth short-circuit for S_{SC} = 250 MVA.

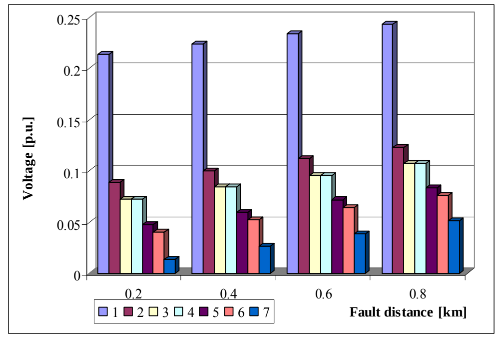

Fig. 4. Voltage variation of nodes on faulted phases in case of phase-to-phase-to-earth short-circuit for S_{SC} = 250 MVA.

Analyzing the results obtained and the Figures 2, 3 and 4, the following conclusions arise:

- In terms of voltages during short-circuit,
  a) case of three-phase short-circuit:
  - residual voltages are identically on the three phases; the values are approximately 12% lower than those of affected phases in case of phase-to-phase-to-earth short-circuit;
  - residual voltages increase when the fault appears to the end of line, with values between 13% and 75% (in different network nodes), from case where the defect occurs at the beginning of the line.

  b) case of phase-to-phase-to-earth short-circuit:
  - values of residual voltages on unaffected phase (V_a) decrease by (0.6÷0.9)% if the defect is located at the end of line;
  - values of residual voltages on affected phases (V_b and V_c), in case of fault towards the end of the line increase with values between 12% (node 1) and 74% (node 7) with respect to cases where the defect appears at the beginning of the line.
- Regarding the electric currents of short-circuit,
  a) case of three-phase short-circuit:
  - values on the three-phase short-circuit, identically on three phases, are approximately 9% higher than in the case of phase-to-phase-to-earth short-circuit;

– short-circuit currents decrease when the defect is located at the end of line by approximately 4% compared to case in which the defect occurs at the beginning of the line;
– in case of operation in radial scheme, short-circuit currents have the same value on the entire path between the place of short-circuit and supplying node.

b) case of phase-to-phase-to-earth short-circuit:

– presents the maximum value if the defect occurs at the beginning of line, dropping when the defect is located at the end of line with approximately 4%, for short-circuit power of 250 MVA case;
– inside the loop, because the distribution on both sides, the short-circuit current registers minimum value.

• In terms of voltage dips, it can be said that, their magnitude depends on the configuration scheme and on the place where the defect occurred [9][11]. This fact can be seen in the diagrams from Figures 4 and 5 that present the area of vulnerability for the two types of fault considered.

Note that for the same defect are recorded different amounts of gap voltage, which must be known to assess the sensitivity of equipment connected to that node.

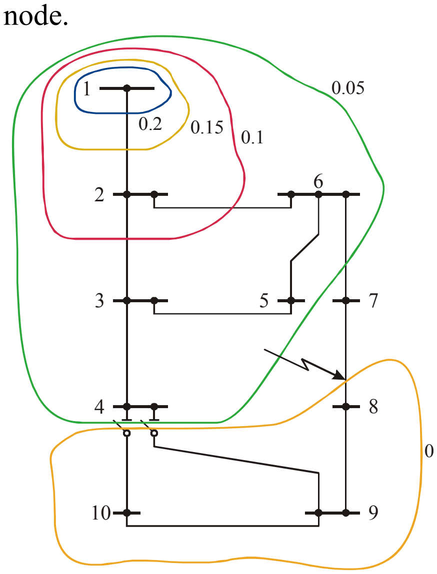

Fig. 5. Vulnerability area in case of a three-phase short-circuit at the distance of 0.8 km from 7 node,for S_{SC} = 250 MVA.

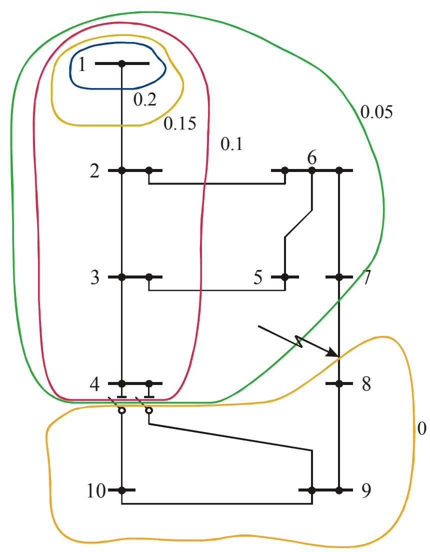

Fig. 6. Vulnerability area in case of a phase-to-phase-to-earth short-circuit at the distance of 0.8 km from 7 node, for S_{SC} = 250 MVA.

In the case of the phase-to-phase-to-earth short-circuits, note that, on the unaffected phase, there is an overvoltage. Thus, it can be defined a vulnerability area for the surge that appear on the unaffected phase..

The diagram in Figure 6, presents the voltage vulnerability area, this aspect being highlighted for the first time in literature (from knowledge of the authors).

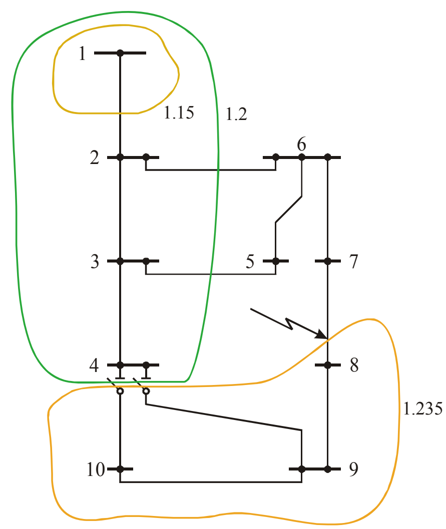

Fig. 7. Vulnerability area of the surge appeared on the unaffected phase in case of a phase-to-phase-to-earth short-circuit at the distance of 0.8 km from 7 node, for S_{SC} = 250 MVA.

Conclusions

Studies related to the area of vulnerability allow knowledge of any sensitive areas of the network and eventually, the adoption of measures to improve the electrical power quality.

Voltage dips are the most common phenomena in electrical networks that cause great damage, and their analysis involves a special attention. To assess the effects of unsymmetrical voltage dips on three-phase receivers, it should be considered the presence, in the power supply, of the star-delta transformers, which leads to deformation of the initial phazorial chart [7],[10].

Sensitive consumers who are not satisfied with the offered quality (resulted from studies into the power grid), must provide themselves local resources to improve the quality, which will allow the restricting of the disturbance level and the reduction of the effects of to deviations from the quality indicators [8][12].

One of the most effective solutions for improving safety in the critical consumer power is the one of using renewable uninterruptible power supply (UPS).

Technical and economic efficiency of the UPS systems can be achieved through an appropriate receivers separation of a consumer, according to the specific quality of electricity. An appropriate choice of scheme for the power system of the consumer allows supplying separately the critical receivers and chose an appropriate type of UPS source, depending on the type of receivers and on the specific conditions of the power quality. The separation cost is relatively small, requiring only a good experience of operating and proper selection of electrical equipment.

Amoung authors contributions is included defining the vulnerability area of surge for unbalanced faults.

This study covers an area with problems of power quality and the obtained results will be use for investments that will take place later in this area. Also, this study falls within the current efforts of specialists to provide and use (efficient and rational) the energy resources.

To ensure efficiency of investment is required an elaborate analysis of consumer receivers and their classification according to the power supply conditions.

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