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COMPATIBILITY BETWEEN EQUIPMENT AND SUPPLY WITH REGARDS VOLTAGE DIPS AND SHORT INTERRUPTIONS PART I: DETERMINATION OF THE SUPPLYING NETWORK CHARACTERISTIC

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***Summary*: This paper describes a simulation method which allows stochastic assessment of voltage dips and short interruptions that may be expected at a given node of an electrical power network due to faults occurring in it. Different types of faults, symmetrical and asymmetrical, were taken into account. The symmetrical component approach was applied. Voltage dips are characterised by voltage symmetrical component vectors. The Monte Carlo method was applied, which allows getting frequency of a given voltage dips and short interruptions. Evaluating such characteristics is needed for assessing compatibility between loads and the supply network.**

The methodology has been used to draw up a simulation tool by means of LABVIEW programme. The paper presents the results of simulation performed for a given electrical transmission and distribution network and discusses them.

Key words: power quality, voltage dips, short interruptions, stochastic assessment, simulation tool

1. INTRODUCTION

In recent years greater emphasis has been placed on the quality of service provided by utilities to consumers who more and more frequently evaluate production losses associated with voltage dips and short interruptions. Supply voltage dips and short interruptions have been recognised as one of the main parameters of the supply voltage, which determine electromagnetic compatibility between loads and the supply network. They are usually caused by faults in utility transmission or distribution systems. The depth of a dip at a given site of the network depends on type of a fault and its location, fault resistance, the supply network configuration and parameters of the network elements. Duration of a dip results from the fault clearing time determined by protection settings and reclosing practice applied by the utility. Dips performance is a process of a stochastic nature due to random nature of faults.

In all types of networks: industrial, commercial and residential, various 1-phase and 3-phase load devices are utilised. One-phase loads are, first of all, those with rather small power, fed from the LV network. Three-phase loads can be fed either from MV or LV network. Their power varies within a wide range. Both single-phase and 3-phase loads have their own tolerance on voltage dips and short interruptions. This should include the behaviour of a piece of equipment, e.g. protection devices, properties of the technological process in which it takes part and control system as well. A tolerance characteristic can be constructed for any single electric load or for a group of loads if it energises one technological process.

Right load operation requires the proper voltage waveform to be kept in the point of common coupling (PCC). Customers supplied from MV or LV networks can be affected by dips due to faults at numerous locations in the system besides the feeder that supplies them. In general, faults can occur in:

— HV transmission and subtransmission networks,
— MV feeder from which the customer is supplied,
— other MV distribution networks which are connected with the customer feeder via the HV network,
— LV network supplying the customers,
— other LV networks that are connected with the customer feeder via the MV network.

To find out whether or not loads are compatible with the supply network, an assessment of the supply voltage is needed. The load tolerance characteristic decides what voltages of the supply network have to be taken into consideration. Usually, single-phase loads require information about phase–to-neutral or phase-to-phase voltages. For 3-phase loads one should know either: three phase-to-neutral voltages or three phase-to-phase voltages or voltage symmetrical components. It depends on a kind of three-phase load connection (delta, isolated star, grounded star) and of a type of the loads (electrical machine, rectifier etc.).

There are two methods available for assessment of the supply voltage: power quality monitoring and stochastic prediction [1, 2]. The first one gives information mainly about common events and can be performed for existing networks. The period of time required for monitoring for the full statistic assessment of the network performance, including also less common events, would have to be very long, and exceed the technical live of the examined network many times. For this reason monitoring method has a limited application in assessment of compatibility between loads and a supplying network.

Stochastic prediction is more suitable in that case. This paper proposes a simulation approach for determination the expected number of voltage dips with selected magnitude and duration. The method could be applied for both one-phase and three-phase load compatibility assessment. This method is an extension of the one presented in [3, 4].

2. DESCRIPTION OF THE METHOD

2.1. Assumptions

The simulation method, and the computer simulator based on it, meet the following requirements:

- allow determining voltages in selected nodes of any configuration supply network during normal operation condition and during a fault, as well as calculating these states durations,
- take into account the random nature of faults, i.e. fault type and fault location,
- consider protection settings as they result in a fault duration, and at the same time in a dip or interruption duration,
- take into account the stochastic nature of a faulted element repair process including reclosing performance applied by the utility.

It has been assumed that the network is represented by an equivalent circuit constructing like for short-circuit calculations. The structure of the network is constant in principle. In general, each network element can be in the state of: switching on, short-circuit or switching off. In the switching on state the element is represented by its short-circuit impedance. While switching it off, it has impedance equal to infinity. Fault occurrence involves making up a new, short-circuit node. If, for example, a short-circuit appears in the branch between nodes A and B then this branch is replaced by the infinity impedance and two new branches are added which connect nodes A and B, respectively, to the short-circuit node. Impedances of the new branches are equal to the faulted element impedance measured from the nodes A and B, respectively, to the fault location.

The state of any element is a function of two random variables: time of operation and time of repair for each element. The probability distribution for these variables can be evaluated on the basis of statistical data. It has been accepted in the method that values of operation and repair times are generated in random-numbers generators. The operation cycle for each element is as follows:

- switching on the element and its operation for the time t_o,
- a fault in the element lasting for the time which is determined by protecting devices settings,
- switching off the element and its repair for the time t_r,
- switching on the element after its being repaired.

2.2. Method of calculation

Voltages in nodes of the considered network are calculated according to the algorithm commonly applied in short-circuit calculations. For symmetrical faults all sources in the network are short-circuited and supplying nodes are connected into the reference node. Loads are usually neglected and short-circuit currents are calculated by means of an equivalent voltage source which is inserted between a faulted node and the reference node. Firstly, a bus admittance matrix **Y** of the network is generated knowing the interconnection structure of the networks elements. Next, a bus impedance matrix **Z** is determined as the inverse $\mathbf{Z} = \mathbf{Y}^{-1}$. If, for example, a short-circuit occurs in the node k then the voltage in a node i can be calculated from the formula:

$$\frac{\underline{U}_i}{\underline{U}} = \frac{\underline{Z}_{ik}}{\underline{Z}_{kk}} \qquad (1)$$

where U is the voltage of an equivalent voltage source, usually equal to the nominal voltage of the short-circuit network, and Z_{ik}, Z_{kk} are elements of the matrix **Z**.

For non-symmetrical faults the method of symmetrical components has been used. The bus impedance matrix is formed for each of the positive-, negative-, and zero-sequence networks. In each of the sequence networks a faulted node is separated. The networks are coupled dependently on the short-circuit type. For the obtained equivalent circuit voltage symmetrical component vectors in nodes of the network are determined for a given fault. Phase-to-neutral or phase-to-phase voltages can be obtained by transforming from sequence domain to phase domain.

2.3. Algorithm

The detailed algorithm of the method is presented on Fig.1. A computer simulator was elaborated by means of the LABVIEW programme. An application of the simulator for stochastic assessment of dips is presented below for the part of real transmission and distribution network, as an example.

3. SIMULATION EXAMPLE

The method will be presented for a part of real transmission and distribution network of 42 nodes, shown in Fig. 2. The network of 110 kV forms a closed loop, which is supplied

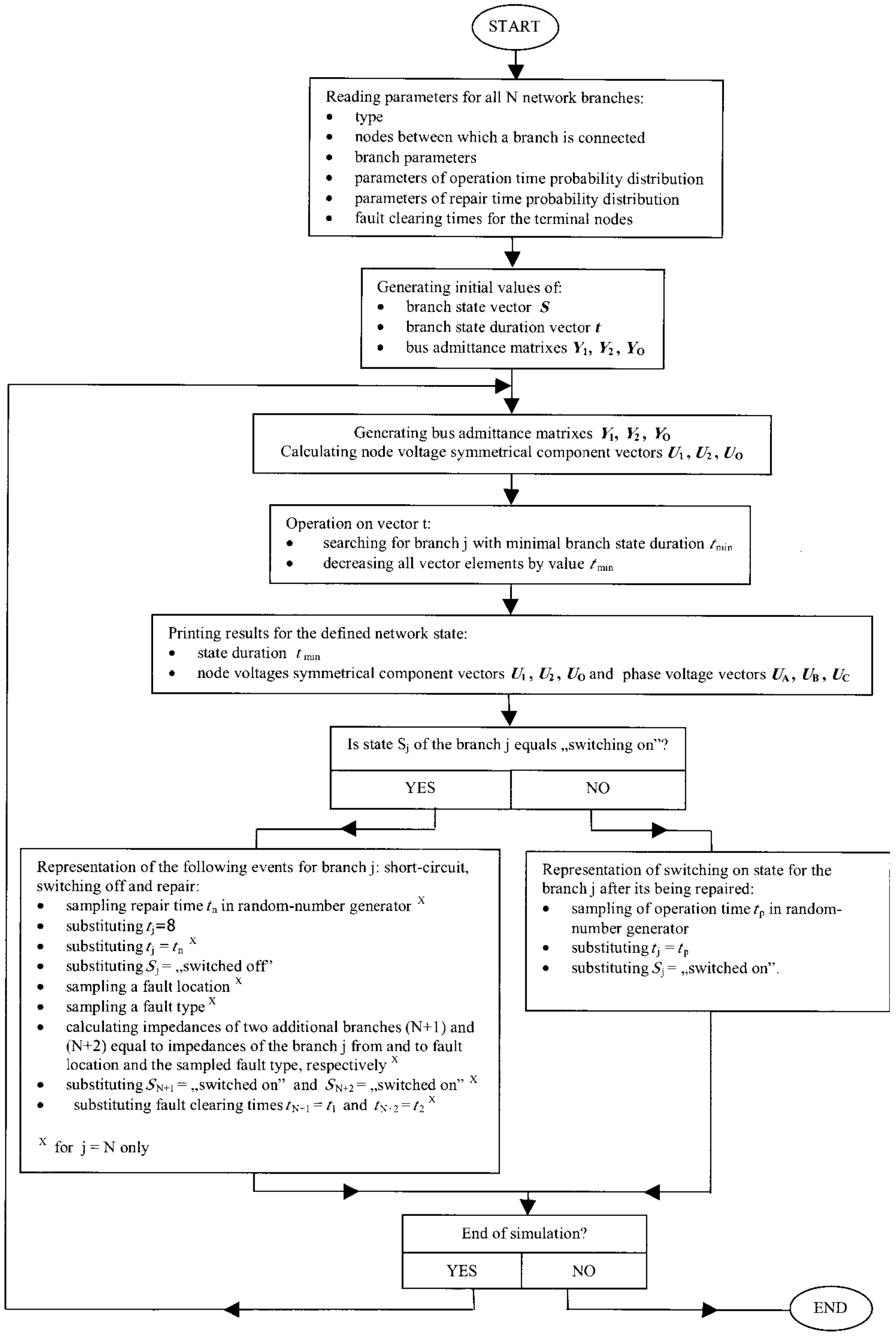


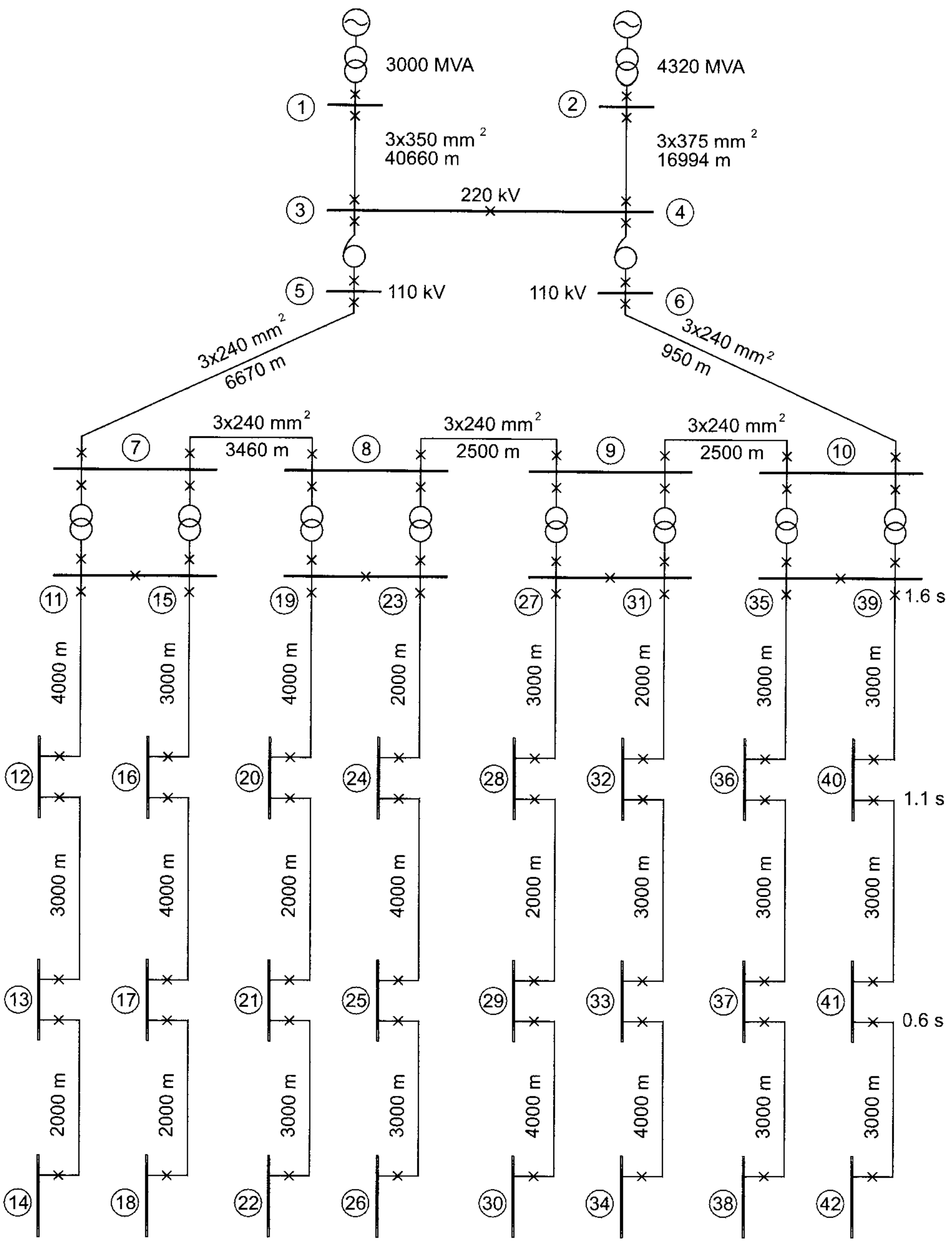
Fig.1. Algorithm of the Probabilistic Method for Evaluation of Voltage Dips in a Given Network

from two 220/110 kV autotransformers. The distribution network of 15 kV works normally as radial.

On the basis of statistical data, it was accepted for each element that the operation time from switching on to a fault, as well as the repair time from clearing the fault to re-switching on are described by the Gaussian distributions. The fault location variable for a line is characterised by a uniform probability distribution. It has been assumed that 5% of all faults are symmetrical ones, 30% are phase-to-phase ones and 65% are phase-to-ground faults. Time of fault clearing for the HV network is constant, equal to 0.2 s, and results from the operation of distance or differential protections. Short-circuits in MV networks are cleared by overcurrent protections with the settings being increased gradually, so in that case fault duration can vary, as shown in Fig. 2 for one feeder.

According to the algorithm described above, a simulation of the network operation was done. After each fault occurrence the following set of values was stored: duration of a dip, voltage positive component, voltage negative component, phase voltages for the phase A, B and C, for every node of the network (see Tab.1).

The simulation was performed for the time that allowed getting stationary results (simulation was stopped after $15*10^6$ events and the last $200*10^3$ events were taken for analysis).



all lines of 15 kV: s = 3x240 mm²

Fig. 2. Diagram of the Network Considered

The number of ways to present results of a stochastic assessment of voltage dips performance is described in [1]. The simplest and the fundamental one is a bar chart giving the number of dips with specified depth and duration. This information can be further used for constructing the cumulative voltage dip bar chart and the voltage dip co-ordination chart, which is recommended in IEEE Standards [1].

The bar chart enables compatibility assessment of single-phase loads. If a tolerance characteristic is given for the load as a function of dip depth and duration and a bar chart is calculated for the node to which the load is connected then one can determine the expected number of dips which interferes with the load operation. The bar charts were presented in the paper [3] and [4].

Such results are not sufficient for assessment of three phase loads in case of asymmetrical faults, where information about three voltages is needed. Describing unbalanced voltage dips by symmetrical components gives such an information. A tolerance characteristic for a three-phase load can be given in the form of:

- — 2D curve being a function of voltage positive component and dip duration or
- — 3D function of voltage positive and negative components and dip duration or
- — 4D function of three phase voltages and dip duration.

If the characteristic is described as a 2D function then stochastic assessment of voltage dips performance can be done by a 3D bar chart as the one presented in Fig. 3. It

Table 1. Exemplary Results of Simulation for the Node 27 of the Network Considered

dip duration	voltage symmetrical components		phase voltages		
	positive	negative	phase A	phase B	phase C
s.	pu	pu	pu	pu	pu
0.2	0.855	0.145	0.799	0.785	1.000
0.6	0.996	0.005	0.017	1.702	1.714
1.6	0.996	0.005	0.002	1.715	1.725
0.2	0.523	0.477	0.864	0.869	0.045
0.2	0.749	0.251	0.895	0.907	0.499
0.6	0.767	0.266	1.000	0.826	0.543
1.6	0.559	0.446	1.000	0.596	0.424
1.6	0.526	0.475	1.000	0.546	0.458
0.2	0.151	0.000	0.151	0.151	0.151
0.2	0.350	0.000	0.350	0.350	0.350
0.6	0.544	0.000	0.544	0.544	0.544
0.6	0.928	0.000	0.928	0.928	0.928
1.1	0.312	0.000	0.312	0.312	0.312
1.1	0.895	0.000	0.895	0.895	0.895
1.6	0.865	0.000	0.865	0.865	0.865
1.6	0.243	0.000	0.243	0.243	0.243

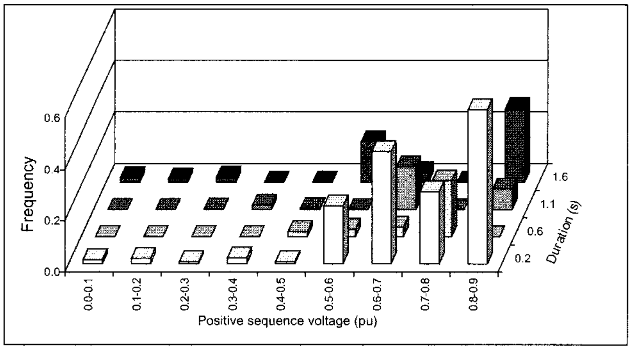


Fig. 3. Bar Charts of the Dip Density Function: Positive Component Voltage Magnitude—Duration

shows the results of simulation obtained for the node 27 of the network under study. Bars on the figure give the expected frequency of dips characterised by the magnitude of voltage positive component and dip duration, so a compatibility assessment of three-phase load is possible.

If the tolerance characteristic is a 3D function then a stochastic assessment of dips requires a 4D bar chart.

If the tolerance characteristic is described by 4D function then stochastic assessment of network dips requires a 5D bar chart.

Having the load tolerance characteristic and the corresponding bar chart for the supplying node one can determine an expected number of dips which can interfere with the load operation.

4. CONCLUDING REMARKS

The presented method and simulation tool enable a stochastic assessment of voltage dips and short interruptions due to symmetrical and asymmetrical faults in the supplying network. Results of simulation presented in the form of bar charts fully characterise the network and are sufficient for compatibility analysis. A dimension of the bar chart (3D, 4D or 5D) depends on the tolerance characteristic given for a load which compatibility is examined.

The simulator may be used by utility or end-user to determine the need for power conditioning equipment.

The simulation method and stochastic assessment seems to be the only effective one in practical application.

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