MEDIUM VOLTAGE NETWORK RELIABILTY EVALUATION: SIMULATION OF PRACTICALLY APPLIED SUPPLY RESTORATION STRATEGIES FOR DOUBLE-FAILURE EVENTS

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ABSTRACT

The first part of the paper deals with the assessment of multiple-fault frequency in networks exposed to progressed component aging. The concept is based on conditional probability for occurrence of a second or third fault location as a consequence of an initial fault. In the second part of the paper algorithms for simulation of efficient post-fault restoration procedures in cable- and overhead-line networks are presented for cases in which fault-clearing personnel has to expect occurrence of more than one fault location per failure-event.

INTRODUCTION

Outage statistics indicate that aging of network components is becoming an increasing problem reducing reliability of supply. Especially in medium-voltage cable networks year-by-year rising numbers of double failures are being observed. A typical event of that kind is initiated by a single-phase-cable fault followed by a single-phase- or a short-circuit-fault in a joint. Reasons for such a chain of events may be voltage raise after single-phase-faults or mechanical strength as an effect of short-circuit-currents.

Evidently, increasing numbers of double or multiple faults occurring per year lead to a not negligible reduction of supply reliability and constitute increasing challenges for fault-clearing personnel. Asset management and network operators are obliged to take appropriate measures against an irreversible degradation of quality of supply. Reliability evaluation software constitutes a valuable tool for planning measures to maintain an acceptable level of network reliability.

Generally, two groups of commercial reliability computation software exist. In the first one sophisticated failure models for different kinds of single and multiple faults are used, whereas post fault restoration is simulated by rather simple approaches. Typically that type of software is adequate for reliability assessment of high-voltage networks consisting of components with individual protection equipment [1]. In the second one fault simulation is restricted to single-order events. Instead, emphasis is set on post-fault restoration by simulating complex strategies like binary stepping of fault-clearing personnel conducted by priority ranking of the fault location steps based on minimization of different object functions such as loss of load probability, consumer energy not supplied or cost of energy not supplied [2]. That type of software is best applicable for medium-voltage networks as long as frequency of higher-order failure events is negligible.

This short overview shows that fault-clearing procedures - implemented in existing algorithms for assessing the influence of higher-order failures on system reliability - do not correspond with fault-clearing processes met in practice. In this paper some approaches to problem solution will be presented. The first part is dedicated to the topic of assessment of multiple-fault frequency in networks exposed to progressed component aging. In the second part algorithms for simulation of efficient supply restoration procedures in mixed overhead-line and cable-networks are presented for cases when fault-clearing personnel has to expect occurrence of more than one fault location per failure-event.

ASSESSMENT OF AGE-DEPENDENT COMPONENT MULTIPLE-FAULT FREQUENCY

The approach is based on modeling short-circuit and single-phase-fault (earth fault) exposition levels caused by past-time failure events for individual network components. It is supposed that the frequency of a secondary failure occurring as a consequence of a primary failure is dependent on the exposition level of the component suffering the secondary failure event.

Theoretically, the concept is based on conditional probability for occurrence of a second or third fault location as a consequence of an initial fault. The classical problem formulation is illustrated by (1) which is valid for the frequency of a dependent outage of two lines with length l_i and l_k, the primary event occurring on line i and the secondary one on line k.

$$f_{2,i,k} = fe.l_i.pe.l_k \qquad (1)$$

fe is the frequency of the primary event, e.g. an earth fault. *pe* is the conditional probability of the second event given a first one has occurred. Frequency *fe* is evaluated by (2). *ne* is the average number of primary events per year observed in the study system. l_Σ represents the average total line length of the study system, valid for the system's observation period.

$$fe = {ne}/{l_\Sigma} \quad 1/\text{yr} \tag{2}$$

Conditional probability is given by (3) where *ned* is the average number of secondary events observed per year in the study system.

$$pe = \frac{ned}{ne.l_\Sigma} \quad 1/\text{yr} \tag{3}$$

In the presented approach the conditional probability concept is extended substituting conditional probability by a "stress-factor" $Sm_{i,k}$ representing the secondary event sensitivity of component k with respect to a primary event occurring at component *i*, see (4).

$$f_{2,i,k}(tp) = ch.Sm_{i,k}(tp).l_i.l_k \tag{4}$$

The stress-factor is dependent on following parameters [3]:

- Age of component *k*, denoted in (4) by *tp*.
- Expectation of short-circuit- and earth fault numbers accumulated during the age of component *k*.
- Position of components i and k within network structure. Components positioned near an injection source usually carry larger short-circuit currents than components in remote positions. In the case of single phase earth faults, level of voltage rises beyond nominal values is dependent on component positions, too. If a fault at component i causes neither short-circuit current flows nor voltage rises in component k, $Sm_{i,k}$ amounts to 0.

Calibration-factor *ch* guarantees that the sum of frequencies of all possible combinations of double-failures delivers the observed number *ned*. The same principle is applicable for failures with orders higher than two.

In the cable failure frequency model, exploitation-time dependent increase of joint numbers is taken into consideration. This concept is outlined in more detail in [4]. Double-outage frequency due to external influences is taken into account by (1).

MEDIUM VOLTAGE NETWORK RELIABILITY EVALUATION

System reliability index

The principle of network reliability evaluation is illustrated by energy not supplied E_U for single and double outages, see (5).

$$E_U = \sum_{i \in nc} f_{1,i} \sum_{n \in nn} (t_{U_{i,n}} L_{U_{i,n}}) + \sum_{i,k \in nc} f_{2,i,k} \sum_{n \in nn} (t_{U_{i,k,n}} L_{U_{i,k,n}}) \tag{5}$$

The first term represents single-, the second one double-failures. *nc* is the number of network components affected by the failure event, *nn* the number of consumer substations affected by the failure event. Symbols $f_{1,i}$, $f_{2,i,k}$ represent single- and double- component outage frequencies; $f_{2,i,k}$ is given by (4). t_U denotes interruption time of the *i*-th consumer affected by the failure event. L_U represents not supplied load of the *i*-th consumer

A similar expression can be derived for cost of energy not supplied [5].

The primary factor influencing consumer interruption time is fault clearing strategy. In this context it has to be stressed that interrupted load L_U is not constant but a function of interruption time - dependent on the special post-fault strategy applied by fault-clearing personnel.

Simulation of post-fault restoration procedures

It follows from (5) that the index representing consumer supply reliability is to a large degree dependent on the efficiency of supply restoration strategy. Thus, algorithms for realistic simulation of corrective activities constitute a central part of medium voltage reliability evaluation software. In principle, the presented algorithms are based on fault location procedures for cases in which fault-clearing personnel has to expect the occurrence of more than one fault location per failure-event. During simulation of the fault-management process for short-circuit events, information provided by fault-locators – if existent - is taken into account. For fault location detection in network parts without fault-locators, switching or measuring actions are simulated.

Some strategies typically practiced in utilities - dependent on exploitation-level of devices - are taken into consideration.

Basic fault-location and supply restoration strategies:

A) Fault-clearing personnel activities are conducted by minimization of energy not supplied according to an algorithm presented in [2].

B) Binary search.

Special supply-restoration strategies (subsets of A and B):

1.) Switching-in of lines for supply restoration is performed during the entire fault-clearing procedure irrespective of the number of switching actions. Risk of connecting faulted line parts and thus of exposing components to additional stress exists.

2.) Supply restoration actions are performed for identified intact parts of the line only. This strategy results in a lower network component stress exposition level than the first one.

3.) Supply restoration actions with uncertain effect are stopped after the first not successful reclosure action. Since this strategy delivers results residing within those of the other strategies, it is not considered in the paper.

Handling of single-phase-faults in compensated networks:
- Line remains in operation, short-time consumer interruptions occur because of switching performed during failure search. Thus, line is permanently exposed to failure effects until fault-location is identified.

+ Line is switched off immediately after fault indication. Short-time switching-in actions are performed for fault locating. Thus, exposure time to failure effects is lower than in the first case (denoted by symbol '-').

* Single-phase-faults are transformed to short-circuit-faults by activating low-impedance-grounding. Subsequently, information provided by fault-locators is used during failure-location procedure.

CASE STUDIES

Network configuration

The study system is a typical compensated medium-voltage network with a mix of overhead-lines and cables, see Fig. 1. The system is composed of 5 lines with a total length of 41 km (32 km cables, rest overhead lines) supplying 100 consumer stations.

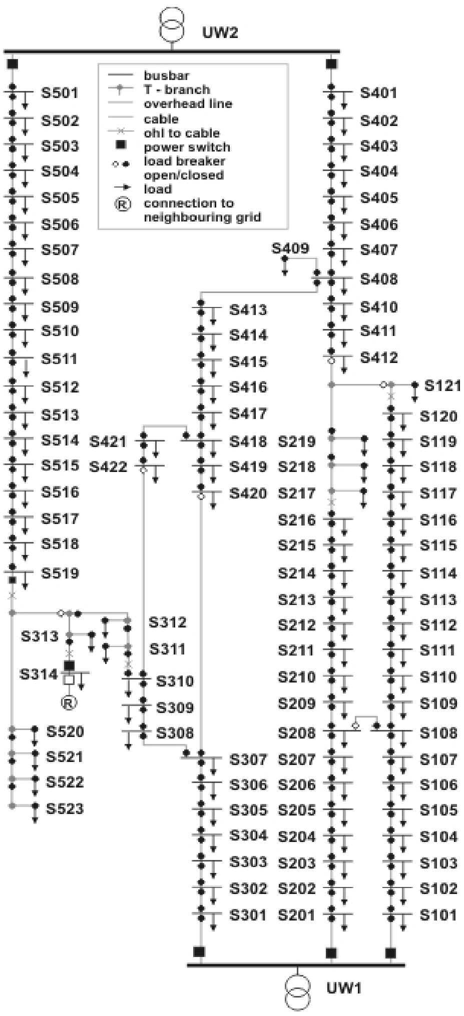

Fig. 1: Network configuration.

Single-outage frequencies amount to 0,069/km.a and 0,021/km.a for overhead-lines and cables respectively. Approximately 52 000 dependent double-outages are simulated. Frequencies of that failure-type were evaluated on the basis of the conditional probability concept described by (4) and cover a wide range from 10^{-9} to 10^{-5} /a. Substation-component faults are taken into account, too.

Results

In Fig. 2 the effects of different strategies are demonstrated for two lines (L1 and L4). Reliability index is loss of load expectation LOLE (quotient of energy not supplied according to (5) and energy consumption per year). Fault simulation is restricted to single and double component outages. Column names indicate strategy types, e.g: A1+ symbolizes "binary search", special restoration strategy type 1.), earth-fault-handling type '+'.

A substantial contribution of double-faults to system non-reliability is indicated by the upper dark column parts in Fig. 2 (LOLE(2)). Of course, the amount of contribution is dependent on the ratio of single- to double-outage frequencies observed in the network.

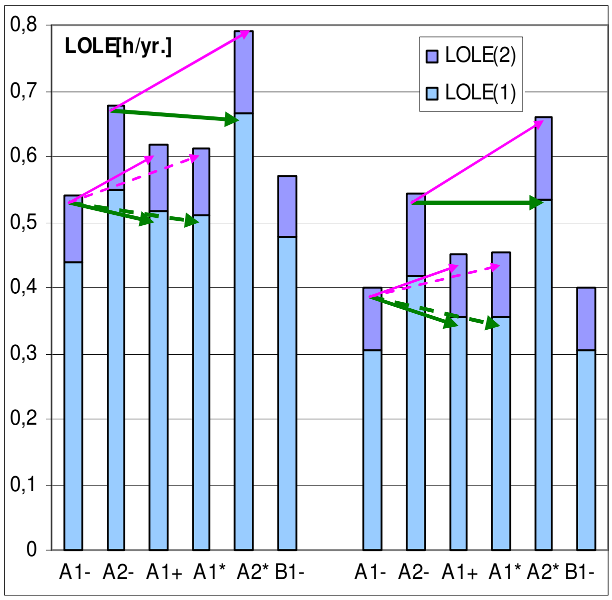

Fig. 2: System-supply-reliability indices for different fault-clearing strategies

A comparison of results presented in Fig. 2 leads to following insights:

Compare A1- with B1- : Proportions of reliability indices are dependent on line structure and load distribution along line. For lines without lateral branches (line L1), the more complex strategy A is preferable to binary search B. For lines with branches (line L4) binary search procedure is conducted by line topology and thus converted to strategy A.

Comparison of strategy A1- with A2- indicates that reduction of stress exposition leads to longer supply interruption times.
Compare A1- with A1+ and A1* : Disconnecting the line immediately after fault occurrence possibly leads to reduction of the probability of double and multiple faults. Provided that this reduction is sufficiently large, improvement of system reliability can be reached, see green arrow. Otherwise an increase of LOLE has to be expected, see red arrow. (Presently, the authors do not dispose of reliable information about possible levels of double-outage frequency reductions reachable by stress minimization). Activating low-impedance-grounding can result in similar effects. Furthermore, information delivered by fault-locators is available for acceleration of fault-location and supply-restoration procedures. Consequently, an additional reduction of LOLE can be observed, compare A1+ with A1*.

CONCLUSIONS

A method for the evaluation of component multiple-outage frequency is presented. Outage frequency is modeled as a function of component age and of failure effects accumulating during component lifetime. This concept is implemented into computer software for evaluating reliability indices of medium voltage networks. Special attention focuses on realistic simulation of supply restoration activities for cases in which fault-clearing personnel has to deal with more than one fault location per failure-event. Different restoration strategies were tested for a typical medium-voltage network consisting of a mix of overhead-lines and cables. Taking solely first-order-failure events into consideration, supply restoration procedures without limitation of not successful switching actions result in the lowest total energy not supplied. However, these strategies impose a large burden on system with the consequence of significant component lifetime reductions. Strategies resulting in lower times of exposure to single-phase-faults seem to be preferable since application can lead to reduction of multiple-fault frequencies and substantial system reliability improvements. In that context low-impedance-grounding activated immediately after occurrence of single-phase-faults seems to be a promising measure.

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