METHODOLOGY OF SUPPLY RELIABILITY ANALYSIS OF MEDIUM VOLTAGE DISTRIBUTION SYSTEMS

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ABSTRACT
Development of MV power grid automation and the possibility of use of local generation sources make it necessary to develop a methodology for reliability analysis of complex functional systems of power medium voltage network structures and dedicate it to assess the reliability of power to local communities. In this paper the reliability analysis methodology for distribution networks is presented.

KEY WORDS
Reliability and security, power system operation, local power generation sub-system, local source of electricity.

1. Introduction
The issue concerning the assessment of reliability of supply in local systems, understood as the structure of medium voltage networks, is an issue that in the face of the anticipated development of medium voltage networks is becoming increasingly important [1]. The growing importance of medium voltage networks is evident due both to its quantitative contribution in the total population of all types of voltage as well, and the transfer of electricity supplied to customers. The growing importance of medium voltage networks, however, is conditioned by the increase in the level of its reliability. The high reliability requirements of grid systems make it necessary to develop new opportunities to shape the structure of medium voltage networks and their evaluation in view of the reliability of power supply. The greatest expectations for improved reliability of electricity supply to customers in the Local Electric Power Subsystem (LEPS), are in improving the reliability of medium voltage networks [2]. Important are the development of grid automation and the use of local generation sources.

2. Methodology for reliability analysis of the subsystem of local electricity supply
Faults at the LEPS can cause the disconnection of power for receiving stations as a result of interruption of electrical connection. In such situation it has been said about the random, unexpected power outages. The occurrence of outages depends on topology of system network and manner and speed of clearing are related to the system configuration as well as equipment, automation and service of distribution network. In the network which is divided into sections working in the one-side supplied system any fault leads to the disconnection of customer nodes. Faults are cleared by maintenance:

- spontaneously by the action of automatic systems to the initial state, e.g. automatic re-closure or automatic reserve closure,
- action of service: exchange of element, emergency repairs on site, manually switching.

Simultaneously in the network the scheduled preventive work are carried out; such as maintenance, inspection and scheduled renovations. From the reliability point of view the most important are the works which are connected with necessity of disconnection of element. This leads to a weakening of the system or to the exclusion of customer nodes so-called "announced disconnections of customers". The sensitivity of consumers to electricity supply disruptions determines the following parameters:

- duration of allowed interruption,
- total duration of interruptions in the time period (usually one year),
- total number of interruptions during analyzed period.

There are different reliability indices at disposal. The mostly used indicators of reliability are:

\[
D = \text{expected number of outages (outage/a)}, \\
Q = \text{factor of inability - relative time of system unfitness}, \\
T_a = \text{expected annual duration of outages (h/a)} \\
t_{av} = \text{average duration of one outage, (h/outage)}, \\
A_{un} = \text{expected annual unserved energy (MWh/a)}. \\
\]

Local Electrical Power Subsystem network nodes are powered from the 110 kV transmission networks and power plants and local sources of electricity. By assessing of the effects of faults in LEPS the following factors must be taken into consideration:

- system configuration,
- dispositional power of local generation subsystem and distribution of power in the nodes of LEPS,
- scheduled maintenance of network components of LEPS,
• impact of action of network automation,
• influence of dispatcher action.

To find a solution of problem the model was proposed, which contains the above mentioned factors and allows obtaining the following indices for cases of complete outages of the power customer stations:
• expected number of outages $D$,
• factor of inability $Q$,
• expected annual unserved energy $A_{ul}$.

2.1 Computational model assumptions

LEPS consists of many devices that are grouped in the model into the following elements: lines, transformers, busbar systems (receiving and power stations) and the generating units.

As a result of faults a new fragmentation may occur in the network with non-connected areas, each may exists in the following situations:
• if in a separate area are only customer stations, then will be disconnected from power supply,
• if a separate area are both customer and supply stations can occur:
  o full coverage of demand of customer station with enough power (or surplus) in the power station,
  o restriction or lack of supply to customers due to power deficit in a separate area.

As power nodes are assumed: node of 110 kV closed network (Main Power Point) or a node which is connected to source local - generation unit connected to the substation MV/LV.

In addition are two aspects:
• problem of continued supply to receiving stations in case of existing faults – it must be determined the supply path after the closure of opened connector,
• the balance of power of areas arising from the splitting due to fault in network.

The solution of both problems requires an algorithm that will search for the states of the network, leading to the situation discussed above. Due to the complexity of the issue and the practical possibilities, the following simplifications are introduced:
• representation of available capacity of source by the average disposable power,
• peak load of receiving stations shall be treated deterministically,
• repair of network equipment are treated in a deterministic manner,
• stability of the system and phenomena accompanying these states are ignored.

The above issues are complementary and end with the determination of unserved energy. The first main task is to determine the supply path with variable point of the cutting network. The algorithm for searching of path of the power supply allows finding the new supply routes after the closure of the opened connector. In the second issue the power balance analysis of the isolated area is made and after determination that there are no power deficit following entry into the matrix of supply routes.

2.2 Mathematical model for calculation of reliability indices

The examined structure of the power network is represented by a network of $S$, clearly defined by a set of nodes, branches and generating units ($X, G$ and $P$ respectively):

$$ S = S (X, G, P) \quad (1) $$

The set of nodes $X$ can be represented as:

$$ X = X_Z \cup X_O \cup X_R \quad (2) $$

where:
- $X_Z$ - set of supply nodes $X_Z = \{X_{Z1}, \ldots, X_{Zn}\}$,
- $X_O$ - set of customer nodes $X_O = \{X_{O1}, \ldots, X_{On}\}$,
- $X_R$ - set of manifold nodes $X_R = \{X_{R1}, \ldots, X_{Rn}\}$.

The set of nodes $G$ can be represented as:

$$ G = G_L \cup G_T \cup G_{LL} \cup G_{LT} \cup G_R \quad (3) $$

where:
- $G_L$ set of linear branches $G_L = \{G_{L1}, \ldots, G_{Ln}\}$,
- $G_T$ set of transformer branches $G_T = \{G_{T1}, \ldots, G_{Tn}\}$,
- $G_{LL}$ set of branches with linear switches $G_{LL} = \{G_{L1}, \ldots, G_{Ln}\}$,
- $G_{LT}$ set of branches with transformer switches $G_{LT} = \{G_{LT1}, \ldots, G_{LTn}\}$,
- $G_R$ set of branches with circuit breaker (reclosers) $G_R = \{G_{R1}, \ldots, G_{Rn}\}$.

Reliability analysis of customer supply from determined network $S$ of LEPS required taking the action in four steps:

Step 1
Analysis of the connection system of LEPS – determination of network structure of analyzed system

Determination of structure of analyzed system requires:
• creating of table of supply path for customer node ($X_O$) – so called matrix of component,

As the supply path for the specified node is determined the set of elements integrated network, connecting node to node power. The number of paths supply to customer node depends on the configuration considered analyzed part of the network.

An array of supply path shall be created during analysis of network structure. It is a list of all the paths feeding the test node, while each of the paths has a set of numbers assigned to all elements comprising the circuit of the path. These numbers are introduced sequentially starting from
the test node and ending by the node of supply. It is assumed that the integrated circuit element is a device or set of devices, which in the case of the failure of any of its constituent units shut down the entire set.

- creating of matrix of supply path for analyzed customer node \( Z \).

**Step 2**

**Determination of indices of non-continuity supply of analyzed customer node**

Determination of indices requires:

- creating of statistic data of components (devices) failures of analyzed network:
  - \( d' \) – failure frequency of \( i^{th} \) device, forming part of the integrated circuit (fault intensity of specified element), number of outages at 100 km or 100 event and year
  - \( t \) - average duration of fault, caused by particular component of system in h/fault

- creating of individual elements, pair of elements, which disconnection cause interruption of supply of analyzed customer node.

On the basis of structure of supply path matrix \( Z \), the network elements are determined which after disconnection causes interruption of supply of analyzed customer node. It was assumed that the probability of simultaneous disconnection of three network components is impossible.

Resultant reliability indices of power for the node are formed from:

- indices of its own node,
- indices related to the exception of individual components integrated network
- indices relating to exemptions pairs of integrated networks.

Relationships for calculating the reliability indices

For each node the following values are calculated:

- expected number of outages \( D \),
- factor of inability \( Q \),
- expected annual unserved energy \( A_{nd} \) (as product of energy taken from node A and w factor \( Q )

\[
A_{nd} = Q \cdot A
\]  

(4)

Average duration of one interruption can be calculated for period \( T_p \):

\[
t_e = \frac{Q}{D} \cdot T_p
\]  

(5)

For analyzed node the failure frequency \( D \), as well as probability of fault \( Q \) are determined from:

\[
D = D_w + \sum_{j \in M} D_j + \sum_{k,l \in N} D_{k,l}
\]  

(6)

\[
Q = Q_w + \sum_{j \in M} Q_j + \sum_{k,l \in N} Q_{k,l}
\]  

(7)

where:

- \( D_w, Q_w \) - respectively, frequency and probability of disconnection of analyzed node in case of own faults taking into account the dependency of disturbances,
- \( D_j, Q_j \) - respectively, frequency and probability of outage of analyzed node as result of disconnection of simply element taking into account the dependency of faults,
- \( D_{j,l}, Q_{j,l} \) - respectively, frequency and probability of outage of analyzed node as result of simultaneous disconnection of pair elements \( k \) and \( l \) taking into account the dependency of faults, but simply disconnection of element \( k \) or \( l \) do not lead to supply interruption,
- \( M \) - set of individual components, which disconnection cause outage,
- \( N \) - set of pair components, which disconnection cause outage.

Frequency and probability of disconnection of analyzed node in case of own and transferred (from cooperating components) faults are determined:

\[
D_w = D_{wi} + \sum_j k_r D_l + \sum_j k_z D_l
\]  

(8)

\[
Q_w = Q_{wi} + \frac{f}{T} \sum_k k_r D_l + \sum_k k_z D_l
\]  

(9)

where:

- \( D_{wi}, Q_{wi} \) - respectively, frequency and probability of own node,
- \( D_j, Q_j \) - respectively, frequency and probability of disconnection of simply element \( i \) taking into account the dependency of faults,
- \( k_r \) - structural factor,
- \( k_z \) - factor including incorrect operation of protective relaying,
- \( f \) - average duration of outage of node because of correlation,
- \( T \) - 8760 h,
- \( J \) - set of cooperated components.

Frequency and probability of own nodes are determined from:

\[
D_{wi} = \frac{1}{100} d_n n
\]  

(10)

\[
Q_{wi} = \frac{D_{wi} t_u}{T}
\]  

(11)
where:

- $d_u$ - fault frequency of $u^{th}$ element,
- $t_u$ - average duration of fault of $u^{th}$ element,
- $n$ - component number.

Frequency of disconnection of simply component $j$ can be determined from analogous relationship as (8-11). Factor for simultaneous disconnection of pair components $k, l$ is calculated as below:

\[
D_{k,l} = D_k D_l \left( \frac{t_k + t_l}{T} \right) \left( 1 - \frac{\nu_k + \nu_l}{T} \right) + D_k \frac{\nu_l}{T} + D_l \frac{\nu_k}{T} + (D_k + D_l) \left( 1 - \frac{\nu_k + \nu_l}{T} \right) k_r
\]

(12)

\[
Q_{k,l} = Q_k Q_l \left( 1 - \frac{\nu_k + \nu_l}{T} \right) + Q_k \frac{\nu_l}{T} + Q_l \frac{\nu_k}{T} + \left( D_k \frac{\nu_l}{T} + D_l \frac{\nu_k}{T} \right) \left( 1 - \frac{\nu_k + \nu_l}{T} \right) k_r
\]

(13)

where:

- $t_k, t_l$ - average time of disconnection of $l$ or $k$ component,
- $\nu_k, \nu_l$ - average time of planned disconnection for maintenance of $l$ or $k$ component.

Taking into account the state of the connector (open), will consider the different path of supply, which will result from the closing state (change of topology).

In this case the new path of supply is determined, wherein determining the probability of disturbance $Q$ will consider time of the switching $t_\nu$.

In such case determined factor results from combination of indices of first and second path of supply.

Factor $Q$ is determined from relations (14):

\[
Q = Q_1 * Q_2 + \frac{D_a t_p}{T}
\]

(14)

But the factors with index 1 or 2 are respectively the probability of disconnection for first or second path of supply for determined node.

For the factor of outage frequency is:

\[
D = D_1
\]

(15)

**Step 3**

**Determination of synthetic discontinuity measure of power supply for the considered system network**

As partial result for each state among other reliability indices is undelivered energy $A_{ud,i}$, which is calculated from relation:

\[
A_{ud,i} = Q_i A_{ri}
\]

(16)

\[
A_{ri} = P_{s,i} T_{s,i}
\]

(17)

**Step 4**

**Analysis of results**

After the calculation the summary of statements is made in an array of indices of outages for all recipients nodes of the system. The criterion for assessing of the value of undelivered energy is introduced as a criterion for the selection of the network system.

The idea of reliability analysis of the of supply customers with a specific network of LEPS is presented in Figure 1 as tasks and interrelationships in the form of the power algorithm for discontinuity.

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**3. Case study**

The proposed algorithm has been tested on the test network and the calculations have been performed for three variants the system operation's. One of the variant is shown in Figure 2.
The sectioning of the main line using the circuit breaker (recloser R₁) and installation of reclosers R₂ and R₃ in the branches of the receiving section III and IV were introduced. From results of calculation is clear that the use of reclosers can reduce the frequency of faults, and the total duration of fault by 37% (compared to the basic system model without reclosers. Note that the number of disconnected customers is limited, and the time location of fault greatly reduced, but the most important is that the value of undelivered energy is reduced by 34% compared to the baseline (without reclosers).

The introduction of local generation of the receiving section IV cause that system allows the automatic location of fault with the help of running reclosers. In addition the sectioning of the main path line and cutting off the damaged section III and IV in the branches with reclosers R₂ and R₃ is available. The local source supplies power to undamaged sections and for such case, a decrease of total time (68%) and the number of interruptions, resulting in a significant reduction of energy not supplied to customers is received. The value of undelivered energy compared to baseline (without reclosers) is 68.5% lower.

4. Conclusion

The article presents the issue of reliability of supply in Local Electrical Subsystems (LEPS). A suitable numbering methodology, which well defines the network topology, is used. Development of the model and a programme for the calculation of basic indicators to assess the reliability of recipients’ supply from a medium voltage grid is realised. Different routines have been developed for sectionalisers considering installation location of the recloser.

The method for improving reliability of power supply customers connected to the LEPS aimed at: reducing down time, reduce the number of recipients of a power failure, prompt location of damage, reconfiguring the network and efficient management of the network in terms of network investment. The presented calculations show that the installation of reclosers used for remote reconfiguration of the network and the ability to work autonomous local sources of electricity can contribute largely to the reduction of total time intervals. In additional it results in reduced energy not supplied to customers.

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