URBAN MEDIUM VOLTAGE DISTRIBUTION NETWORK WITH CROSS CONNECTION

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The article sets out to evaluate the effectiveness of use of a cross connection in urban MV distribution network, from both the engineering and economical point of view. The cross connections consist of a cable interconnected in between two feeders. The cable is connected in 22/0.4 kV distribution stations, mostly in the middle point between these feeders. One end of the cross connection has a switch-isolator installed, while the opposite end is provided with a remote controlled circuit-breaker. The cross connection serves as a backup for the case of MV feeder failure. The criterion used for the evaluation of the engineering and economical effectiveness of the cross connection consists in the identification of changes in the investment and annual costs to be disbursed on analogous variants equipped with a cross connection, as compared with those without the latter.

INTRODUCTION

The reliability of electric energy, supplied by urban distribution medium-voltage (MV) networks, can generally be increased by improving the network operation control using remote controlled devices, installed in the network, from the load dispatching centre, and by signalling the network-generated errors into the load dispatching centre, as well as by the implementation of other measures. For this purpose the following can be used:

a) remote-controlled circuit-breakers and switch-isolator.
   The use of these switching devices provides for a significant decrease of the period of energy interruption in case of failure in the MV feeders. At present, the following modes of signal transmission at a similar price level do exist:
   - wireless transmission network,
   - metallic or optical cable network,
   - signal transmission via the MV cable screening;

b) sensors of short-circuit current passage. These eliminate the necessity to switch off the network in a step-by-step way when searching for the failure. The sensors can be equipped in a way to provide for:
   - local failure indication at the distribution station (DS) which reduces the time necessary for the searching of the failure, thus reducing the time of energy supply interruption,
   - the indication of failure using a short-range wireless transmitter, which gives the serviceman the possibility to check the state of distribution station, e.g. from a running car. This provides for significant reduction of the period for failure finding and, consequently, the reduction of the period of energy supply interruption,
   - remote-controlled failure indication to the load dispatching centre. This will enable the dispatcher to identify the location of the failure in the network. The period necessary to search for such failure is practically equal to zero and, therefore, the period of energy supply interruption becomes reduced to a significant extent;

c) cross connection (CC) established between two MV feeders. In a steady operation state the cross connection is disconnected and serves as a reserve for the case of feeder failure. The article investigates and evaluates the efficiency of usage of the cross connection in an urban MV distribution network, from the point of view of engineering properties and the economy.

MODEL OF THE PRIMARY AND SECONDARY NETWORK

We will investigate a model of primary MV network, the variants of which are configured with four, three and two feeders, which are:

a) consistently transposed, without cross connection, and marked as 4t, 3t and 2t variants,

b) consistently transposed, with cross connection, and marked as 4tc, 3tc and 2tc variants,

c) partially transposed, without cross connection, and marked as 4p, 3p and 2p variants,

d) partially transposed, with cross connection, and marked as 4pc, 3pc and 2pc variants,

e) non-transposed, without cross connection, and marked as 4n, 3n and 2n variants,

f) non-transposed, with cross connection, and marked as 4nc, 3nc and 2nc variants.

The four-feeder variants (4tc, 4pc and 4nc) are equipped with two cross connections, one installed between the first and the second feeder, and between the third and fourth feeder, respectively. The three-feeder variants (3tc, 3pc and 3nc) contain also two cross connections, installed between the first and the second, and between the second and the third feeders, respectively. The two-feeder variants (2tc, 2pc and 2nc) incorporate one cross connection. Consequently, we will investigate nine variants of MV primary network model with cross connection, and nine variants without cross connection. The variants differ in the number and the configuration of feeders, and also the installation/non-installation of cross connection.
Electrical model of a MV primary network with two non-transposed feeders and a cross connection (the 2nc variant) is shown in Fig. 1. The feeders are connected into two switching stations (SS), located each opposite the other, of rated voltage level of $U_n = 22$ kV. The feeders consist of 22-AXEKVCEY 3x (1x240 mm²) cables of the same cross-section, with permitted current of $I_{max1} = 422$ A. Each feeder is equipped with three remote-controlled circuit-breakers, with two of which installed in the switching stations, and the third one inside the distribution station at the middle of the feeder. The feeders are looped via the switch-isolators installed in the distribution stations. Each distribution station is equipped with one distribution transformer (DT) of $S_n = 22/0.4$ kV rated ratio and the rated power of $S_n = 630$ kVA. The transformers are featured by $\beta = 0.65$ load factor and by power factor of $\cos \varphi_n = 0.95$. The cross connection embodies a cable of the same type as used in the feeders. One end of the cross connection is provided with remote-controlled circuit-breaker, the other end with a switch-isolator, and connected in the inside of the distribution stations, located at the middle of each of the feeders. Each variant of the MV network model under scrutiny contains in total forty distribution stations, with the station’s diagram shown in Fig. 2.

The topological model of the layout of the distribution stations in the territory supplied with energy, with regular pattern of streets and configured as two non-transposed feeders without cross connection (the 2n variant) is shown in Fig. 3. Another topological model of distribution stations layout, configured as four consistently transposed feeders without cross connection (the 4t variant) is shown in Fig. 4. In all the variants the topological model is shaping a rectangular of 1 km² surface, and $\sigma = 16$ MVA/km² surface-related load density.

The electrical model of the LV secondary network is identical for all the MV primary network model variants. The LV network uses 1-AYKY type cable of the same cross-section (3x185 + 95 mm²), with permitted current of $I_{max2} = 250$ A. The practical arrangement of the branches of the LV secondary network corresponds with that of the civil constructions. The branches are connected into nodes at the crossover points. The LV network is operated as forty autonomous radial networks (ARN) powered from the corresponding distribution stations, which means that in some of the nodes of opportunity the network is disconnected. The possibility of reconnection of two and more autonomous radial networks at these nodes can be used, for example, in case of failure of the distribution transformer or the MV
feeder, to ensure that energy shall be supplied to the area concerned from the adjacent or the opposite distribution stations, as shown by dashed line in Fig. 1. The reliability of energy supply from the distribution network may be assessed by using the \((n-1)\) criterion. The feeders and the distribution transformers have to be dimensioned in a way to meet this criterion in case of failure. In our case, a failure occurs at one feeder or one distribution transformer, this criterion shall be considered to be met when energy supply will resume within the period of \(t_{\text{max}} \leq 105\) minutes, providing the feeders or distribution transformers for the backup energy supply shall not be loaded or overloaded above specified limits. The energy outage period depends strongly on the time necessary for the identification of the failure, and on the capability to handle the network, i.e. on the possibility and the kind of manipulations carrying through in the network. A reliable MV distribution network is allowed to exhibit only a small number of failures. Yet, in case a failure still happens, the possibility of a quick restoration of energy supply to the consumers has to be ensured. In our considerations we will exclude the reliability of energy supply from higher-level voltage networks and will assume that energy from the HV into the MV distribution network is always ensured. The increase of energy supply reliability, on the one hand, leads to the modernization of the engineering equipment and the network operation control, followed with the increase in investment costs. On the other hand, should this network modernization be carried out with efficiency, reduction of annual (production) costs might be expected, climbing up to some limits of the investment cost increase. This is here where an optimum between the investment and annual costs is situated. Further increase of investment costs is followed also with the increase of annual costs. In such a way two contradictory requirements come up, i.e. the high reliability of energy supply on the one hand, and cheap erection and operation of the distribution network on the other hand. As we have said above, one of the possibilities for the increase of energy supply reliability may by the installation of cross connection. Its use in urban MV distribution network will be considered to be effective if the following inequalities for two analogous variants, i.e. variants with the same number and the same configuration of feeders, differing only in the installation or non-installation of the cross connection, will be met:

\[
K_1 < K_2 \quad \text{(CZK) and} \quad N_1 > N_2 \quad \left( \frac{\text{CZK}}{\text{year}} \right) \tag{1}
\]

where:
- \(K_1\) are investment costs on a MV network without cross connection,
- \(K_2\) are investment costs on a MV network with cross connection,
- \(N_1\) are annual costs on a MV network without cross connection,
- \(N_2\) are annual costs on a MV network with cross connection.

### FACTORS OF THE MV PRIMARY NETWORK MODEL

The probable rate of failures in a MV network is expressed by the formula:

\[
f_j = f_{ij} + f_{vj} + f_{aj} \quad j = 1,2,\ldots, n \quad \left( \frac{1}{\text{year}} \right) \tag{2}
\]

where:
- \(j\) is the number of variant of the MV network model,
- \(n\) is the number of variants,
- \(f_{ij}\) is the failure rate of feeders,
- \(f_{vj}\) is the failure rate of circuit-breakers and switch-isolators,
- \(f_{aj}\) is the failure rate of protection relays.

Failure of any operating element at a MV network results in the breakdown of such an element, causing also the interruption of energy supply in one or more autonomous LV networks arranged and operated as radial networks. Therefore, the failure rate to (2) may also be considered as the probable failure rate of energy outage during one year. Adequately, the same assumptions can apply also for the \(f_{ij}, f_{vj}\) and \(f_{aj}\) failure rates.

The probability of a failure in the MV network is expressed by the formula:

\[
q_j = f_j \cdot \frac{t_v}{8760} \quad \left( -\frac{1}{\text{year}} \right) \tag{3}
\]

where \(t_v\) is the average time period of a failure for which the applies that: \(t_v \leq t_{\text{max}}\).

According to the formula (3) the \(q_j\) probability can also be conceived as the probable relative energy supply outage period during one year, i.e. the probable relative energy supply interruption during one year. The energy supply reliability can also be expressed as \((q_j \cdot 8760)\) hours/year, being the probable outage period per year.

The probable non-supplied energy caused by failures in the MV network is expressed by the formula:

\[
W_j = P_{\text{maxj}} \cdot f_j \cdot t_v \cdot B \quad \left( \frac{\text{kWh}}{\text{year}} ; \frac{\text{kW}}{\text{year}} ; \frac{1}{\text{hour}} \right) \tag{4}
\]

where:
- \(P_{\text{maxj}}\) is the highest load of the feeder,
- \(B\) is the medium filling factor of annual load diagram of the area supplied with electric energy by the corresponding MV distribution network.

Further it holds that:

\[
P_{\text{maxj}} = x_j \cdot \beta \cdot S_n \cdot \cos \varphi_n \quad \left( \frac{\text{kW}}{\text{year}} ; \frac{\text{kVA}}{\text{year}} \right) \tag{5}
\]

where:
\( x_j \) is the number of distribution transformers fed from the feeder in question, 
\( \beta \) is the distribution transformer load factor, for which it applies that: 
\( \beta = \frac{S}{S_n} \), 
\( S_n \) is the rated power of distribution transformer, 
\( \cos \varphi_n \) is the rated power factor, and 
\[
B = \frac{T_u}{8760} \left( \text{hour/year} \right)
\]
(6)

where \( T_u \) is the period of maximum load exploitation in the 22 kV network.

In the course of the evaluation of economic factors we shall neglect the costs to be expended on the distribution transformers and on the LV network, similarly to the calculation of engineering factors where the failure rate of the same has been neglected, too. We may do this because the examination occurs to the model of MV network only, and both the components represent the engineering and economical constants which are identical for all the variants of the model of MV network. These constants shall not affect the process of comparison of the analogous variants, i.e. those which differ one from another in the installation or non-installation of the cross connection.

The annual costs to be spent on the \( j \) variant of the MV network model are:
\[
N_j = N_y + N_{\Delta j} + N_{Ej} \quad j = 1,2,...,n \left( \frac{\text{CZK}}{\text{year}} \right)
\]
(7)

where:
\( N_y \) is the permanent component of annual costs, deduced from investment costs,
\( N_{\Delta j} \) is the variable component of annual costs, deduced from losses,
\( N_{Ej} \) is the component of annual costs to be expended on non-supplied electrical energy.

It holds that:
\[
N_{ij} = N_{ikj} + N_{ij} + N_{ij} + N_{ijij} \left( \frac{\text{CZK}}{\text{year}} \right)
\]
(8)

where:
\( N_{ij} \) are annual costs on feeders, deduced from the investment costs,
\( N_{ij} \) are annual costs on circuit-breakers and switch-isolators, 
deduced from investment costs,
\( N_{ij} \) are annual costs to be expended for the remedy of feeder failures,
\( N_{ij} \) are annual costs to be expended on the repair of circuit-breakers and switch-isolators,
\( N_{ij} \) are annual maintenance costs expended on the network.

Further it holds that:
\[
N_{\Delta j} = \Delta P_{\max j} \cdot \left( c_p + c_w \cdot T_d \right)
\]
\[
\left( \frac{\text{CZK}}{\text{kW\cdotyear}} \right) \cdot \left( \frac{\text{CZK}}{\text{kWh\cdotyear}} \right) \cdot \left( \frac{\text{CZK}}{\text{kWh}} \right)
\]
(9)

where:
\( \Delta P_{\max j} \) are the power losses in the MV network, at the highest load of the feeders (\( P_{\max j} \)),
\( c_p \) are annual costs to come up for 1 kW of power loss,
\( c_w \) are costs to come up for 1 kWh loss of electrical energy,
\( T_d \) is the period of full losses in the 22 kV network.

Annual costs of non-supplied electric energy are:
\[
N_{Ej} = W_j \cdot c_E \left( \frac{\text{CZK}}{\text{kWh\cdotyear}} \right)
\]
(10)

where \( c_E \) are costs to be spent on 1 kWh of not-supplied electric energy from the 22 kV network.

Consequently, the investment costs to be spent on the \( j \) variant of the MV network model are:
\[
K_j = K_{ikj} + K_{ijij} \quad (\text{CZK})
\]
(11)

where:
\( K_{ikj} \) are investment costs on MV cable,
\( K_{ijij} \) are investment costs on circuit-breakers and switch-isolators.

The basic engineering and economical factors to apply for the primary MV network were calculated using input data received from the JME a.s. Brno, distributor of electrical energy (South Moravian Electricity, Plc.). The calculated values are shown in Table 1. The detailed calculation is described in [1].

### ANALYSIS OF THE RESULTS

The analysis of the results identified and shown in Table 1, provides for the following conclusions to be made for MV distribution network, both with and without a cross connection:
- the amount of non-supplied electric energy \( W_j \) increases with the decreasing number of feeders,
- the \( q_j \) probability of failures arising in the network increases with the increasing number of feeders.

<table>
<thead>
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<th>Variant</th>
<th>( l_j )</th>
<th>( f_j )</th>
<th>( 10^4 q_j )</th>
<th>( W_j )</th>
<th>( 10^{-3} N_{ij} )</th>
<th>( 10^{-3} N_{ij} )</th>
<th>( 10^{-3} N_{ij} )</th>
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</table>

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the $K_{ij}$ investment costs increase with the increasing number of feeders,
- the $N_j$ annual costs increase with the increasing number of feeders,
- the values of $W_j$, $q_j$, $K_{ij}$ and $N_j$ quantities, for the same number of feeders, become increasing the higher is the degree of feeder transposition, and achieve the highest values in a network with consistently transposed feeders,
- secondary LV networks operated as a series of autonomous radial networks give no engineering substance to the idea of transposition. Feeder transposition is of significance only when the LV secondary network is operated as a grid network, which allows for higher load capability of the MV network. Cross connection may also secure the supply of backed-up energy to an area affected by blackout, in parallel to the already existing current passage through a closed circuit-breaker installed in the middle of the feeder. The cross connection represents another way of option to use of circuit-breaker installed in the middle of the feeder. Use of cross connection in urban distribution networks does not seem to be effective, both from the engineering and the economical point of view. For analogous variants with cross connection in urban distribution MV networks does not seem to be effective, both from the engineering and the economical point of view. For analogous variants with cross connection the cross connection both the annual and the investment costs are higher in the average by 4.1 per cent and 3.9 to 4.9 per cent, respectively. With three feeders this makes 4.4 to 5.3 per cent and 3.9 to 4.9 per cent, and with two feeders 2.7 to 3.2 per cent and 3.1 to 3.8 per cent, respectively. The lower is the degree of transposition of the feeders, the higher are the costs.

Based on the analysis of the results identified we can say that the use of cross connection in urban distribution MV networks does not seem to be effective, both from the engineering and the economical point of view. For analogous variants with cross connection both the annual and the investment costs are higher in the average by 4.1 per cent and 3.9 to 4.9 per cent, respectively. With three feeders this makes 4.4 to 5.3 per cent and 3.9 to 4.9 per cent, and with two feeders 2.7 to 3.2 per cent and 3.1 to 3.8 per cent, respectively. The lower is the degree of transposition of the feeders, the higher are the costs.

### Table

<table>
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<th>j</th>
<th>mark</th>
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### CONCLUSION

The installation of a cross connection causes an increase in annual and investment costs for the analogous variants with four feeders by 4.1 to 4.9 per cent, and 3.5 to 4.3 per cent, respectively. With three feeders this makes 4.4 to 5.3 per cent and 3.9 to 4.9 per cent, and with two feeders 2.7 to 3.2 per cent and 3.1 to 3.8 per cent, respectively. The lower is the degree of transposition of the feeders, the higher are the costs. The (1) inequalities were not met and, therefore, the use of cross connection in an urban distribution network was identified to be not effective.
serve as a means to interconnect the halves of two different feeders into a loop, i.e. the establishing of a ringed network. The feeders, however, are operated mostly as radial beams, which means that this option will not materialize. In case of doubled failure, one at each half of the same feeder, the cross connection will provide for the supply of backup energy to the area affected and thus eliminate the otherwise large number of manipulations at the LV network level. The idea of double failure to arise, however, is only of small probability. Despite of the above, the use of cross connection can be well founded from the view of engineering and economy in those urban MV distribution networks, through which clients are supplied with energy who, based on contractual agreements, have made an agreement on the payment of high compensation fines for not supplied electric energy with the power distributor.

The JME a.s. Brno, distributor of electrical energy, operates two cross connections in the downtown part of the city of Brno. These cross connections are the result of step-by-step erection of the urban MV distribution network. After having established one half of the network the construction works were interrupted and the necessity arouse to interconnect the two different feeders. This was done using a cable with corresponding equipment in the distribution stations, and connected to the end of both halves of the feeders. In the course of the next erections stage the network was finalized, but the cable with equipments remained installed in the network and used currently as the cross connection.

LITERATURE