NUMBER OF DISTRIBUTION FEEDERS OF PRIMARY MEDIUM VOLTAGE NETWORK UTILIZED IN THE RADIAL OPERATION OF SECONDARY LOW VOLTAGE GRID NETWORK

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The number of MV(medium voltage) distribution feeders and their transposition especially in town centres corresponded in the past to the intended operation of grid LV (low voltage) networks. Nevertheless, LV networks were not often operated as grid networks. This article shows that the design of MV distribution feeders ignoring the actual operation practice in the LV network is economically unjustifiable and that the demand for reliable power supply in most cases does not justify higher number of MV feeders when LV network is operated as a radial network.

1. INTRODUCTION

The first grid network (GN) in the Czech Republic started to be operated in 1951, in the historical part of the city of Brno. That time the network was operated by the company RBR, n.p.Brno (Distribution Energy Works, national enterprise), one of the predecessors of the current operator, the company JME a.s. Brno (South Moravian Electricity, Plc.). This GN was originally established by an appropriate interconnection of the radial network (RN), at an area of 1 km^2, with a specific load of $\sigma = 3$ MVA/km^2, which rose to the currentt 8.5 MVA/km^2. During the time the GNs were established not only in the downtown part of the large cities but also in the suburban areas, usually with three to five feeders, consistently transposed within the network being fed. One of the concerns of the operation of GNs became the decomposition of such a network due to the low number of feeders which, along with the intensity of use of the same and the subsequent distribution transformers (DTs), should allegedly never be less than four.

The opinion in the past was that the establishing of GNs in cities is a correct approach, despite some problems that never succeeded to be resolved, insisting that GNs are more appropriate than the RNs from the technical and economical point of view. Specialists stressed the high quality or power supplied and the high reliability of GNs. The reliability level was always linked with the increased margin requirements and, consequently, with higher investments. The operating personnel was given the order to check, once in a week, the switching state of LV circuit-breakers in the distribution stations (DS), and once in a month to inspect the fuses mounted at the nodes of the LV network. The demands imposed on the GN operation were very high and the inspections sometimes were not appropriate. This resulted in a subsequent disconnection of DTs and, consequently, to the overload of the remaining DTs, and to the disconnection of GNs at the node points. Would this process not be stopped by the operators in time, the result must have ended in a complete decomposition of the GN.

At the suburbs, since its very beginning, the GN was never operated as such and, if really operated as a grid network, this kind of operation brought serious problems to the operator, who did not succeed to operate it over a longer time. Similar problems arouse with the GN operation in downtown parts of the cities. This was one of the reasons why, in the end, the GN was disconnected in some of the nodes, and operated as an autonomous radial network (ARN) and fed from the respective DS. The number of distribution feeders of the primary MV network and their consistent transposition, however, was designed as though the LV secondary network should be operated as a grid network.

This article shows the lack of economy in such an approach for a MV network design when the LV network is actually operated as a radial network and tries to find an appropriate number and arrangement, the economical configuration of MV feeders for that kind of operation of LV network.

2. MODELS OF PRIMARY AND SECONDARY NETWORK, AND THE (n-1) CRITERION

Now we shall investigate a model of primary MV network which is provided, as an option, with four, three or two consistently transposed feeders, with the variants marked as 4t, 3t and 2t, or non-transposed feeders with the respective 4n, 3n or 2n variants. The index $_L$ or $_M$, suffixed to the respective MV network model, represents the particular LV network model option. In principle we have 6 options of how to configure the feeders in a MV network for each variant of the LV network model. The feeders are installed in two switching stations (SS), located one

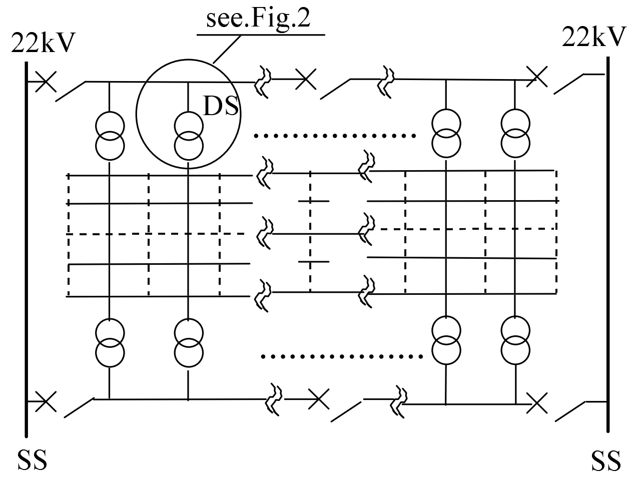

Fig. 1 Model of 22 kV primary network with two non-transposed feeders, with radial operation of the secondary 0.4 kV grid network

opposite the other, with a rated voltage level of Un = 22 kV, and connected through the 22-AXEKVCEY 3x (1x240 mm^2) type cables, with the highest permitted current of $I_{max\ 1}$ = 484 A. Each feeder is provided with three circuit breakers. In a steady operation state the circuit breaker installed in the middle is disconnected (OFF) and one half of the feeder represents a back-up for the other half. The circuit breakers are remote controlled from a dispatcher control room. The feeders operate in a loop with load-disconnectors installed at the DS. The load-disconnectors are not remote controlled. A model of 22 kV network, installed in a 0.4 kV grid network and operating in "radial-like" kind of operation with two non-transposed feeders, is shown in Fig.1.

The model of LV network, as an option, consists of two GNs marked as L or M, located at an area of 1 km^2, with a specific load of σ_L = 32 MVA/km^2 and σ_M = 16 MVA/km^2. The LV networks are based on 1 - AYKY cables, with the same cross-section and type 1x (3 x 185 + 95 mm^2), and of maximum permitted current of I_{max2} = 250 A. The networks are operated as a series of ARNs, fed from the respective DS. It is assumed that each of the DS's is equipped with one DT, having the rated transformer ratio of p_n = 22/0.4 kV, the rated power of S_n = 630kVA, and a load factor of 65 % with power factor cos φ = 0.95. The DS wiring diagram is shown in Fig. 2. The L or M option of LV network model is then provided with 80 or 40 distribution stations, respectively. Location of the distribution stations is shown in Fig. 3, at an example of rectangular arranged city streets.

The reliability of power supply taken out from a distribution network can be assessed by using the (n-1) criterion. This criterion for a radial operated LV network is considered to be fulfilled when in case of a defect of one single element of the network the power consumer is prevented to receive the electric power during the t_v period. The t_v time period is named as "average blackout period" and depends mainly on the capability to handle the network

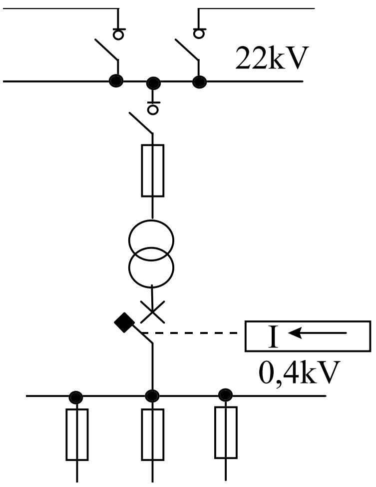

Fig. 2 Wiring diagram of a distribution station 22/ 0,4kV

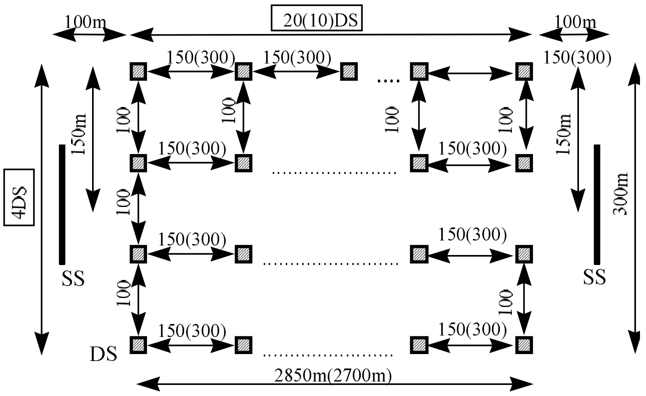

Fig. 3 Layout model of 22/0.4 kV distribution stations at an area supplied by power, when using the L (M) option of the secondary network with specific load density of 32 (16) MVA/km^2

abnormal states. The average blackout period in our urban distribution networks is in the order of tens of minutes. In fact, the power consumers connected to the LV network are affected by other subsequent failures at other voltage levels, along the whole feeding chain. In this study we shall assume that outage time periods, caused by failures at those voltage levels, are independent of the configuration of MV feeders and, therefore, we will consider them to be constant, without any effect on the result of the task solved. This is why we neglect them.

A reliable power supply system should be affected with only a small number of failures and should be capable of resuming the operation after a short time period. The requirements on such a system are of controversial nature:
on one side it is the reliability level of power supply, on the other side it is the requirement of reduced costs for the system erection and its operation. The issue is then concerned with the technical and economical assessment of the power supply reliability.

3. BASIC TECHNICAL AND ECONOMICAL FACTORS OF MEDIUM VOLTAGE PRIMARY NETWORK

The total failure rate of all the respective elements of MV network is expressed by the formula:

$$f_j = f_{kj} + f_{vj} + f_{oj} \quad (j=1,2,...,n) \quad (1/\text{year};\ 1/\text{year}) \qquad (1)$$

where:

j is the variant number of the model of MV network

n is the number of variants (options) for σ = constant

f_{kj} is the failure rate of feeders

f_{vj} is the failure rate of circuit breakers and load-disconnectors

f_{oj} is the failure rate of protections (protection relays)

It holds that:

$$f_{kj} = l_j * \alpha_k \qquad (1/\text{year};\ \text{km},\ 1/\text{km*year}) \qquad (2)$$

where:

l_j is the total length of feeders

α_k is the failure rate of 1 kilometer of feeder per year

$$f_{vj} = v_j * \alpha_v \qquad (1/\text{year};\ -\ ,\ 1/\text{year}) \qquad (3)$$

v_j is the total number of circuit breakers and load-disconnectors

α_v is the failure rate of a circuit breaker or load-disconnector per year

$$f_{oj} = o_j * \alpha_o \qquad (1/\text{year};\ -\ ,1/\text{year}) \qquad (4)$$

where:

o_j is the total number of protections

α_o is the failure rate of a protection relay per year

Failure of any operating element of a medium voltage network results in a blackout of the power supply within the radial operated LV network. Therefore the f_j failure rate according the formula (1) can also be considered as a total probable failure rate of power supply. In the same way the f_{kj}, f_{vj} and f_{oj} failure rates can be understood.

The total failure probability of all the considered elements of a MV network is expressed by the formula:

$$q_j = f_j * t_v / 8760 \quad (\ -\ ;\ 1/\text{year, hour, hour/year}) \qquad (5)$$

where:

t_v is the average time period of a failure

According to the formula (5) the q_j probability can also be conceived as the total probable relative outage period of power supply per year, i.e. the total probable outage per year. The same scale of power supply reliability can be expressed as to be equal to q_j* 8760 hour/year which is the probable average outage time per year.

The total probable average non-supplied power due to the failure of all considered elements installed in the MV network is expressed by the formula:

$$W_j = P_{maxj} * f_j * t_v * B \ (\ \text{kWh/year; kW,1/year, hour,-}\ ) \quad (6)$$

where:

$P_{max\ j}$ is the feeder highest load

B is the medium fill factor of a load diagram of an area to be supplied with power by the respective network

Further it holds that:

$$P_{maxj} = x_j * 0{,}65 * Sn * \cos\varphi \qquad (\ \text{kW};\ -\ ,\ \text{kVA},\ -\ ) \qquad (7)$$

where:

x_j is the number of distribution transformers fed from the feeder

S_n is the DT rated power

$\cos\varphi$ is an average power factor of the load, and

$$B = T_u / 8760 \qquad (\ -\ ;\ \text{hour/year, hour/year}) \qquad (8)$$

where:

T_u is the maximum exploitation time

In the evaluation of economic factors we shall neglect the costs to be expended for 22/0.4 kV transformation and costs for the erection of 0.4 kV network, because both these constant factors do not have any influence on the chosen economical option of feeder configuration. Yearly (production) costs for the “j” option of the MV network model are:

$$N_j = N_{ij} + N_{Dj} + N_{Ej} \quad (j = 1,2,..,n) \quad (\ \text{CZK/year; CZK/year}\ ) \qquad (9)$$

where:

N_{ij} is the permanent component of yearly costs

N_{Dj} is the variable component of yearly costs

N_{Ej} is the component of production costs for not supplied power

It applies:

$$N_{ij} = N_{ikj} + N_{isj} + N_{kj} + N_{sj} + N_{uj} \quad (\ \text{CZK/year; CZK/year}\ ) \qquad (10)$$

where:

N_{ikj} are the yearly costs deduced from the feeder investment costs

N_{isj} are the yearly costs deduced from the circuit breaker and load-disconnector investment costs

N_{kj} are the yearly costs to be expended for the remedy of feeder failures

N_{sj} are the yearly costs to be expended for the repair of circuit breaker and load-disconnector failures

N_{uj} are the yearly maintenance costs expended on the network

Further it applies that:

$$N_{ikj} = K_{ikj} * p_k / 100 \quad \text{(CZK/year; CZK, \%/ year, \%)} \qquad (11)$$

where:

K_{ikj} are the feeder investment costs

p_k is the feeder depreciation rate in per cent

$$N_{isj} = K_{isj} * p_s / 100 \quad \text{(CZK/year; CZK, \%/ year, \%)} \qquad (12)$$

where:

K_{isj} are the investment costs for the purchase of circuit breaker and load-disconnector

p_s is the circuit breaker and load-disconnector depreciation rate in per cent

$$N_{kj} = f_{kj} * c_k \quad \text{(CZK/year; 1/year, CZK)} \qquad (13)$$

where:

c_k are the average costs expended on a repair of feeder failure

$$N_{sj} = (f_{vj} * c_v + f_{oj} * c_o) \quad \text{(CZK/year; 1/year, CZK, 1/year, CZK)} \qquad (14)$$

where:

c_v are the average costs expended on a repair of circuit breaker and load-disconnector failure

c_o are the average costs expended on a repair of protection relay failure

$$N_{uj} = v_j * t_u * c_u \quad \text{(CZK/year;- , hour/year, CZK/hour)} \qquad (15)$$

where:

t_u is the maintenance average time period spent for the circuit breaker or load-disconnector per year

c_u are the average costs for one hour of maintenance works

Further it holds that:

$$N_{Dj} = \Delta P_{maxj} (c_p + c_w * T_d) \qquad (16)$$
$$\text{(CZK/year;kW,CZK /kW*year, CZK/kWh*year, hour)}$$

where:

ΔP_{maxj} are the power losses during the maximum load

c_p are specific costs to eliminate the power losses

c_w are specific costs to eliminate energy losses

T_d is a period of full losses

$$N_{Ej} = W_j * c_E \quad \text{(CZK/year; kWh/year, CZK/kWh)} \qquad (17)$$

where:

c_E are the specific costs to cover not supplied energy

Total investment costs of the MV network model are:

$$K_{ij} = K_{ikj} + K_{isj} \quad \text{(CZK; CZK)} \qquad (18)$$

The basic technical and economical factors have been calculated from the entry data, received from the JME a.s. Brno. The respective values are shown in Table 1 and 2. A detailed calculation is shown in [1].

Table No. 1: Engineering and economical factors of various options used for a model of 22 kV primary network when providing power supply to an “L” model of 0.4 kV secondary network, with a specific load density of σ_L= 32 MVA/km^{2}.

Variant		l_j	f_j	$10^4 q_j$	W_j	$10^{-6} N_j$	$10^{-6} K_{ij}$	$\frac{q_{kj}}{q_j}$	$\frac{N_{ikj}}{N_j}$	$\frac{K_{ikj}}{K_{ij}}$	$\frac{N_{Dj}}{N_j}$	$\frac{N_{Ej}}{N_j}$
j	mark.	km	$\frac{1}{year}$	-	$\frac{kWh}{year}$	$\frac{CZK}{year}$	CZK	-	-	-	-	-
1	$4t_L$	24,2	1,56	3,10	3027	3,83	76,75	0,78	0,39	0,60	0,022	0,080
2	$3t_L$	21,8	1,43	2,86	3699	3,71	70,91	0,76	0,36	0,58	0,037	0,100
3	$2t_L$	18,1	1,24	2,48	4812	3,62	62,64	0,73	0,31	0,54	0,067	0,133
4	$4n_L$	13,4	1,02	2,03	1975	3,01	56,56	0,66	0,28	0,44	0,018	0,065
5	$3n_L$	12,1	0,95	1,89	2447	2,95	52,77	0,64	0,25	0,43	0,036	0,083
6	$2n_L$	10,7	0,87	1,74	3372	2,92	48,80	0,62	0,23	0,41	0,055	0,115

Table No. 2: Engineering and economical factors of various options used for a model of 22 kV primary network when providing power supply to an “M” model of 0.4 kV secondary network, with a specific load density of σ_M= 16 MVA/km^2.

Variant		l_j	f_j	$10^4 q_j$	W_j	$10^{-6} N_j$	$10^{-6} K_{ij}$	$\frac{q_{kj}}{q_j}$	$\frac{N_{ikj}}{N_j}$	$\frac{K_{ikj}}{K_{ij}}$	$\frac{N_{Dj}}{N_j}$	$\frac{N_{Ej}}{N_j}$
j	mark.	km	$\frac{1}{year}$	-	$\frac{kWh}{year}$	$\frac{CZK}{year}$	CZK	-	-	-	-	-
1	$4t_M$	18,0	1,08	2,16	1045	2,28	52,12	0,83	0,49	0,65	0,007	0,046
2	$3t_M$	15,2	0,94	1,87	1209	2,14	45,53	0,81	0,44	0,62	0,012	0,057
3	$2t_M$	13,0	0,82	1,64	1591	2,00	40,06	0,79	0,36	0,61	0,030	0,080
4	$4n_M$	12,8	0,82	1,64	796	2,02	42,40	0,78	0,39	0,57	0,006	0,039
5	$3n_M$	10,6	0,71	1,41	912	1,82	36,93	0,75	0,36	0,54	0,012	0,050
6	$2n_M$	8,4	0,59	1,18	1145	1,63	31,46	0,71	0,32	0,50	0,019	0,070

The calculation method, i.e. the determination of feeder configuration in a medium voltage network, from the economy point of view, is aimed at finding that option of distribution system for which the yearly costs would be minimal. For the economical option holds the following:

$$N_{ECON} = \underset{j}{MIN}\, \{N_j\} \qquad (j = 1,2,...\ ,n) \qquad (19)$$

The equation (19) is complied with the options $2n_L$ and $2n_M$. This means that an economical configuration consists of two non-transposed MV feeders to supply both options of the low voltage network model.

4. ANALYSIS OF THE RESULTS

The analysis of the factors of MV network model, as shown in Table 1 and 2, along with the consideration of all the knowledge acquired from the design and operation of urban distribution networks brings us to the following conclusions:

The probability q_{kj} of a feeder failure has a decisive share on the q_j total probability of a failure for all the options examined. The lowest value of this share is 62 % (71 %) for the $2n_L$ ($2n_M$) options and achieves its highest value of 78 % (83 %) for the 4 t_L ($4t_M$) option. The share of a q_{oj} probability of protection relay failurs makes less than 1.1 % for all the options considered and the remainder falls upon the q_{vj} failure probability of circuit breakers and load-disconnectors.

The probable average time period of power supply interruption per year, caused by failures that appear in the MV network, makes approximately 1.5 hours (1.0 hour) or 2.7 h (1.9 h) for the $2n_L$ ($2n_M$) option, respectively $4t_L(4t_m)$. In reality, however, this period is longer than the above.

In the options examined the amount of electric energy W_j, not supplied by the MV network, increases with a decreasing number of the feeders, or with transposition of the same. The W_j value may be decreased by decreasing the feeder load, by decreasing the f_j failure rate and by shortening the t_v power interruption (outage) period. Efforts experienced generally and consisting in the balancing of load diagram by suppressing its significant maxima leads to the increase usage of T_u maximum exploitation time and, consequently, to the increase of W_j value.

The load of feeders can be decreased by reducing the number of DS powered by those feeders, i.e. increasing the number of feeders. This causes an increase of the f_j value. In respect of the relationship between the t_v parameter and the number of DSs, we have fixed this number to be 20. This number has been verified in practical live and satisfies approximately the equation for t_v = 105 minutes.

A contribution to the reduction of f_j value and, consequently, the increase of power supply reliability can be brought about by the manufacturers of the respective elements of network, by increasing the quality of such elements. The network operator supports these goals with an appropriate selection of high-quality elements on the market and by consistent maintenance of the same. The operator, however, can not prevent the occurrence of specific failures within the network.

Other possibility of reduction of the W_j value consists in the reduction of t_v. This can be achieved mainly by the improvement of handling capabilities of the network which is to be considered to be the current tendency in the Czech distribution networks. This means, in particular, a higher level of remote control to be achieved and the implementation of automatic control systems to the operation of distribution networks.

This occurs mainly by remote controlled switching nodes that are established in the MV network and equipped with appropriate switching elements. Another useful innovation component is the short-circuit indicator, in the best case installed in all the DS, with an indication of its operation state in the central control room. An essential part of an up-to-date distribution network is the dispatchers' control and information system.

A significant difference in the investment or yearly costs can be found in the comparison of $4t_L$ (4 t_M) and the $2n_L$ ($2n_M$) options. The cost difference makes 27.95 mil. CZK (20.66 mil. CZK) in the investment and 0.91 mil. CZK/year (0.65 mil. CZK/year) in the yearly costs to the advantage of the option with two non-transposed feeders. The investment costs of these options two options are lower by 36 % (40 %) and the operation costs by 24 % (29 %), respectively, as compared to the four network options with consistently transposed feeders.

This economical number of feeders and its arrangement (two non-transposed feeders) must not be conceived in a dogmatic way. Admittedly, the economy is one of of the basic criteria during the network design but it is also necessary to take the sometimes very critical approach of the public to the power interruptions which may arise occasionally. Such a power outage could jeopardize the image of utility companies and cause a large sums to be payed as a compensation to some of the power consumers who would insist on the recompensation for production losses. Consequently, in some cases the higher number of feeders may be considered to be an economic measure, too.

Feeder transposition in a radial operation of the LV network is reasonable only in case when there is a chance to come up for a MV network power failure by steps to be implemented at the LV level, and when there is no possibility to implement such a measure in networks with non-transposed feeders. Such an operation state can occur, for example, during a duplicate failure of the feeder or during some revision or maintenance works on the MV network. Sometimes the transposition comes up as a logical step due to the arrangement of the area supplied by power. If we choose the transposition then it is adequate to choose a lower level of it, i.e. the partial transposition.

A low voltage network should be erected as a series of ARN with branches arranged conformably to the construction plan of the urban area. These networks consist of cables with identical cross section and each ARN fed from the respective DS. The networks must be erected in a way to provide for a back-up interconnection between them.

5. CONCLUSION

We have been successful in determining the economical variant of a 22 kV network with a radial operation of a model of 0.4 kV grid network, by using the criterion of minimum yearly costs. For a defined level of specific load density of 32 MVA/km^2 or 16 MVA/km^2 it is always the option with two non-transposed feeders which has proven to be the optimum one. In case of some failures the partial transposition may be justified. An economical approach to the number of feeders and the stage of their transposition can not be regarded as dogmatic rule and it is necessary also to consider the respective situation at the area, with respect to the necessity to keep to the good image of the utility company.

A tendency in the development of urban power distribution networks consists, when compared with the past, in the reduction of the number of MV feeders and in the extent of the transposition of the same, by using a back-up interconnection. The LV network is always being established as a series of ARNs, fed from the corresponding DSs, also with the possibility of back-up interconnection. In order to increase the reliability of power supply and in order to satisfy the ever increasing needs of power consumers the Czech urban distribution networks experience a period of further extension of remote control and automation, aimed at the improvement of handling capabilities of the networks. Each retrofitting or a new design of a network should take a higher number of options into consideration, in order to find an optimum between the reliability increase by implementing new innovated components, and the increased investment costs caused by the use of latest technology. In our example the network modernization can use investment means made available by a reduced number of feeders.

Currently there are three grid networks operated in the Czech Republic, two in Prague and one in the centre of Brno, while there is a number of networks established, with 15 of them only in the city of Brno. No further grid networks are currently being established nor designed.

6. REFERENCES

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