

**A MULTI-OBJECTIVE APPROACH TO OPTIMAL
ALLOCATION OF DISTRIBUTION AUTOMATION DEVICES
IN RADIAL MEDIUM VOLTAGE NETWORK ***

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Abstract. *In this paper a method for selection of optimal scenario for distribution automation is proposed. For a part of distribution network that can be considered as the smallest functional unit, the service zones are determined based on the heuristic rules, all possible automation scenarios are searched, and the values of selected objective functions are determined. After that, the method uses fuzzy multi-criteria evaluation and grey relational analysis in the application of evaluating a set of alternatives in terms of decision criteria. Automation scenarios are ranked on the basis of objective function values. The method is demonstrated on test example of real medium voltage distribution network.*

Key words: *distribution automation, multi-objective optimization, medium voltage network*

1. INTRODUCTION

Electric power utilities tend to run their businesses as efficient enterprises providing energy at an acceptable level of quality. The emergence of deregulation has dramatically changed the business environment. This radical shift in business goals, now occupying power companies, in many countries as a result of deregulation, open access, and privatization, is causing a significant review of network design and operating practices. Network control and automation are playing a key role in enabling the network owners to adapt to the changing situation and opportunities to achieve their business goals [1]. One of the most important reasons for introducing distribution automation is efficient fault management [2, 3].

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Increasing the automation level of distribution network, above all, affects the reduction of outage duration time when a fault occurs. With reduction of outage duration time, the unsupplied amount of energy to the customers is decreased. To determine the optimal solution of this problem, it is necessary to cover a very large amount of data. Distribution network optimization problem is an extremely complex non-linear optimization problem with large number of constraints. As a criterion of optimality, different parameters can be adopted (benefit of the electric power utility over the planned time period, cost to benefit ratio over the planned time period or the effects achieved in improving the reliability indicators). However, to consider the problem in total, it is not sufficient to consider only one objective function, but it is necessary to consider the problem as a multi-objective optimization problem.

Distribution network covers a very large territory, contains a very large number of elements (lines, substations etc.) and they are developing dynamically. Considering very rapid development of technology, the lifetime of control and communication equipment applied in distribution automation is short compared to the lifetime of electric power equipment. Equipment prices of different manufacturers are in a relatively wide range and largely depend on purchased amount of the equipment, business interest of the manufacturer for entering the particular market and other factors. In addition, it should be noted that the installation process of medium voltage network automation devices is long-term and cannot be implemented over one year but the investments are distributed over a period of several years. It is obvious that during the analysis of optimal device selection for distribution network automation and location selection, it is almost impossible to include all relevant influences, but certain simplification must be introduced.

A large number of papers presenting this issue are directed toward the optimal location selection for only one, known in advance, type of distribution network automation device. The paper [4] presents a method for sectionalizer relocations for customer interruption cost minimization which uses simple analytical computations and heuristic rules to search for the new locations. To determine the number of sectionalizing switches and their location, an optimization technique of simulated annealing is proposed in [5], while in [6] a genetic algorithm procedure is proposed. In [7] immune algorithm is used to solve the optimal placement of line switches. The objective function is formulated by considering the outage cost and investment cost of line switches. The paper [8] proposes a two-stage decomposition approach to optimal remote controlled switch allocation in distribution systems.

A small number of papers consider different types of automation equipment simultaneously [3,9,10]. The paper [3] proposes methodology for optimal level of investment in medium voltage network, based on heuristic combinatory search algorithm with simultaneous consideration of scenarios with different types of automation equipment: local automation and remote control. The essence of the algorithm is decomposition of an optimal automation problem with different types of automation equipment to subproblems with one type of equipment. The optimization problem is defined as multi-objective with three objective functions (benefit, reliability indicators and cost/benefit). The three-state approach inspired by the discrete version of particle swarm optimization is presented in [9] to determine optimal number and locations of two types of switches (sectionalizes and breakers) in radial distribution system. A technique to carry out optimized placement of control and protective devices in the same optimization process simultaneously is

presented in [10]. The problem is modelled through mixed integer non-linear programming model, and solved using reactive tabu search algorithm.

There is a large number of distribution network planning and exploitation problems that can be classified as a multi-objective optimization problems, for example, the selection of optimal distribution network restoration plan [11-13]. In [11] a hybrid fuzzy-grey method is proposed to obtain satisfactory restoration plan for distribution system restoration.

In this paper a method for selection of optimal scenario for distribution automation is proposed. For a part of distribution network that can be considered as the smallest functional unit, the service zones are determined based on the heuristic rules, all possible automation scenarios are searched, and the values of selected objective functions are determined. After that, the method uses fuzzy multi-criteria evaluation and grey relational analysis in the application of evaluating a set of alternatives in terms of decision criteria. Automation scenarios are ranked on the basis of objective function values.

2. METHODOLOGY

The selection of device for distribution automation and location selection for their installation is a very complex problem. From the point of global optimum, it is necessary to consider simultaneously the entire distribution network. However, the total number of possible scenarios that should be counted when considering entire distribution network and all types of distribution automation devices is extremely large. Considering dimension of a problem, computational time is very long. Regardless of the remarkable progress of computer technology, finding the optimal solution by direct searching all possible solutions is practically impossible for a network that contains tens of thousands of elements. The alternative to direct searching of the optimal solution is the use of heuristic methods that do not analyze all possible combinations for allocation of different elements. A difficulty for heuristic methods is low sensitivity of objective functions. Namely, when location of an element is changed or one type of element is changed by the other type within some automation scenario that contains hundreds or thousands of elements, the values of criterion functions are almost unchanged.

Based on previous consideration, it is obvious that is necessary to decompose the problem into subproblems that will be solved independently. For this reason, distribution network is divided into parts which represent the smallest functional unit that can be considered independently. Medium voltage feeders that supply rural areas are usually radial and can be considered independently, or with the ability for backup supply when it is necessary to consider several feeders simultaneously. But that is not the case for urban cable networks. In case of urban cable networks that are meshed, division cannot be done unambiguously, but taking into account the power line limitations it can still be done. Because strictly division is not possible, the number of strategies is chosen in terms of separation points within the network. A larger network, of course, corresponds to a larger number of strategies. After the optimal solution for all strategies is found, the synthesis of solutions should be done.

The next question is how to allocate planned investments for automation of the entire network in certain parts of the network. One approach is to allocate investments in certain parts with respect to annual supplied energy. However, optimization procedure is not in-

cluded in allocating the investments. Contrary to this approach, after division of distribution network into functional units, the desirable level of automation can be defined by defining the desirable values of objective functions. For each objective function a criterion is defined for evaluating scenarios as "good" or "bad". Considering the fact that scenario quality is described with linguistic terms "good" or "bad", it is obvious that application of fuzzy logic is very suitable.

For optimality criterion a maximal benefit or minimal cost to benefit ratio are usually used. Reliability indicators can also be used as optimality criteria, but they do not take into account the information about supplied energy and customer category. Since none of the criteria can include all relevant factors for selection of optimal solution, the best option is simultaneous consideration. Increasing the investments will improve reliability indicators, which means that optimal solution cannot be found with respect to these criteria only. Increasing the investments will also increase the benefit but only to some boundary value and after that the benefit starts to decrease, but application of only this criterion favours a more expensive solution. On the other hand, cost to benefit ratio is the most suitable for solutions with low level of investments. After analyzing all parts of the network, total investments can be determined. If total investments are close to desirable values, the problem is solved. Otherwise, desirable values of objective functions are increased or decreased and the whole procedure is repeated.

Division of the network in functional units will significantly reduce the problem dimension; however, solving the subproblems is also very demanding when considering a large number of different devices. Namely, if there is an optimal allocation of N_{eq} different devices for the network with N_{line} branches, assuming that every device can be installed at the beginning of every branch (on feeder or in the substation from which the feeder starts), the total number of scenarios which should be considered is $N_{line}^{N_{eq}}$. For the 60-branch network that will be considered in the test example and 4 different types of devices, there are about 13 million scenarios. Because of that, it is suitable to use some of the heuristic methods for solving the subproblems. Since the analysis tends to include all types of devices, dimension of subproblem can only be reduced by reducing the number of potential locations for device installation, which can be achieved by dividing the network into service zones. Potential locations for the installation of devices for distribution automation are at the beginning of service zones, reducing the number of analyzed scenarios. The criteria for service zone forming could be minimal length of power lines, maximal number of power substations, locations of existing pole mounted switching equipment or ring main units in distribution substations, etc. The division of the 60-branch network into eight zones will reduce the total number of scenarios to 4096 for four different types of devices.

2.1. Characteristic reliability indices in distribution systems

Nowadays, electric power utilities use a variety of different reliability indicators [14-16], which is a consequence of the absence of unique criteria for reliability assessment. System Average Interruption Frequency Index (SAIFI) represents the average number of outages longer than 3 minutes per customer and it is measured over the course of a year.

$$SAIFI = \frac{\sum_i f_i N_i}{N} \quad (1)$$

In previous equation f_i is the frequency of fault i , N_i is the number of customers interrupted by fault i , and N is the total number of customers.

System Average Interruption Duration Index (SAIDI) represents the average duration of outage per customer and it is measured over the course of a year.

$$SAIDI = \frac{\sum_i D_i N_i}{N} \quad (2)$$

In the previous equation D_i is the cumulative outage duration of customers interrupted by fault i during the year. Beside SAIFI and SAIDI, the following indicators are also used: Customer Average Interruption Duration Index (CAIDI), Average Service Availability Index (ASAI), Average Service Unavailability Index (ASUI), Customer Interruptions (CI), Customer Minutes Lost (CML), Average System Interruption Duration Index (ASIDI), Energy Not Supplied (ENS), etc.

For analysis in this paper, reliability indicators SAIFI and SAIDI will be used because of their widespread use (except in Austria, Great Britain and Spain) [16]. The introduction of penalties, for the case when reliability indicators are worse than the ones prescribed by the regulator, creates the need of including these indicators as objective functions in distribution automation optimization problem. It can be included as a separate objective function at multi-objective optimization, or, with respect to the values of penalties, included in the economic objective function (actualized total costs function or cost/benefit function).

2.2. Outage duration assessment

Reliability indicators, SAIFI and SAIDI are determined on the basis of fault data and outage data. On the basis of historical data about faults, reliability indicators of system elements, which are usually expressed through the fault rate, can be also determined.

To determine the expected value of reliability indicator SAIFI and SAIDI for one assumed automation scenario, beside the value of reliability indicators of system elements, outage duration for a fault on each element should be assessed for each customer. Outage duration depends largely on the position of the observed customer node, with respect to the power source and a faulted section. In general, outage duration of a customer node due to a faulted section is a function of: network conception, organization of finding a faulted section (isolating procedure), searching a location in the faulted section, the way of communicating with control center [3,7].

When fault occurs on some section of a distribution feeder, the breaker in supply substation is opened due to activation of the protection. As consequence, outage of all customers supplied by this feeder occurs. After receiving information about fault, operator determines feeder under fault and send field crew to isolate faulted section. Bisectional search method is very popular isolating procedure because of its simplicity, although approaches that take into account the information about configuration and network state appeared in recent time. Because of this fact, when outage duration is estimated in this paper, isolating procedure by the bisectional search method will be used.

Under this method, distribution substation or pole-mounted switch in the mid-point of the faulted feeder represents the first place visited by the field crew. On arrival, the crew opens the sectionalizer and disconnects the half of feeder. After receiving information about opening the sectionalizer, the operator closes the breaker in supply substation. If the protection is activated again, the fault has occurred at the first half of the feeder. Otherwise, the fault has occurred at the second half of the feeder. After determination of the faulted half, the crew closes the previously opened sectionalizer and moves to the faulted half. Repeating these actions will lead to the isolation of the faulted section.

Customers supplied by the faulted feeder will start receiving electrical energy again after a period of time. This time period depends on the fault location and their position with respect to that location. If the customer is "in front of" the fault location, the energy will be resupplied after time period T_A which is the sum of alert time T_{alert} , arriving time of field crew T_{arrive} , and time needed to find and isolate the faulted section $T_{isolate}$.

$$T_A = T_{alert} + T_{arrive} + T_{isolate} \quad (3)$$

Alert time represents the time that elapses between the moment when the fault occurs and the moment when the operator receives the information about that fault. Arriving time represents the time interval during which the operator determines the faulted feeder and the field crew arrives at the starting point of the fault isolating procedure. Time needed to find and isolate the faulted section depends on the distance travelled, velocity of the field crew and the number of performed manipulations.

If the customer is "behind" the fault location, the energy will be resupplied after time period T_B , which is longer than the time period T_A . If there is no backup supply, this time period can be expressed as:

$$T_B = T_A + T_{micro} + T_{repair} \quad (4)$$

In the previous expression T_{micro} is time needed for finding the microlocation of the fault on the previously isolated section, and T_{repair} is repairing time of the faulted element. The presented method for determination of the fault location corresponds to the network without any automation.

2.3. Economic objective functions

Objective function of actualized total cost takes into account the investment in network automation, operation and maintenance costs as well as the costs of unsupplied energy due to outages for a period of time. The total cost of the scenario S is determined by the following expression:

$$C_{tot}^S = C_{inv,0}^S + \sum_{j=1}^n (C_{inv,j}^S + C_{ENSI,j}^S + C_{M,j}^S)(1+a)^{-j} - (1+a)^{-n} I_{rem}^S \quad (5)$$

In previous expression n is the duration of the planned period in years, j is the considered year during the planned time period, $C_{inv,0}^S$ is the investment cost till the beginning of the first year, $C_{inv,j}^S$ is the investment cost during the j -th year, $C_{ENSI,j}^S$ is the outage cost during the j -th year, $C_{M,j}^S$ is the operation and maintenance cost during the j -th year, I_{rem}^S is the remaining value of the equipment at the end of the planned period, and

a is the actualization rate. The remaining value of the element at the end of the planned period can be expressed as:

$$I_{rem}^S = \sum_m I_{rem,m} \quad (6)$$

$$I_{rem,m} = \begin{cases} I_{life,m} + \left(1 - \frac{n}{n_{life,m}}\right)(I_{0m} - I_{life,m}); & n < n_{life,m} \\ I_{life,m}; & n \geq n_{life,m} \end{cases} \quad (7)$$

In these expressions m is equipment index, $n_{life,m}$ is lifetime of the equipment m , I_{0m} is investment cost of the equipment m , $I_{rem,m}$ is value of the equipment m at the n -th year, and $I_{life,m}$ value of the equipment m at the end of lifetime.

When calculating the investment cost of one scenario, in addition to the equipment cost (C_{eq}^S), it is also necessary to consider the additional costs (C_{ad}^S) which include designing costs, installation costs, functional testing costs and commissioning costs. Equipment cost includes the prices of power equipment, control equipment and telecommunication equipment if the object is introduced into the remote monitoring and control system.

The outage cost during the j -th year is determined as follows:

$$C_j = \sum_i \sum_k c_{pik} f_k \Delta P_{ik} \quad (8)$$

In the previous expression, i is the customer category index, k is disturbance index, ΔP_{ik} is cut-off power of the customer i caused by disturbance k , f_k is frequency of disturbance k , and c_{pik} is outage cost of the customer i per cut-off power.

For calculating the outage cost of customer i per cut-off power, the following expression can be used:

$$c_{pik} = C_{1i} + C_{2i} d^{C_{3i}} \quad (\text{€/kW}) \quad (9)$$

In this expression, d is duration of outage, C_{1i} , C_{2i} and C_{3i} are coefficients whose values depend on the customer category. The coefficients also depend on the price of electricity and differ from one country to another.

As the second economic criterion of optimality, what can be used is the cost to benefit ratio (cost/benefit) which should be minimized. The cost includes all investment costs actualized at the beginning or at the end of the considered time period, while benefit represents the difference between the total cost due to the current state and the total cost when automation equipment of one scenario is installed. All the costs must be actualized at the same moment in time. The cost to benefit ratio for scenario S can be represented with the following relation:

$$CB^S = \frac{I^S}{B^S} \quad (10)$$

In this expression I^S is the investment cost for the scenario S , B^S is benefit (total cost reduction) due to the reduction of outage cost and reduction of operation and maintenance costs for the scenario S .

2.4. Fuzzy multi-criteria evaluation

In the analyses of optimal location of distribution automation equipment, the scenario is considered more preferable if reliability indicators SAIFI and SAIDI are "better" and total cost as well as cost/benefit indices are "smaller". Obviously, the vague terms "better" and "smaller" are very imprecise in nature and can be conveniently handled by the fuzzy set theory.

The fuzzy multi-criteria evaluation [12] consists of a basic rule, membership functions, and a conclusion procedure. The basic rule formed with fuzzy rules, which describe relationships in a linguistic sense, are written as pairs of "IF-THEN" statements. The fuzzy rules are expressed in following forms:

IF $f_i(\vec{X})$ is Low, THEN the plan is Good.

IF $f_i(\vec{X})$ is Moderate, THEN the plan is Moderate.

IF $f_i(\vec{X})$ is High, THEN the plan is Bad.

All values of objective functions $f_i(\vec{X})$ are described using three fuzzy sets: Low, Moderate and High. The related membership functions are shown in Fig. 1. Consequently, the fuzzy sets Good, Moderate and Bad are clearly defined as 1, 0.5 and 0, respectively. This can simplify the computation process and completely satisfy the needs of the study. In the inference procedure, the real value of each objective function is firstly calculated to get the boundary values in fuzzy IF-THEN rules. The weighted average is applied in order to obtain real values:

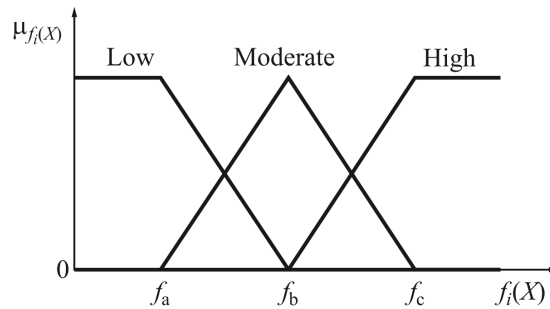


Fig. 1. Fuzzy numbers which represent linguistic variables

$$f_i^* = \frac{\sum_{j=1}^{N_F} \mu_j y_j}{\sum_{j=1}^{N_F} \mu_j} \quad (11)$$

In the previous expression, μ_j and y_j are boundary value and fuzzy result in the j -th fuzzy rule, respectively. N_F presents a number of fuzzy rules. The values of f_i^* represents the fitness degree of objective functions f_i for each scenario.

2.5. Grey relational analysis

The grey relational analysis (GRA) is an important approach of the grey system theory in the application of evaluating a set of alternatives in terms of decision criteria. In GRA, the data that contain same features are regarded as sequence. As a tool of quantitative analysis, the GRA can be used to measure the relationship between two sequences by calculating their correlative degrees, which is called grey relational grade (GRG). The GRG is expressed by a scalar between 0 and 1. Up to now, the method has been successfully applied in many fields and has attracted many researchers who will continue exploring this study. The principal formulas of the GRA are briefly described in further text.

Considering a reference sequence $x_0=(x_0(1), x_0(2), \dots, x_0(n))$ and m comparative sequences $x_i=(x_i(1), x_i(2), \dots, x_i(n))$, $i=1, 2, \dots, m$, where $x_i(k)$ represents the k -th entry in x_i , $k=1, 2, \dots, n$. The grey relational coefficient (GRC) of x_i with respect to x_0 in k -th entry is as follows:

$$\gamma(x_0(k), x_i(k)) \equiv \frac{\Delta_{\max} - \Delta_{0i}(k)}{\Delta_{\max} - \Delta_{\min}} \quad (12)$$

$$\Delta_{\max} \equiv \max_{\forall i} \max_{\forall k} |x_0(k) - x_i(k)| \quad (13)$$

$$\Delta_{\min} \equiv \min_{\forall i} \min_{\forall k} |x_0(k) - x_i(k)| \quad (14)$$

$$\Delta_{0i}(k) \equiv |x_0(k) - x_i(k)| \quad (15)$$

The GRGs between each comparative sequence x_i and the reference sequence x_0 can be derived from the average of the GRC, which is denoted as:

$$\Gamma_{0i} = \sum_{k=1}^n \frac{1}{n} \gamma(x_0(k), x_i(k)) \quad (16)$$

Γ_{0i} represents the degree of relation between each comparative sequence and the reference sequence. Higher degree of relation means that the comparative sequence is more similar to the reference sequence.

3. TEST EXAMPLE

The selection of the optimal scenario for distribution automation of one small part of the network will be demonstrated on the example of real radial medium voltage 10 kV distribution network shown in Fig. 2. The network element data and customer data are shown in Table 2. The analysis is made under the following assumptions. Supplying substation is remotely controlled, annual fault rate level of lines is 0.15 1/km, arriving time of the field crew 2 h, speed of field crew moving during the fault management procedure is 1 m/s, manipulation time 0.15 h, time for repairing the faulted element 2 h, and time needed for fault isolation with remote controlled switching equipment 0.25 h. The duration of the planned time period is 10 years, actualization rate 8%, lifetime of control equipment 10 years, lifetime of power switching equipment 30 years, value of the equipment at the end of lifetime is 10% from the investment cost of the equipment. The

total cost and benefit for the planned time period will be actualized to starting year. As objective functions, in addition to the economic functions, the reliability indicators SAIFI and SAIDI are used.

For division of distribution network into service zones, the following criteria are used: a zone contains maximum 5 distribution substations, the length of all branches in the zone is more than 2 km. The locations of the already installed switches are also taken into account when defining the service zones. When the proposed criteria are applied, eight zones on considered feeder, marked with Roman numerals in Table 1, can be identified. Firstly, an analysis is conducted over the current state, reliability indicators are determined, and outage cost is evaluated.

The coefficients used for the calculation of the outage cost for different customer categories are shown in Table 2. Table 3 shows summary data about the zones and these data are: the number of distribution substations that belong to the zone (N_{dt}), the sum of rated power of transformers that belong to the zone (S_{rT}), the average real power of all residential category customers that belong to the zone ($P_{av\ res}$) and the average real power of all commercial customers that belong to the zone ($P_{av\ com}$).

The following path of movement is assumed for the field crew, during fault isolating in the current state network (before automation). First, the field crew should go to the switching device S3 and open it. If the fault is not isolated, the crew should go to the location of the switching device S5 and manipulate it. Again, if the fault is not isolated, the crew should go to the location of the switching device S2 and manipulate it. The analysis of distribution network before installation of the automation equipment leads to the following values: SAIFI₁₀ 7.7265 1/yr.custom., SAIDI₁₀ 14.13 h/yr.custom., and total cost 150,560 €.

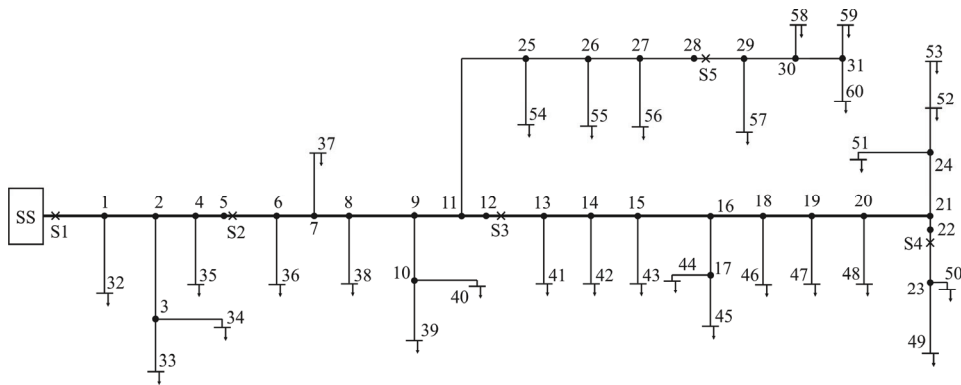


Fig. 2. Distribution test system

Table 1. Test system data

Line	Zone	Length	Line	Zone	Length	S_r	$P_{av.res}$	$P_{av.com}$
1	I	1220	32	I	240	160	75.175	2.067
2	I	870	33	I	500	160	14.175	0
3	I	350	34	I	115	250	55.105	1.645
4	I	360	35	I	80	100	0.581	7.611
5	I	860	36	II	60	160	16.544	2.355
6	II	405	37	II	350	160	15.333	0
7	II	690	38	II	85	160	31.771	1.568
8	II	1040	39	II	435	250	13.118	0.23
9	II	300	40	II	195	250	11.103	0
10	II	1025	41	III	50	160	6.839	0
11	II	520	42	III	540	250	22.975	1.058
12	II	30	43	III	340	250	23.669	3.2
13	III	665	44	III	885	45	7.648	0
14	III	770	45	III	20	50	1.168	0
15	III	310	46	IV	155	45	6.151	0
16	III	810	47	IV	850	160	20.479	0
17	III	550	48	IV	350	160	21.821	1.439
18	IV	365	49	V	410	160	8.876	0
19	IV	1625	50	V	280	100	17.393	0
20	IV	650	51	VI	500	160	14.412	0
21	IV	310	52	VI	520	160	5.705	0.136
22	IV	50	53	VI	900	250	37.863	0.368
23	V	1320	54	VII	120	250	39.315	3.78
24	VI	375	55	VII	70	100	13.164	0.566
25	VII	330	56	VII	45	160	23.943	1.23
26	VII	1420	57	VIII	100	160	10.761	0.24
27	VII	920	58	VIII	40	160	19.536	0.207
28	VII	290	59	VIII	290	100	12.499	0.537
29	VIII	1940	60	VIII	1295	160	21.331	0
30	VIII	510						
31	VIII	810						

Table 2. Coefficients for outage cost evaluation

Customer category		C_1	C_2	C_3
Commercial		1.65	7	1
Residential	$0.3 \text{ h} \leq d < 1 \text{ h}$	-0.58	1.97	1
	$1 \text{ h} \leq d < 5 \text{ h}$	1.1	0.3	2.5
	$5 \text{ h} \leq d \leq 48 \text{ h}$	15.3	0.11	2

To show the results obtained by the application of multi-criteria fuzzy-grey evaluation, 8 scenarios out of the set of scenarios with approximately the same automation level are taken and shown in Table 4. In this table S represents the switch; D represents the fault detector, C represents the recloser, while R represents remote control.

Table 3. Summary data about service zones

Zone	I	II	III	IV	V	VI	VII	VIII
N_{ds}	4	5	5	3	2	3	3	4
L_{line} [km]	4.596	5.135	4.94	4.355	2.01	2.295	3.195	4.985
S_{rT} [kVA]	670	980	755	365	260	570	510	580
$P_{av\ res}$	145.04	87.869	62.299	48.451	26.269	57.98	76.422	64.127
$P_{av\ com}$	11.323	4.153	4.258	1.438	0	0.504	5.576	0.984

Table 4. Distribution automation equipment for eight selected scenarios

Scenario\Zone	I	II	III	IV	V	VI	VII	VIII
1	RC	S	RSD		S	RSD		S
2	RC	S	RSD	RD	S	RSD		S
3	RC	S	RSD		S	RSD		SD
4	RC	RSD	RSD		S	RSD		S
5	RC	RSD	RSD	RD	S	RSD		S
6	RC	S	RC		S			S
7	RC	SD	RC	RD	S			SD
8	RC	S	RC	RD	S		S	S

Table 5 shows objective function values for eight selected scenarios, the investment cost of the equipment for every scenario, as well as additional costs (installation cost, technical documentation cost, functional testing and commissioning cost, training cost, and estimated value of telecommunication equipment infrastructure cost). The table also contains calculated values of reliability indicators SAIFI₁₀ and SAIDI₁₀ which represents the impact of faults on 10 kV network on supply reliability, calculated values of outage cost, obtained profit from network automation in the 10-year time period and cost to benefit ratio (cost/benefit).

On the basis of the objective functions shown in Table 5, it is obvious that total cost function has its minimum for scenario 5, but the investment is the greatest. Scenarios 2 and 3 have approximately the same value of total cost function but scenario 2 has slightly lower value of cost to benefit ratio. A potential solution is also scenario 8, which demands slightly higher value of investment and has worse cost to benefit ratio, but on the other hand, it has a lower value of reliability indicator SAIFI₁₀ than scenario 2. For fuzzy multi-criteria evaluation shown in Table 5, the following characteristic values of fuzzy numbers for selected objective functions are used: $f_{1a} = 1.05$, $f_{1b} = 1.15$, $f_{1c} = 1.25$, $f_{2a} = 0.3$, $f_{2b} = 0.35$ and $f_{2c} = 0.4$, $f_{3a} = 3$, $f_{3b} = 4.5$, $f_{3c} = 6$, $f_{4a} = 6$, $f_{4b} = 8$ and $f_{4c} = 10$. Now, grey relational grade is calculated using expressions (13)-(16) and scenarios are ranked as shown in the last row of Table 5. The optimal solution is represented with scenario 2 which has the investment value of 20,200 €. If investment for the obtained optimal solution deviates much from the planned value, then with a modification of the characteristic values of fuzzy numbers, a different ranking of potential solutions can be obtained.

Table 5. Objective functions and fuzzy-grey evaluation for eight selected scenarios

Scenario	1	2	3	4	5	6	7	8
C_{eq}	13500	14500	15500	19200	20200	13000	16000	16000
C_{ad}	5300	5700	6100	8100	8500	4500	5700	6550
I_{rem}	2220	2250	2270	2160	2640	2450	2320	2450
C_{tot}	95217	82873	83960	97673	76758	113375	89892	85000
f_1 ($C_{tot}/C_{tot \min}$)	1.2405	1.0797	1.0938	1.2725	1	1.4771	1.1711	1.1074
f_2 (C/B)	0.3397	0.2984	0.3243	0.5162	0.3889	0.4706	0.3577	0.3401
f_3 ($SAIFI_{10}$)	4.7265	4.7265	4.7265	4.7265	4.7265	3.4803	3.4803	3.4803
f_3^* ($SAIDI_{10}$)	8.792	8.042	8.011	8.278	6.867	10.24	8.484	8.259
f_1^*	0.0476	0.8517	0.7808	0	1	0	0.3944	0.7131
f_2^*	0.603	1	0.7567	0	0.1112	0	0.4231	0.5986
f_3^*	0.4245	0.4245	0.4245	0.4245	0.4245	0.8399	0.8399	0.8399
f_4^*	0.3	0.49	0.5	0.43	0.78	0	0.38	0.44
Γ_{oi}	0.4385	0.7856	0.709	0.3079	0.674	0.3042	0.6033	0.7409
Rank	6	1	3	7	4	8	5	2

4. CONCLUSION

A method for selection of the optimal scenario for distribution automation is proposed in this paper. The problem of distribution automation is a complex, non-linear and discrete optimization problem of enormous dimensions and it is not possible to apply an appropriate optimization procedure directly. Because of this, the proposed method firstly determines the service zones based on the heuristic rules for a part of distribution network that can be considered as the smallest functional unit. Then, all possible automation scenarios are searched, and the values of the selected objective functions are determined. After that, the method uses fuzzy multi-criteria evaluation and grey relational analysis in the application of evaluating a set of alternatives in terms of decision criteria. Automation scenarios are ranked on the basis of objective function values. The method is demonstrated on the test example of a real medium voltage distribution network.

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VIŠEKRITERIJUMSKI PRISTUP ODREĐIVANJU OPTIMALNE LOKACIJA UREĐAJA DISTRIBUTIVNE AUTOMATIKE U RADIJALNOJ SREDNJENAPONSKOJ DISTRIBUTIVNOJ MREŽI

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U radu je predstavljen jedan pristup izboru optimalne vrste opreme za automatizaciju distributivne mreže, i njene optimalne lokacije. Problem automatizacije distributivne mreže je složen, nelinearni diskretni optimizacioni problem izuzetno velike dimenzionalnosti zbog čega je praktično nemoguća direktna primena optimizacionih procedura. Zbog toga je u radu najpre predložena podela problema na podprobleme, koji su nakon toga sagledani kao višekriterijumski optimizacioni zadatak. Za donošenje odluke primenjeni su metodi višekriterijumskog fuzzy ocenjivanja i "grey" relacionog rangiranja. Prezetovani metod testiran je na primeru realne radijalne srednjenaponske distributivne mreže.

Ključne reči: automatizacija, srednjenaponska distributivna mreža, višekriterijumska optimizacija