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Optimal Allocation of Distribution Automation Devices in 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 four different methods are applied in evaluating a set of alternatives in terms of decision criteria: hybrid fuzzy-grey method, maximin method, simple additive weighting method and analytic hierarchy process. The method is demonstrated on test example of real medium voltage distribution network.**

***Index Terms*—Decision making, optimization, power distribution, power system reliability.**

I. INTRODUCTION

The emergence of electricity market deregulation has dramatically changed the business environment. Distribution automation plays 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]. Increasing the automation level of distribution network, above all, affects the reduction of outage duration time, when a fault occurs.

Optimal distribution automation is an extremely complex non-linear optimization problem with constraints. As a criterion of optimality, a 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. A number of papers that present this issue are directed toward the selection of optimal locations for only one, known in advance, type of distribution network automation device [4]–[8].

A small number of papers consider installation of different types of automation equipment simultaneously [3], [9]–[11]. 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 (sectionalizers and breakers) in radial distribution system. Paper [10] presents technique to carry out optimized placement of control and protective devices in the same optimization process, simultaneously. The problem is modelled through mixed integer non-linear programming model, and solved using reactive tabu search algorithm. The paper [3] proposes methodology for optimal level of investment in medium voltage network. This methodology is 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 complex automation problem with different types of automation equipment to more simple subproblems with one type of equipment. The optimization problem is defined as multi-objective with three objective functions (benefit, reliability indicators and cost/benefit).

A method for selection of optimal scenario for distribution automation with simultaneous consideration of different types of devices is proposed in [11]. For a part of distribution network that can be considered as the smallest functional unit, the service zones are firstly determined based on the heuristic rules. After that, all possible automation scenarios are searched, and the values of four objective functions are determined. Proposed 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. When applying the hybrid fuzzy-grey method, as well as any other methods of multi-objective decision making, there is a certain subjectivity level. This subjectivity emerges when membership functions of fuzzy numbers are defined.

This paper proposes an approach to multi-objective deciding for optimal selection of distribution automation devices and location selection for their installation in a part of distribution network that can be considered as the smallest functional unit. Problem definition, i.e. objective functions and constraints, are identical to ones used in [11]. Instead of hybrid fuzzy-grey method, in this paper four different evaluation methods are applied. Final ranking of automation scenarios are made by considering all of these evaluation methods.

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II. METHODOLOGY

Optimal selection of distribution automation devices and location selection for their installation is a very complex problem. From the point of global optimum, for distribution utility it is necessary to simultaneously consider 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. Regardless of the remarkable progress of computer technology, finding the optimal solution by direct searching all possible solutions is practically impossible for 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 scenarios. For this reason, distribution network is divided into the smallest functional units that can be considered independently. Problem dimension can be additionally reduced by dividing analyzed functional unit of 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.

Selection of optimization criteria is also very complex. Since none of criteria can include all relevant factors for selection of optimal solution, the best option is simultaneous consideration. Four criteria functions, which should be minimized, are considered in this paper: total cost during the planning period, cost to benefit ratio, System Average Interruption Frequency Index (SAIFI), and System Average Interruption Duration Index (SAIDI):

$$f_1(s) = C_0^s + \\ + \sum_{j=1}^{n} (C_j^s + C_{o,j}^s + C_{m,j}^s)(1+a)^{-j} - (1+a)^{-n} I_r^s, \quad (1)$$

$$f_2(s) = \frac{I^s}{B^s}, \quad (2)$$

$$f_3(s) = SAIFI_{MV}^s, \quad (3)$$

$$f_4(s) = SAIDI_{MV}^s. \quad (4)$$

In previous expressions n is the duration of planned period in years, j is the considered year during planned time period, a is the actualization rate, and s is index of scenario, C_0^s is the investment cost till the beginning of the first year, C_j^s is the investment cost during the j-th year, $C_{o,j}^s$ is the outage cost during the j-th year, $C_{m,j}^s$ is the operation and maintenance costs during the j-th year, I_r^s is the remaining value of the equipment at the end of planned period, I^s is the investment cost, and B^s is benefit (total cost reduction) due to reduction of outage cost and reduction of operation and maintenance costs.

Objective function of actualized total cost (f_1) takes into account the investment in network automation, operation and maintenance costs as well as the outage cost for some period of time. When calculating the investment cost of one scenario, in addition to the equipment cost it is also necessary to consider the additional costs which include designing costs, installation costs, functional testing costs and commissioning costs.

The second criterion of optimality is 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 considered time period, whereas the benefit represents the difference between the total cost due to the current state and total cost when automation equipment of one scenario is installed. Investment cost and total cost reduction for scenario s are calculated as follows:

$$I^s = \sum_{j=0}^{n} C_j^s (1+a)^{-j}, \quad (5)$$

$$B^s = f_1^0 - f_1(s), \quad (6)$$

where f_1^0 is the total cost for the network without automation equipment during the planned period. All the costs must be actualized at the same moment in time. Two remaining objective functions are reliability indicators [12], [13] of scenario s which comprehend only faults on medium voltage network under consideration.

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

$$C_{o,j}^s = \sum_i \sum_k c_{pik} f_k \Delta P_{ik}. \quad (7)$$

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

$$c_{pik} = C_{1i} + C_{2i} d^{C_{3i}}, \quad [\text{€/kW}]. \quad (8)$$

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 values of coefficients C_{1i}, C_{2i} and C_{3i} also depend on the price of electricity and differ from one country to another.

III. DECISION MAKING METHOD

In general, decision making models can be divided into two main groups, multiple attribute decision making (MADM) and multi-objective decision making models. By adopting MADM approach, the decision maker selects among a finite set of alternatives (a_i, i=1,...,m), where each alternative is also evaluated by more than one attribute

$$x_{ij} = f_j(a_i), i = 1,..,m, \ j = 1,..,n. \quad (9)$$

These attributes are usually in conflict with each other. Furthermore, their importance is different from the point of view of the decision maker. Multiple attribute decision models are usually represented by decision matrix, as follows

$$O = \begin{array}{c} \\ a_1 \\ a_2 \\ \vdots \\ a_m \end{array} \begin{array}{c} \begin{array}{cccc} f_1 & f_2 & \cdots & f_n \end{array} \\ \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{bmatrix} \end{array}. \quad (10)$$

The decision matrix should be linearized in order to scale attribute values in the range (0,1), and to translate different measure units in unnamed numbers. If criterion function is maximized, linearization is made by expression

$$l_{ij} = \frac{x_{ij}}{\max_i \{x_{ij}\}}. \quad (11)$$

If criterion function is minimized than:

$$l_{ij} = \frac{\min_i \{x_{ij}\}}{x_{ij}}. \quad (12)$$

There are a large number of MADM methods: Simple additive weighting (SAW), maximin and maximax method, conjunctive method, disjunctive method, Analytic hierarchy process (AHP), etc. Due to simplicity and practicality, SAW is the most popular method of classical MADM. In this method alternatives are measured by some attributes. Then, each alternative is assigned a score which is the weighted sum of these attributes.

The maximin method is the method based upon a strategy that tends to avoid the worst possible performance, maximizing the minimal performing criterion. The alternative for which the score of its weakest criterion is the highest is preferred. These methods require satisfactory rather than best performance in each criterion. The maximin method can be used only when all criteria are comparable so that they can be measured on a common scale, which is a limitation. Conjunctive and disjunctive methods are applied in combination with other methods. The conjunctive method requires that an alternative must meet a minimal performance threshold for all criteria. The disjunctive method requires that the alternative should exceed the given threshold for at least one criterion. Any alternative that does not meet the conjunctive or disjunctive rules is deleted from the further consideration.

The Analytic Hierarchy Process is one of the more widely applied multiple attribute decision making methods. It was proposed by Saaty (1980). The basic idea of the approach is to convert subjective assessments of relative importance to a set of overall scores or weights. For each pair of criteria, the decision maker is required to respond to a pairwise comparison question asking their relative importance. In the simplest form, the responses can use the following nine-point scale expressing the intensity of the preference for one criterion versus another:

1 – Equal importance or preference;
3 – Moderate importance or preference of one over another;
5 – Strong or essential importance or preference;
7 – Very strong or demonstrated importance or preference;
9 – Extreme importance or preference.

Even numbers are intermediate values which are used when compromise are needed. Let c_{ij} denote the value obtained by comparing criterion f_i relative to criterion f_j. Because the decision maker is assumed to be consistent in making judgments about any pair of criteria and since every criteria will always rank equally when compared to themselves, we have $c_{ji}=1/c_{ij}$ and $c_{ii}=1$. The entries c_{ij}, $i,j=1..n$ can be arranged in a pairwise comparison matrix C of size nxn. The next step is to estimate the set of weights that are most consistent with the relativities expressed in the comparison matrix. The logarithmic least square method [14] is used in this paper for calculation of weight coefficients. This method at first calculates geometric mean of each row in comparison matrix, and then normalizes geometric means by dividing them with their sum.

The grey relational analysis [11], [15] is also used in the evaluating a set of alternatives in terms of decision criteria. The method measures the relationship between two sequences by calculating their correlative degrees, which is called grey relational grade. Grey relational grade is a scalar between 0 and 1 which 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 one.

IV. TEST EXAMPLE

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. 1. The network element data and customer data are shown in Table I. 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 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 faulted element 2 h, and time needed for fault isolation with remote controlled switching equipment 0.25 h. Duration of 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. 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 $SAIFI_{10}$ and $SAIDI_{10}$ which consider only faults in 10 kV network, 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 zone is more than 2 km. Locations of already installed switches are also taken into account when defining the service zones.

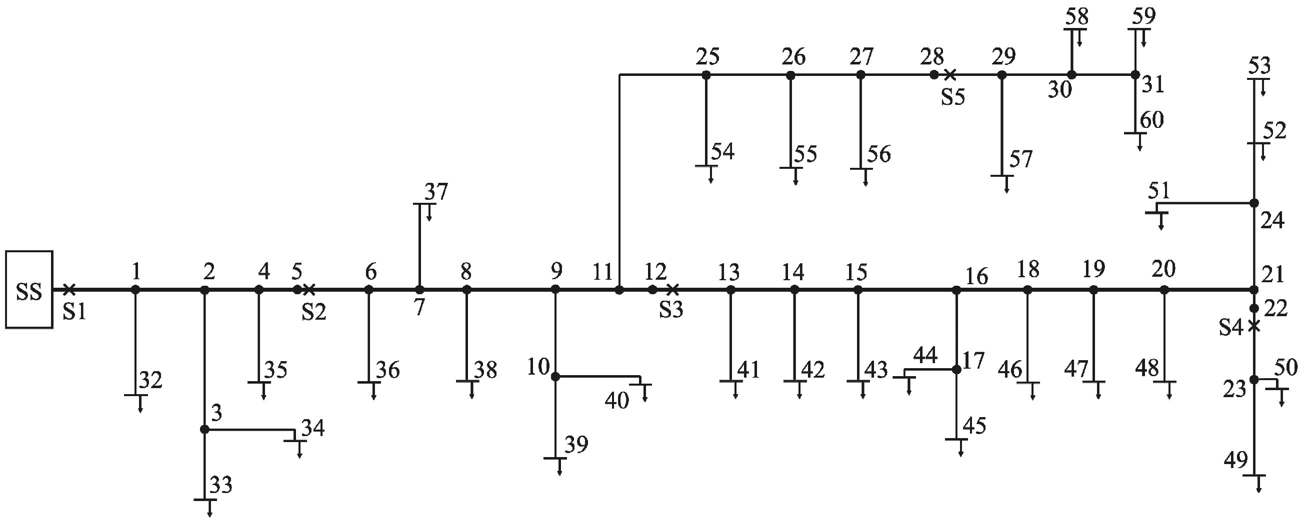

Fig. 1. Distribution test system.

When the proposed criteria are applied, eight zones on considered feeder, marked with Roman numerals in Table I, can be identified. Firstly, an analysis is conducted over the current state, reliability indicators are determined, and outage cost is evaluated. Coefficients used for calculation of the outage cost for different customer categories are shown in Table II.

TABLE I. TEST SYSTEM DATA.

No	Zone	L [km]	No	Zone	L [km]	S_r [kVA]	$P_{av\ res}$ [kW]	$P_{av\ com}$ [kW]
1	I	1.220	31	VIII	0.810			
2	I	0.870	32	I	0.240	160	75.175	2.067
3	I	0.350	33	I	0.500	160	14.175	0
4	I	0.360	34	I	0.115	250	55.105	1.645
5	I	0.860	35	I	0.080	100	0.581	7.611
6	II	0.405	36	II	0.060	160	16.544	2.355
7	II	0.690	37	II	0.350	160	15.333	0
8	II	1.040	38	II	0.085	160	31.771	1.568
9	II	0.300	39	II	0.435	250	13.118	0.23
10	II	1.025	40	II	0.195	250	11.103	0
11	II	0.520	41	III	0.050	160	6.839	0
12	II	0.030	42	III	0.540	250	22.975	1.058
13	III	0.665	43	III	0.340	250	23.669	3.2
14	III	0.770	44	III	0.885	45	7.648	0
15	III	0.310	45	III	0.020	50	1.168	0
16	III	0.810	46	IV	0.155	45	6.151	0
17	III	0.550	47	IV	0.850	160	20.479	0
18	IV	0.365	48	IV	0.350	160	21.821	1.439
19	IV	1.625	49	V	0.410	160	8.876	0
20	IV	0.650	50	V	0.280	100	17.393	0
21	IV	0.310	51	VI	0.500	160	14.412	0
22	IV	0.050	52	VI	0.520	160	5.705	0.136
23	V	1.320	53	VI	0.900	250	37.863	0.368
24	VI	0.375	54	VII	0.120	250	39.315	3.78
25	VII	0.330	55	VII	0.070	100	13.164	0.566
26	VII	1.420	56	VII	0.045	160	23.943	1.23
27	VII	0.920	57	VIII	0.100	160	10.761	0.24
28	VII	0.290	58	VIII	0.040	160	19.536	0.207
29	VIII	1.940	59	VIII	0.290	100	12.499	0.537
30	VIII	0.510	60	VIII	1.295	160	21.331	0

Table III shows summary data about the zones and these data are: number of distribution substations that belong to the zone (N_{ds}), sum of rated power of transformers that belong to the zone (S_T), average real power of all residential category customers that belong to the zone ($P_{av\ res}$) and 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, field crew should go to the switching device S3 and open it. If the fault is not isolated, crew will go to the location of the switching device S5 and manipulate it. Again, if the fault is not isolated, crew should go to the location of the switching device S2 and manipulate it. If the fault is isolated by opening the switch S3, field crew will go to the location of switch S4.

TABLE II. COEFFICIENTS FOR OUTAGE COST EVALUATION.

Customer category	C_1	C_2	C_3
Commercial	1.65	7	1
Residential (0.3 h ≤ d < 1 h)	-0.58	1.97	1
Residential (1 h ≤ d < 5 h)	1.1	0.3	2.5
Residential (5 h ≤ d ≤ 48 h)	15.3	0.11	2

TABLE III. 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 [km]	4.596	5.135	4.94	4.355	2.01	2.295	3.195	4.985
S_T [kVA]	670	980	755	365	260	570	510	580
$P_{av\ res}$ [kW]	145	87.87	62.3	48.45	26.27	57.98	76.42	64.13
$P_{av\ com}$ [kW]	11.32	4.153	4.258	1.438	0	0.504	5.576	0.984

TABLE IV. DISTRIBUTION AUTOMATION EQUIPMENT FOR EIGHT SCENARIOS.

Scenario	Zone								Invest. €
	I	II	III	IV	V	VI	VII	VIII	
1	RC	S	RSD		S	RSD		S	18800
2	RC	S	RSD	D	S	RSD		S	20200
3	RC	S	RSD	D	S	RSD		SD	21600
4	RC	RSD	RSD		S	RSD		S	27300
5	RC	RSD	RSD	D	S	RSD		S	28700
6	RC	S	RC		S			S	17500
7	RC	SD	RC	D	S			SD	21700
8	RC	S	RC	D	S		S	S	22300

The reliability analysis of distribution network before installation of the automation equipment leads to the following values: $SAIFI_{10}$ 7.7265 1/yr.custom., $SAIDI_{10}$ 14.13 h/yr.custom., and total cost 150560 €. Eight scenarios out of the set of scenarios with approximately the same automation level are taken and shown in Table IV. In this table *S* represents a switch, *D* represents a remote fault detector, *C* represents a recloser, whereas *R* represents remote control.

Decision matrix for eight automation scenarios for distribution test network (Table IV) is

$$O=\begin{bmatrix} 95.22\cdot 10^3 & 0.34 & 4.727 & 8.79 \\ 82.87\cdot 10^3 & 0.299 & 4.727 & 8.042 \\ 83.96\cdot 10^3 & 0.324 & 4.727 & 8.011 \\ 97.67\cdot 10^3 & 0.516 & 4.727 & 8.278 \\ 76.76\cdot 10^3 & 0.389 & 4.727 & 6.867 \\ 113.4\cdot 10^3 & 0.471 & 3.48 & 10.24 \\ 89.89\cdot 10^3 & 0.358 & 3.48 & 8.484 \\ 85\cdot 10^3 & 0.34 & 3.48 & 8.259 \end{bmatrix}. \quad (13)$$

The first column of decision matrix represents total cost which includes 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 second column represents cost/benefit, whereas the remaining two columns represent reliability indicators $SAIFI_{10}$ and $SAIDI_{10}$, respectively. The number of rows in matrix *O* corresponds to number of considered scenarios. For this reason, dimension of matrix *O* can be very large. However, it can be reduced retaining only noninferior solutions.

On the basis of the objective function values shown in decision matrix (13), it is obvious that total cost function has its minimum for scenario 5, but the investment is the greatest as can be seen in Table IV. 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. Potential solution is also the scenario 8, which demands slightly higher value of investment and has worse cost to benefit ratio, but on the other hand it has lower value of reliability indicator $SAIFI_{10}$ than the scenario 2.

Having in mind the members of decision matrix (13), it is clear that optimal solution lies among scenarios 2, 3, 5, and 8. Namely, the scenario 1 has greater or equal value of all objective functions in relation to scenario 2, scenario 4 compared to scenarios 2 and 3, and scenarios 6 and 7 compared to scenario 8. Reduced decision matrix, which includes only scenarios 2, 3, 5, and 8 is

$$O'=\begin{bmatrix} 82.87\cdot 10^3 & 0.299 & 4.727 & 8.042 \\ 83.96\cdot 10^3 & 0.324 & 4.727 & 8.011 \\ 76.76\cdot 10^3 & 0.389 & 4.727 & 6.867 \\ 85\cdot 10^3 & 0.34 & 3.48 & 8.259 \end{bmatrix}. \quad (14)$$

To apply the multiple attribute decision methods, decision matrix should be linearized. For minimization of objective functions the (12) is applied, which gives

$$O_l'=\begin{bmatrix} 0.926 & 1 & 0.736 & 0.854 \\ 0.914 & 0.92 & 0.736 & 0.857 \\ 1 & 0.767 & 0.736 & 1 \\ 0.903 & 0.877 & 1 & 0.831 \end{bmatrix}. \quad (15)$$

Table V shows final results of hybrid fuzzy-grey, maximin, SAW, and AHP methods. Results of hybrid fuzzy-grey method shown in Table V are taken from [11] where full decision matrix *O* is used, with the normalized values of the first objective function ($C_0^s / C_0^{\min}$), and with the following characteristic values of fuzzy numbers for selected objective functions:

$$\begin{cases} f_{1a}=1.05, f_{1b}=1.15, \; f_{1c}=1.25, \\ f_{2a}=0.3, \quad f_{2b}=0.35, \; f_{2c}=0.4, \\ f_{3a}=3, \quad f_{3b}=4.5, \quad f_{3c}=6, \\ f_{4a}=6, \quad f_{4b}=8, \quad f_{4c}=10. \end{cases} \quad (16)$$

As the reference sequence in [11], one with the smallest values for each objective function is used. This reference sequence, of course, does not correspond to any possible scenario.

When applying SAW method, it is necessary to define the vector of weighted coefficients. Given the fact that economic objective functions have an importance greater than non-economic functions, the following vector of weighted coefficients can be selected

$$T=\begin{bmatrix}0.4 & 0.3 & 0.15 & 0.15\end{bmatrix}^T. \quad (17)$$

Using previously described nine-point scale expressing, the following pairwise comparison matrix can be selected for AHP method

$$C=\begin{bmatrix} 1 & 3 & 7 & 7 \\ 0.333 & 1 & 3 & 3 \\ 0.143 & 0.333 & 1 & 1 \\ 0.143 & 0.333 & 1 & 1 \end{bmatrix}. \quad (18)$$

Weight coefficients, which correspond to comparison matrix (18) are calculated using the logarithmic least square method, which gives:

$$W=\begin{bmatrix}0.6074 & 0.2296 & 0.0815 & 0.0815\end{bmatrix}^T. \quad (19)$$

Table V also contains the ranking of scenarios for different evaluation methods. Scenario 2 is obtained as optimal one in two of four used multiple attribute decision methods. Maximin method, which equally respects all criteria, gives the scenario 8 as an optimal, whereas scenario 2 is ranked as the second. The last row of Table V gives sum of scenarios ranking for each of decision methods.

Optimal solution is represented with scenario 2 which has investment value of 20200 €. If investment for the obtained optimal solution deviates much from planned value, then with modification of characteristic values of fuzzy numbers, weighted coefficients, and pairwise comparison matrix values, it can be obtained the different ranking of potential solutions.

TABLE V. RESULTS OF DIFFERENT MULTIPLE ATTRIBUTE DECISION METHODS.

Customer category	Scenario			
	2	**3**	**5**	**8**
fuzzy-grey	0.786	0.709	0.674	0.741
maximin	0.736	0.736	0.736	0.831
SAW	0.909	0.881	0.891	0.899
AHP	0.922	0.896	0.925	0.899
	Rank			
fuzzy-grey	1	3	4	2
maximin	2	2	2	1
SAW	1	4	3	2
AHP	2	4	1	3
Σ	6	13	10	8

V. CONCLUSIONS

In this paper a method for selection of optimal scenario for distribution automation is proposed. The 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. Under assumption that distribution automation devices can only be installed at the beginnings of service zones, all possible automation scenarios are searched, and the values of selected objective functions are determined. After that, the four different methods are applied for evaluating a set of alternatives in terms of decision criteria: hybrid fuzzy-grey method, maximin method, simple additive weighting method and analytic hierarchy process. Proposed method is demonstrated on test example of real medium voltage distribution network. It is shown that results of different evaluation methods are well matched. The optimal solution is finally selected considering results of all four applied evaluating methods.

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