Multicriteria Analysis of the Smart Grid Project Efficiency

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Abstract – **In this paper, the key performance indicators related to the smart grid efficiency have been analyzed. The authors are proposing multicriteria fuzzy AHP methodology for the determination of overall smart grid efficiency. After this evaluation, the ranking of different development alternatives including costs has been enabled. The methodology is illustrated on the choice of smart grid development strategy for the medium size power distribution company.**

Keywords –**AHP, Multicriteria analysis, Smart Grid**

I. INTRODUCTION

With the development of the Smart grid architecture, the perspective of the traditional energy indicators has changed, introducing new goals and objectives. Smart Grid generally refers to an electricity network that can intelligently integrate the actions of all users connected to it – in order to efficiently deliver sustainable, economic and secure electricity supplies. These systems are made possible by two-way communication technology and computer processing that has been used for decades in other industries. According to [1] main objectives of smart grids are: increased use of renewable electricity sources, grid security, energy conservation and energy efficiency, and deregulated energy market. Therefore, the strategy for sustainable, competitive, and safe energy primarily implies: competitiveness, use of different energy sources, sustainability, innovation, and technological improvement [2], while possible benefits brought by any smart grid initiative have to be evaluated by the degree of the approach to the ideal smart grid.

A measure of the contribution of projects to the ideal Smart Grid is quantified in terms of benefits, via a set of KPIs. The European Electricity Grid Initiative [3] has divided the ideal Smart Grid system into thematic areas (clusters) and is currently mapping Smart Grid projects into clusters. In USA, the ideal characteristics of the Smart Grid and a set of metrics to measure progresses toward the ideal Smart Grids has been defined [4]: build metrics that describe attributes that are built in support of a Smart Grid (e.g. percentage of substations using automation) and value or impact metrics that describe the value that may derive from achieving a Smart Grid (e.g. percentage of energy consumed to generate electricity that is not lost, or quantity of electricity delivered to consumer compared to electricity generated expressed as a percentage).

Due to the presence of both quantitative and qualitative criteria, and many uncertainties related to the smart grid operation environment, the paper proposes a new algorithm for the assessment of renewable energy integration in the smart grid, which uses the fuzzy AHP method for multi-criteria decision making. Based on fuzzy matching of alternatives, the method determines the optimal set of activities concerning smart grid projects. We proved that the method is highly successful in the evaluation of alternatives in the presence of heterogeneous criteria. After the brief overview of key performance indicators for the smart grid evaluation, the fuzzy AHP methodology has been presented. Finally, the methodology is illustrated on the choice of four different alternatives (of different size, location and technology) of distributed generator insertion in the IEEE 33 bus test radial distribution feeder.

II. SMART GRID ASSESSMENT

A. Smart grid evaluation metrics

The implementation of a Smart Grid is useful to achieve strategic policy goals, such as the smooth integration of renewable energy sources, a more secure and sustainable electricity supply, full inclusion of consumers in the electricity market, helping them to better understand their own energy use, which in turn allows consumers to identify energy saving opportunities.Smart grid and Advanced Metering Infrastructure (AMI) systems also could open up opportunities for energy management companies, hired by consumers, to use data from consumers' smart meters to identify opportunities for energy savings or to measure the success of energy savings measures after they are undertaken.For utilities, a better understanding of the electrical grid's status at a second-by-second level allows the grid to be operated at much tighter tolerances, resulting in greater efficiencies and reliability.

The characteristics of the ideal Smart Grids and defined metrics to measure progresses and outcomes resulting from the implementation of Smart Grid projects have been defined in [5]-[7]. The ideal Smart Grid has been defined in terms of characteristics in the US and in terms of services in the European Union, including:

- Enabling the network to integrate users with new requirements;
- Enabling and encouraging stronger and more direct involvement of consumers in their energy usage and management;

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- Improving market functioning and customer service;
- Enhancing efficiency in day-to-day grid operation;
- Enabling better planning of future network investment;
- Ensuring network security, system control and quality of supply

Together with the list of these services, the list of benefits has been identified deriving from the implementation of a Smart Grid.Smart Grid services and benefits are strongly linked to the policy goals that are driving the Smart Grid deployment (sustainability, competitiveness and security of supply), and consequently, they can be considered as useful indicators to evaluate the contribution of projects toward the achievement of these policy goals. A clearly defined framework can concretize where exactly the project contributed to a smart electricity grid.The mixture of quantitative and qualitative indicators is one of the major reasons for introducing the multi-criteria decision analysis techniques.

B.Multi-criteria assessment model

Starting from the list of main services and corresponding benefits (section*A*) in order to get a thorough understanding of the status of smart grid development,an adapted list of main criteria can be defined, including:

- Technology, covering all aspects of advanced services and new requirements imposed to the distribution and transmission network;
- Optimized asset utilization, including the costs reduction, enhanced efficiency and better planning of future investment;
- Customer satisfaction, encompassing different options of customer choice, new energy services and market participation;
- Environmental impact.

After the first level of benefits defined, the second set of performance indicators has been chosen, for the particular assessment aspects, out of the complete indicator list. For instance, the indicators that can be measured are: the quantified reduction of carbon emissions, voltage quality performance of electricity grids (e.g. voltage dips, voltage and frequency deviations and the level of losses in distribution networks (absolute or percentage). If new projects are evaluated, the net present value of the investment can be added. Qualitative indicators are the evaluated environmental impact and societal benefits of the project.

All indicators (quantitative and qualitative) are influencing all of four main criteria, according to the decision maker preferences. For instance, reduced voltage deviation and stable voltage profile in the network will enable the usage of advanced technologies and services; they will reduce the costs of low power quality, increasing the customer satisfaction.

The assessment framework proposed by [5] is based on a merit deployment matrix, where benefits and corresponding KPIs are reported in the rows, whereas functionalities (which are univocally linked to a service) are reported on the columns. For each project, the matrix is filled in two main steps:

a) Identify links benefits/KPI and functionalities. Select the corresponding cell.

b) For each cell, explain how the link between benefits/KPI and functionalities is achieved in the project. Assign a weight (in the range 0-1) to quantify how strong and relevant the link is.

However, the described method doesn't offer the tradeoffs between different criteria, which is the main reason of introducing advanced multicriteria methodology for the smart grid evaluation.

III. SMART GRID EVALUATION METHOD

In this paper fuzzy AHP method is used for the evaluation of efficiency of smart grid projects. Mathematical basis for fuzzy AHP method is based on fuzzy sets, fuzzy numbers and fuzzy arithmetic.

A.Fuzzy AHP method

The fuzzy AHP method involves the following steps:

Step 1. The overall goal (objective) is identified and clearly defined;
Step 2. The criteria, sub-criteria, and alternatives are identified;
Step 3. The hierarchical structure is formed;
Step 4. Pair-wise comparison is made using fuzzified Saaty's evaluation scale;
Step 5. The priority weighting vectors are evaluated using the Row Geometric Mean Method (RGMM);
Step6. Consistency of the judgments is checked by Geometric Consistency Index (GCI);
Step 7. The defuzzification and the final ranking of alternatives are defined.

In this study the fuzzy AHP method is applied to the ranking smart grid projects, as presented in the following text.

1. Goal identification. The goal is to evaluate the efficiency of the renewable energy plant integration in the smart grid context.

2. Identification of criteria, sub-criteria, and alternatives. Criteria for smart grid projects selection are: Technology, Costs reduction, Customer satisfaction, encompassing different options of customer choice, and Environmental impact reduction. Finally, the different smart grid projects are identified as alternatives.

3. Hierarchical structure formation. The Fuzzy AHP method presents a problem in the form of hierarchy: the first level represents the goal; the second level considers relevant criteria (four identified criteria); the third level considers relevant sub-criteria; and the fourth level defines smart gridproject alternatives.

4. Pair-wise comparison. Pairs of elements at each level are compared according to their relative contribution to the

elements at the hierarchical level above, using fuzzifiedSaaty's scale, as shown in Table I.

TABLE I
CRISP AND FUZZIFIED SCALE FOR PAIRWISE COMPARISONS [8]

Crisp values (x)	Judgment description	Fuzzy values
1	Equal importance	(1, 1, 1+δ)
3	Week dominance	(3-δ, 3, 3+δ)
5	Strong dominance	(5-δ, 5, 5+δ)
7	Demonstrated dominance	(7-δ, 7, 7+δ)
9	Absolute dominance	(9-δ, 9, 9)
2, 4, 6, 8	Intermediate values	(x-1, x, x+1)

In this paper fuzzification is implemented by triangular fuzzy numbers, and the value of fuzzy distance of 2 is used, as recommended in [8], because the most consistent results can be expected.

5. Priority weights vectors evaluation. The priority weighting vectors on each level are evaluated using the RGMM. The ranking procedure starts with the determination of criteria weighting vector:

$$W_c = (w_{c1}, w_{c2}, w_{c3}, w_{c4})^T \qquad (1)$$

wherew_{ci} is the fuzzy weight of i-th criterion:

$$w_{ci} = \frac{\left(\prod_{j=1}^{4} a_{ij}\right)^{\frac{1}{4}}}{\sum_{i=1}^{4}\left(\prod_{j=1}^{4} a_{ij}\right)^{\frac{1}{4}}},\ i = \overline{1,4} \qquad (2)$$

Sub-criteria weighting vectors are defined by pairwise comparison of performance indicators according to each criterion. Appropriate elements of these vectors are calculated as follows:

$$w_{sci}^{p} = \frac{\left(\prod_{j=1}^{6} a_{ij}\right)^{\frac{1}{6}}}{\sum_{i=1}^{6}\left(\prod_{j=1}^{6} a_{ij}\right)^{\frac{1}{6}}},\ i = \overline{1,6},\ \ p = \overline{1,4} \qquad (3)$$

wherew^{p}_{sci} represents the fuzzy weight of the i-th performance indicator with respect to the p-th criterion. The final sub-criteria weighting vector is obtained by multiplying the matrix of the sub-criteria weights according to all criteria (W_1) and the matrix of the criteria weights (Wc):

$$W_{sc} = W_1 \otimes W_c \qquad (4)$$

Finally, the projects are compared according to the each performance indicator. Proper weights of projects, i.e. alternatives with respect to the individual performance indicator are determined as follows:

$$w_{ai}^{r} = \frac{\left(\prod_{j=1}^{4} a_{ij}\right)^{\frac{1}{4}}}{\sum_{i=1}^{4}\left(\prod_{j=1}^{4} a_{ij}\right)^{\frac{1}{4}}},\ i = \overline{1,4},\ \ r = \overline{1,6} \qquad (5)$$

wherew^{r}_{ai} represents the fuzzy weight of the i-th project with respect to the r-th performance indicator. Final projects weights are obtained by multiplying the matrix of the projects weights according to all alternatives (W_2) and the matrix of sub-criteria weights:

$$W_a = W_2 \otimes W_{sc} = (w_{a1}, w_{a2}, w_{a3}, w_{a4})^T \qquad (6)$$

6. Consistency control. Consistency in this case means that the decision procedure is producing coherent judgments in specifying the pairwise comparison of the criteria, sub-criteria or alternatives. When the RGMM is employed as the priorization procedure, the geometric consistency index (GCI) is used for consistency control [9].

7. Defuzzification and the final ranking of alternatives. In this paper triangular fuzzy numbers are ranked by applying the mean value method. For the given triangular fuzzy number M=(a,b,c), the mean value method for defuzzification is defined crisp number value as follows:

$$m = \frac{a+b+c}{3} \qquad (7)$$

The highest rank has the alternative with the highest value m.

IV. CASE STUDY

The proposed methodology is illustrated on the choice of the technology, size and location of one distributed renewable generator. Four possible alternatives are evaluated on IEEE radial 33 bus test feeder, with parameters, including the nominal active power (P_{nom}), the node the generator is connected to (*Bus No*), type of renewable source (*RS*) and expected annual energy production of generator (*W*), represented in table II.

TABLE II
PROJECT SCENARIOS

Project	**P_{nom}**	**Bus Nº**	**RS**	**W (GWh)**
Project 1	1,8MW	6	Wind	5, 2
Project 2	1 MW	10	Biomass	7,0
Project 3	2 MW	17	Hydro	4,0
Project 4	1 MW	17	Biomass	5,00

Sub-criteria that are aggregated for this particular smart grid project including the renewable source integration, and their calculated values are presented in table III. The columns in the table are representing: (1) – project number, (2) - net present value of the project in millions of Euros, (3) – total voltage drop in percents, (4) – power losses in kW, (5) – reduction in CO_2 emission in tons per year, (6) – environmental impact and (7) – social benefits.

TABLE III
QUANTITATIVE AND QUALITATIVE PROJECT EFFICIENCY INDICATORS

(1)	(2)	(3)	(4)	(5)	(6)	(7)
Pr. 1	4,2	29,6	156,4	5 148	Moderate	High
Pr. 2	5,1	30,5	176,8	6 930	Moderate	Moderate
Pr. 3	2,7	22,0	265,3	3 960	Low	Very high
Pr. 4	3,8	26,3	190	4 950	Very low	Moderate

These four smart grid projects (Project 1, Project 2, Project 3and Project 4) are compared in relation to four criteria presented in section B, and six sub-criteria (SC) presented in TableIII. The pairwise comparison of alternatives in relation to performance indicators is presented in table IV with following abbreviations (BS-Basis of comparison; EI – Equal importance; WD Week dominance; SD – Strong dominance.)

TABLE III
QUANTITATIVE AND QUALITATIVE PROJECT EFFICIENCY INDICATORS

	SC1	SC2	SC3	SC4	SC5	SC6
A1	WD	EI	SD	WD	BC	WD
A2	BC	BC	WD	SD	EI	BC
A3	SD	SD	BC	BC	WD	SD
A4	WD	WD	WD	WD	SD	EI

The final fuzzy weights for smart grid projects, according to Equation(6) and the results of pairwise comparison of alternatives in relation to all performance indicators calculated from values given in Table II, are:

$$W_a = \begin{bmatrix} (0.0140,\ 0.2067,\ 3.3081) \\ (0.0121,\ 0.1589,\ 2.5160) \\ (0.0251,\ 0.3982,\ 5.0638) \\ (0.0176,\ 0.2363,\ 3.7016) \end{bmatrix} \quad (8)$$

The Project 1 is dominant in relation to the power losses, Project 2 – in relation to the carbon emission reduction, Project 3 – in relation to net present value of investment, voltage deviation and the societal benefits (however, it is the worst in relation to the power losses and the carbon emission reduction), Project 4 – in relation to environmental impact.

The final rank of the projects indicates that the highest rank has the Project 3, followed by the Project 4 and the Project 1; the lowest priority has the Project 2 (Equation 8). This means that for the implementation of the smart grid Project 3 should be selected.

V. CONCLUSION

To evaluate to what extent the smart grid projects are contributing to progresses toward the “ideal smart grid” and itsexpected outcomes (e.g. sustainability, efficiency, consumer inclusion), the new approach has to be adopted. In this paper, starting from a general set of smart grid performance indicators, a new assessment framework for the evaluation of smart grid project efficiency has been established,based on fuzzy AHP methodology.

The proposed methodology is illustrated on the choice of the optimal size, location and technology of renewable resources planned for the integration in the existing distribution network. Using four main criteria and six sub criteria derived from the adopted set of smart grid benefits, we proved that the method is highly successful in the evaluation of alternatives in the presence of heterogeneous criteria. This method allows the decision makers to incorporate unquantifiable information, incomplete information, non-obtainable information and partially ignorant facts into decision model.

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