ACCUMULATION SYSTEMS OF ELECTRIC ENERGY SOLVED BY MULTICRITERIA ANALYSIS METHODS IPA AND TOPSIS

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Summary This work deals with utilization of multicriteria analysis methods IPA and TOPSIS to assess three storage systems (Fuel Cells, Lead Acid Batteries and Pumped Storage Hydro Plants). Procedures of IPA and TOPSIS methods are described here as like as calculation of mentioned problem. Storage systems are assessed in terms of four criteria (Start up Time, Efficiency of Accumulation, Lifetime and Specific Costs/ kW of Power Output). Weights of criteria are also focused here. They are suggested by experts and statistically calculated.

1. INTRODUCTION

Installed capacity of wind power plants is growing in Czech Republic as like as worldwide. However power of wind which is available to generate electric energy is very difficult to predict and fluctuating. These effects force transmission system operators to provide regulating reserves which are generally kept in conventional power plants. Accumulation of electric energy can serve to reduce these demands. Pumped storage hydro plants are used as accumulator in power system. Lead acid batteries are used in power plants and in industry. Other systems are under research and development. Fuel cells, systems of compressed air (CAES), redox – flow batteries and heat accumulation belong to these category.

It is possible to use multicriteria analysis methods to choose optimal storage system in terms of appropriately selected criteria set.

2. CRITERIA PROPOSAL

Let's suppose that proposed storage system accumulates electric energy from renewable energy sources (wind power plants) that are connected to distribution network. Storage system works as peak source to make up for failure power in power system or in case of blackout. It is assumed that storage system will supply power approximately twice a day and every time for a period from 1 to 2 hours.

Assessing convenience of various storage systems we should consider criterion Efficiency of accumulation. Criterion Start up Time is important with regard to ability of storage system to retrieve sudden drop out of power of wind power plants or of power system. Criteria Lifetime and Specific Costs per kW of Power Output are important from economical point of view.

To gain information about importance of criteria we asked several experts about their opinion. We send them question-form to evaluate weights of proposed criteria. Weights of criteria according addressed experts are listed in tab. 1.

Tab. 1 Weights of criteria suggested by experts

	Criterion			
	Start up time	Efficiency	Lifetime	Costs 1000kč/ kW
Expert 1	40	25	5	30
Expert 2	25	35	25	15
Expert 3	41,67	25	16,67	16,67
Expert 4	30	40	10	20
Expert 5	35	30	15	20
Expert 6	40	40	15	5
Expert 7	60	20	16	4
Expert 8	40	30	15	15
Expert 9	60	20	16	4
Expert 10	16,67	16,67	0	66,67
Expert 11	35	10	25	30
Expert 12	10	20	20	50

Data listed in tab. 1 present random sample. To get "final" weights of criteria we must convert these data. We can use arithmetic average but we can also use more sophisticated methods to avoid affecting by outliers - for example median coordinate [1]:

$$\frac{x_i - med}{1{,}483 \cdot MAD} > 3 \qquad (1)$$

where x_i is investigated item of data set, *med* is median of data set and *MAD* is median of absolute deviation from median of data set.

$$m_s = 3 \cdot 1{,}483 \cdot MAD + med \qquad (2)$$

m_s is median coordinate. If $x_i > m_s$ then we must remove x_i from data set. After it arithmetic average is computed from data set.

Median coordinate method was applied on data set. No outliers were found out. So it is sufficient to compute arithmetic average. Weights of criteria are as follows.

f_1 Start up Time – v_1=36,11 %
f_2 Efficiency – v_2=25,97 %
f_3 Lifetime – v_3=14,89 %
f_4 Specific Costs/ kW of Power Output – v_4=23,03 %

It is important to keep in mind that criteria f_2 and f_3 are maximizing while criteria f_1 and f_4 are minimizing. This information is essential for subsequent proper solution.

3. VARIANTS PROPOSAL

a_1 Fuel Cells

Storage system based on fuel cells contains clean hydrogen processing fuel cells, electrolyser, inverter and rectifier, hydrogen tanks (eventually also oxygen tanks) and water reservoir. This system also includes other arrangements as like as compressors, electric fans etc. (Below in MCA we will think about PEM regenerative fuel cell which is fuel cell and electrolyser in one facility).

a_2 Lead acid batteries

These storage systems are based on commercially available lead acid batteries. Charger and inverter are also necessary for their operation.

a_3 Pumped storage hydro plants

Pumped storage hydro plant are proven to accumulation electric energy and contrary to lead acid battery systems and fuel cell systems they are used in electricity supply system for storage larger amounts of electric energy. Installed capacity of these arrangements is several hundred MW in Czech Republic.

Tab. 2 Enter data for MCA

	Criterion			
Variant	Start up Time (s)	Efficiency (%)	Life time (year)	Specific costs (1000 Kč/kW)
Fuel Cells	15 [3]	46 [2]	0,171 [3]	4,4 [6]
Lead Acid Batteries	0,004 [5]	65 [4]	20 [4]	4,2 [6]
Pumped Storage H.	100 [7]	75 [8]	40*	30,7 [8]

*Standard lifetime of an arrangement in electric power engineering

4. MULTI CRITERIA ANALYSIS (MCA) – IDEAL POINT ANALYSIS (IPA) [10]

The initial step of each MCA analysis is to form an evaluating matrix, the elements of which reflect the evaluation of particular criteria for each alternative. The matrix Y consists then of elements y_{ij} where $i=1,\dots,I$ alternatives and $j=1,\dots,J$ criteria.

The evaluating matrix:

$$Y = \begin{bmatrix} y_{11} & \text{K} & y_{1J} \\ \text{K} & & \text{K} \\ y_{I1} & \text{K} & y_{IJ} \end{bmatrix} \qquad (3)$$

Because particular evaluations are not measured against the same units, it is necessary to carry out the standardization of the matrix to the standard condition. For the case when the higher evaluation of the criterion means also the better evaluation (i.e. 1 = max, 0 = min) we can write the standardization as follows:

$$e_{ij} = \frac{y_{ij} - \min_i y_{ij}}{\max_i y_{ij} - \min_i y_{ij}} \qquad (4)$$

In the contrary case, when the higher evaluation means the worse evaluation (i.e. 1 = min, 0 = max), the standardization will be as follows:

$$e_{ij} = \frac{\max_i y_{ij} - y_{ij}}{\max_i y_{ij} - \min_i y_{ij}} \qquad (5)$$

The Ideal Point Analysis rests upon the deviation between the set of ideal solutions and the set of effective solutions. Although the ideal solution surely almost does not exist, it serves as an important reference model. The best compromise solution is determined as that solution that is the nearest to the ideal one. The increasing distance from the ideal solution for factors located upper on the scale of importance induces greater consequences than the increasing distance from the ideal solution for factors located lower on the scale of importance. The IPA model can be described as follows:

$$d_i = \sum_{j=1}^{J} v_j \cdot (1 - e_{ij}) \qquad (6)$$

where: d_i is the minimum distance from the ideal solution, v_j is the j-th weight of criterion and e_{ij} is the standardized evaluation.

We rank the alternatives according to the growing distance from ideal solution.

5. MCA - TOPSIS [10]

In case of TOPSIS method this is the question of principle of minimization of distance from ideal variant. The ideal variant means that all criteria have the best assessments. Ideal variant is mostly suppositional; the best of variants is that one which is the nearest to ideal variant. Vector $(H_1,H_2,\ldots,H_J)$ represents ideal variant, vector $(D_1,D_2,\ldots,D_J)$ represents basal variant.

The initial step is conversion of minimizing criteria to maximizing - when the higher evaluation means the worse evaluation (i.e. 1 = min, 0 = max), the standardization will be as follows [1]:

$$y_{ij\,\max} = \max_i y_{ij} - y_{ij} \tag{7}$$

Next step is construction of criteria – normalized matrix $R=(r_{ij})$, for calculation of normalized values is proposed following formula:

$$r_{ij} = \frac{y_{ij}}{\sqrt{\sum_{i=1}^{I} \left(y_{ij}\right)^2}} \tag{8}$$

After this transformation vectors with unit size are in columns of matrix R. The next step is calculation of criteria – weighted matrix W so that each j – th column of criteria – normalized matrix R multiplies by appropriate weight v_j.

$$W = \begin{bmatrix} w_{11} & \Lambda & w_{1J} \\ M & & M \\ w_{I1} & \Lambda & w_{IJ} \end{bmatrix} = \begin{bmatrix} v_1 r_{11} & \Lambda & v_J r_{1J} \\ M & & M \\ v_1 r_{I1} & \Lambda & v_J r_{IJ} \end{bmatrix} \tag{9}$$

Now we define the ideal variant $(H_1,H_2,\ldots,H_J)$ and the basal variant $(D_1,D_2,\ldots,D_J)$ respecting values of criteria – weighted matrix:

$$H_j = \max_i (w_{ij}) \tag{10}$$

$$D_j = \min_i (w_{ij}) \tag{11}$$

The next step is calculation of distance of variants from ideal variant:

$$d_i^+ = \sqrt{\sum_{j=1}^{J} \left(w_{ij} - H_j\right)^2} \tag{12}$$

and distance of variants from basal variant:

$$d_i^- = \sqrt{\sum_{j=1}^{J} \left(w_{ij} - D_j\right)^2} \tag{13}$$

The calculation of relative index of distance of variants from basal variant is following:

$$c_i = \frac{d_i^-}{d_i^+ + d_i^-} \tag{14}$$

We rank the alternatives according to the declining indicator c_i.

6. MCA APPLICATION AND RESULTS

First step is creating evaluating matrix from values listed in tab. 2.

$$Y = \begin{bmatrix} 15 & 46 & 0{,}171 & 4{,}4 \\ 0{,}004 & 65 & 20 & 4{,}2 \\ 100 & 75 & 40 & 30{,}7 \end{bmatrix} \tag{15}$$

Next steps vary depending on method which is used.

In case of IPA method we create matrix E according equations (4) and (5). Equation (5) is used for columns 1 and 4 and equation (4) is used for columns 2 and 3:

$$E = \begin{bmatrix} 0{,}85 & 0 & 0 & 0{,}992 \\ 1 & 0{,}655 & 0{,}498 & 1 \\ 0 & 1 & 1 & 0 \end{bmatrix} \tag{16}$$

According to the equation (6) d_i of each variant is computed:

Tab. 3 di index of assessed variants

Variant	d_i
Fuel Cells	0,464
Lead Acid B.	0,164
Pumped St. H.	0,591

We rank the alternatives according to the growing distance from ideal solution. So the first is variant Lead Acid Batteries, Second is variant Fuel Cells and third is Pumped Storage Hydro Plants.

In case of TOPSIS method, columns 1 and 4 in evaluating matrix must be adapted according to the equation (7), then members of R matrix are computed according equation (8):

$$R = \begin{bmatrix} 0{,}648 & 0{,}421 & 0{,}004 & 0{,}704 \\ 0{,}762 & 0{,}594 & 0{,}447 & 0{,}709 \\ 0 & 0{,}685 & 0{,}894 & 0 \end{bmatrix} \quad (17)$$

The next step is calculation of criteria – weighted matrix W according equation (9).

$$W = \begin{bmatrix} 0{,}234 & 0{,}109 & 0{,}001 & 0{,}162 \\ 0{,}275 & 0{,}154 & 0{,}067 & 0{,}163 \\ 0 & 0{,}178 & 0{,}133 & 0 \end{bmatrix} \quad (18)$$

We define the ideal variant according equation (10) and the basal variant according equation (11) respecting values of criteria – weighted matrix:

$$H = (0{,}275;0{,}178;0{,}133;0{,}163) \quad (19)$$

$$D = (0;0{,}109;0{,}001;0) \quad (20)$$

The next step is calculation of distance of variants from ideal variant according to equation (12) and distance of variants from basal variant according to equation (13) and the calculation of relative index of distance of variants from basal variant according equation (14):

Variant	d_i^+	d_i^-	c_i
Fuel Cells	0,155	0,285	0,647
Lead Acid B.	0,071	0,330	0,824
Pumped St. H.	0,320	0,149	0,318

We rank the alternatives according to the declining indicator c_i. So the first is variant Lead Acid Batteries, second is variant Fuel Cells and third is variant Pumped Storage Hydro Plants.

7. CONCLUSION

MCA comparing three storage systems was carried out. Storage systems were compared in terms of four criteria: Start up Time, Efficiency of Accumulation, Lifetime and Specific Costs/ kW of Power Output. There were used two MCA methods IPA and TOPSIS. In this case utilization of both these methods has similar output. There was found out that Lead Acid Batteries are the best possibility according specific criteria. The second one is variant Fuel Cells and third is variant Pumped Storage Hydro Plants. All of calculations including criteria weights were verified by MCA7 program.

Technical, economical and ecological parameters must be considered when new storage system is designed. Significance, capacity and integration storage system to electricity supply system also should be considered. Storage system must support stable and reliable operation of electricity supply system with minimal losses and optimal utilization of current distribution networks and transmission lines.

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