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Postprint

This is the accepted version of a paper presented at *International Symposium on Smart Electric Distribution Systems and Technologies (EDST) CIGRE SC C6 Colloquium, Vienna, Austria - September 8-11, 2015*.

Citation for the original published paper:

Pham, C-T., Månsson, D. (2015)

Suitability analysis of Fuzzy Logic as an evaluation method for the selection of energy storage technologies in Smart Grid applications.

In: *Smart Electric Distribution Systems and Technologies (EDST), 2015 International Symposium on IEEE*

<http://dx.doi.org/10.1109/SEDST.2015.7315251>

N.B. When citing this work, cite the original published paper.

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Suitability analysis of Fuzzy Logic as an evaluation method for the selection of energy storage technologies in Smart Grid applications

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Abstract—Energy storage systems are a key element in the development of the smart grid. The complexity of the power grid necessitates energy storages to provide various services with each having distinct requirements. Each energy storage technology comes with its own unique characteristics, which makes it difficult to select suitable energy storages for specified applications. This paper reviews the suitability of using Fuzzy Logic as a selection method. The main objective of this study is to compare the results of the multi-criteria analysis with the present experience and literature of energy storage applications.

Keywords—Energy Storage, Fuzzy Logic, Multicriteria Evaluation Method, Smart Grid Application

I. INTRODUCTION

The power grid, as we know it today, is a dynamic system undergoing vigorous changes over the past decades. These permanent changes are the result of occurring challenges and requirements, set by current events and needs for a clean, reliable, efficient and sustainable system. The driving factors for the Smart Grid encompass the interests of environmental issues, security and quality of supply and economic growth [1].

The increasing use of renewable energy sources (RES) such as wind and solar power has great impact on our energy infrastructure, which is predicted to reach a share of 35% in Europe's electricity generation in 2020, and presumably 50% by the end of 2050 [2]. One of the RES predominant attributes is the volatile availability of the resources, meaning that the power generation strongly relies on the environmental conditions. Due to this intermittency both the supply and demand sides are introduced to an inherent uncertainty in power balancing. Normally, those imbalances are compensated by operating reserves and/or ancillary services with short

response time. However, in the event of large-scale fluctuations the amount of those reserve services has to be likewise increased [3]. Another feature of RES is the widely spread geographical distribution in the power grid, especially seen for wind and solar power. This gives rise to decentralized power generation with multidirectional power flow, which adds up to the unpredictability of RES [4-6].

Energy storage systems (ESS) are a promising solution to these obstacles, as they can offer the benefit of managing energy more efficiently, making them indispensable when introducing RES into the power grid. ESSs are already being used in various grid applications such as load management, spinning reserves, and power quality etc. Each application requires different specifications, which the ESS needs to comply with in order to provide the necessary service. For instance, load management can require up to months of storage duration, whereas power quality services may only need a short amount of storage time, but necessitates very fast response in milliseconds instead [7,8]. Another point is that the technical criteria alone will not suffice the demands. Pumped-hydro storages (PHS) might be useful in terms of seasonal bulk storages, but are limited to geographical conditions, which makes them unsuitable for distributed installations. Other technologies such as batteries may technically be optimal, but fall out due to environmental risks, concerning handling and the end-of-life procedure. And even apart from that, many technically possible solutions may not be economically feasible [7-13]. Hence, finding the appropriate ESS for specified applications turns out to be a challenging task. So far, there is a lack of adequate methods to deal with the variety of parameters.

The current research shows that there is an interest and the need of finding a comprehensive evaluation method. Considerable effort has already been put in comparing various storage technologies by regarding their technical and economic aspects. For example, Schoenung and Hassenzahl (2003) analyzed the life-cycle costs of ESS including investment, operation, maintenance and recurrent costs [14]. Barin et al. (2009) proposed multi-criteria decision tools such as the Analytic Hierarchy Process (AHP) and the Fuzzy Logic as a method for selecting ESS for Power grid applications. In their study they pointed out the differences between both methods, applying them on a limited set of parameters [15]. T.U. Daim et al. (2014) went one step further, also using those methods, but considering a wider range of parameters. They included an expert pool as basis for the decision making comparing the ESS parameter to another [16]. A different attempt was presented by S. Raza et al. (2014). S. Raza suggested a sustainability index, a number generated from a weighted sum of different parameters, to measure the strength and weaknesses of a storage system [17].

This paper focuses on the Fuzzy Logic approach, evaluating the suitability of this method as a selection tool. The first part of the study concentrates on the model design including 12 different storage technologies. Those 12 storage technologies are then evaluated and ranked after their suitability at the example of two small-scale power grid applications (Power Quality and Energy Time-Shift). In the second part the results are compared with the experience in the field (i.e. literature review).

II. ELECTRICAL ENERGY STORAGE PARAMETERS

ESS parameters are divided into quantitative and qualitative values. In most cases properties can be represented as quantities, which allow us to easily describe the quality of ESS. Efficiency, energy density and energy cost are just some examples, where either the highest or the lowest value portrays the best quality. But not all parameters can be evaluated after “the higher the better” principle. For example, rated power and discharge time are quantitative characteristics describing the range of operation. In this case, the applicability of the ESS is measured in how far the operation range matches the requirements of the application. A basic way of classifying ESS is illustrated in Figure 1.

Qualitative parameters imply vagueness to their description. Those parameters are mostly represented in linguistic terms. Thereby, the interpretation of such values is subjective and the basis for these assumptions remains unclear, especially when it comes to comparing. For example, the environmental impact of ESS can be described in terms of positive, neutral or negative effects. It is reasonable to argue that pumped-hydro storages and battery systems affect our environment negatively as they potentially change landscape or contain toxic substances. But, this classification does not allow an accurate comparison between the two technologies [9,10]. One way to deal with qualitative expressions is to convert the linguistic terms into values and there has been an endeavor to comprise several factors into a single index as proposed in few studies in case of sustainability [17,21]. The other way is presented in this study using Fuzzy Logic (Chapter IV).

Figure 1: Applicability of Electrical Energy Storages adopted from [24]

As the development of the Smart Grid progresses, new opportunities for ESS emerge. This means that more and more factors have to be considered, which cannot be limited to technical and economic properties alone. Several independent studies suggest different parameters to be included, adding up environmental and social aspects to previous ones [15,16]. The assessment of ESS is then rendered difficult, increasing the need for a solid method to evaluate numerous parameters at once.

This paper studies only the applicability of the Fuzzy Logic method itself, focusing on just the technical properties. Additional parameters and ESS technologies can be included in future work. Further information on the ESS technologies is comprehensively summarized in the studies [7-12]. TABLE I. lists the technical properties of the investigated ESS. Note, the data given can vary from reference to reference as they include or exclude subcategories of each storage technology (e.g. high speed and low speed flywheels) which also operate under different conditions (e.g. stand-alone, hybrid configuration etc.).

III. POWER GRID APPLICATION

The application possibilities of ESS in the power grid are numerous e.g. power quality, uninterruptable power supply, load management etc. [11,22]. Note, that one ESS is not limited to one application only, but can be used for several applications at once [8]. Hybrid systems for the integration of RES are under investigation, showing promising results as presented in [19,20]. Here however, we only concentrate on the suitability of one ESS for one application at a time. Here, the ESSs are evaluated after their ability of preserving the power quality in the grid and their capability of energy time-shifting.

Power Quality (PQ) refers to a set of electromagnetic phenomena causing disturbances in the voltage level, frequency and waveform of the power system [21]. In this study we refer PQ to phenomena including variations in voltage (e.g. short-term spikes or dips), frequency fluctuations, harmonics and interruptions in the power supply [23]. Any deviation from the nominal set points can lead to losses, performance problems of the components or even to system failures.

TABLE I. TECHNICAL PROPERTIES OF ELECTRIC ENERGY STORAGES [7-14]

Technology	Properties							
	<i>Rated power</i>	<i>Response Time</i>	<i>Discharge Time</i>	<i>Efficiency</i>	<i>Cyclic Life</i>	<i>Lifetime</i>	<i>Storage Time</i>	<i>Self-Discharge</i>
	[MW]	[time]	[time]	[%]	[-]	[years]	[time]	[%/d]
PHS	100-5000	mins	1-24h+	65-85	20,000-50,000	30-60	hours-months	Very small
CAES	5-300	secs-mins	1-24h+	70-80	5000-30,000	20-40	hours-months	small
Flywheel	0-20	msecs-secs	msecs-hours	90-95	20,000+	15-20	secs-mins	100
Lead-Acid	0-100	msecs	secs-hours	70-90	200-1800	5-15	mins-days	0.1-0.3
NiCd	0-40	msecs	secs-hours	60-70	2000-3500	10-20	mins-days	0.2-0.6
NaS	0.05-50	msecs	secs-hours	75-90	~2500	10-20	secs-hours	Negligible
NaNiCl	0-0.3	msecs	secs-hours	85-90	2500+	10-14	secs-hours	~15
Li-Ion	0-100	msecs	mins-hours	75-95	1000-10,000	4-16	mins-days	0.1-0.3
Fuel cells	0-50	secs	secs-24h+	20-50	1000+	5-15	hours-months	Negligible
VRB	0.03-50	msecs	secs-10h	65-85	1000-13,000	5-20	hours-months	Small
SMES	0.1-10	msecs	msecs-8secs	80-95	10,000-100,000	20+	mins-hours	10-15
Capacitor	0-0.05	msecs	msecs-1 hour	60-70	50,000+	~5	secs-hours	40
Super-capacitor	0-0.3	msecs	msecs-1 hour	65-95	100,000+	8-20	secs-hours	5-40

Having a “good” PQ in a power grid is therefore of essence which involves securing the continuity of service, dealing with voltage fluctuations and unwanted harmonic contents in the waveform of AC. Disturbances have to be eliminated as fast as possible, usually requiring response times of milliseconds to seconds. The average storage time lasts around seconds. The ESS has to deliver high power in a short period of time, rather than large energy capacities [16,22,23].

Load management involves a set of application, where energy storages are utilized to balance the energy supply and demand. Classifying the load management then depends on the purpose of how the energy should be stored. For example, the intention behind load-levelling is to smooth out the overall electricity generation or load, by either storing excess energy or delivering in times of high loads. Energy time-shift (ETS) involves storing energy in times of low electricity prices and selling it at peak demand times. In this case, ETS serves economic benefits. Consumers can use ESS to regulate their electricity costs. According to M. Beaudin (2010) small-scale ETS requires at least four hours storage duration and rated power around 1-1000 kW [7,16,22,23].

TABLE II. POWER GRID APPLICATION REQUIREMENTS (POWER QUALITY&ENERGY TIME-SHIFT) [7,16,21,22]

	Properties					
	<i>Rated power</i>	<i>Storage Time</i>	<i>Discharge Time</i>	<i>Response Time</i>	<i>Life-time</i>	<i>Life-cycle</i>
PQ	100kW-10MW	secs	10secs-15mins	msecs-secs	10	~2000
ETS	1kW-1MW	4h+	1-6h	mins	15	~3750

TABLE II summarizes the available technical requirements of the applications. Self-discharge and efficiency are not listed in the table due to the lack of information, but are still assessed in the evaluation process. High conversion efficiencies are advantageous in PQ and ETS. However, the importance of self-discharge depends on the storage duration where high self-discharge ratios are still acceptable in PQ because of the short storage time.

IV. THE FUZZY LOGIC ANALYSIS

Fuzzy Logic was first introduced by Dr. Lofti Zadeh as an approach of computing input data based on “degrees of truth” rather than relying on Boolean logic (1 or 0). One can understand Fuzzy Logic as an approach of emulating human decision making. The idea behind this concept is to teach the computer system to deal with vague input data and process it in a way to achieve the desired outcome. Fuzzy Logic is used in many different applications ranging from industrial automation, ventilation and air-conditioning to whole subway systems. For example, the Sendai subway system has been highlighted as one of the most successful implementations of Fuzzy Logic [25]. Engineers had spent years to automate train operations based on traditional computer logic, which never led to satisfactory solutions. By using Fuzzy Logic they were able to effectively control acceleration and breaking of trains based on experienced train drivers, achieving energy savings and smooth starting and breaking.

For this study the Fuzzy Logic toolbox of MATLAB[®] is used. The model is based on the Mamdani controller [26]. The structure of the Fuzzy Logic can be described in three main steps (Fuzzification, Fuzzy Processing and Defuzzification) [27] (see Figure 2).

Figure 2: Fuzzy Logic control system

The first step is to translate the input data into numbers by defining grading functions, so called “membership-functions”. In other words, we grade our input data in a scale from 0 to 1 after defined criteria e.g. very low, low, medium, high, very high. Trapezoidal and triangular shapes are used as membership-functions. From the eight parameters in TABLE I. the mean values of lifetime, efficiency and number of cycles (cyclic life) directly serve as an input into the membership-functions, whereas for the rest (e.g. rated power, discharge time etc.) the data is rated from 0-1 according to the matching between the ESS range of operation and the applications requirements.

The second step involves interpreting the “fuzzified” numbers and compares them via rules, based on the “IF...THEN” concept. The number of rules is dependent on the number of membership-functions and parameters in one operation. In order to reduce the necessary rules, we compare two parameters pair-wise; take the output and compare it with the next parameter as presented in Figure 4. The rules are adjusted to the requirements of the applications listed in TABLE II in addition to the assumptions made for efficiency and self-discharge.

After comparison, the final result is achieved by reversing the fuzzification from the output function back into a number. The output function is generated out of the rules applied and then evaluated after the Center of Gravity (CoG) method [27]. This method chooses the value corresponding to the center of the area of the output function. The highest value then represents the best solution, in this case highest suitability of ESS for the application.

An example of Fuzzy Logic processing is shown in Figure 3. Outcome1 is compared with the parameter lifetime which generates Outcome2. An input with 10 years of lifetime would achieve a grading value of 0.33 low and 0.66 medium. If we assume an output value of 0.5 and the following rules in TABLE III two rules will apply:

- IF Outcome1 = Medium AND Lifetime = Low THEN Outcome2 = Low
- IF Outcome1 = Medium AND Lifetime = Medium THEN Outcome2 = Medium.

TABLE III. SET OF RULES FOR LIFETIME IN POWER QUALITY

	Lifetime		
Outcome 1	Low	Medium	High
Very low	Very Low	Very Low	Very Low
Low	Very Low	Low	Low
Medium	Low	Medium	Medium
High	Medium	High	High
Very high	High	Very high	Very high

Figure 3: Fuzzy Logic Processing Methodology

The output function combines the results of the applied rules. In rule 1 Outcome1 is 0.5 and lifetime is 0.33 which gives us 0.33 as the Outcome2 due to the logical AND operator. The second rule returns an output of 0.66. With both values we receive the following output function and the output value of 0.41 through the CoG method.

Figure 4: Fuzzy Membership-functions

TABLE IV. FUZZY LOGIC CLASSIFICATION FOR POWER QUALITY AND ENERGY TIME-SHIFT SCENARIO; COMPARISON WITH LITERATURE, WHERE $\checkmark$ AGREES AND $\times$ DISAGREES WITH THE SUITABILITY OF THE STORAGE TECHNOLOGIES FOR THE SELECTED APPLICATION

Power Quality				(small-scale) Energy Time-Shift			
Technology	Fuzzy Logic output	Literature		Technology	Fuzzy Logic output	Literature	
		$\checkmark$	$\times$			$\checkmark$	$\times$
1. Flywheel	0.75	[7,8,9,10,11,12]		1. Li-Ion	0.65	[9,10,11,12]	
2. NaS	0.68	[7,9,10,11,12]		2. NiCd	0.63	[9,10,11,12]	
3. Li-Ion	0.65	[7,9,10,11,12]		3. VRB	0.63	[8,9,10,11,12]	
4. NiCd	0.64	[7,9,10,11,12]		4. Lead-acid	0.58	[9,10,11,12]	
5. VRB	0.63	[8,9,10 ^{*1} ,11,12]		5. NaS	0.5	[7,8,9,10,11,12]	
6. Lead-acid	0.58	[7,9,11,12]	[8,10]	6. NaNiCl	0.5		[9]
7. NaNiCl	0.38	[9]		7. Fuel cell	0.36	[9,10,11,12]	
8. Super-capacitor	0.37	[7,8,9,10,11,12]		8. PHS	0.36	[7,8,9,10,11 ^{*2} , 12]	
9. Fuel cell	0.36	[10 ^{*1} ,12]	[9,11]	9. CAES	0.35	[7,8,9,10,11 ^{*2} , 12]	
10. Capacitor	0.33	[7,9,10,11]		10. SMES	0.25		[9,10,11]
11. SMES	0.25	[7,8,9,10,11,12]		11. Super-capacitor	0.25	[12 ^{*3}]	[9,10,11]
12. PHS	0.25	[8,12 ^{*3}]	[7,9,10,11]	12. Capacitor	0.25		[9,10,11]
13. CAES	0.25	[12 ^{*3}]	[7,8,9,10,11]	13. Flywheel	0.08	[12 ^{*3}]	[9,10,11]

^{*1} partly suitable for bridging power
^{*2} only large-scale level 1-100MW+, otherwise technically suitable
^{*3} partly suitable as ancillary storage

V. RESULTS: COMPARISON WITH LITERATURE

TABLE IV shows the final results and the ranking according to the two applications. In the PQ-scenario flywheels are ranked as the best option for this application, followed by various battery types down to pumped-hydro stations and compressed-air storages (CAES). Flywheels provide the best technical properties when it comes down to efficiency and cyclic life compared to batteries. Several studies support the results, although no ranking between the ESS technologies is stated. In a few cases such as capacitors and superconducting magnetic energy storages (SMES) the statements in the literature contradicts the results here. However, the range of application of capacitors and SMES is limited due to their technical maturity. Only few facilities with relatively low power rates exist. Current research on these storage technologies states that they show potential for PQ-applications, which is not yet reflected in the literature [11].

For SMES the discharge time range lies below the required range of PQ-applications, which result in a low output value. Capacitors on the other hand are excluded due to the low rated power, though all other parameters fit in very well. In this sense the discrepancy originates from the vague input data. PHS and CAES are not suitable for PQ as for their slow response.

VI. DISCUSSION

The results of the Fuzzy Logic method in most cases agree with the experience of used ESS technologies as described in the literature. Though, the results on capacitors and SMES in the PQ-scenario differ from the expectations, the problems can be traced back to the quality of the input data. For instance, SMES and capacitors are still uncommon and large-scale utility

is still scarce. Most of the parameters refer to existent facilities, meaning that SMES are currently being used in small power applications. But it does not imply that SMES will never be of interest in the future. Hence, for now the parameters do not reflect the potential of each technology.

Another problem concerns the design of the Fuzzy Logic model. The definition of the rules and membership-functions are subjective, which can alter the outcome significantly. The rules can partly be justified by the requirements for each application, but the shape of the member-ship functions relies on the experience of the user. Fuzzy Logic has been used in various situations dealing with control problems, but with the difference that the rules and functions are manipulated in a way to achieve a desired outcome. For the use as a selection method, this freedom of manipulation poses a threat to the validity of the results. A solution to this problem can be the consultation of an expert pool, whose consensus acts as a validation for the method.

VII. CONCLUSION

In this study, the model was kept as simple as possible but as accurate as believed needed. Overall, the results reflect the expert's opinion on the field and allow a basic ranking between the ESS technologies. Existing and also new storage systems can easily be implemented and compared through this approach. Fuzzy Logic shows potential as a basic selection method for ESS in smart grid applications. It has the advantage of flexibility and intuitive model design, which makes it very attractive as a basic reference. The next step includes additional economic and environmental parameters.

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