Fuzzy Logic Based Determination of Battery Charging Efficiency Applied to Hybrid Power System

Priyanka Paliwal, N. P. Patidar, and R. K. Nema

***Abstract*—**Battery storage system is emerging as an essential component of hybrid power system based on renewable energy resources such as solar and wind in order to make these sources dispatchable. Accurate modeling of battery storage system is essential in order to ensure optimal planning of hybrid power systems incorporating battery storage. Majority of the system planning studies involving battery storage assume battery charging efficiency to be constant. However a strong correlation exists between battery charging efficiency and battery state of charge. In this work a Fuzzy logic based model has been presented for determining battery charging efficiency relative to a particular SOC.

In order to demonstrate the efficacy of proposed approach, reliability evaluation studies are carried out for a hypothetical autonomous hybrid power system located in Jaisalmer, Rajasthan, India. The impact of considering battery charging efficiency as a function of state of charge is compared against the assumption of fixed battery charging efficiency for three different configurations comprising of wind-storage, solar-storage and wind-solar-storage.

***Keywords*—**Battery Storage, Charging efficiency, Fuzzy Logic, Hybrid Power System, Reliability

I. Introduction

RECENT years have seen tremendous growth in the renewable energy based generation. This can be attributed to increased environmental concerns, increasing oil prices, decreasing fossil fuel reserves along with increased government support. For the technology to sound and prove promising it should be able to deliver power in the volume needed and at the time needed. The intermittent nature of these sources is one of the greatest problems posed by them and has to be taken care of in order to maintain uninterrupted supply of power. The problems caused by the variable nature of these resources can be partially overcome by integrating the two resources in proper combination, using the strengths of one source to overcome the weakness of the other[1].Energy storage is a must with such systems for maintaining adequate levels of reliability and to make them more dispatchable. During the decision-making process of the planning phase, information regarding the effect of energy storage option on system reliability is required before it can be introduced as a decision variable in the long term planning model [2]. There is several battery models described in the literature. Yang et al [3] have presented a battery model for determining battery SOC, floating charge voltage and battery lifetime considering various factors such as self discharge rate, battery charge/discharge characteristics and battery capacity. The battery charging efficiency has been assumed to be constant. Lopez et al. [5] have focused on presenting a model for determination of battery lifetime, an approximate value of roundtrip efficiency has been assumed in the work. Zhou et al. [5] have carried out the analysis with battery storage assuming separate constant values of charge and discharge efficiencies. Teleke et al [6] have represented the battery by a third order model for modeling the charge/discharge characteristics and estimation of battery SOC.

Various battery models are also described in [7-12] however majority of them focus on Voltage, SOC, temperature and battery lifetime and do not take into account the variation of battery charging efficiency with respect to SOC. An approach to determine battery charging efficiency based on Peukert's equation has been used by Lu et al.[13].Stevens and Corey[14] have developed a test procedure for assessment of battery charging efficiency as function of battery SOC and have found that charge efficiency is a non-linear function of battery SOC.

Thus, it can be concluded from the literature review that researchers have invested significant efforts in developing battery models for determination of SOC, voltage and battery lifetime. However, evaluation of battery charging efficiency has not been given due consideration. The battery SOC varies significantly when it is in used in conjunction with the renewable energy sources due to their essentially variable nature. Thus assumption of a constant battery charging efficiency can lead to misleading analysis resulting in sub optimal system planning.

In the present work, a fuzzy logic based model has been used for determining battery charging efficiency in relation with battery SOC. The effectiveness of the proposed methodology has been demonstrated by conducting reliability evaluation studies for a hypothetical autonomous hybrid power system (AHPS) based on renewable energy sources and storage. The reliability evaluation is conducted using Analytical technique. The remainder of the paper is organized as follows: Section II of the paper briefly discusses the reliability evaluation of hybrid power systems incorporating

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storage using Analytical technique. In Section III, fuzzy logic based model for determining battery charging efficiency has been presented. Section IV elaborates the application of proposed approach to reliability evaluation of AHPS based on RES and storage. In Section V, relevant conclusions have been drawn.

II. Reliability Evaluation of Hybrid Power System Incorporating Storage

The reliability assessment of power system using analytical technique has been adequately dealt in literature owing to its superior computational efficiency over Monte Carlo Simulation [15-19]. The authors have developed a novel approach for implementation of analytical technique for hybrid system comprising of RES and storage and have duly validated the approach using MCS. The developed analytical technique has been utilized in this work, however due to space constraint the formulation has not been discussed in detail. The steps for carrying out reliability assessment are briefly discussed as follows.

A. Development of Hardware Availability Model

The hardware availability model is an array of output levels of generating units and the associated probabilities of existence based on their respective forced outage rates [15, 16]. The individual hardware availability models for each generating source are then convolved to develop an overall system hardware availability model which comprises of all possible combinations of output states of different generating sources.

B. Development of Renewable Energy Source Model

If the considered hybrid system configuration comprises of RES then adequate modeling of meteorological information such as wind speed, solar radiation & temperature is required in order to take into account the stochastic nature of these sources. The work presented in this paper models solar irradiance using standard Beta probability density function and wind speed using Weibull probability density functions [16]. The output power from PV modules corresponding to a particular state of solar irradiance and wind turbine corresponding to a particular state of wind speed are calculated as explained in [20].

C. Development of Probabilistic Storage Model

A novel probabilistic battery state model has been developed by the authors in order to apply analytical technique for reliability evaluation of hybrid power system incorporating battery storage. In the probabilistic battery storage model, Battery SOC, like wind speed or solar irradiance, is treated as a discrete random variable over each time frame. The probabilities associated with each wind speed or solar irradiance is obtained from their respective pdfs. However the probability of a particular battery SOC has to be evaluated based on the charge/discharge operation which the battery undergoes over each time frame. For every time frame the probability vector of battery SOC is updated depending on the power flows into and out of the battery.

The probabilistic battery model has not been discussed in detail in this work in order to avoid deviation from the topic. The focus of this work is to present a fuzzy logic based model for determination of battery charging efficiency.

D. Calculation of Reliability Indices

The probabilistic generation model, load model and for configurations incorporating storage, probabilistic storage model, are combined for calculating reliability indices.

The reliability indices of interest in this study are Loss of Load Expectation (LOLE) and Expected Energy not served (EENS).

III. Fuzzy Logic Based Determination of Battery Charging Efficiency

In this work, the effect of State of charge on the battery charging efficiency has been modeled through Fuzzy logic. Battery charging efficiency is a function of battery SOC, having a high value at low states of charge and drops off near full charge. In this work a Fuzzy logic based model has been presented for determining battery charging efficiency relative to a particular SOC.

A fuzzy system is a rule-based mapping of inputs to outputs for a system. Fuzzy system is regarded as a universal approximator [21]. Thus charging efficiency can be easily approximated using this approach.

The fuzzy model can he expressed in the form of rules of the type:

$$If \quad x \ is \quad A \ Then \quad y \ is \quad B$$

Where, x, y are linguistic variables and A, B are fuzzy sets. Each rule gives an estimation of the output y corresponding to input x according to the conditions defined by fuzzy sets. Fig. 1 shows the block diagram for implementation of Fuzzy Logic to determination battery charging efficiency.

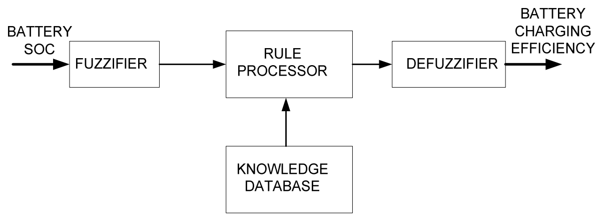

Fig. 1 Implementation of Fuzzy Logic for determination of Battery charging efficiency

The input variable in the present work is battery SOC and output variable is the battery charging efficiency.

Four membership functions are formulated for SOC. They are Very Low (VL), Medium (M), High (H), and Very high (VH). Four membership functions are formulated for Efficiency. They are VL, L, M and H. Fig. 2 and Fig. 3

represent the membership functions for input and output variable respectively.

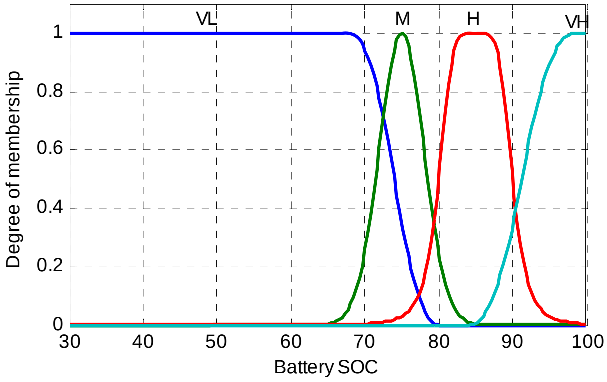

Fig. 2 Membership function plot for Battery SOC

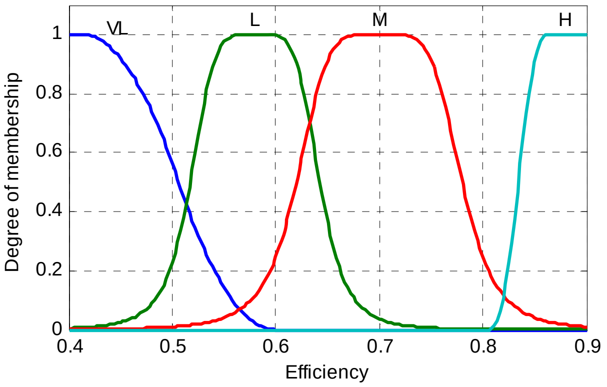

Fig. 3 Membership function plot for Battery Charging Efficiency

IV. Results and Discussion

In order to demonstrate the efficacy of proposed approach, reliability assessment study has been carried out for a hypothetical small AHPS located in Jaisalmer, Rajasthan, India. The effect on various parameters such as battery charge/discharge power, battery SOC and reliability indices is analyzed by considering battery charging efficiency as a function of SOC against considering constant value of battery charging efficiency.

The data for the solar irradiance and ambient temperature for the site has been taken from [22] and wind speed data has been obtained from [23]. The peak load of the AHPS considered in this study is assumed to be 70 KW and the chronological load shape has been obtained from [24]. The load is assumed to be constant for a particular time segment. Each time segment is assumed to be of one hour and thus the study period of one year comprises of 8760 time segments.

The specifications of PV modules rated 0.075kWp has been obtained from reference [25]. The details of Polaris 50 KW Wind turbine used in the study have been obtained from [26]. The technical data for GFM 1000Ah Lead Acid batteries used in the analysis has been taken from [27]. The nominal capacity of battery is 2V, 1000 Ah for each battery cell; 24 of them are connected in series to form a string which gives a nominal output voltage of 48 V. The maximum discharge current which the battery is capable of delivering in one hour is 550 A. Thus the energy rating of each string of battery is 26.4 kWh for one hour. The failure and repair rates of PV and WTG units have been taken from [19]. Battery storage system and Converters are assumed to be 100% reliable.

Three different system configurations have been considered as follows:

Configuration I: Wind and Storage

Configuration II: Solar and Storage

Configuration III: Wind, solar and Storage

The capacity of generating units and storage for different configurations is as given in Table I.

TABLE I
System Sizing for Different Configurations

Configuration	WTG Capacity (kW)	PV Capacity (kW)	Storage Capacity (kWh)
I	300	-	739.2
II	-	360	1135.2
III	250	30	739.2

Fig. 4, Fig. 5 and Fig. 6 compare the effect of considering constant charging efficiency assumed as 0.75 against the charging efficiency obtained relative to battery SOC for each time segment through fuzzy logic.

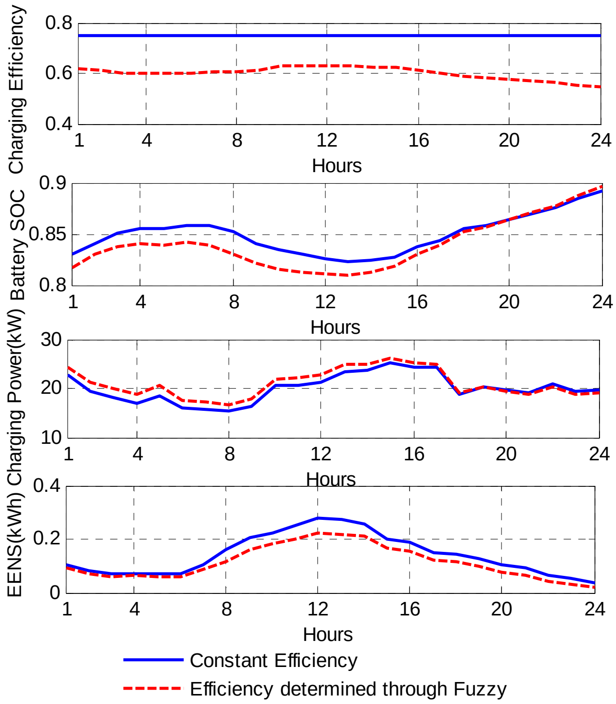

Fig. 4 Effect of Efficiency determined through Fuzzy on parameters of Configuration I

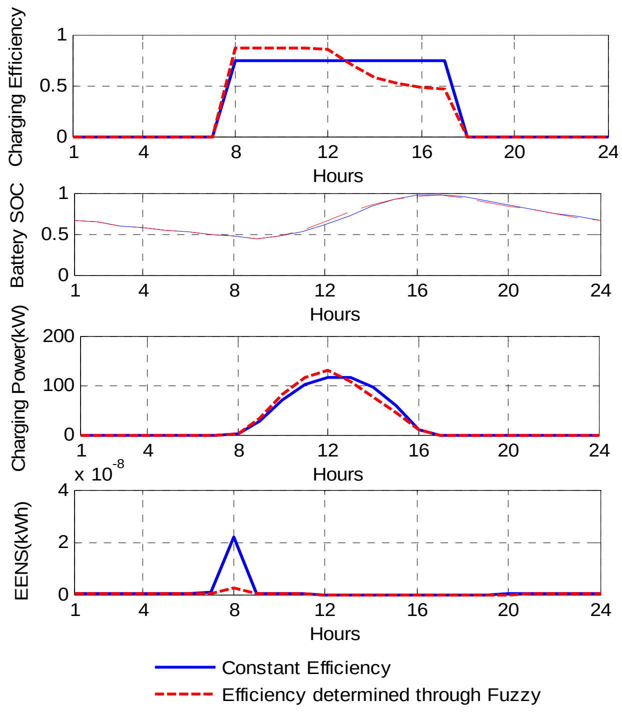

Fig. 5 Effect of Efficiency determined through Fuzzy on parameters of Configuration II

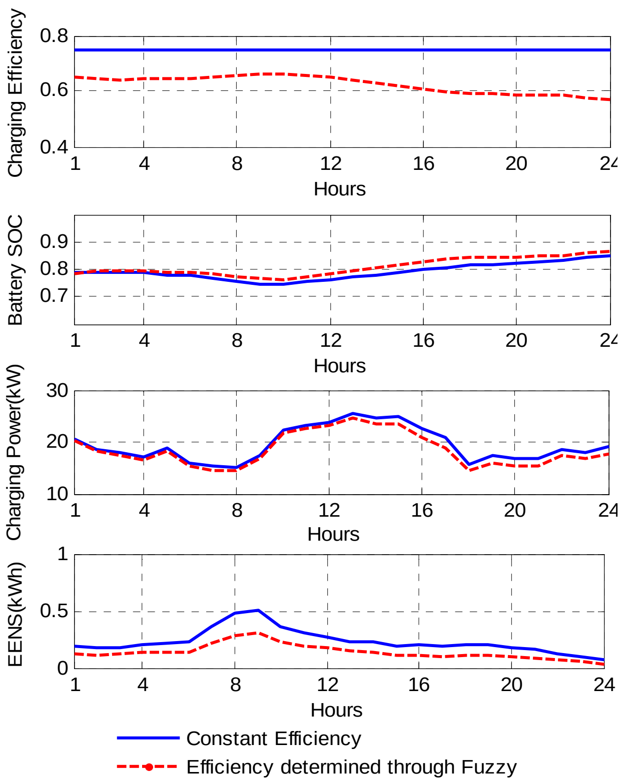

Fig. 6 Effect of Efficiency determined through Fuzzy on parameters of Configuration III

The analyses are shown for a typical day of winter month with respect to different configurations presented in Table I. Similar analyses are obtained for other time segments as well. The charging efficiency shown in the figures represent expected value of efficiency.

It can be observed from Fig. 4, Fig. 5 and Fig. 6 that charging efficiency obtained relative to battery SOC can be higher or lower than the constant assumed value of efficiency thus affecting charging power drawn by storage and consequently the energy availability in the battery. Since for renewable energy based systems, storage provides the requisite reliability back up, misinformation regarding energy availability in the storage can result in sub optimal planning.

This is further evident from Table II which shows a comparison of reliability indices obtained by assuming a constant value of efficiency and the efficiency obtained through proposed approach.

TABLE II
COMPARISON OF RELIABILITY INDICES

Configuration	EENS (kWh/year)		LOLE (Hours/year)	
	Constant Efficiency	Efficiency determined through Fuzzy	Constant Efficiency	Efficiency determined Through Fuzzy
Wind-Storage	175.24	158.35	7.81	7.026
Solar-Storage	4.72	0.3131	1.106	0.0714
Wind-Solar-Storage	220.48	142.5	11.25	7.44

V. CONCLUSION

This paper presented a fuzzy logic based model for determining battery charging efficiency relative to battery SOC. The effectiveness of proposed model is compared for three different hybrid system configurations for an AHPS. It has been observed that assuming a constant value of efficiency can hamper the efforts to come up with a well planned system.

The incorporation of battery charging efficiency as a function of SOC offers a more practical approach in system planning. Fuzzy logic based model for assessment of battery charging efficiency presented in this paper offers a simple solution to this problem.

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