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Design of Hybrid Renewable Energy Systems with Battery/Hydrogen storage considering practical power losses: A MEPoPA (Modified Extended-Power Pinch Analysis)

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A B S T R A C T

EPoPA (Extended-Power Pinch Analysis) is a technique to integrate Hybrid Renewable Energy Systems with Battery/Hydrogen storage. Power losses of the storage components due to their inefficiency have not been considered in EPoPA as of yet. This study proposes the MEPoPA (Modified Extended-Power Pinch Analysis) to modify EPoPA to consider the power losses in Hydrogen Storage System components. The MEPoCC (Modified Extended-Power Composite Curve) and MEPoSCT (Modified Extended-Power Storage Cascade Table) are introduced as the MEPoPA graphical and numerical tools to determine the minimum targets of Required External AC (Alternating-Current) and DC (Direct-Current) Electricity Sources as well as the Hydrogen Storage System component sizes. The sensitivity analysis is conducted to investigate the effect of various Hydrogen Storage System components, such as the inverter, converters, Fuel Cell, Electrolyzer and rectifier efficiencies, on the Hydrogen Tank Electricity Capacity and the Required External AC and DC Electricity Sources. The graphical and numerical results of the MEPoPA obtained from a case study showed that the system designed by MEPoPA requires 62.19% more outsourced electricity than the system designed by EPoPA. This means that the integration potential of the Renewable Energy System with Battery/Hydrogen storage is decreased with an increase in the power losses of the storage system.

1. Introduction

Finding RERs (Renewable Energy Resources), such as solar, wind, and biomass energies, as an alternative to fossil fuels for off-grid power generation has garnered increasing attention over the last few decades. The biggest problem inhibiting the utilization of Renewable Energy Resources is matching the intermittence of the power supplied by RERs with the dynamic load demand of the consumers [1]. This intermittence is due to the dependence of RERs on the unpredictable nature of weather and the climate [2]. This problem can be solved by the integration of two or more resources to form a HRES (Hybrid Renewable Energy System) and by utilizing appropriate energy storage systems. Among the many energy storage systems available, hybrid BH (Battery/Hydrogen) systems, which are a combination of a battery bank and a hydrogen storage system, have recently been used for Hybrid Renewable Energy System to form HRES-BH system that is a highly reliable and cost efficient off-grid system [2]. Several studies have been done by researchers to monitor, investigate and optimize the design and operation of the off- and on-grid HRES-BH systems using, mathematical modeling and, more recently, using Pinch Analysis [2] base on energy management strategies. Bruni et al. [3] found an optimal management strategy for the Fuel Cells utilization to evaluate the Hybrid Power System environmental performance. Fares and Webber [4] integrated a dynamic battery model with a mathematical program for economic operational management of the grid battery energy storage. Batista et al. [5] provided a new comprehensives field tests using open source tools for monitoring Hybrid Power System and home energy management. In

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addition to evaluation and monitoring of the Renewable Energy Systems by energy management strategies, different optimization approaches have been proposed by researchers. Ippolito et al. [6] applied an efficient MOO (Multi-Objective Optimization) algorithm to minimize the energy losses in the grid, the total energy generation cost and the green gas emissions. Niknam et al. [7] proposed a probabilistic approach for the energy and operation management of renewable micro grids under uncertain environment. Soares et al. [8] used an MOO to optimize the time allocation of domestic load in an energy management system. Further, Stoppato et al. [9] implemented a particle swarm optimization for the optimal energy management of a small PV-hydro energy storage system in a rural dry area.

The Pinch Analysis as an alternative of mathematical modeling can be used to address the optimum operation of the system based on energy management strategies. Indeed, implementing Pinch Analysis is simpler than using mathematical modeling and can provide good insights by graphical tools into system design. However, it cannot be applied graphically for multiple iterations and should be used in combination with mathematical tools in order to address the issue of iterations.

The Pinch Analysis is a family of methodologies for combining operations within a process or several processes to reduce consumption of resources and/or harmful emissions such as heat, mass, water, hydrogen, and power [10].

Recently, the PoPA (Power Pinch Analysis) technique has been proposed by Bandyopadhyay [11] to design an off grid PV/Battery system by combination of pinch and design space approach. The Power Pinch Analysis was also used by Wan Alwi et al. [12] to determine graphically the minimum outsourced electricity for Total Site Integration of an off-grid Hybrid Renewable Energy System. Wan Alwi et al. [13] later, applied ‘Outsourced and Storage Electricity Curves’ to determine current storage capacity. Ho et al. [14], and Mohammad Rozali et al. [15] proposed numerical methods based Electricity System Cascading Analysis to determine the optimal size of the battery system. Ho et al. [16] further considered conversion of AC/DC and weather variability to determine the renewable sources power generation. Giaouris et al. [17] proposed the use of the PGCC (Power Grand Composite Curve) method to identify energy recovery targets in renewable energy smart grid and to adaptively adjust their operation in short-term energy requirements through appropriately selected power management strategy. Mohammad Rozali et al. [18] introduced a new systematic generic framework to determine the most cost-effective storage technology for Total Site Integration of a Hybrid Power System.

Following Wan Alwi et al. [12] and Mohammad Rozali et al. [15], the EPoPA (Extended-Power Pinch Analysis) was proposed by Janghorban Esfahani et al. [2] to determine the optimal size of the Hydrogen Storage System components, including the Electrolyzer, Fuel Cell, and Hydrogen Tank, for a HRES-B (Hybrid Renewable Energy System combined with a Battery). They introduced the EPoCC (Extended-Power Composite Curve) to graphically determine the minimum outsourced electricity of the HRES-BH system, and used the EPoCA (Extended-Power Cascade Analysis) and EPoSCT (Extended-Power Storage Cascade Table) to numerically determine the minimum outsourced electricity and the optimal size of the hydrogen storage system. As investigated in the literature, among all researches the Power Pinch Analysis concept has been extended and used only by Janghorban Esfahani et al. [2] for hydrogen storage issues. However, the types of the generated electricity and consumed electricity including AC (Alternating-Current), and DC (Direct-Current) electricity as well as inefficiencies of the components have not been considered in their study.

Similar to conventional energy systems, energy losses occur in Renewable Energy Systems, especially in conversion stages (e.g., AC to DC rectifiers and DC to AC inverters) and in storage parts (e.g., battery, Electrolyzer, and Fuel Cells). Since the total delivered electricity to the consumer is greatly affected by the losses which subsequently decrease the systems' efficiency and reliability, power losses should be considered when designing a Renewable Energy System. Recently, Mohammad Rozali et al. [19] considered the losses in a Hybrid Power System with a lead-acid battery as the storage system. They extended the Power Pinch Analysis, developed by Mohammad Rozali et al. [15], and considered the power losses that occurred during the conversion, transfer, and storage of the electricity. In their research, the effect of the losses on the minimum outsourced electricity targets and the storage capacity were evaluated. Following Mohammad Rozali et al. (2013) research [19], Lee et al. [20] presented a generic mathematical optimization model for designing of the Hybrid Power Systems. In their model, power losses were considered during allocation of the generated power to the loads, which were formulated as a linear program.

As investigated recently in the literature, battery storage systems have been optimally designed by considering the power losses in Hybrid Renewable Energy Systems using Power Pinch Analysis and mathematical modeling. However, the power losses as well as AC–DC concept have not been considered during the optimal design of the Battery/Hydrogen storage system through graphical and numerical tools of EPoPA, presented by Janghorban Esfahani et al. [2]. Further, since in the HRES-BH system the electricity is transmitted from energy sources to demand loads through different energy flow routes with different amount of power losses, an algorithm different from that of proposed by Mohammad Rozali et al. [19] and Lee et al. [20] is needed to keep the overall power losses of the system as low as possible.

Therefore, this study aims to improve the EPoPA with the MEPoPA (Modified Extended-Power Pinch Analysis) by considering the efficiencies of the Hydrogen Storage System components and the AC–DC coupled system concept based an energy management strategy to high reliable design of a Hydrogen Storage System with an practical HRES-B system. The MEPoCC (Modified Extended-Power Composite Curve), used as the MEPoPA graphical tool, and the MEPoSCT (Modified Extended-Power Cascade Storage Table), used as the MEPoPA numerical tool, are introduced to determine 1) the Minimum External AC and DC Electricity Sources during the First Operation Year ($MEESFOY_{AC/DC}$), 2) the Accessible Surplus AC and DC Electricity for the Next (normal) Operation Year ($ASSENOY_{AC/DC}$), 3) the Required External AC and DC Electricity Sources ($REES_{AC/DC}$) during a normal operation year, 4) the WE (Wasted Electricity) sources during a normal operation year, and 5) the Hydrogen Storage System capacity. This paper consists of five major parts. First, the configuration of HRES-BH system and an energy management strategy for its operation are described. Second, a case study investigating the yearly operation is defined by considering the AC and DC electricity for the supply and demand loads. Third, the MEPoCC and MEPoSCT, as the graphical and numerical tools of MEPoPA, are constructed for Total Site Integration. Forth, the sensitivity analysis is carried out to investigate the effect of each component's efficiency on the HTEC (Hydrogen Tank Electricity Capacity), and Required External Electricity Source. Finally, the optimal system designed by MEPoPA and EPoPA for the case study is compared with respect to the hydrogen storage component capacities and to the Required External AC and DC Electricity Sources.

2. Methodology

2.1. HRES-BH system configuration

Fig. 1 shows the electricity flows detail and components in a HRES-BH. The AC electricity provided by a wind turbine and