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Modified Electric System Cascade Analysis for optimal sizing of an autonomous Hybrid Energy System

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A B S T R A C T

Ensuring sufficient generation for covering the power demand at minimum cost of the system are the goals of using renewable energy on isolated sites. Solar and wind capture are most widely used to generate clean electricity. Their availability is generally shifted in time. Therefore, it is advantageous to consider both sources simultaneously while designing an electrical power supply module of the studied system.

A specific challenge in this context is to find the optimal sizes of the power generation and storage facilities, which would minimise the overall system cost and will still satisfy the demand. In this work, a new design algorithm is presented minimising the system cost, based on the Electric System Cascade Analysis and the Power Pinch Analysis. The algorithm takes as inputs the wind speed, solar irradiation, as well as cost data for the generation and storage facilities. It has also been applied to minimise the loss of power supply probability (LPSP) and to ensure the minimum of the used storage units without using outsourced electricity.

The algorithm has been demonstrated on a case study with daily electrical energy demand of 18.7 kWh, resulting in a combination of PV Panels, wind turbine, and the batteries at minimal cost. For the conditions in Oujda city, the case study results indicate that it is possible to achieve 0.25 €/kWh Levelised Cost of Electricity for the generated power.

1. Introduction

In a Hybrid Energy System (HES), it is important to improve the system reliability by adding storage facilities, at the same time minimising the number of batteries because of their high cost and shorter lifetime compared to the other renewable energy technology used in HES.

Hybrid systems have the advantage of providing flexibility to the designer and users in choosing the rating of the wind and solar generators, based on particular site's resource availability and load conditions [1]. A set of methods was developed previously to improve the system, to maximise the power produced or decrease the cost of the system (installation and maintenance). Among these, Genetic Algorithm (GA) is used to optimise a hybrid system in the Palestinian Territories. The objective function minimises the Cost of Energy production while covering the load demand with a specified value for the loss of load probability (LLP) [2]. Particle Swarm Optimization (PSO) has been widely applied to the optimisation problems in a dispatch-coupled way and derives the optimal size of battery for systems with different penetration levels of renewables [3]. Akbar et al. [4] have presented a comparison between a set of three well-known heuristic algorithms: particle swarm optimisation (PSO), tabu search (TS) and simulated annealing (SA), as well as four recently invented metaheuristic algorithms: improved particle swarm optimization (IPSO), improved harmony search (IHS), improved harmony search-based simulated annealing (IHSBSA), and artificial bee swarm optimisation (ABSO), are applied to the system and the results are compared in terms of the TAC, for the maximum allowable loss of power supply probability $LPSP_{max}$ is also considered to have a reliable system. Diaf et al. [5] have presented configurations, which can meet the desired system reliability, are obtained by changing the type and size of the

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devices systems. The configuration with the lowest LCE represents the optimal choice. These design techniques can be used for small sites. But for a large site, some the obstacles can be noticed, including the calculation time, the great number of combinations.

Power Pinch Analysis (PoPA) method, based on the Pinch Analysis ideas [6] has been applied to set the guidelines for proper Hybrid Power Systems sizing [7]. Conservation, optimisation of the raw materials such as heat, mass, water, carbon, gas, properties and solids during the design process of the networks has been successfully achieved using Pinch Analysis [8].

Ho et al. [9] present a numerical method called the Electric System Cascade Analysis (ESCA). ESCA is developed based on Pinch Analysis principles and useful for designing and optimising systems for non-intermittent power generation based on biomass, biogas, natural gas, diesel, etc., also including energy storage for Distributed Energy Generation (DEG). Despite the advantages of ESCA, there are still several limitations to this approach. The technique assumes that in order to design and size the non-intermittent back-up generator, the worst case scenario without intermittent resource is considered. This is only applicable if the system consists of solar PV or solar thermal system.

Ho et al. [10] applied the ESCA methodology for designing and optimizing an intermittent DEG system or specifically a stand-alone solar PV system for isolated communities, the new ESCA was applied to optimize a solar PV system for an isolated rural house with daily energy consumption of 5.575 kWh.

Rozali et al. [11] developed two new digital tools PoPA (Power Pinch Analysis) known as Power Cascade Analysis (PoCA) and the Storage Cascade Table (SCT). The tools can be used to determine the minimum outsourced electricity supply and the available excess electricity, the maximum storage (e.g. Battery), the battery capacity of the stand-alone system, the amount of electricity demand necessary to be outsourced each time interval and the time interval in which the maximum power occurs. While graphical techniques provide an overview and useful visualisation, numerical tools provide faster and more accurate allocation of power and they enable to set goals for optimisation. Wan Alwi et al. [12] determine the minimum electricity targets via the introduced graphical representation of composite electricity variation with time, providing a useful visualisation tool for energy managers, electrical and power engineers called PoPA. Rozali et al. [13] showed how PoPA can reduce the storage capacity, also accounting for the losses during the electric conversion (DC/DC or AC/DC) and charging/discharging of the battery. Maximising the use of renewables with variable availability, which is frequently a key issue for using renewables, has been studied by Nemet et al. [14]. The main goal of this group of the methodologies is the reduction and possibly minimisation of Greenhouse Gas (GHG) [15] and Nitrogen footprints [16]. GHG footprint contributes to global warming and Nitrogen footprint to both global warming and creating of the haze [17].

In previous work [18], the ratio of the power generation between two sources (PV and wind turbine) were determined according to the climate conditions alone. The ESCA method was applied for the optimal design of hybrid systems taking into account the climatic conditions of the site, to minimise the total storage capacity and the analysis time is 24 h. However, the decision on this ratio should also account for the costs – most notably those for investment and maintenance.

This paper presents the modelling and optimization for stand-alone hybrid solar-wind systems for electrification of a remote area located in the vicinity of Oujda, Morocco. The ratio of solar to wind capture is based on the minimum of the total annualised cost of the system and the climate conditions of the site. The maximum allowable loss of power supply probability and the Power pinch analysis are implemented together to optimise the sizing of the hybrid system. For the newly proposed method, a Modified ESCA (MESCA) algorithm is introduced for each system's component with their electrical parameters and discrete based Power Pinch Analysis as a guideline. For performance evaluation, the MESCA method begins with a search of the optimal sizes of the electricity generation and storage facilities, which would minimize the total annual cost (TAC) and will still satisfy the demand, and then to optimize the number of each component (Photovoltaic Panels PVPs, Wind turbines and batteries). The Final Excess of the energy (FEE) and the Total Annual Cost (TAC) are considered as the objective functions and the MESCA is employed to find the optimal number of the system components, but take in consideration the climate conditions for each remote area chosen.

2. Methodology

When two or more forms of energy supply are used in combination, the energy system is referred to as a hybrid one. In the current article two forms of renewable energy are considered – solar and wind. The idea of combining them is to provide increased system efficiency as well as greater balance in energy supply.

2.1. Hybrid Energy System

The system in this work uses a number of components – wind turbines, PV Panels, converters (DC/DC, AC/DC and DC/AC), DC bus and an electricity storage unit (Fig. 1). The combination of the two renewable types allows them to complement each other in terms of capture in time and facilitate the efficient operation of the system. Photovoltaic and wind generators can work together to meet the load demand with a voltage adaptation depending on the load. The MESCA method is applicable to whatever the chosen architecture is. For the specific cases, the appropriate conversion efficiencies should be specified. The connection of all energy sources to a DC bus simplifies power management, based on the fractions of the energy production from renewable sources (PV system 62% and wind system 38%).

When the capture of renewable energy (solar and wind) is in excess, the remainder after meeting the load demand is used to charge the battery, until the latter it is fully charged. In contrast, when energy generation is insufficient, the battery releases power to help covering the load requirements, until storage is exhausted.

2.2. Modified Electric system cascade analysis

Based on Power Pinch Analysis, the presented method is an extended adaptation of the ESCA [10] method for isolated systems relying on renewables. The first step of MESCA requires the extraction of relevant data for analysis. The list of data includes time period of analysis (design horizon), hourly energy demand, hourly wind speed and solar radiation, type of the PV panel, power generation capacity of a single solar PV module, solar PV module

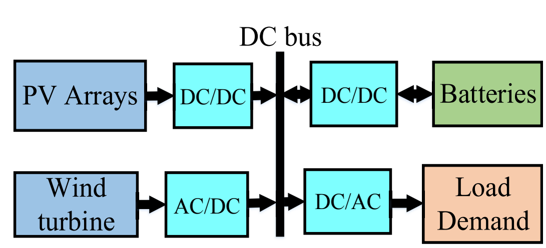

Fig. 1. Overall configuration of the system.