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A review on planning, configurations, modeling and optimization techniques of hybrid renewable energy systems for off grid applications

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ABSTRACT

Hybrid renewable energy (HRE) system based power generation is a cost effective alternative where power grid extensions are expensive. This system utilizes two or more locally available renewable energy resources such as wind, solar, biomass, biogas and small hydro power with or without conventional fossil fuel energy sources to create standalone mode to meet the energy needs in rural remote areas. This study offers a comprehensive review of the research work carried out in planning, configurations, and modeling and optimization techniques of hybrid renewable energy systems for off grid applications. Hybrid renewable system utilities today are more dependent on an optimal design to minimize the cost function. This paper presents a review of various mathematical models proposed by different researchers. These models have been developed based on objective functions, economics and reliability studies involving design parameters. The present study will familiarize the reader with various optimization techniques of system modeling and enable them to compare these models on the basis of their cost functions. Researchers may consider the most suitable model from the various hybrid renewable system models proposed in this study to develop customized designs for optimizing system size while incurring least cost.
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1. Introduction

In a developing country like India, majority of the population live in remote rural areas and a number of small isolated communities in such areas live without access to electricity from the power grid [1]. Extension of the grid to these remote regions is not cost-effective or feasible. It is therefore necessary to find alternative power solutions that could be employed in place of the power grid. Possible options for off grid rural electrification include single technologies and hybrid based power generation [2]. Hybrid based energy systems have proven effective in supplying the required electrical load in off grid applications. The most important characteristic of an HRE system is that it utilizes two or more renewable energy sources with or without connecting to conventional generators which improves system efficiency and reliability, and overcomes the economic limitations arising from single renewable energy sources [3–5]. Further, HRE systems are becoming increasingly popular for decentralized power generation at remote sites due to improvements in power converter and renewable energy technologies which enhance system efficiency [6,7]. However, many remote areas have insufficient renewable energy resources and it becomes necessary to use conventional options like diesel/petrol/gasoline based generator to complement the available renewable energy resources in order to meet the load demand [8–10]. It is clear that the decision of employing only HRE systems or using HRE system in combination with diesel/petrol/gasoline based generator depends on the availability of the renewable energy resources in the considered region. Any intended plan to set up a power plant must consider the availability of renewable resources in the considered area. Next, several alternative plans must be developed out of which the most suitable one should be selected [11–14].

To utilize the available renewable energy resources efficiently and economically, optimal models are required to be developed based on prediction of the renewable energy resources data using suitable techniques [15]. Thus, decentralized energy planning entails discovering a set of resources and power conversion devices to fulfill the energy needs of an optimally modeled system in a cost-effective and efficient manner while ensuring quality and reliability [16,17].

The modeling of an HRE system is a very complex task which requires the development of mathematical models for each component. The mathematical models of renewable energy sources need to be optimized through various optimization techniques in order to minimize total system cost of the hybrid energy system [18–21]. The selection of optimum combination of HRE system components depends on the reliability and economy of the components. Where there are multiple well-defined hybrid system models, the model which provides consistent and adequate power at lowest cost is selected [22,23]. Different geographical areas have specific renewable energy resources which vary according to season. This random nature of natural resources warrants the making of a hybrid system configuration that would extract maximum possible energy from these resources so that the supply of energy from such a system is uninterrupted and consistent. To this end, it is necessary to develop a well-defined hybrid based model for combining natural resources with or without conventional fossil fuel energy resources to form a micro-grid used in off-grid applications [24].

The present study aims to address the issues related to HRES with a detailed review of system planning, mathematical modeling, optimization and other aspects of economic and reliability based models. The paper is structured as follows: Section 2 presents schemes and summaries of different hybrid renewable energy systems in off-grid applications; Section 3 discusses the works carried out on system planning with a summary of various HRE systems; Section 4 presents different mathematical modeling and optimization techniques based objective functions aimed at developing a cost effective design, as well as a summary of the HRE systems; Sections 5 and 6 present an economic and reliability based model for evaluating the least costs and optimal sizes, with a summary of the HRE systems; finally, conclusions are made based on the extensive review of the hybrid renewable energy systems.

2. Hybrid renewable energy system configurations for off grid applications

Renewable energy resources randomly occur in nature and, to make a standardized framework, these resources are integrated to construct a hybrid system configuration for fulfilling the energy requirements of consumers in distant areas. Appropriate interfacing power conversion circuits and controllers to the AC bus, reduces the number of power conversion stages and losses in power transferred to the load/utility [25]. The assortment of schemes with their merits and demerits of various hybrid renewable energy configurations in off grid applications are discussed below:

2.1. DC-coupled HRE configuration

In a dc-coupled configuration, the dc renewable energy resources may be connected, either directly or through a dc/dc power converter, to a dc bus line to which the dc loads are connected. The ac renewable energy resources are connect with the same dc bus line through an ac/dc power converter. This system's configuration can also supply ac power to the ac loads through a dc/ac converter. The storage system can also be connects to the dc bus line through a bi-directional converter to supply dc power to the dc loads in response to the demand. Fig. 1 shows a schematic representation of an off grid dc-coupled HRE system [24,26–29].

2.2. Power frequency ac-coupled HRE configuration

In power frequency ac-coupled configuration, an ac renewable energy resource may be connected, either directly or through an ac/ac power converter, to the power frequency ac bus line to which the ac loads are connected. The dc renewable energy resources are connected through a dc/ac power converter to the same bus line. This system configuration can also be used to supply dc power to dc loads through an ac/dc converter. A schematic of an off grid power frequency ac-coupled HRE system is shown in Fig. 2 [24,27–29].

2.3. Hybrid-coupled HRE configuration

The hybrid-coupled hybrid configuration has both the dc and power frequency ac bus lines. In this configuration, an ac renewable energy resource is directly connected to the power frequency ac bus line and the dc renewable energy resources is connected to the dc bus line through proper power converters. This can reduce the conversion losses and eliminate the use of converters in the configuration. As a result, a hybrid-coupled hybrid system configuration minimizes the cost and increases the system efficiency as compared to the ac and dc coupled configurations. But a hybrid coupled configuration is relatively complex in terms of control and energy management. A schematic representation of a hybrid-coupled HRE system is shown in Fig. 3 [11,24].

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