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A novel smart grid theory for optimal sizing of hybrid renewable energy systems

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Abstract

Smart grid enables interaction between the generation and load to optimally deliver energy based on the operating conditions. Although smart grid solves many of the contemporary problems, it gives rise to new control and optimization problems especially with the growing role of renewable energy sources. Load shifting technique has been applied in this paper by dividing the load into two categories, high priority load (HPL) and low priority load (LPL). HPL is that must be supplied whatever the generation conditions, but LPL can be supplied when the generation from renewable sources is available. This paper introduces a new proposed design and optimization program for techno-economic sizing of standalone hybrid PV/wind/diesel/battery energy systems under smart grid theory for the lowest cost of generated energy at highest reliability. An accurate methodology for pairing between five Saudi Arabia sites and ten wind turbines (WTs) from different manufacturers to maximize energy production and minimize the price of kWh generated has been introduced. The new proposed program is implemented in flexible fashion which is not available in many market available programs. Many valuable results can be extracted from the proposed program that could help researchers and decision makers.

Keywords: Smart grid; Hybrid renewable energy systems; Load shifting; Load priority; Sizing; Optimization

1. Introduction

Nowadays, increasing energy demand and dependence on exhaustible fossil fuel became important issues facing the energy sector in the whole world. Therefore, there is a big trend to use renewable energy sources (RES) to address the electricity generation especially in remote communities. Using many RES can increase the system reliability and reduce the cost of generated energy considerably. But, as the penetration of RES increases, serious improvements and modifications for the existing electric grid would be needed to accommodate and integrate these intermitted nature sources (Posadillo and Luque, 2008). Smart grid system is used to add management, control and communication capabilities to the national electrical delivery infrastructure to move electricity around the system as efficiently and economically as possible (Datta et al., 2014). Hybrid renewable energy system (HRES) integrated into smart grid system need an accurate and optimum design, matching between sites, PV cells, WT types, and sizing of each component to minimize the cost of the generated energy and maximize the system reliability. Several approaches

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were developed to achieve the optimal configurations of HRESs and demand profile shaping based on smart grid theories (Conejo et al., 2010; Caron and Kesidis, 2010; Mohsenian-Rad and Leon-Garcia, 2010; Barley et al., 1997). Optimal configuration and demand profile shaping can be carried out by adjusting the hourly load level in response to the hourly electricity prices (Conejo et al., 2010). Incentivizing consumers to achieve a synoptic load profile was one of the solutions has been used to get an ideal load profile suitable for utilities depending on how much information did the utilities share (Caron and Kesidis, 2010). Mohsenian-Rad and Leon-Garcia (2010) proposed an optimal and automatic scheduling framework for residential energy consumption. The authors have used linear programming optimization, to achieve a trade-off between minimizing the electricity payment and minimizing the waiting time for the operation of loads in presence of a real-time pricing tariff. Sizing of the HRES components and control of the generated energy price have been accomplished in Barley et al. (1997) based on the trade-off between the system cost and the percent unmet load using Hybrid2 software in conjunction with a simplified time-series model. Most of the optimization approaches described above depend on the user efforts or incentivizing users to improve the load profile or decrease peak demand to be suitable for utilities that makes it difficult to be achieved. Also, most of these approaches depend on the presence of a real-time pricing tariff for cost or peak demand reduction which is not an ideal solution.

This paper introduces a new proposed program (NPP) using load shifting as one of smart grid principles for sizing the components of standalone HRES in order to meet the load demand with the lowest cost of the generated energy (LEC) and lowest loss of load probability ($LOLP$). Two types of loads based on priority have been considered, high priority load (HPL) and low priority load (LPL). HPL should be supplied from any available sources (renewable, battery or conventional), while LPL is that can be fed from surplus generation time of RES. Demand profile improvement has been carried out by shifting the LPL from low generation to high generation time. The logic used in this program is designed to follow the $LOLP$ and the dummy energy to satisfy the aggregate load demand with minimum value of LEC. PV area (PVA), number of wind turbines (NWT), diesel generator size (DG), battery capacity and LEC were the optimization parameters in this program. Diesel generator rated power, maximum and minimum value of battery state of charge; $E_{B,max}$ and $E_{B,min}$ have been sized to insure the load demand in the time of deficit generation. Hourly data of wind speed, solar radiation, temperature and load power for five sites in Saudi Arabia and ten WTs from different manufacturers have been used as the NPP inputs. The sites used in this study are Yanbu, Dhahran, Dhalm, Riyadh and Qaisumah. The penetration ratio (the ratio of wind generation to the total renewable generation) has been changed with certain increments to meet the load requirements of the sites under study. Applying NPP, the best site and the most economic WT for the selected site can be determined. Furthermore, a detailed economical methodology to calculate the price of generated energy has been introduced.

2. Mathematical modeling of the hybrid system components

The configuration used in this paper consists of wind energy subsystem, PV energy subsystem, DG, battery bank, charge controller, bi-directional converter, HPL, LPL and dummy load as shown in Fig. 1. The dispatch of this configuration is easy to be understood where the HPL is supplied primarily from WTs and then PV, respectively. The excess power from wind energy subsystem or/and PV energy subsystem above the HPL demand is stored in the battery until the battery is fully charged. If the battery is fully charged, the excess power will be used to supply the LPL. The excess power above the LPL demand (i.e. dummy power) will be used to supply certain special loads (dummy loads), such as cooling and heating purposes, water pumping and charging batteries of emergency lights. If the power is not sufficient to supply the LPL, the unmet LPL will be shifted to the time of surplus generation. When the HPL demand is greater than the generated power, the deficit power will be compensated by the batteries unless the batteries reach $E_{B,min}$. When the battery storage is exhausted and the HRES fail to meet the HPL demand, the DG will be in service. For a good performance of the HRES, each component has been designed and modeled as explained in the following subsections.

2.1. Wind energy subsystem model

Wind resources and electric power output from WT at a particular location depends on wind speed at hub height, the WT speed characteristics and the type of land surface. Wind speed at hub height can be determined from the following equation (Yeh and Wang, 2008):

$$u(h) = u(h_g)\left(\frac{h}{h_g}\right)^{\alpha} \tag{1}$$

where $u(h)$ is the wind speed at hub height, m/s, $u(h_g)$ is the measured wind speed, m/s, and α is roughness factor. The value of α differs from site to site and from time to time in the same site (Yeh and Wang, 2008). In this paper α has been taken by (1/7).

The actual WT output power, P_W can be calculated from the typical power curve characteristics of the WT as the following (Lepa et al., 2008).

$$P_W(u) = \begin{cases} 0, & u < u_c \text{ or } u > u_f \\ P_r \frac{u^2 - u_c^2}{u_r^2 - u_c^2}, & u_c \leqslant u \leqslant u_r \\ P_r, & u_r \leqslant u \leqslant u_f \end{cases} \tag{2}$$

where P_r is the rated WT output power; u_c is the cut-in wind speed, u_r is the rated wind speed, and u_f is the cut-off wind speed.