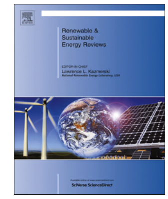
Renewable and Sustainable Energy Reviews 44 (2015) 436–446

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser



A review of process and operational system control of hybrid photovoltaic/diesel generator systems

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A R T I C L E I N F O

Article history:
Received 26 January 2014
Received in revised form
5 December 2014
Accepted 25 December 2014

Keywords:
Photovoltaic
Hybrid photovoltaic system
Diesel generator
Operational control

A B S T R A C T

Integrating renewable energy resources such as photovoltaic system with diesel generator in a hybrid power system is widely spread in the worldwide due to the economic and technical aspects. These systems prove their feasibility in the remote areas, where the grid extension is not available. An optimum dispatch strategy for these systems is a very important factor that affects the cost of the energy generated. Therefore, the main objective of this review is to show the state of art of hybrid photovoltaic/diesel generator system control strategies. Research work in the period of 1998–2014 is covered and analyzed. In addition to that, a summary of the latest technologies in this field is provided. Finally, challenges to this science are concluded. These challenges are accurate estimation of load demand and meteorological data, system performance prediction, system's component models, optimal sizing of the system and operation set points optimization. In optimizing the operation set points there are many aspects to consider such as system reliability, emitted emission by the system and the cost of the energy generated.

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1. Introduction

Renewable energy based power systems are considered reliable, cost-effective and environmentally friendly power systems. These systems can utilize local renewable energy resources at high security levels especially in remote areas [1]. Renewable energy resources (RERs) such as solar, wind, biomass, hydroelectric, ocean and geothermal energy proved their effectiveness and efficiency in supplying electrical power at acceptable prices [2,3]. For a remote area, having an independent energy source and decreasing the transmission line losses and voltage drops are considered the main benefits of the RERs based power systems. RERs based power systems can be standalone or hybrid systems. An example of RERs based hybrid power systems is photovoltaic/diesel generator power system.

Hybrid PV/diesel generator power systems can be classified based on system operation into two topologies namely series topology and parallel topology [4]. In case of series topology system, the PV energy resource and the diesel generator are used to charge the battery storage. Meanwhile, the diesel generator is connected in series with the inverter to supply the load. On the

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http://dx.doi.org/10.1016/j.rser.2014.12.035
1364-0321/

other hand, the diesel generator can't supply the load directly in the series topology based systems. The design principles of series topologies based hybrid system are generally simple to carry out, but series topology has the following disadvantages [5]:

- Low overall system efficiency due to the series configuration of system elements. A certain amount of the energy is lost due to the battery and inverter conversion efficiencies.
- A large inverter size should be used such that the capacity is substantially larger than the maximum peak-load demand.
- When the renewable energy sources are incorporated in the system, it leads to a limited control of the diesel generator.

On the other hand, the parallel hybrid system topology has a superior performance over the series hybrid system topology. In the parallel hybrid system, the diesel generator and the RER can supply a part of the load demand directly, resulting in higher overall system efficiency. Thus, such a scheme has the following advantages [6]:

- System's load demand can be met optimally.
- Diesel fuel efficiency can be maximized due to higher average operating power.
- Diesel maintenance can be minimized due to reduction of the running time.
- Reduction in the capacities of diesel, battery and renewable sources.
- The ability of supplying the load demand at higher reliability including peak load demand.

A typical hybrid PV/diesel power system usually consists of a PV array that converts the sunlight to a DC current, a diesel generator that provides AC current, storage device to store the excess energy and power electronic features including DC–DC converters, AC–DC converters, automatic transfer switches and charge controllers. The widest application of PV/diesel system is the installation of these systems in remote areas, where the grid extension is not available. Recent research and development have shown excellent potential of these systems, as a form of supplementary contribution to conventional power generation systems [7].

The main objective of this review is to show the state of art of hybrid PV/diesel generator system control strategies. Research work in the period of 1998–2014 is covered and analyzed. In addition to that, a summary of the latest technologies in this filed is provided. Finally, a list of challenges to this science is concluded in order to put the researchers in the form of the problems that face such technology.

2. Modeling of PV/diesel power systems

A typical hybrid PV/diesel system is usually consisted of PV array, controller (such as maximum power point tracking MPPT), battery, inverter, diesel generator and load. Usually the PV array is considered as the main source with the backup battery in the hybrid power system. Meanwhile the diesel generator is operated in deficit time. The deficit time can be defined as the time in which the instantaneously produced energy from the PV array and battery is not enough to cover the load demand [8]. For the PV array model, various mathematical models have been introduced in order to describe it [8]. The general working concept of the PV system is that the incident radiation of the sun on the PV array is collected and converted to a DC current. This DC current will feed the load after passing through a controller and an inverter. As a fact, the output power of a PV array strongly depends on the solar radiation and the ambient temperature. Hence, the equation below describes the output power of a PV array [8,9].

$$P_{pv}(t) = \left[P_{\text{peak}}\left(\frac{G_t}{G_{\text{stander}}}\right) - \alpha_T[T_c(t) - T_{\text{stander}}]\right] \times \eta_{\text{inv}} \times \eta_{\text{wire}} \quad (1)$$

where G_t is the collected solar radiation in (W/m^2), G_{stander} is the solar radiation at reference conditions in (W/m^2), α_T is the temperature coefficient of the PV module power which is given by the manufacturer, T_{stander} is the ambient temperature at reference conditions, η_{inv} and η_{wire} are the efficiencies of the inverter and the wires, respectively. T_c is the cell temperature and it can be calculated by the following equation:

$$T_c(t) = T_{\text{amb}}(t) + \left(\left(\frac{\text{NOCT} - 20}{800}\right) \times G_t\right) \quad (2)$$

where T_{amb} is the ambient air temperature in °C and NOCT is the normal operating cell temperature in °C. The NOCT is one of the PV module specifications and given by the manufacturer [10]. It is the cell temperature measured at solar radiation of 800 W/m^2, a wind speed of 1.5 m/s and an ambient temperature of 20 °C.

The energy at the front end of a PV/diesel generator hybrid power system or at the load side is given by [8,11]

$$E_D(t) = \sum_{i=1}^{366} [E_T(t) - E_L(t)] \quad (3)$$

where

$$E_T(t) = E_{pv}(t) + E_{\text{Gen}}(t) \quad (4)$$

E_D is the energy difference, E_{Gen} is the diesel generator capacity and E_L is the load energy demand.

From Eq. (3) above, it can be conclude that the result is either positive ($E_T > E_L$) or negative ($E_T < E_L$). If the energy difference is positive, then there is an excess in energy (E_E). While if the energy difference is negative then there will be an energy deficit (E_D). The excess energy is stored in batteries in order to be used in case of energy deficit. Therefore, the energy flow across the battery can be expressed by [8,11],

$$E_{\text{Battery}}(t) = \begin{cases} E_{\text{Battert}}(t-1) \times \eta_{\text{inv}} \times \eta_{\text{wire}} \times \eta_{\text{discharging}} - E_L(t) & E_D < 0 \\ E_{\text{Battert}}(t-1) \times \eta_{\text{charging}} + E_{pv}(t) & E_D > 0 \\ E_{\text{Battert}}(t-1) & E_D = 0 \end{cases} \quad (5)$$

Diesel generator is provided in the hybrid power system to act as a backup energy source. When there is no output power from the PV panel and the battery bank is fully discharged, the diesel generator will start working and its power rating should be at least equal to the maximum peak load in the daily load curve. The fuel consumption of the diesel generator (FC_G) can be calculated by using the following equation [12]:

$$FC_G = A_G \times P_G + B_G \times P_{R-G} \quad (6)$$

where P_G, P_{R-G} are the output power and the rated power of the diesel generator, respectively. A_G, B_G are the coefficients of the fuel consumption curve, respectively. Typical values for these two coefficients are A_G=0.246 l/kW h and B_G=0.08145 l/kW h [8,11].

3. Hybrid PV/diesel generator systems versus standalone systems

One of the most important PV systems research hypotheses is the feasibility of hybrid PV systems as compared to standalone PV systems. The comprising of photovoltaic array and diesel generator provides greater system reliability and reduces the cost of the generated energy by the system [5]. The system simplicity and light required maintenance are the superior advantages of the PV system. However, the uncertainty of the output of PV systems is