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Optimal mix of solar and wind distributed generations considering performance improvement of electrical distribution network

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ABSTRACT

Renewable energy sources are gaining more and more interest because they are nonpolluting and sustainable. Recently, a notable number of renewable distributed generations (DGs) having intermittent generation patterns are being interconnected with the distribution network to meet growing load demand and nullify environmental threats. Appropriate integration of renewable DGs in distribution networks is crucial to guarantee the qualitative network operational benefits. In this paper a simple but efficient approach has been proposed for optimal placement and sizing of solar and wind DGs in distribution territory by considering electrical network power loss minimization, voltage stability and network security improvement. The stochastic nature of solar irradiance and wind speed are accounted using suitable probabilistic models. Weighted aggregation particle swarm optimization technique is employed to optimize the objective functions considering bus voltage limit, line loading capacity, discrete size limit and penetration constraints of DGs. Strategic weight selection technique has been adopted to assess the well trade-off solution by persuasion of multiple objectives regarding the performance of distribution network. The proposed method has been applied to a typical Indian rural distribution network, and the satisfactory results are obtained.

1. Introduction

With the rapid exhaustion of fossil fuel, limitation of transmission corridors and the gradual increase in the global temperature [1,2] has given momentum to the application of distributed generation (DG). DG is small scale power generation unit that can be connected directly to distribution network or inside the facilities of the large consumers [3]. DG utilizes traditional power generation paradigms like diesel generator, micro turbine, gas turbine and reciprocal engine, and renewable power generation technologies such as photovoltaic (PV), wind turbine (WT) and fuel cell. However, present global scenario with strict environmental regulations and sustainable development policy makes solar and wind based DGs as paramount choice for distribution grid operators. But, the integration of renewable DGs leads to major challenges due to its uncertain power generation characteristics. Interestingly, solar and wind power resources in most of the regions are almost complementary. So, appropriate combination of solar and wind based DGs can magnify the efficiency and reliability of the system by resolving the problems caused by their variable nature [4,5]. DGs are strategically located and operated in the network to defer major system upgrades, better voltage regulation, minimize distribution power losses, relieve the heavy loaded feeders and extend the equipment's reliability [6–8]. Proper location and size of PV arrays and WTs in the network are vital as unplanned allocation may lead to many negative impacts on the system [9,10].

To solve the above problem, many past researches have been aimed to solve the problem optimally. In the last few years significant contribution has been observed in the field of hybrid renewable resource planning. Although the hybrid system sizing problems were being solved by deterministic approaches, the recent trend follows the application of heuristic optimization techniques. An analytical method for optimal sizing of stand-alone hybrid solar-wind system has been presented in Ref. [11] accounting the time fraction for specified load supply and the cost of the system. A mixed solar-wind system sizing technique was proposed in Ref. [12] considering loss of power supply probability and levelized cost of energy model. Near similar approaches for obtaining the suitable type and number of DG units in terms of

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technical and economical concepts is seen in Refs. [13–15]. In Ref. [16], the deterministic method is extended to incorporate the effects of probabilistic power generation model. An optimization technique based approach has been proposed by Koutroulis et al. [17] to design autonomous hybrid system with battery storage. Genetic algorithm (GA) is utilized to evaluate the optimal number and type of PV modules, WTs and battery chargers considering minimization of 20-year round total system cost. In Ref. [18], optimal PV array and WT parameters were assessed by GA keeping the objective of annualized cost function minimization. Ekren et al. [19] have proposed simulated annealing algorithm based method for optimal sizing of integrated PV-wind system with battery storage.

While most of the studies concentrate on standalone solar-wind generation system, few studies analyze grid connected hybrid energy systems. Mikati et al. have examined how the grid dependency is affected by integration of renewable subunits according to the relationship between the power demand and renewable resource patterns. The study reveals that the coupling of renewable DGs reduces grid usage and hence avoids losses during large scale import and transformation of power through distribution substation [20]. Determination of appropriate size for solar and wind the generators with battery, and best combination (solar fraction) in hybrid systems have been studied in Ref. [21]. Line power flows and associated energy losses due to interaction of hybrid systems with the grid are also discussed. An evolutionary programming based technique has been presented by Khatod et al. [22] for optimal placement of renewable DGs in distribution network on viewpoint of annual energy loss minimization. However, the technical impacts associated with deployment of renewable DGs were not well addressed in the papers.

This paper proposes a more accurate method for reinforcement of solar and wind generation units into distribution network to bring the parameters close to the desired values considering wide ranges of technical and operational issues. Suitable probabilistic power generation model of renewable DGs are utilized to assess the new facilities' impact on the network. In order to admire multiple planning objectives, weighted aggregation particle swarm optimization (WAPSO) algorithm [23,24] is employed. A weight selection strategy has been developed for better performance of the algorithm. This paper is structured as follows.

Probabilistic power generation model of solar and wind based DGs are portrayed in Section 2. Section 3 presents mathematical formulation of hybrid system design problem. Weight selection strategy is elaborated in Section 4. The computational procedure regarding optimal allocation of PV arrays and WTs are described in Section 5. Study on test network and local weather are given in Section 6. Simulation results are discussed in Section 7 and conclusions of the work are summarized in Section 8.

2. Probabilistic power generation model

Solar and wind power generations are highly influenced by meteorological condition such as solar irradiance, wind speed and ambient temperature which are directly related to geographical location. So, the characteristics of solar radiation and wind conditions at installed location should be critically analyzed at the primary stage for efficient utilization of PV arrays and WTs.

2.1. Renewable resource model

Probability distribution functions (PDF) can be used to characterize stochastic behavior of renewable resources (wind speed and solar irradiance) in a statistical manner.

2.1.1. Solar irradiance modeling

The probabilistic nature of solar irradiance is considered to follow Beta PDF [25,26]. Beta distribution for solar irradiance s^t (kW/m^2) over time segment 't' is given by,

$$f_s^t(s) = \frac{\Gamma(\alpha^t + \beta^t)}{\Gamma(\alpha^t)\cdot\Gamma(\beta^t)}\cdot(s^t)^{\alpha^t-1}\cdot(1-s^t)^{\beta^t-1} \quad \text{for} \quad \alpha^t > 0; \quad \beta^t > 0 \tag{1}$$

where α^t and β^t are the shape parameters at 't'; and Γ represents Gamma function.

Shape parameters of Beta PDF can be calculated using mean (μ_s^t) and standard deviation (σ_s^t) of irradiance for corresponding time segment.

$$\beta^t = \left(1-\mu_s^t\right)\cdot\left(\frac{\mu_s^t(1+\mu_s^t)}{(\sigma_s^t)^2} - 1\right) \tag{2}$$

$$\alpha^t = \frac{\mu_s^t * \beta^t}{(1-\mu_s^t)} \tag{3}$$

2.1.2. Wind speed modeling

In order to describe stochastic behavior of wind speed in a predefined time period, Weibull PDF has been chosen [22,25]. Weibull distribution for the wind speed v^t (m/s) at tth time segment can be expressed as

$$f_v^t(v) = \frac{k^t}{c^t}\cdot\left(\frac{v^t}{c^t}\right)^{k^t-1}\cdot\exp\left(-\left(\frac{v^t}{c^t}\right)^{k^t-1}\right) \quad \text{for} \quad c^t > 1; \quad k^t > 0 \tag{4}$$

The shape parameter (k^t) and scale factor (c^t) at tth time segment are calculated as follows.

$$k^t = \left(\frac{\sigma^t}{\mu_v^t}\right)^{-1.086} \tag{5}$$

$$c^t = \frac{\mu_v^t}{\Gamma(1+1/k^t)} \tag{6}$$

μ_v^t and σ_v^t are mean and standard deviation of wind speed at time segment 't'.

2.2. Power generation model

To calculate output power of solar and wind based DGs, the continuous PDF for a specific time frame has been divided into states (periods), in each of which the solar irradiance and wind speed are within specific limits [26]. Power generation of PV array and WT are governed by probability of all possible states for that hour.

2.2.1. Power generation by PV array

The hourly average output power of PV array correspond to a specific time segment 't' (P_{PV}^t) can be calculated as follows.

$$P_{\text{PV}}^t = \sum_{g=1}^{N_s} \text{PG}_{\text{PV}g} * P_s\left(s_g^t\right) \tag{7}$$

where 'g' signifies the state variable and N_s is the number of discrete solar irradiance state. s_g^t is the gth level/state of solar irradiance at tth time segment.