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Strategic approach for reinforcement of intermittent renewable energy sources and capacitor bank for sustainable electric power distribution system

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ABSTRACT

To meet ever increasing load demand in a sustainable way, reinforcement of photovoltaic (PV) array, wind turbine (WT) and capacitor bank in distribution network is proposed in this paper. A comprehensive planning model is presented to determine location and required installation capacity of multiple PV array, WT and capacitor units in an electric power distribution network under heavy load growth situation. Intermittent power generation of renewable energy sources (RESs) are quantified with suitable probability distribution functions and incorporated in the planning model. The planning approach considers several welfare areas in the distribution systems, viz., increment of profit margin, reduction of carbon-di-oxide emission, minimization of distribution power losses, enhancement of voltage stability level and improvement of the network security considering power flow, voltage limit, line capacity, RES penetration, capacitor penetration and utility economy constraint. Non-dominated sorting based multi-objective particle swarm optimization algorithm along with fuzzy decision making criteria is used to find the best allocation alternative for mix RES and capacitor planning problem. The effectiveness of the proposed model has been tested on a typical 28-bus Indian rural distribution network. The results show that more efficient techno-eco-environmental optimization can be obtained from combined RES and capacitor planning model.

Introduction

Power utilities around the world are faced with great challenges to keep up to the increasing demand of electric power. Global warming threat, dwindling resources of fossil fuels, economic and infrastructural constraints to build new power plants, and limited transmission and distribution corridors are driving the utilities to seek alternative methods to meet the increased demand. Solar and wind energy are the two most viable and environmental friendly RESs which have attracted the attention of utilities worldwide [1]. Unlike centralized bulk power stations RESs are small scale power generation units and can be directly installed in a distribution network. However, a common drawback of solar and wind power generation is their unpredictable nature and high dependency on weather conditions. The problems can be partially overcome utilizing the two resources in a proper combination as they are usually complementary in nature [2,3]. The application of two different RESs together in the network increases the complexity and makes such hybrid systems more difficult to analyze. Planning of distribution network with only RESs is not very fruitful because of high implementation cost and limited reactive power support. So, reinforcement of combined RES and capacitor could be an attractive option for proper design and exploitation of distribution network. The parallel use of capacitor bank improves power quality parameters by injecting the reactive power into the network with low expense. Moreover, proper allocation of RESs and capacitor banks in the distribution network defers major system upgrade, reduces overall energy loss and improves reliability. However, connection of new facilities in the network is not a simple plug and play problem. Sitting and sizing of PV arrays and wind turbines (WTs) along with shunt capacitors need to be investigated carefully to avoid voltage rise and line over loading problems. The planning of RESs and capacitors in the distribution network should be modelled in the form of an optimization problem to get maximum benefit.

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Although numbers of paper have appeared on sizing optimization of autonomous hybrid solar–wind system very less effort was devoted towards grid interactive renewable energy system design. In Refs. [4,5,7–10], the authors have focused on planning of RESs considering different technical, economic and environmental prospects. PV array, WT and storage battery were used for optimum design of a hybrid system considering cost, reliability and emission in Ref. [4]. Bayod-Rujula et al. [5] have analyzed the interaction of hybrid PV–Wind systems plus batteries with the utility network and tried to find the best combination of the RESs and the size of the battery. However, it has been observed that configuration without battery storage is more graceful for social, economic and environmental sustainability [6]. In Ref. [7], the authors have utilized multi-objective artificial bee colony (MOABC) algorithm to determine the capacity of hybrid PV/WT/FC energy system and the open tie switch numbers. The objectives considered for the optimization were power loss minimization, voltage stability maximization, cost reduction of energy generated and total emission. Khatod et al. [8] have proposed an evolutionary programming based approach to find optimum locations of PV arrays and WTs in distribution network. Stochastic nature of solar and wind power generation was considered in the paper to minimize active energy loss. Alsayed et al. [9] have investigated combined PV–WT sizing problem with multi criteria decision making algorithm (MCDA). Environmental and economical attributes are weighted based on their entropy variation due to change of generation and load. Later in Ref. [10], they have exploited non-dominated sorting genetic algorithm (NSGA) along with MCDA for optimum design of the hybrid system configuration.

Capacitor placement problems for distribution network were discussed in Refs. [11–13]. The optimal locations and sizes of capacitor banks were obtained using a direct search algorithm in Ref. [11]. The aim of the study was to minimize the cost related to capacitor planning. A bacterial foraging based solution methodology was proposed in Ref. [12] to find the optimal location and size of capacitors in radial distribution systems. A teaching learning based optimization algorithm was presented in Ref. [13] to minimize active network power loss, capacitor installation cost and energy loss cost. However, there is hardly any paper addressing the issues regarding combined planning of PV array, WT and capacitor bank.

Few recent researches have examined distribution planning problem incorporating local generation and capacitor unit [14–16]. An analytical based approach for allocation of distributed generation (DG) and capacitor was presented by Naik et al. [14] on view point of minimization of total real power loss. Sensitivity analysis has been performed to identify the candidate locations for DG and capacitor placement, and the heuristic curve fitting technique used to determine their capacity. In Ref. [15], authors have proposed simultaneous placement of DG and capacitor in radial distribution system considering the objectives of energy loss minimization and voltage profile improvement. A combinatorial form of local search and genetic algorithm was utilized to solve the optimization problem. Moradi et al. [16] presented imperialist competitive algorithm approach to identify location and capacity of DG and capacitor in distribution network for power loss reduction and voltage stability improvement. In these studies DGs were considered as constant power sources (constant PQ model). However, integration of intermittent RESs cannot guarantee constant power output throughout the planning period. Therefore, it is important to assess and quantify the relative system performance with the integration of RES units whose generation varies daily or seasonally.

This paper presents a novel multi objective particle swarm optimization (MOPSO) technique based planning method for appropriate location and size selection of non-dispatchable RESs and capacitor banks in an existing operation situation. Load growth is a continual phenomenon of distribution network which is unavoidable. The network operational characteristics would likely to be affected by the additional demand. In previous studies the effect of load growth was not considered. In this paper, a proper approach for a well-planned distribution system is convinced while considering the impact of yearly load growth. The rest of this paper is organized as follows. In Section 'Modelling of intermittent RESs', probabilistic power generation model of RESs considering stochastic nature of resources has been presented. Section 'Planning problem' illustrates the proposed planning problem with formulation of objective functions and constraints as well. In Section 'Application of MOPSO', MOPSO technique based solution strategy to design sustainable distribution network is discussed. Section 'Test network and local weather' contains description of test network and details about the weather affecting the distribution system. Simulation results are discussed in Section 'Results and discussion' and finally the conclusions are reported in Section 'Conclusion'.

Modelling of intermittent RESs

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

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.

Solar irradiance modelling

The probabilistic nature of solar irradiance is considered to follow Beta PDF [17,18]. 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.

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

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

Wind speed modelling

In order to describe stochastic behavior of wind speed in a predefined time period, Weibull PDF has been chosen [8,18]. Weibull distribution for the wind speed v^t (m/s) at tth time segment can be expressed as

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