Applied Energy 231 (2018) 985–996

Contents lists available at ScienceDirect

Applied Energy

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

Stochastic multi-objective optimization of photovoltaics integrated three-phase distribution network based on dynamic scenarios☆

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HIGHLIGHTS

- A novel dynamic scenarios method considering power time correlation is designed.
- A modified multi-objective algorithm is proposed to solve stochastic optimization.
- The dynamic scenarios have smallest Brier Score for each event.
- The modified multi-objective algorithm has stronger global search capability.
- Voltage unbalance caused by single-phase photovoltaics has a significant decrease.

ARTICLE INFO

Keywords:
Distribution network
Optimization method
Voltage unbalance
Photovoltaics
Modified multi-objective algorithm

ABSTRACT

With the increasing number of single-phase photovoltaics integrated into three-phase distribution network, voltage unbalance problem is becoming serious, which leads to the abnormal operation of distribution network. Therefore, in distribution network, not only energy efficiency needs to be enhanced, but also voltage unbalance needs to be decreased to ensure the security of system. This paper establishes a stochastic multi-objective optimization model for three-phase distribution network to minimize active power losses and voltage unbalance simultaneously, where the discrete decision variables are coordinated with continuous regulation of solar reactive outputs. For the purpose, the stochastic processes of solar active power are modelled in a scenarios-based framework. A novel dynamic scenarios method is designed to describe the uncertainty of solar power as well as power time correlation based on the time covariance obtained by the forgetting factor identification, which not only reflects forecast errors, but also power fluctuation. Hence, the stochastic processes are converted into a series of equivalent deterministic scenarios. In order to better solve the multi-objective problem, a modified non-dominated sorting genetic algorithm-II is proposed, in which crossover rate and mutation rate are dynamically revised by a fuzzy logic controller. Besides, a two-stage constraint handling strategy is constructed to ensure the solutions with smaller constraints deviation and better fitness have higher priority to be reserved. Finally, simulation is conducted on the modified IEEE 123 node distribution network with lots of single-phase photovoltaics. The results show that with more accurate scenarios and stronger algorithm global search capability, the multi-objective optimization gains significant decrease of active power losses and voltage unbalance.

1. Introduction

Distributed photovoltaic (PV), which is a kind of renewable energy, has attracted wide attention and support from the whole world [1]. Many countries encourage the micro feed-in tariff projects, which are initiated for integrating single solar generators with a rated power of 10 kW into distribution network [2]. The National Energy Administration reports that Chinese cumulative installed PV capacity is 110 GW in 2017, including 29.66 GW capacity installed in distribution system that accounts for 27% of the total [3]. In Germany, approximately 70% of all installed PV systems are allowed to feed in unsymmetrically, whose nominal power are below 13.8 kV A [4]. Amounts of distributed PVs are

☆ This work was supported in part by the National Key R&D Program of China [2017YFB0902900], in part by the National Natural Science Foundation of China [51707136], in part by the Natural Science Foundation of Hubei Province, China [2018CFA080].

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https://doi.org/10.1016/j.apenergy.2018.09.168
Received 14 May 2018; Received in revised form 20 August 2018; Accepted 20 September 2018
0306-2619/

installed on household and commercial rooftops. However, the increasing integration of rooftop single-phase PVs into distribution network aggregates the asymmetry of distribution network and makes voltage unbalance become increasingly significant [5]. Additionally, the uneven distribution of three-phase loads and asymmetric distribution of lines result in voltage unbalance being more common. IEEE standards give limit for voltage unbalance to be less than 2% in low voltage and medium voltage distribution network [6]. An increase in voltage unbalance leads to the fast thermal ageing of induction machines and shortened life span of distribution transformers [7]. It also leads to power oscillations and fast derating of transformers, cables and lines [8]. The above considerations reveal that voltage unbalance is a critical power quality problem and must be decreased to avoid abnormal operation of distribution network.

Some studies have been conducted to employ the optimization for decreasing voltage unbalance in distribution network. In Ref. [9], a two-stage voltage regulation approach of unbalanced radial distribution system is developed and the upper limit of voltage unbalance is 2%. Minimizing voltage unbalance factor is an only objective function in Ref. [10]. A dynamic voltage regulation approach is proposed, and voltage unbalance is constrained below 3% based on American national standard ANSIC84.1-2011 [11]. A three phase optimal power flow algorithm is proposed to achieve the objective of minimizing negative sequence system voltage [12]. The literature considers voltage unbalance as a constraint or a single objective function to minimize. However, about 10% of electricity energy generated by power plants is lost in the power delivery system, and around 40% of these losses occur in distribution network [13]. Besides, loss reduction is a critical function in the distribution network to enhance energy efficiency. Therefore, it is necessary to decrease voltage unbalance together with active power losses.

In the traditional approach, voltage regulators (VRs), switched capacitors (SCs), and secondary transformer online tap changers are utilized to regulate voltage so as to decrease voltage unbalance [14]. Since PV inverter control does not require extra investments, the reactive power capability and active power curtailment of single-phase PVs inverters are utilized to improve power quality [15,16]. The commercial products described in [17] and [18] are the real examples of existing rooftop and pole-mount PVs that can provide reactive power support. Distributed reactive power resources are considered as control devices to minimize negative sequence voltage in Refs. [19,20]. An optimal voltage control strategy with considering irradiance forecast errors is proposed in Refs. [21,22]. Refs. [15,16,19–22] have verified the advantages of controlling reactive power output of PVs to decrease voltage unbalance. However, PV generations are stochastic processes that have strong correlation in time [23], and the optimal decision of the optimization problem at each time affects each other due to the cross-time section constraints of VRs and SCs. It is vital to obtain the aggregated uncertainties of PV active power in the optimization problems [24]. Nevertheless, the above studies neglect the issue.

The time correlation is the dependency between the variables at two time. Ref. [25] verifies that additional generations are required for balancing the additional power fluctuations caused by inaccurate PV active power. Ref. [26] indicates that there is high time correlation for adjacent lead-time, and providing inaccurate trajectories to the operational problem leads to suboptimal decisions. There are lots of scenarios generation methods to describe the stochastic processes of PV active power [27,28], however, few scenarios generation methods have considered power time correlation in modelling. The typical method is modelling the time correlation of PV active power with a multivariate Gaussian copula [29–32]. Ref. [29] proves that it is difficult to obtain the time correlation of PV active power according to the historical data, and the recursive approach of covariance matrix can be viewed as an effective alternative. A probability model of PV generations with randomness and correlation is presented in Ref. [30]. Ref. [31] takes a recursive matrix to describe the time correlation of renewable generations and assumes that the forgetting factor is 0.999. In Ref. [32], the interdependence structure is modelled by a covariance matrix of multivariate Gaussian distribution and assumes that the forgetting factor is 0.995. At existing studies, the forgetting factor in adaptive approach to estimate covariance matrix is constant, and there is no theoretical definition to obtain an optimal forgetting factor. However, the structure of covariance matrix that reflects the strength of time correlation is affected by the value of forgetting factor. Thus, the forgetting factor is a key parameter determining the accuracy of describing time correlation.

For the multi-objective model, there are mainly two kinds methods to solve it. One of them is to convert the multi-objective model into a single objective model, such as the weighted sum method [15,33,34]. The drawback of the method is that the different selection of weighted coefficient leads to different results and it does not allow finding all solutions in a feasible set [35]. Another method is to use Pareto optimality to optimize all objectives simultaneously, which includes the widely recognized improve strength Pareto evolutionary algorithm (SPEA2) [36] and non-dominated sorting genetic algorithm-II (NSGA-II). NSGA-II is one of the most prevalent algorithms to solve the multi-objective problem due to its elite strategy [37–39]. Ref. [40] validates that NSGA-II outperforms Pareto-archived evolution strategy (PAES) and strength Pareto evolutionary algorithm (SPEA). Whereas, the high performance of NSGA-II is dependent on its evolution strategy, crossover, mutation and so on [41]. Crossover rate and mutation rate of traditional NSGA-II are fixed, which make the algorithm easily be trapped in local optimum [42]. Moreover, the crossover rate and mutation rate determine the diversity of population. Fuzzy logic is a branch of artificial intelligence, which uses linguistic variables and heuristic associations to approximate human reasoning and intuition [43]. Hence, it is suitable for combining quantitative value with qualitative empirical concepts.

In light of the above issues, the paper considers the decrement of voltage unbalance for a three-phase distribution network with a large number of PVs. The tap position of voltage regulators, capacitors switching status, and reactive power outputs of PVs are coordinately controlled to decrease voltage unbalance and active power losses. The simulation is conducted on a modified IEEE 123 node distribution network with amounts of PVs, which demonstrates that both voltage unbalance and active power losses are decreased significantly with the stochastic multi-objective optimization. Besides, the time correlation structure affects the performance of scenarios and the optimization results are more accurate by inputting dynamic scenarios with time correlation to the multi-objective model. The main contributions of this paper are summarized as below:

(1) A novel dynamic scenarios method is designed to describe the stochastic processes of PV active power. The generated scenarios not only contain forecast errors distribution, but also power fluctuation distribution. To characterize the time correlation of PV active power more accurately, a new approach is proposed to identify the optimal forgetting factor based on power fluctuation distribution, namely identifying the key parameter in recursively estimating the time covariance matrix.
(2) A stochastic multi-objective optimization for three-phase distribution network is constructed, which simultaneously minimizes active power losses and voltage unbalance by controlling the status of existing system tools. In addition, a modified NSGA-II algorithm (MNSGA-II) based on a fuzzy logic controller and a two-stage constraints handling strategy is proposed to solve the problem. The fuzzy logic controller is designed to improve the algorithm global search capability, and a two-stage constraints handling strategy is constructed to ensure that constraints are strictly satisfied.

The following of this paper is organized as follows: The dynamic scenarios method is introduced in Section 2 to obtain scenarios