Applied Energy 223 (2018) 215–228

Contents lists available at ScienceDirect

Applied Energy

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

An affine arithmetic-based multi-objective optimization method for energy storage systems operating in active distribution networks with uncertainties

Shouxiang Wang[a,*], Kai Wang[a], Fei Teng[b], Goran Strbac[b], Lei Wu[c]

[a] Key Laboratory of Smart Grid of Ministry of Education, Tianjin University, Tianjin 300072, China
[b] Electrical Energy Systems, Imperial College London, London SW7 2AZ, UK
[c] Electrical and Computer Engineering Department, Clarkson University, Potsdam, NY 13699, USA

HIGHLIGHTS

- An uncertain multi-objective optimization model is built for optimal ESS operation.
- Affine arithmetic is used to handle uncertainties associated with DGs and loads.
- Performance indices concerning convergence, diversity, and uncertainty are defined.
- Test results show the superiority of affine arithmetic over interval arithmetic.
- A multi-period case considering seasonality of DGs and loads is simulated.

ARTICLE INFO

Keywords:
Energy storage system
Distributed generation
Uncertainty
Affine arithmetic
Multi-objective optimization
Performance indices

ABSTRACT

Considering uncertain power outputs of distributed generations (DGs) and load fluctuations, energy storage system (ESS) represents a valuable asset to provide support for the smooth operation of active distribution networks. This paper proposes an affine arithmetic-based multi-objective optimization method for the optimal operation of ESSs in active distribution networks with uncertainties. Affine arithmetic is applied to the optimization model for handling uncertainties of DGs and loads. Two objectives are formulated with affine parameters including the minimization of total active power losses and the minimization of system voltage deviations. The affine arithmetic-based forward-backward sweep power flow is first improved by the proposed pruning strategy of noisy symbols. Then, the affine arithmetic-based non-dominated sorting genetic algorithm II (AA-NSGAII) is used to solve the multi-objective optimization problem for ESSs operation under uncertain environment. Furthermore, three types of indices with respect to convergence, diversity, and uncertainty are defined for performance analysis. Numerical studies on a modified IEEE 33-bus system with embedded DGs and ESSs show the effectiveness and superiority of the proposed method. The optimization results demonstrate that the obtained Pareto front has better convergence and lower conservativeness in comparison to the interval arithmetic-based NSGA-II. A multi-period case considering seasonality of DGs and loads is further simulated to show the applicability in real applications.

1. Introduction

The penetration of distributed generations (DGs) is being significantly increased in active distribution networks (ADNs) due to the ability to provide cleaner energy and more flexible power supply as compared to the bulk power system supply [1]. However, renewable energy sources such as solar and wind energy are inherently time-varying on various timescales from minutes to seasons [2]. The intermittent and stochastic properties of such renewable energy sources will cause the intermittence and randomness of power outputs of DGs, which greatly increases uncertainties of power injections in ADNs [3,4]. Moreover, unlike transmission networks, ADNs present radial topology with high resistance/reactance ratio of lines. Thus, fluctuations of active power injections could have significant effects on power flows and nodal voltages [5,6]. Energy storage system (ESS) is commonly used as an effective device to mitigate fluctuations of active power injections by means of flexible active power control [7,8]. The ancillary services provided by ESSs can support the integration of DGs to the existing

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* Corresponding author at: Key Laboratory of Smart Grid of Ministry of Education, Tianjin University, Nankai District, Weijin Road No. 92, Tianjin 300072, China.
E-mail addresses: sxwang@tju.edu.cn (S. Wang), tju337wangkai@tju.edu.cn (K. Wang), fei.teng09@imperial.ac.uk (F. Teng), g.Strbac@imperial.ac.uk (G. Strbac), lwu@clarkson.edu (L. Wu).

https://doi.org/10.1016/j.apenergy.2018.04.037
Received 31 December 2017; Received in revised form 29 March 2018; Accepted 12 April 2018

Nomenclature

Abbreviations

AA	affine arithmetic
AA-NSGAII	affine arithmetic-based nondominated sorting genetic algorithm II
ADN	active distribution network
DG	distributed generation
ESS	energy storage system
IA-NSGAII	interval arithmetic-based nondominated sorting genetic algorithm II
SOC	state of charge

Sets

A_l	set of buses that are directly connected to bus l
B	set of branches
K_{error}	set of indices of error symbols
N	set of nodes
P	set of optimal solutions
S	set of all solutions

Parameters

E_N	nominal capacity of ESS
$E_{min,i}$, $E_{max,i}$	lower and upper limits of energy capacity of ESS$_i$
G_{ij}	real component of complex admittance matrix
$I_{min,ij}$, $I_{max,ij}$	lower and upper limits of current magnitude for the line connecting nodes i and j
$P_{ESS,i,max}$	maximum allowable charging and discharging power
$P_{min,DG,i}$, $P_{max,DG,i}$	lower and upper limits of active power generated by DG_i
$P_{min,i}$, $P_{max,i}$	lower and upper limits of active power injection at node i
$\widehat{I}_b^p$, $\widehat{I}_j^p$	current injections of phase p (p = A, B, or C) at node b and j
$\widehat{P}_{ESS,i,t}$, $\widetilde{P}_{ESS,i,t}$	charging and discharging power of ESS$_i$ in affine and interval forms during the tth time period
$\widehat{P}_{DG,i,t}$, $\widehat{P}_{LOAD,i,t}$, $\widehat{P}_{ESS,i,t}$	active power of DG, load, ESS at node i in affine form during the tth time period
$\widehat{P}_{ij}$, $\widehat{Q}_{ij}$	active and reactive power flows between nodes i and j
$\widehat{Q}_{DG,i,t}$, $\widehat{Q}_{LOAD,i,t}$	reactive power of DG and load at node i in affine form during the tth time period
$S\widehat{O}C_{ESS,i,t}$, $S\widehat{O}C_{ESS,i,t+1}$	initial SOC of ESS$_i$ in affine form at the tth and the $(t+1)$th time periods
$\widehat{S}_b^p$	apparent power injection of phase p (p = A, B, or C) at node b
$Q_{min,i}$, $Q_{max,i}$	lower and upper limits of reactive power injection at node i
r_{ij}, x_{ij}	resistance and reactance of the line connecting nodes i and j
$SOC_{min,i}$, $SOC_{max,i}$	lower and upper limits of SOC
T	duration of each time period
$\widetilde{U}_s$	voltage magnitude of source bus in interval form
$U_{i,base}$	nominal voltage magnitude of node i
$U_{min,i}$, $U_{max,i}$	lower and upper limits of voltage magnitude at node i
$\Delta U_{i,max}$	maximum allowable voltage deviation of node i
α_{imax}	maximum allowable fluctuation rate at node i
φ_i	power factor angle of DG_i
η	overall charge and discharge efficiency of ESS

Variables

$\widehat{E}_{ESS,i,t}$, $\widehat{E}_{ESS,i,t+1}$	initial energy of ESS$_i$ in affine form at the tth and the $(t+1)$th time periods
$\Delta\widehat{E}_{ESS,i,t}$	variation of ESS$_i$ energy in affine form during the tth time period
$\widehat{f}_k(x_i)$, $\widetilde{f}_k(x_i)$	the kth objective values of solution x_i in affine form and interval form
$\widehat{I}_{ij,t}$	current magnitude between nodes i and j in affine form during the tth time period
$\widehat{U}_b^p$, $\widehat{U}_j^p$	voltage magnitudes of phase p (p = A, B, or C) at node b and j
$\widehat{U}_{i,t}$, $\widehat{U}_{j,t}$	voltage magnitudes for nodes i and j in affine form during the tth time period
$\underline{U}_i$, $\overline{U}_i$	lower and upper bounds of voltage magnitude at node i
ΔU	total voltage violations
$\widetilde{\boldsymbol{x}}$, $\widehat{\boldsymbol{x}}$	complex interval variable and complex affine variable
$\widehat{y}_i^{(k)}$	the kth objective value of solution x_i in affine form
$\alpha_{i,t}$	fluctuation rate of voltage i during the tth time period
$\widehat{\theta}_{ij}$	voltage angle difference between nodes i and j in affine form

network by smoothing wind and solar energy [9]. Consequently, it is of great significance to optimize ESSs operation while considering all possible conditions of ADNs under such an uncertain environment.

Optimal operation of ESSs in an ADN with multiple DGs has been studied in some existing works. New devices have been developed for the control and integration of collocated DGs and ESSs to the network, which facilitates the joint optimization of the above elements in ADNs [10]. An active-reactive optimal power flow (A-R-OPF) model was developed for the optimal operation of ESSs in distribution networks with embedded wind generations [11–13]. The proposed A-R-OPF in [11] was based on a fixed charge and discharge cycle of ESSs in each day. Then, the A-R-OPF was extended in [12] by developing a flexible battery management system, which optimized the charging and discharging hours in each day. Furthermore, a new scheme of the flexible A-R-OPF method was introduced in [13] while considering the optimal operation of wind generations, ESSs, and on-load-tap-changer control systems. Meanwhile, recent researches have focused on the optimal operation of ESSs collocated with photovoltaic (PV) systems in distribution networks [14–16]. In [14], the proposed method could obtain the ESS cost and benefit under different PV penetration level for any selected ESS size. The tradeoff between economic profits and operational benefits could be evaluated quantitatively. Reference [15] investigated the impacts of PV systems on low voltage networks and proposed a mitigation strategy via ESSs operation. In [16], a novel method was proposed for the long term sizing of ESSs, aided by artificial neural networks directed towards the reduction of technical losses on distribution networks with PV systems. In addition, the growth rates of both demands and DGs were considered in the optimization process. Moreover, reference [17] solved the problem of optimally operating a given hybrid energy storage and generation system, under the assumption of perfect load and renewable generation forecasting. However, above works adopt deterministic optimization approaches, while uncertainties of DG power outputs and load fluctuations have been neglected.

Probability method, fuzzy method, and interval method are among possible methodologies that have been explored for handling uncertainties of DGs and loads in optimization problems. The probability method was proposed for handling uncertainties by means of probability density functions of load and DG power variables [18–20]. The charging and discharging power of ESSs were optimized in [21] using probabilistic power flow while uncertainties of loads and wind generations were modeled by point estimate method. Reference [22]