ARTICLE IN PRESS

Applied Energy xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Applied Energy

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

Optimal voltage regulation for distribution networks with multi-microgrids

Xiaoxue Wang[a], Chengshan Wang[a], Tao Xu[a,*], Lingxu Guo[b], Peng Li[c], Li Yu[c], He Meng[a]

[a] Key Laboratory of Smart Grid of Ministry of Education, Tianjin University, Tianjin, China
[b] State Grid Tianjin Electric Power Co., Tianjin, China
[c] Electric Power Research Institute of China Southern Power Grid, Guangzhou, China

HIGHLIGHTS

- A fully decentralized approach to calculate voltage sensitivities is proposed.
- Participants approach final decision through a bi-level game bidding process.
- Microgrids are utilized to provide ancillary services of voltage control.
- The proposed method can be implemented in radial and weakly meshed distribution networks.

ARTICLE INFO

Keywords:
Decentralized approach
Voltage control
Multi-microgrids
Ancillary services
Bi-level game model

ABSTRACT

With the increasing penetration of renewables, microgrid integration has been considered as one of the most promising approaches to enhance the utilizations of various types of energy resources in smart distribution systems. In the near future, with the higher levels of intermittent renewables are envisaged, the distribution network operators will face significant challenges to the control and operation of distribution networks dispersedly. Consequently, the development of effective and motivating ancillary service schemes in a decentralized way for executing real-time control and reducing calculation and communication burden is still in its infancy and needs to be researched. To address this issue, this paper explores an optimal voltage regulation method with the participants of multi-microgrids based on multiple agent systems. Without an arbitration agent, peer agents in the multiple agent system calculate voltage sensitivities by local and neighbourhood measurements only. In this paper, a bi-level game model is proposed for voltage control process. In the upper-level, the distribution network operator searches the reasonable incentive mechanism based on the Stackelberg game. In the lower-level, microgrids make voltage control strategies autonomously based on a static game among microgrids. In the proposed method, microgrids participate in voltage control in distribution networks as ancillary service providers while maximizing their own profits. Meanwhile, the distribution network operator reduces the infrastructure reinforcement and avoids unnecessary renewable energy curtailment. Finally, the feasibility and effectiveness of the proposed method has been demonstrated on a modified IEEE 33-bus system.

In this paper, all active, reactive and apparent power quantities have the units [MW], [MVAr], and [MVA] respectively.

1. Introduction

Due to the severe environmental pollution and decrease in primary energy, the dramatic increase of renewable energy resources (RESs) in distribution networks (DNs) has been significant, and expected to continue to increase. In the near future, with the higher levels of intermittent renewable energy resources are envisaged, the existing systems will not be able to get benefits from remaining excess capacity of dispatchable generation or other grids without network reinforcement. Consequently, the distribution network operators (DNOs) are expecting to face significant challenges to the control and operation of DNs including protection, voltage and overloading, among which the voltage variation has been considered as one of the most significant issues [1–3].

In DNs, controllable energy units, flexible loads and distributed storage systems, are normally installed dispersedly. Numerous voltage control methods combine coordinated control of controllable resources with traditional approaches, such as utilizing on load tap changers (OLTCs), shunt capacitor banks and network reconfiguration in a

* Corresponding author.
E-mail address: taoxutju@126.com (T. Xu).

http://dx.doi.org/10.1016/j.apenergy.2017.08.113
Received 1 June 2017; Received in revised form 9 July 2017; Accepted 12 August 2017
0306-2619/

Nomenclature

Abbreviation

DER	distributed energy resource
DG	distributed generator
DN	distribution network
DNO	distribution network operator
MAS	multi-agent systems
MG	micro-grid
OLTC	on-load tap changer
PCC	point of common coupling
PMU	phasor measurement unit
PV	photovoltaic system
RES	renewable energy resources
SVC	static var compensator
SVG	static var generator

Variables

λ_P	electricity price of active power
λ_Q	electricity price of reactive power
π_{DNO}	total reward provided by the DNO
π_{MGi}	subsidy for MGi
$cv\ (\boldsymbol{V})$	voltage cost of $\boldsymbol{V}$
P_n	injected active power at Node n
$P_{to.n}$	active power into Node n from upstream
Q_n	injected reactive power at Node n
$Q_{to,n}$	reactive power into Node n from upstream
R_n	resistance of line between Node $n-1$ and Node n
V_n	Voltage of Node n
$\boldsymbol{V_{before}}$	nodal voltage vectors before voltage control
$\boldsymbol{V_{after}}$	nodal voltage vectors after voltage control
X_n	reactance of line between Node $n-1$ and Node n
$X^{(i)}$	value of X at the ith iteration step
X'	dummy bus of the prime bus X
ΔP_{MGi}	MGi's active power increment during voltage control
ΔQ_{MGi}	MGi's reactive power increment during voltage control
ΔV_{err}	maximum allowable value of voltage deviation during voltage control
ΔV_i	voltage variation of Node i
ΔS_{MGi}	power increment of MGi during voltage control, $\Delta S_{MGi} = \Delta P_{MGi} + j\Delta Q_{MGi}$
$\frac{\partial V_m}{\partial P_n}$	voltage sensitivity meaning how V_m changes with P_n
$\frac{\partial V_m}{\partial Q_n}$	voltage sensitivity meaning how V_m changes with Q_n

centralized architecture [4–9]. A comprehensive coordinated voltage management approach utilizing remotely controlled switches, OLTCs and shunt capacitor banks while maximizing distributed generation's (DG) active power outputs is proposed in [4]. In [5], DGs take part in voltage control as reactive power resources. However, with the huge calculation and communication burden, centralized methods are difficult to cope with the massive information from distributed resources in real-time. Instead, decentralized control methods divide DNs into sub-networks and solve voltage issues locally by the regional autonomy or collaboration. Without a central controller, decentralized control can provide voltage support with a quick response [10–18]. Decentralized architectures decrease the huge investment of communication devices and measurement units in centralized architectures, and increase the reliability and security of control systems. In a decentralized architecture, each control unit controls one sub-network locally and coordinates with other units for a global goal. In [10], a decentralized automatic method is proposed to alleviate the voltage rise, and guarantee the DG power injection. In [11], a two-stage architecture for voltage control is proposed to manage DG's reactive power. In order to minimize the active power losses and the total reactive power consumptions in radial networks, a nearly decentralized voltage control that coordinates the operation of various DGs is presented in [12]. Authors in [13,14] develop a self-organizing architecture for voltage control in DNs, which obtains voltage information based on consensus theory and controls voltage in a fuzzy logic approach.

Recently, grid codes of many countries, such as Denmark, Germany, Italy and the UK, require distributed energy resources (DERs) to provide ancillary services of voltage control in DNs. However, with the popularity of the electricity market, massive distributed resources installed in DNs belong to different independent operators which cannot be controlled and dispatched directly by the DNOs. Therefore, DNOs need to define reasonable incentive mechanisms to motivate the independent systems to participate in voltage control. As independent systems, microgrids (MGs), entities that integrate DERs including DGs, loads, and distributed storages with inner management systems in a more decentralized way [19], can be considered as controllable cells of DNs. DERs with power electronic devices in MGs have faster response than traditional OLTCs and capacitors, making MGs responsive in the event of dynamic variations [20]. However, the existing applications of MGs are mainly focused on economic operation and energy management to control the point of common coupling (PCC) power or optimize energy interaction among MGs [21–25]. The research of MGs providing ancillary services in DNs is rare. In [25], MGs participate in DN energy management based on a bi-level optimization. In order to minimize the losses in DNs, a day-ahead pricing mechanism is utilized to encourage MGs' participation. However, the MGs have not been considered as independent operators [26].

In this paper, a fully decentralized voltage control method with the participants of multi-MGs is proposed based on a multiple agent system (MAS), applicable for radial and weakly meshed DNs. MGs are motivated by incentives from the DNO to provide voltage supports while maximizing their own profits. The proposed method takes advantages of MGs to supply ancillary services of voltage control in DNs, which can both reduce the investment of voltage regulating devices in DNs and guarantee the profits of MGs during voltage control.

To summarize, the main contributions of this paper are as follows:

(1) A fully decentralized method is proposed to calculate voltage sensitivities in radial and weakly meshed DNs. Peer agents in MAS calculate voltage sensitivities by local and neighborhood measurements only.
(2) A bi-level game scheme is proposed for the DNO and MGs. DNO defines a reasonable incentive mechanism in the upper-level game and MGs' final strategies are approached to a Nash equilibrium in the lower-level game.
(3) MGs are utilized to provide ancillary services of voltage control in DNs, which increases the effectiveness of energy and asset utilization.

The reminder of this paper is organized as follows: Section 2 presents a fully decentralized method to calculate voltage-power sensitivities in a MAS platform. Section 3 discusses the game bidding process of voltage control in electricity markets. Case studies are presented in Section 4, while Section 5 concludes this paper.

2. Decentralized voltage control based on sensitivities in radial and weakly meshed networks

Sensitivity analysis is one of the most common voltage control methods. Voltage sensitivity shows how much the nodal voltage