Electrical Power and Energy Systems 87 (2017) 27–42

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

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

Decentralized reactive power control of distributed PV and wind power generation units using an optimized fuzzy-based method

F. Rezaei [1], S. Esmaeili *,[2]

Shahid Bahonar University of Kerman, Kerman, Iran

ARTICLE INFO

Article history:
Received 25 October 2015
Received in revised form 7 September 2016
Accepted 28 October 2016

Keywords:
Distributed generation
Distribution system
Fuzzy logic
Mathematical optimization
Reactive power control and coordination

ABSTRACT

The presence of power electronic-based wind turbines and photovoltaic systems in distribution networks has provided distribution companies an opportunity to implement voltage control through using the reactive power of these systems. In this paper, a decentralized method based on fuzzy logic is proposed to control the reactive power of distributed generations (DGs) regarding the technical constraints. The fuzzy system is optimized by gradient descent algorithm (GDA) and then implemented on various DG technologies including a photovoltaic (PV) system, permanent magnet synchronous generator (PMSG) wind turbine and also a doubly fed induction generator (DFIG) wind turbine. The system under study is tied to a real distribution network. Having simulated the system, the paper shows that the fuzzy system can appropriately determine the desired reactive power that should be produced by each DG based on the voltage variation of the bus at which the DG is connected. Furthermore, a centralized voltage control is also applied to the same network to verify the performance of the method proposed. The verification indicates that the method is capable of finding the near-optimal solution. A scenario in which an unwanted conflict appears in the DGs' function is defined in detail and then a strategy is presented to resolve the situation. In addition to this, the coordination between the stator of the wind turbines and grid side converter (GSC) is examined. To investigate the robustness of the proposed method in different distribution networks, simulation results are also presented for IEEE 33-bus distribution test system. The numerical results show that the fuzzy system can effectively control the voltage of the DG connection bus.

1. Introduction

Most of the distributed generations (DGs) use inverters to connect to the power grid such as photovoltaic (PV) systems, wind turbines with full-power converters and wind turbines made up with doubly fed induction generators (DFIG). These DG technologies have become very popular for their benefits and now they are a part of the distribution systems [1]. DGs can supply the load active and reactive power locally, which results in a reduction in line losses [2]. Also, voltage and stability of the power system can be improved by integrating DG into the power grid [3]. An interesting feature of inverter-based DGs is their capability of reactive power control and some grid codes now require that PV systems and wind turbines participate in reactive power control of the power system [4]. To comply with new grid codes, solar inverter manufacturers are presenting their photovoltaic inverters with reactive power control capability. These inverters have different control modes and can even produce reactive power at night [5]. Application of PV systems for voltage regulation at night is proposed in the literature. PV systems can be used to regulate the voltage of the connection bus such as a static synchronous compensator (STATCOM) [6]. Similarly, wind turbines are capable of supporting reactive power to the grid when the wind turbines are generating active power or even when the wind speed drops below the cut-in threshold and they are not generating active power [7,8]. Wind turbines can provide the optimum reactive power by means of their converters. The reactive power capability of DGs is limited by several factors which are discussed in the papers [4,9,10]. Reactive power capability of DG increases with the decrease in its active power. Larger reactive power capability means larger inverters, and certainly a larger investment.

Reactive power control of the renewable energy-based DGs not only helps the power grid, it can also mitigate the voltage rise and voltage fluctuations due to the high penetration of DGs. In the high R/X distribution system, active power curtailment is suggested to avoid voltage rise of DGs [11]. However, active power curtailment

---

* Corresponding author.

E-mail addresses: f.rezaei@eng.uk.ac.ir (F. Rezaei), s_esmaeili@uk.ac.ir (S. Esmaeili).

[1] Msc student, Department of Electrical Engineering.

[2] Associate Professor, Department of Electrical Engineering.

http://dx.doi.org/10.1016/j.ijepes.2016.10.015
0142-0615/

Nomenclature

b_{ij}, c_{ij}	points of the membership functions
c_1, c_2	learning coefficients
$\cos(\varphi)$	DG power factor
E_{loss}	active energy consumed by the lines
f	grid frequency
F	objective function
G_{best}	global best position
I_{INV}	inverter current
I_R	rotor current
I_S	stator current
P_{best}	personal best position
P_{DG}	active power of DG
P_{GSC}	active power of the grid side converter
P_L	active load demand at the connection bus
P_R	active power of the rotor
P_S	active power of the stator
$Q_{I,max}$	reactive power limit related to inverter current
$Q_{DG,max}$	reactive power capability of DG
$Q_{GSC,max}$	reactive power capability of grid side converter
Q_L	reactive load at connection bus
Q_{loss}	reactive energy consumed by the lines
$Q_{RC,max}$	reactive power limit related to rotor current
$Q_{S,max}$	reactive power capability of stator
$Q_{SC,max}$	reactive power limit related to stator current
$Q_{V,max}$	reactive power limit related to inverter voltage
r_1, r_2	random numbers between 0 and 1
S	slip of the doubly fed induction generator
S_{GSC}	apparent power of grid side converter
Vel_i	velocity of particle i
V_{CB}	voltage at connection bus
V_{INV}	inverter voltage
VR	voltage profile regulation
X_{EQV}	total equivalent reactance
X_i	position of particle i
X_M	mutual reactance
X_S	stator leakage reactance
ω	inertia weight
η	step size in gradient descent algorithm

is not appealing to owners of renewable energy power plants as the loss of unproduced power is not economical for them [12]. Another solution is reactive power control of PV systems and wind turbines by means of their inverters. These solutions are either centralized or decentralized. Centralized methods require extensive data from the distribution system usually to determine an optimum response. A centralized control method is proposed in [10] to improve the voltage profile and to decrease system losses. A particle swarm optimization (PSO) algorithm is used to determine the optimal reactive power output of wind turbines and power grid reconfiguration, simultaneously. In [13], optimal coordination of PV systems and transformer tap changers are considered based on centralized information of the distribution system. Another centralized method is presented in [14] to coordinate the reactive power of PV systems with capacitor banks and tap changers with the aim to improve voltage profile and reduce power losses.

The centralized control methods need high investment in reliable communication channels and sensors, also communication malfunction or slow response of centralized methods could be a problem, whereas decentralized methods do not require extensive communications infrastructure. However, decentralized methods are unable to reach the global optimum since they are implemented on the base of local data. A decentralized voltage control method based on sensitivity analysis is proposed in [15,16]. In this method, the optimal reactive power of DG is obtained by using the sensitivity of voltage at a specific bus to the active and reactive power of DGs. In [17], DG's reactive power output is considered by using a fuzzy logic-based voltage control method. The fuzzy control system provides a gentle response with a lower reactive power consumption than the sensitivity-based method. The design of fuzzy control system is not dependent on the knowledge of distribution system parameters and it can be easily implemented without investment in communication infrastructure.

To increase the reactive power capability of DFIG wind turbine, several researchers have considered the reactive power support of the grid side converter (GSC) [18,19]. They have proposed a strategy to coordinate stator and GSC in reactive power control. One strategy defines DFIG stator as the main supply of reactive power and the GSC of DFIG wind turbine as the second voltage controller. When the optimum reactive power exceeds the stator's reactive power limits, GSC provides the excess reactive power required to regulate the bus voltage.

Simultaneous responses of DGs and voltage regulating devices for regulating voltage profile might result in operational conflicts [20]. Also, "hunting behavior" between DGs with mutual interactions are possible [21]. Therefore, coordination of DGs and voltage regulating devices might be required in distribution systems. Ref. [20] proposes to consider time delays for DGs and voltage regulating devices such as OLTC and SVRs to avoid simultaneous operations.

In this paper, reactive power limiting factors of PV systems, the PMSG wind turbines and also DFIG wind turbines are discussed and their reactive power capability is determined. Furthermore, Reactive power capability of the GSC is introduced and coordinated reactive power control of GSC and DFIG stator is investigated. A decentralized voltage control method based on fuzzy logic is presented and the gradient descent algorithm (GDA) is proposed to optimize the fuzzy system. The proposed method is implemented on DGs to determine the desired reactive power that should be produced by each DG by considering DG's reactive power capability. A centralized voltage control method based on the PSO is also applied to the distribution network to verify the performance of the proposed decentralized method. Finally, the simulation results and discussions are presented.

2. Reactive power capability of DGs and power flow modeling

PV systems and wind turbines have limited capabilities to supply or absorb reactive power. In the following, reactive power limiting factors of these technologies are presented.

2.1. Reactive power limiting factors of DGs with full-power converters

Fig. 1 shows a schematic of DG with full-power converters. The generator in Fig. 1 refers to either permanent magnet synchronous generator (PMSG) of the wind turbine or PV arrays in this paper. PMSG wind turbine and PV system have the same reactive power limiting factors. All of produced active and reactive power is transferred to the grid through the inverter. Maximum inverter current ($I_{INV,max}$) and maximum inverter voltage ($V_{INV,max}$) impose reactive power constraints of $Q_{I,max}$ and $Q_{V,max}$ respectively as follows [4,9]:

$$Q_{I,max} = \sqrt{(V_{CB}I_{INV,max})^2 - P_{DG}^2} \tag{1}$$