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

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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...
Nomenclature

- $b_{ij}$, $c_{ij}$: points of the membership functions
- $c_1$, $c_2$: learning coefficients
- $\cos(\varphi)$: DG power factor
- $E_{\text{loss}}$: active energy consumed by the lines
- $f$: grid frequency
- $F$: objective function
- $G_{\text{best}}$: global best position
- $I_{\text{inv}}$: inverter current
- $I_r$: rotor current
- $I_s$: stator current
- $P_{\text{best}}$: personal best position
- $P_{\text{DG}}$: active power of DG
- $P_{\text{GSC}}$: 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
- $Q_{I,\text{max}}$: reactive power limit related to inverter current
- $Q_{S,\text{max}}$: reactive power capability of DG
- $Q_{\text{loss}}$: reactive load at connection bus
- $Q_{\text{GSC, max}}$: reactive power limit related to rotor current
- $Q_{\text{S, max}}$: reactive power capability of stator
- $Q_{\text{V, max}}$: reactive power limit related to inverter voltage
- $r_1$, $r_2$: slip of the doubly fed induction generator
- $S$: apparent power of grid side converter
- $V_{\text{CR}}$: voltage at connection bus
- $V_{\text{INV}}$: inverter voltage
- $V_{\text{VR}}$: voltage profile regulation
- $X_{\text{cDV}}$: total equivalent reactance
- $X_j$: position of particle $i$
- $X_M$: mutual reactance
- $X_S$: stator leakage reactance
- $\omega$: inertia weight
- $\eta$: step size in gradient descent algorithm

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 ($I_{\text{inv,max}}$) and maximum inverter voltage ($V_{\text{inv,max}}$) impose reactive power constraints of $Q_{I,\text{max}}$ and $Q_{\text{V, max}}$ respectively as follows [4,9]:

$$Q_{I,\text{max}} = \sqrt{(V_{\text{CR}}I_{\text{inv,max}})^2 - P_{\text{DG}}^2} \quad (1)$$
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