Electric Power Systems Research 83 (2012) 247–254

Contents lists available at SciVerse ScienceDirect

Electric Power Systems Research

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

Review

Reactive power control for improving voltage profiles: A comparison between two decentralized approaches

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ARTICLE INFO

Article history:
Received 2 November 2010
Received in revised form
14 September 2011
Accepted 17 October 2011
Available online 12 November 2011

Keywords:
Voltage regulation
Reactive power control
Distributed generation
Wind turbine
Fuzzy logic

ABSTRACT

This paper is concerned with a local regulation of the voltage profiles at buses where wind power distributed generators are connected. In particular, the aim of the work is to compare two voltage control methods: the first based on a sensitivity analysis and the second on the designing of a fuzzy control system. The two methods are tested by means of simulations on a real distribution system and the results indicate that both methods allow the voltage profiles to be regulated at the wind generator connection bus within voltage standard limits, by taking into account the capability curves of the wind generators. Nevertheless, the fuzzy method presents more advantage in comparison with the sensitivity method. In fact, (i) it provides a gentler action control with a lower reactive power consumption during control operations as the reactive power profile follows better the voltage variations; (ii) the design of the fuzzy controller is independent from the knowledge of network parameters and its topology.

Contents

1. Introduction

Distribution utilities have the obligation to supply the customers at voltage levels within specified limits. As voltage rise problems are a concern against the connection of high penetration of distributed generation (DG) to distribution systems, the development of new voltage control techniques represents an important requirement to deliver power to loads safely [1].

In the past, two alternative approaches have been investigated for voltage regulation: in the first one DG does not participate to the control voltage, which is referred only to other devices (LTC, capacitor banks, etc.) [2–4]; the second one considers the positive contribution of DG to the voltage regulation [5–7].

These analyses are exhaustive: the Distribution System Operators' (DSOs) role is both to facilitate the connection of Independent Power Producers (IPPs) to distribution networks and ensure safe operation. Both proposed approaches are focused typically on an effective centralized voltage control strategy. In particular, considering an active participation of DG to the voltage regulation with a centralized approaches, a significant investment in sensors,

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doi:10.1016/j.epsr.2011.10.010

communications, and control systems is required, which makes their application to voltage control in distribution grids difficult to implement [8].

A decentralized voltage control is an alternative solution. It is based on a local voltage compensation, making the ability to control the reactive power by means of voltage source converters, which are commonly used for grid-connected DG. A decentralized control method, able to assure that generator injections alone do not cause a significant voltage rise, was introduced by Carvalho et al. [8]. Furthermore, local voltage control techniques were proposed in [9], in order to limit the voltage rise in feeders, where load and generation were considered continuously distributed. A voltage regulation algorithm for a grid-connected DG was used also in [10], in which an action on the active power was considered when the reactive power control was not sufficient to keep the voltage in an appropriate range. In order to regulate the voltage within specified limits, an adaptive decentralized voltage control for PV systems, tested on different LV grids, was presented in [11].

In this paper we introduce the novelty both to maintain the voltage levels within permissible limits and favour the maximum active power generation at the bus where DG is connected. This approach, which would be convenient both for the IPPs and the DSOs, is particularly suitable for renewable energy sources with availability of primary resources not deterministically predictable (e.g. solar, wind). Moreover, considering that currently renewable penetration targets are met by wind power, in this paper analytical approaches that take into account the time-varying characteristics of this source are considered, starting from the approach proposed in [12].

The proposed control strategy is implemented by means of two alternative methods both based on the capability curves of the grid connected wind generators. In the first method, in order to determine how a change of the reactive power affects the voltage, a network sensitivity analysis is performed; the second one is based on the designing of a fuzzy controller. The two methods are applied to a real radial distribution system with wind turbines and in simulation phase a comparison between the two methods is presented and the results discussed.

2. Control methods of voltage profiles in distribution systems with DG

The existing MV distribution networks are designed and calibrated for a passive and radial use, involving unidirectional power flows from the higher voltage grid to the lower one. Consequently, voltage profiles fall along the lines with a slope depending on both the line characteristics and the power demanded. Thus, in the passive distribution networks, passive voltage control strategies were required. Simplifying, they were based on: (i) Automatic Voltage Controller (AVC) applied to On-Load Tap Changer (OLTC) installed on HV/MV transformer; (ii) off-line setting of MV/LV tap position; (iii) local regulation of capacitor banks, along the lines [13].

The connection of DG to distribution systems modifies voltage levels at customer's end and introduces different degrees of complexity in the voltage control strategies. In fact, according to the criterion by which DG is connected, the voltage control strategy could change. If DG connection is planned considering the extreme conditions of minimum load ($P_{load}=0$) and maximum generation, and assuming operation under unity power factor, the voltage at the connection bus depends mainly on both the real part of the network impedance and the active power injected (if the probability of this extreme situation occurring is low, it may be beneficial to accommodate a larger generation with the condition that DG is curtailed when the voltage at the connection bus rises to that of the statutory limits); if the planning of DG also depends on the reactive flows (assuming operation under power factor less than one), the value of the X/R ration of line influences greatly the voltage at the bus connection; if the OLTC regulates the voltage at the connection bus, the voltage control method must take into account the OLTC control strategy and the injected power from DG at the connection bus. Generally, these three situations of regulating voltage can occur in combination, thereby increasing the complexity of the control strategy to adopt [14,15].

2.1. Proposed methods for voltage regulation

In this paper, the problem to control the voltage levels is solved by means of a local regulation of the active and reactive power produced by DG, at the DG connection bus. In particular, we propose a voltage control strategy in which the regulation is carried out, firstly by modulating only the reactive power (in order to maximize the active power generation), then, by acting on the active power if the control on the reactive power is not enough. This voltage control strategy is formalized by using two different and alternative methods. The first is based on the sensitivity of the distribution bus voltages to the reactive power injections. In particular, an off-line evaluation of the suitable reactive power amount to inject or absorb is performed (sensitivity method). The second method consists in designing of an on-line fuzzy controller. The details of the two methods are explained below.

2.2. Sensitivity method

In order to present the sensitivity method it is necessary to introduce the concept of threshold levels. Fig. 1a shows a voltage plane in which four threshold levels are defined, set symmetrically with the optimal value ($V_{opt}=1$ p.u.). Taking into account the allowable voltage range [V_{min}, V_{max}], in order to identify the normal operation of the system a *safety voltage range* is defined between $V_{max}-\varepsilon$ and $V_{min}+\varepsilon$. The overlapping areas outline the *voltage control area* (VCA), in which the voltage control action is carried out. If the control action is not able to keep the voltage within the allowable limits, the DG is disconnected, as required both from DSO and fixed in the interconnection rules.

This method requires the knowledge of the bus voltage sensitivity to injection/absorption of active and reactive power at a given bus. Thus, if the voltage value enters in a warning voltage range, an amount of reactive power is injected/absorbed proportionally to the absolute value of the distance between the actual voltage (within the VCA) and the previous voltage value (within safety voltage range). The proportionality coefficient is the sensitivity value and it is calculated as in [16].

In Fig. 1b, the flow chart shows the control procedure considering only the case that the voltage enters in the VCA [$V_{max}-\varepsilon$; V_{max}]. The term ρ_Q is the reactive sensitivity value and the terms V_{act} and V_{prev} indicate the actual voltage and the voltage measured at the previous step, respectively. Symmetrically, the control acts if the voltage exceeds the lower limit $V_{min}+\varepsilon$.

In detail, the procedure begins by evaluating the difference between the voltage measurement (V_{act}) and its previous value:

$$\Delta V = V_{act} - V_{prev} \tag{1}$$

The evaluation of ρ_Q is obtained by fixing all network parameters including the load and the generation profile and solely incrementing the reactive power of each bus where the reactive sensitivity must be calculated. For each considered bus is plotted a voltage/reactive power curve in which the angular coefficient represents ρ_Q. The same procedure is used in order to calculate the active sensitivity value ρ_P. This approach requires the knowledge of the topology of the network with its parameters, and it will be illustrated in the next case study.

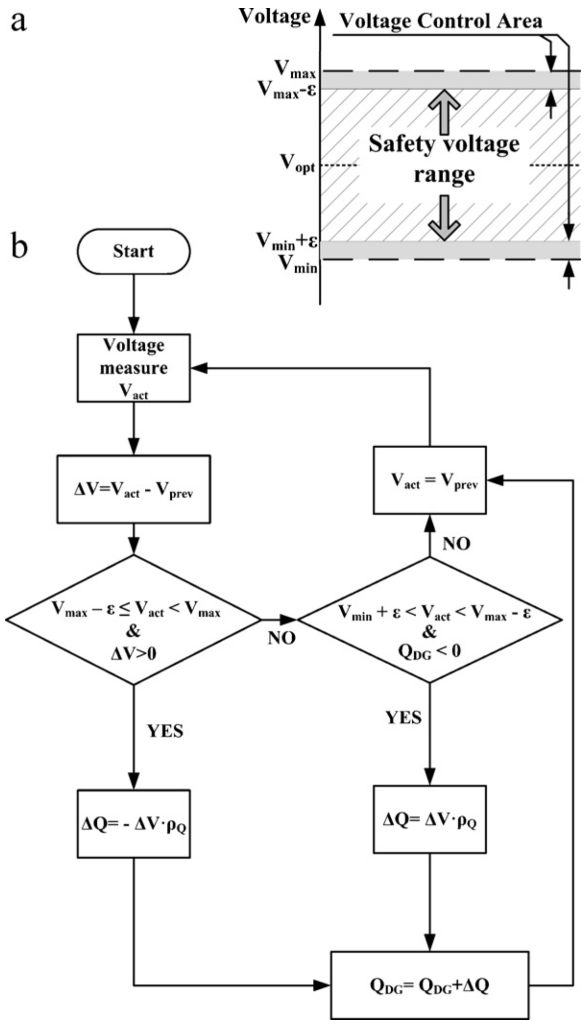

Fig. 1. (a) Control ranges; (b) flow chart of the sensitivity method.

If the measured voltage is in the VCA and the voltage variation is greater than zero, in order to lower the voltage, the generator absorbs an amount of the reactive power proportional to the voltage variation. If the measured voltage is in the *safety voltage range* and the generator is absorbing reactive power, the voltage at the DG bus is falling. In order to avoid that the voltage drops further, the generator produces an amount of the reactive power proportional to the voltage variation. The procedure is repeated at the next step after that the voltage value is updated until the DG power curve is able to furnish reactive power. When the limit of power curve in terms of reactive power is reached, it begins to limit the active power in order to restore the voltage to safe values. The procedure to change the active power is based on the active sensitivity value ρ_P and it is carried out according to the same flow chart (Fig. 1b) as long as it refers to variables concerning the active power.

2.3. Fuzzy method

The voltage control system by means of the fuzzy method consists in designing a fuzzy controller able to set the suitable reactive power to regulate the voltage levels. Thus, the fuzzy controller receives two inputs (voltage and its variation) and evaluates the reactive power to absorb/inject. As for the sensitivity method, if the reactive power absorption/injection is not enough, taking into account the DG power curve described in the next Section, the regulation is carried out by varying the active power. In Fig. 2, only the membership functions of the fuzzy controller with the reactive power output are shown because the control with the active power is the same (the output is the active power and the inputs are the voltage and the voltage variation). In details, the input representing the voltage is modeled by five fuzzy membership functions, as the fuzzy system is required to distinguish five basic situations as follows: Very Low, Low, Optimum, High and Very High. The linguistic variables are referred to the voltage magnitude in p.u., in correspondence of the bus where the controller is applied. The second input is the voltage variation, already defined in (1), and it is mapped over the entire data space of voltage deviations by three membership functions: Negative, Zero and Positive, according as the actual measured voltage is higher or lower than the voltage level measured at the previous step. The linguistic output variable, reactive power, is mapped by five membership functions (the membership functions of the active power are designed only for the positive part and they have almost the same shapes of the positive reactive fuzzy sets. They can be obtained by cutting the third plot in Fig. 2 in correspondence of the zero crisp value and considering only the right part): Large Negative, Negative, Zero, Positive, Large Positive, according as the generator absorbs reactive power (Negative and Large Negative), or produces reactive power (Positive, Large Positive), or works with unitary power factor (Zero with unitary degree of truth), by using Mamdani fuzzy control.

In the voltage control strategy, the fuzzy system acts as an input-pattern classifier. The output has to be interpreted to infer an action on the reactive power. The rule base stored in the proposed controller contains 15 fuzzy rules of the IF-THEN type (Table 1).

Max–min inference is adopted in the voltage control fuzzy system, and the crisp (nonfuzzy) real-number output is again obtained by the centroid of area defuzzification.

2.4. The capability curve

In order to regulate the injection/absorption of the reactive or active power of a generator, it is necessary to know the generator capability curve. In the paper we consider distributed wind turbines (DWTs) with electronic interface, so that the capacity to vary the active or reactive power is constrained by electronic converters.

In order to obtain a capability curve for a wind turbine with electronic interface, the results presented in [16] are considered. The capability curve, in terms of reactive power, is limited by

$$Q = \min\{Q_c, Q_v\} \tag{2}$$

with

$$\begin{aligned} Q_c &= \sqrt{(V_g I_{c,\max})^2 - P^2} \\ Q_c &= \sqrt{\frac{(V_{c,\max} V_g)^2}{X} - P^2} - \frac{V_g^2}{X} \end{aligned} \tag{3}$$

where V_g, $V_{c,max}$ represent the voltage at the grid connection point and the maximum voltage converter, which depends on the dc-link voltage, respectively. $I_{c,max}$ is the maximum converter current, X represents the total reactance of the transformer of the wind turbine and the filters, including the reactance of the transformer adapting the DWTs medium voltage. P is the produced active power. The values of $V_{c,max}$ and $I_{c,max}$ depend on the ratio between the produced reactive and active power [16]. In the following, both the proposed control methods take into account the capability constraints.

3. Application of the methods to a case study

In order to illustrate the introduced local distributed voltage control methods by means simulations, a real radial distribution

Table 1
The fuzzy rules of the controller.

	Voltage				
	Very Low	Low	Optimum	High	Very High
Voltage variation					
Negative	Large Positive	Positive	Zero	Negative	Large Negative
Zero	Large Positive	Positive	Zero	Negative	Large Negative
Positive	Large Positive	Positive	Zero	Negative	Large Negative

network, located in Sicily (Italy), has been considered. The single line diagram of the distribution system is presented in Fig. 3.

The considered network consists of a 132 kV, 50 Hz subtransmission system with short-circuit level of 750 MVA, which feeds a 20 kV distribution system through a 150/20 kV Δ/Y_g transformer with rated power equal to S_T = 25 MVA, V_{cc} = 15.5% and X/R = 0.1. The primary substation transformer's tap is fixed at 1.006 p.u. according to one of the two classical control strategy used in Italian distribution systems [3]. Such a value allows the voltage to be maintained within the allowable range for minimum and maximum demand without DG.

The control systems have been applied to four DWTs characterized by the same rated power S_{rated} = 2.5 MVA. They work by using unitary power factor in normal condition, each DWT is connected

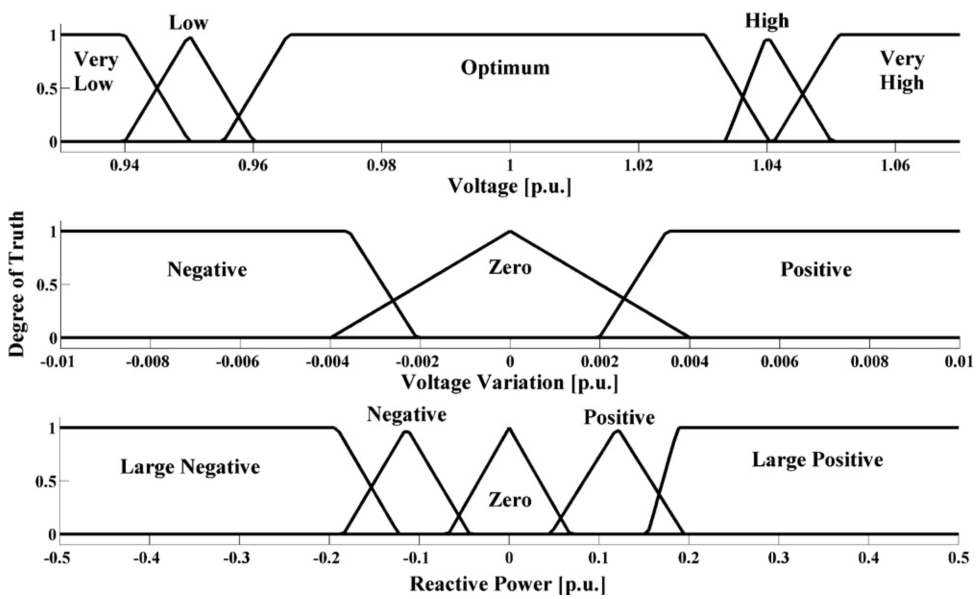

Fig. 2. Membership functions of the fuzzy controller.

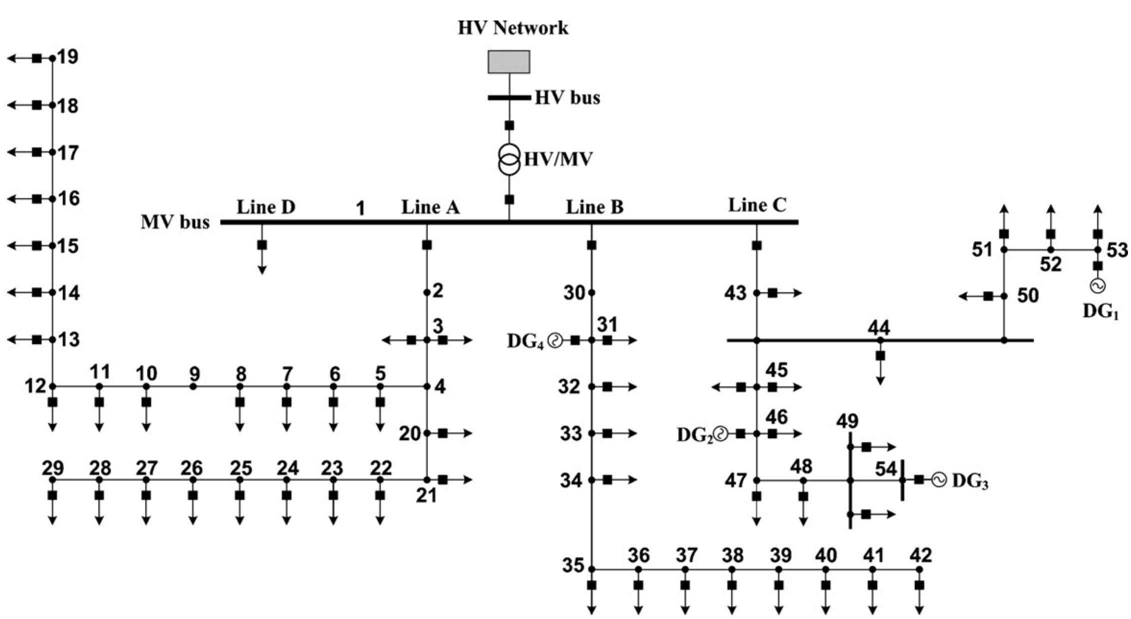

Fig. 3. Italian radial network for test case.

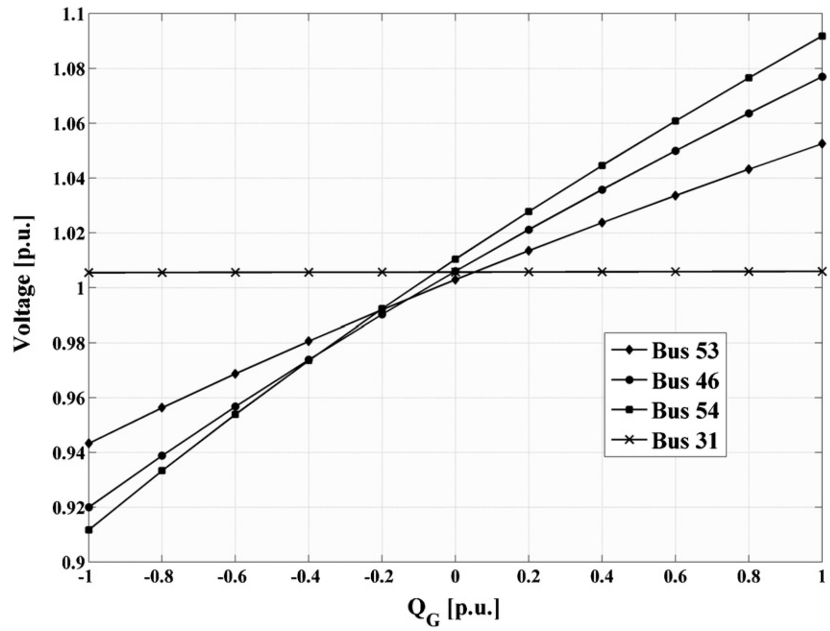

Fig. 4. Bus voltage as a function of reactive power injections at the same bus.

to the grid by means of an electronic interface and the capability curve, the same for each DWT, is shown in Fig. 7b for three different power factor values. The DWTs are connected at the buses 31, 46, 53 and 54. In order to carry out the simulations by the sensitivity method, the sensitivity coefficients have been evaluated according to the previously presented procedure and applied following.

3.1. Reactive and active power bus voltage sensitivities

As described in Section 2, the sensitivity coefficients are calculated by fixing all network parameters including the load and the generation profile and solely incrementing the reactive (active) power of each DWT plant in turn.

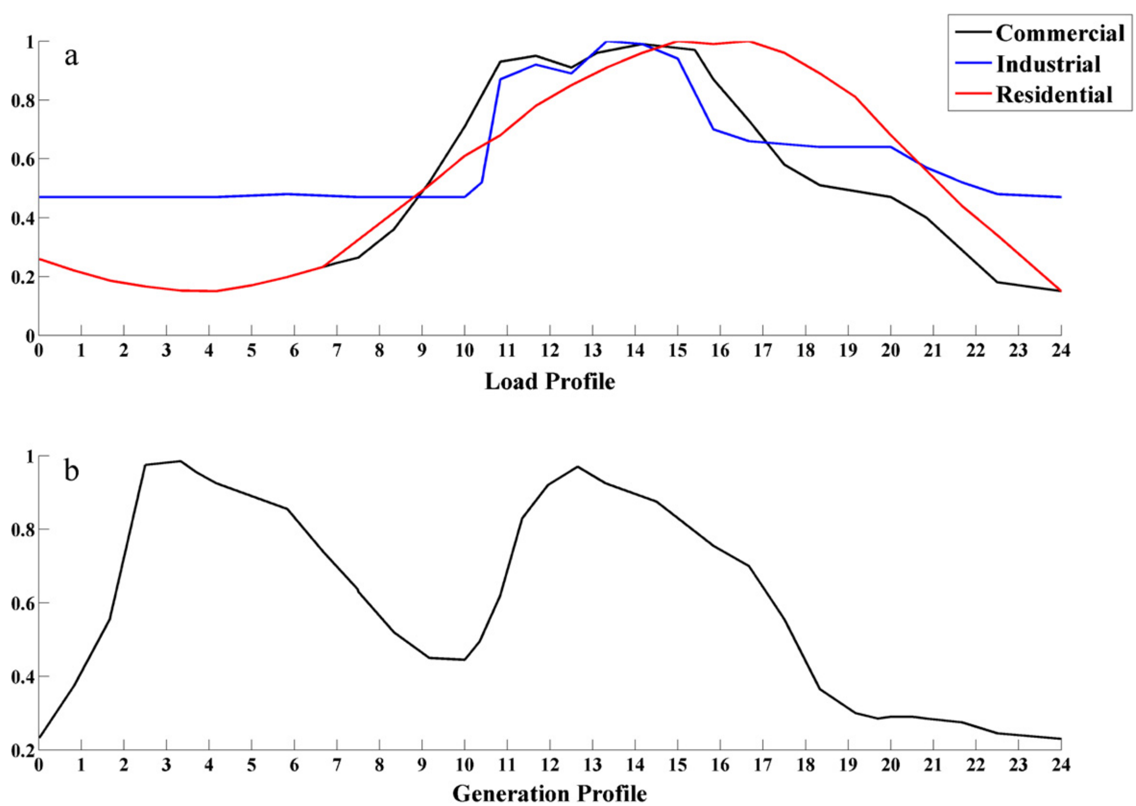

Fig. 5. (a) Load demand profiles; (b) power generation profile.

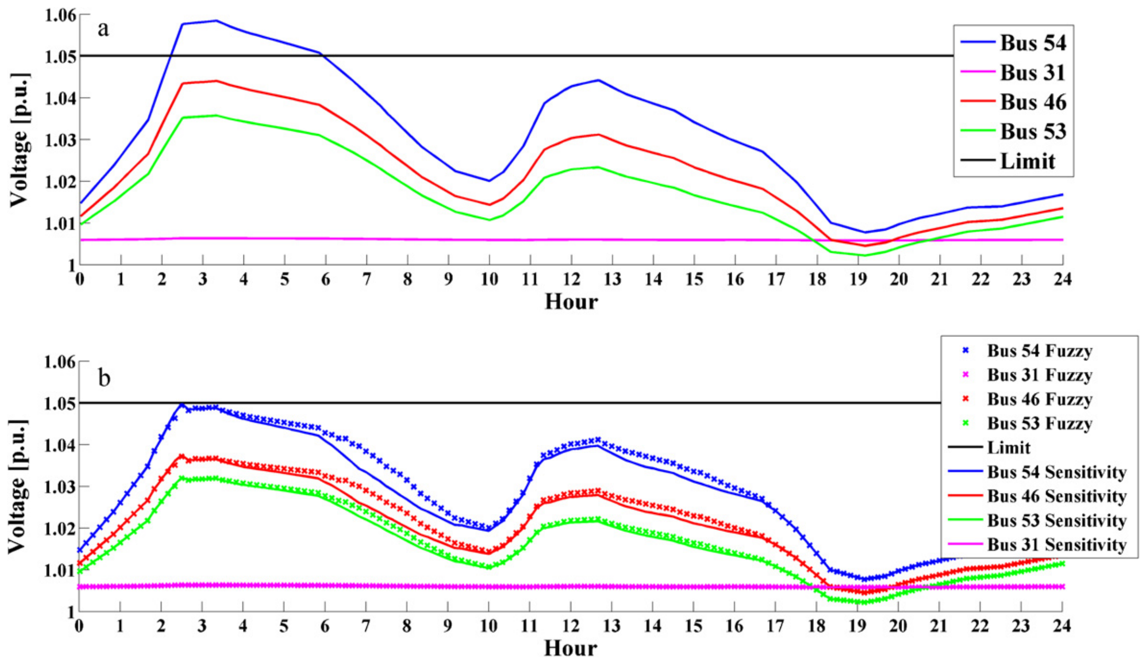

Fig. 6. (a) Voltage profiles without voltage regulation at DWT buses; (b) voltage profiles with voltage regulation at DWT buses.

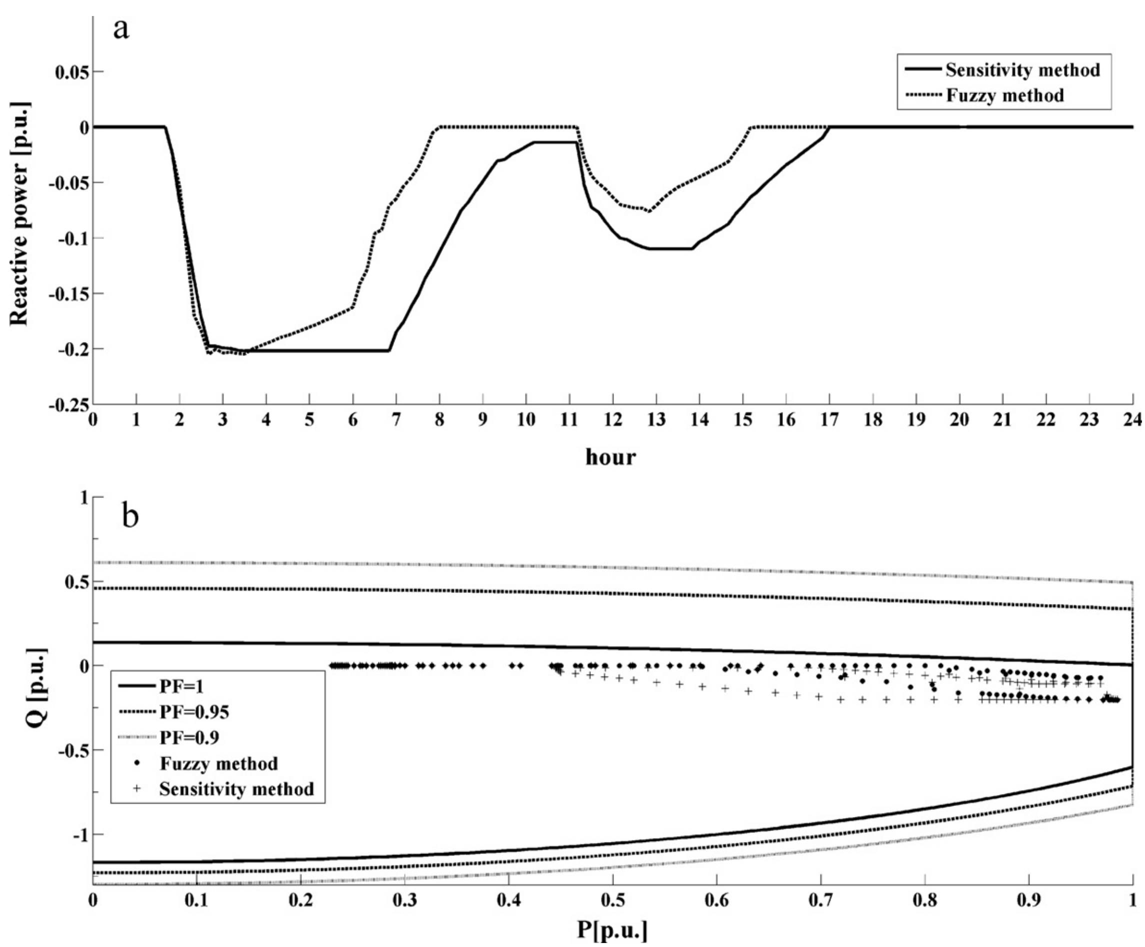

Fig. 7. (a) Reactive power at bus 54; (b) capability coverage with capability curve.

Table 2
Reactive power voltage sensitivity.

DG	ρ_Q	Bus
DG1	0.0203	53
DG2	0.0290	46
DG3	0.0330	54
DG4	0.0001	31

The resulted voltage values at the DWT connection buses are recorded at each step and a linear profile in voltage/reactive power plane has been determined (Fig. 4). The sensitivity coefficients are represented by the angular coefficients of the curves and their values are in Table 2 for each considered bus.

The parameters are evaluated only for the DWT connection buses because the voltage control is performed at each DWT bus [7].

3.2. Simulations, results and discussion

The carried out simulations have been based on a one-day-ahead load forecast with 15 min interval between two subsequent states. The load demand has been modeled by considering three different load profiles, commercial, residential and industrial. Real peak power absorptions data have been acquired by the local DSO and the profile shapes have been obtained according to typical daily load curves [17]. The power generation profile (Fig. 5b) is the same for the four DWTs and the load profiles are depicted in Fig. 5a (the peak demand is 13.65 MW and it occurs at 2:15 p.m.).

Initially, the power factor is set to 1 and a voltage limit of ±5% around the rated voltage value has been taken into account [18]. The safety voltage range is completely defined specifying $\varepsilon = 0.015$.

Fig. 6a and b shows the voltage profiles at the DWT buses without and with the two presented voltage control methods, respectively. It can be noted that, without the regulation, the voltage around the third hour exceeds the voltage limit. By means of the two control methods the voltage is restored within the allowable limit.

The worst cases in terms of voltage levels (maximum and minimum) in correspondence of each bus with the two methods are indicated in Table 3.

As the most significant result in terms of voltage control is related to the bus 54, Fig. 7a shows the amount of reactive power used by the two control methods for each hour.

The control methods presented here allow the voltage to be regulated within the limits at the wind turbine connection points (Fig. 6b), but they differ in terms of advantages and disadvantages. The sensitivity method is very simple to implement on hardware platforms, only modifying the interconnection inverter, provides acceptable performances; however, it requires knowing of the network topology with its parameters and this is the main drawback to its application. In this paper, it has been applied to a real distribution grid, but it allows dealing with any voltage network level. The fuzzy method offers the benefits of being more independent of network topology with its parameters; moreover, the superiority of this approach is doubtless in determining a gentler action control and a lower consumption of reactive power in comparison with the first method.

The proposed control methods are well suited if the voltage at MV side of the HV/MV primary substation is kept to a fixed value. In fact, otherwise, an uncorrelated control between DWTs and OLTC could lead to serious problems in voltage regulation. For instance, if the load demand should be minimal and the wind power production should be maximum at the same time, the OLTC would measure a low current value and at the DWT connection buses the voltage would rise (assuming that all generators are sufficiently far from the HV/MV primary substation). In this condition OLTC would regulate the TAP to a lower voltage level and if a line without DWTs is connected to HV/MV secondary side (the line *C* in the presented case study), the OLTC control action could drive to dangerous voltage drop. In this paper the problem of coordination between OLTC and DWT is not covered, since it is beyond the main goal of the paper and because the case study refers to the Italian OLTC control mode in which, typically, the secondary side of the HV/MV transformer is set to a constant value, as defined in the planning stage [19].

Table 3
Worst cases for voltage levels.

Hour	Fuzzy method				Sensitivity method			
	Max values		Min values		Max values		Min values	
	Bus	V (p.u.)	Bus	V (p.u.)	Bus	V (p.u.)	Bus	V (p.u.)
1	54	1.026	19	0.987	54	1.026	19	0.987
2	54	1.041	19	0.988	54	1.041	19	0.988
3	54	1.049	19	0.989	54	1.049	19	0.990
4	54	1.047	19	0.990	54	1.046	19	0.990
5	54	1.045	19	0.990	54	1.044	19	0.989
6	54	1.043	19	0.989	54	1.041	19	0.988
7	54	1.038	19	0.988	54	1.033	19	0.987
8	54	1.031	19	0.987	54	1.027	19	0.984
9	54	1.029	19	0.984	54	1.022	19	0.984
10	54	1.020	19	0.981	54	1.019	19	0.981
11	54	1.032	19	0.977	54	1.032	19	0.977
12	54	1.040	19	0.964	54	1.039	19	0.964
13	54	1.040	19	0.960	54	1.038	19	0.961
14	54	1.037	19	0.957	54	1.034	19	0.957
15	54	1.034	19	0.954	54	1.031	19	0.955
16	54	1.030	19	0.954	54	1.028	19	0.955
17	54	1.024	19	0.962	54	1.024	19	0.962
18	54	1.014	19	0.963	54	1.014	19	0.963
19	54	1.008	19	0.965	54	1.008	19	0.965
20	54	1.010	19	0.968	54	1.010	19	0.968
21	54	1.012	19	0.972	54	1.012	19	0.972
22	54	1.014	19	0.978	54	1.014	19	0.978
23	54	1.015	19	0.983	54	1.015	19	0.983
24	54	1.017	19	0.987	54	1.017	19	0.987

A significant issue for comparing the two competing approaches is the reactive power consuming. In Fig. 7a the reactive power production, by using fuzzy and sensitivity methods, is shown. It is clear that by the sensitivity method a higher consumption of reactive power is necessary. In fact, by using the fuzzy method the saving in terms of reactive power is about 9 MVAr in 24 h. It can be noted that the major saving of reactive power (by fuzzy method) is obtained between 4:00 and 9:00 a.m. and between 12:00 and 4:00 p.m., when the power demand is low and the power generation is close to the rated power (at minimum demand and maximum generation, which would likely increase the voltage to exceed the limits). In correspondence of the second power production peak (11–17 h), the high power production coincides with a high power demand, so that the reactive power production is lower than the previous case. During this hour the voltage peak is regulated automatically by the absorption of the active power and a smaller amount of the reactive power is necessary. In terms of active power losses, in this case study, the two methods are almost equivalent. They have been calculated by summing the active power losses evaluated at each state, on a one day, with 15 min interval between two subsequent states and very similar results have been obtained. However, it can be noted that by using local control methods it is difficult to get general trends about this aspect, which depends on all network parameters. Finally, in Fig. 7b it can be noted that both the control methods allow the produced active and reactive power to be inside the capability curve even though the voltage at connection point is kept to 1.05.

4. Conclusions

In this research we have investigated two local voltage control methods in order to regulate voltage profiles at DG connection buses.

In the first method we have used a sensitivity approach based on the off-line calculation of the sensitivity coefficients of the distribution bus voltages to reactive power to evaluate the suitable reactive power amount injections for voltage control. The presented second method has been based on the designing of a fuzzy logic controller to regulate the voltage profiles. The fuzzy system receives two inputs (voltage and its variation) and evaluates the reactive power to absorb/inject to control the voltage. The two methods have been tested on a real radial distribution system and the results proved that both the approaches allow the voltage to be regulated within the limits. Furthermore, the two methods present the merit of guarantying the maximum injection of active power by modulating only the available reactive power.

From a practical viewpoint, both presented methods can be easily implemented and without network investment, in order to control the inverter stage of each DG. In particular, as an alternative to the standard power factor control, the proposed controls can be used to realize an external power factor control loop only modifying the control law in the interconnection grid inverter. In this way, if it decides not to use the external control loop, the power factor would be regulated by the standard control (default).

Summarizing, by comparing the two approaches, fuzzy method is more efficient than sensitivity method for two reasons: (i) it provides a gentler action control with a lower reactive power consumption during control operations because the reactive profile follows better the voltage variations; (ii) the tuning of the fuzzy controller is independent from the knowledge of network parameters and its topology.

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