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COMBINED CENTRAL AND LOCAL CONTROL OF REACTIVE POWER IN ELECTRICAL GRIDS WITH DISTRIBUTED GENERATION

Yury Chistyakov[1], Elena Kholodova[2], Kirill Netreba[3], Andrei Szabo[4], Michael Metzger[5]

[1]Siemens LLC/Corporate Technology, St. Petersburg, Russia, yury.chistyakov@siemens.com
[2]Siemens LLC/Corporate Technology, Moscow, Russia, elena.kholodova@siemens.com
[3]Siemens LLC/Corporate Technology, St. Petersburg, Russia, kirill.netreba.ext@siemens.com
[4]Siemens AG/Corporate Technology, Munich, Germany, andrei.szabo@siemens.com
[5]Siemens AG/Corporate Technology, Munich, Germany, michael.metzger@siemens.com

ABSTRACT

The wide spread of distributed generation from renewable power sources may cause severe degradation of electricity quality due to its hardly predictable nature. In order to maintain the desired electricity quality, new actuators and advanced control techniques needs to be developed and integrated in the grid. The reactive power injection of photovoltaic (PV) inverters provides an effective mean for the control of voltage levels and their fluctuation. This paper describes a combined central and local control scheme for the reactive power. The use of local controllers based only on local measurements enables a fast reaction of the controllers on changes in generated and consumed powers, while the central optimization of their parameters ensures an optimal use of the resources and minimization of losses. MATLAB simulations prove the concept for a realistic distribution grid.

Index Terms - power grid control, distributed control, reactive power optimization, local measurements, distributed generation, renewable generation, grid losses optimization, power quality

1. INTRODUCTION

The integration of renewable generation in the existent electrical grids brings several new challenges. On the transmission level, high power plants are tightly integrated, using dedicated communication and control links. On the distribution level, the problem is to integrate and control many small distributed sources in the grid. Each of these different generation technologies constitutes a challenge which varies according to the location of its connection [1].

Smart Grid technologies have the potential to solve these challenges also minimizing the costs required for an expensive network expansion. The Smart Grid is characterized by a two-way flow of electricity and information. It is equipped with means of monitoring and control of electrical infrastructure, e.g. load and generation control, reactive power control and on load tap changers. Using these characteristics, the utilities have an opportunity to improve electrical network performance significantly [2].

One of the key features of the new grids is the availability of the communication down to the level of distribution grid. However, the communication is usually quite unreliable and it still cannot be assumed that it has high capacity or that it is real time.

The grid control solution proposed in this paper combines the global optimization of the grid properties based on a slow, not real time communication and the fast reactions of local controllers. The inputs of the central optimization are the forecasted power generation and consumption of the grid elements, e.g. from the weather forecast for the renewable sources and/or from profiles of the traditional generators or consumers. The actuators in the grid, e.g. the converters of the photovoltaic generators, are equipped with fast local controllers of the active and the reactive power that have only local measurements as input. The central optimization computes the parameters for the local controllers so that the grid requirements are satisfied while maximizing the power generation of the renewable sources and/or minimizing the losses in the grid. The local controller parameters are not changing very often, depending on how accurate the power prognosis is, so the central controller has plenty of time for the optimization and for the downlink transmission of the parameters. In this way, the power generation and the losses are optimized and also the local controllers can react fast to changes in the local measured values.

Some papers have been proposed for the optimization of the dispatch of reactive power for the purpose of voltage regulation including works [3], [4], [5] and [6]. However, these studies are somewhat specialized to optimal placement and/or control a few large sources of reactive power where the problem at hand includes many small sources. In [8] local control scheme that dispatches reactive power from each PV inverter are presented. The scheme is based on local instantaneous measurements of the real and reactive components of the consumed power and the real power generated by the PVs. However, information about local voltages was not included while it may be beneficial for improving the power quality characteristics. The paper [9] focuses mainly on the rapid transitions in loading that a high PV penetration circuit can experience during changes in solar irradiance. However, there are still open questions related to dispatch of reactive power from the PV inverters during other times, for instance, during nighttime hours when there is no PV generation and little concern about rapid changes in loading. The authors of [10] present an extensive research of voltage control based on local proportional-integral controllers. The benefit of the scheme presented in current paper is the coordination of such controllers and their joint parameter optimization.

The remainder of this manuscript is organized as follows. Section 2 describes the capability of an inverter to inject reactive power. Section 3 presents the general control scheme in general. Section 4 describes optimization problem and its constraints. Section 5 presents approaches for optimization process. Section 6 provides a description of the grid conditions for which optimization problem solved. Section 7 presents the results of simulations and Section 8 concludes the study.

2. INVERTER'S CAPABILITY FOR REACTIVE POWER PRODUCTION

Photovoltaic generators as well as other inverter coupled generators (e.g. batteries) are able to produce and consume reactive power. The instantaneous reactive power capability of an inverter attached to a solar panel is limited by its maximum apparent power capability and the variable real power generation. Well-known formula shows the ability of the inverter to generate reactive power:

$$Q\,(t) = \sqrt{S_{\max}^2 - P_{\mathrm{PV}}^2(t)} \quad (1)$$

where Q is current reactive power value; S_{max} is total power capacity; P_{PV} is current active power of the PV. Maximum apparent power (current) of inverter in turn depends on maximum current of power electronic elements.

As it is shown in (1), reactive power production depends on maximum apparent power and current value of active power of inverter. At the same time PV active power utilization can be quite small because high dependence on weather conditions (e.g. about 900 h/a for Germany). Thus, reactive power capacity can be rather high. Statistical data of PVs' utilization as reactive power generators are given in [11]. According to the statistics the inverter is available for reactive power producing in 99.9% of time with capacity about half from maximum apparent power.

From 2010 in Germany PV plants have to remain connected to grid during outages and provide needed reactive power. Moreover, from 2011, in extreme cases, the PV plants have to be able to produce 100% of nominal reactive current to the grid [8], [9].

3. CONTROL SCHEME

The control scheme is based on communication between central and local controllers. Fig. 1 shows block diagram of the proposed concept. Its components are described below.

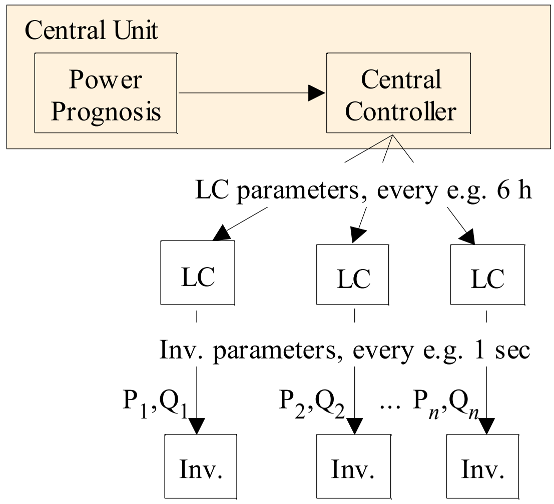


Fig. 1. Block diagram of the control scheme (LC is a local controller)

3.1. Central Controller

The central controller gathers all the required grid information and periodically solves the grid regime optimization problem described in details in Section 4. The optimization considers a given range of active and reactive powers injected in the grid, which is given for example by a weather prognosis service or from user power profiles, and computes the optimal local controller parameters, so that only using these local controllers the grid requirements will be satisfied and the reactive power use is minimized. These parameters are then sent to the local controllers.

The central controller sets the local controller parameters so that for any injected powers in the grid in the forecasted ranges, the voltage magnitude remains between given constraints. Thus, the control of the reactive power is local, based only on the magnitude of the locally measured voltage.

Every time the power prognosis changes the central controller computes new parameters and send them down. If the communication between the central and the local controllers breaks, the prosumers are supposed to continue to use their previous parameters. In this situation, if the prognosis is correct everything works properly. Otherwise, or if the communication break is longer than the validity period of the prognosis, the constraints might be broken. The optimization should be done so that some guard margins are kept, e.g. for errors in the prognosis.

3.2. Local Controllers

The active and reactive power produced by the inverters is locally controlled, using as input measurements of the local voltage[1]. Most of the publications and standards propose that the local control is a so called droop function, i.e. a linear dependency of the reactive power on the local voltage [13]. We will also use this formulation for the local controllers.

Thus, the bounded droop function is introduced as

$$Q_n = \begin{cases} \alpha_n\left(u_n - u_n^{\mathrm{nom}}\right), Q_n^{\min} \le \alpha_n\left(u_n - u_n^{\mathrm{nom}}\right) \le Q_n^{\max} \\ Q_n^{\min}, \alpha_n\left(u_n - u_n^{\mathrm{nom}}\right) < Q_n^{\min} \\ Q_n^{\max}, \alpha_n\left(u_n - u_n^{\mathrm{nom}}\right) > Q_n^{\max} \end{cases} \quad (2)$$

[1] In principle, the frequency of the system is also influenced by the distributed generation, so the local controllers should also consider the frequency. Since we assume that the overall ratio of distributed generation is small compared to classical synchronous generators, we focus in this paper only on the voltage control.

where Q_n is the reactive power injection by the n^{th} prosumer, α_n and u_n^{nom} are the droop parameters and u_n is the locally measured voltage. Q_n^{min} and Q_n^{max} are the reactive power limits of the inverter according to Section 2.

Fig. 2 shows the principle of reactive power regulation using locally measured voltage magnitudes. When the local voltage is lower than the nominal voltage inverter generates reactive power proportionally its droop coefficient. When the local voltage is higher than the nominal voltage, the inverter consumes reactive power proportionally to a given coefficient.

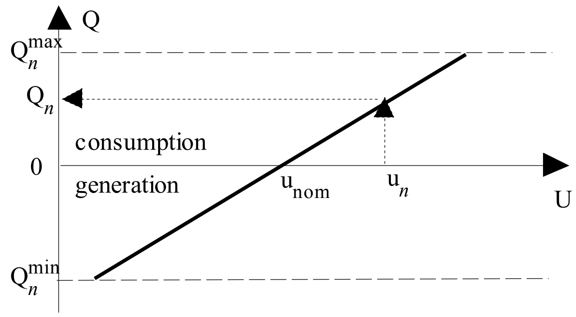


Fig. 2. Inverter's Q(U) droop characteristic

4. OPTIMIZATION PROBLEM

The main novelty of the paper comes from the adaptation of the droops parameters jointly, depending on the forecasted generation and consumption. The aim of the optimization is to allow maximum active power injection from the renewable energy devices, while keeping the grid voltage in the desired bounds. The free parameters for the optimization are the local controller parameters and implicitly the reactive power generation, which on one hand is limited by the capabilities of the inverters and on the other hand produces additional losses in the grid. Consequently, we have to solve a constraint optimization to minimize the losses in the grid while satisfying voltage constraints and capabilities of the actuators. So, the optimization problem can be expressed as the minimization of the reactive power which is transferred in the medium voltage grid over the local transformer (Q_{SJ}), which is desired by the grid operators. This problem is formulated in the following.

Let $n = 1 \dots N$ be the index of the controllable devices, which we are going to term from now on as prosumers. Let $m = 1 \dots M$ be index of all generator and the consumers in the grid, including the ones which are controllable and those that are not controllable. Let us assume that for a given interval of time there exists a prognosis of the active powers for all the elements in the set M. The central optimization must compute the droop parameters for each local controller (α_n and $u_{n,\text{nom}}$ for $n = 1 \dots N$) so that for each combination of the active powers inside the prognosis ranges:

$$P_{\min,m}^{\text{prognosis}} \le P_m \le P_{\max,m}^{\text{prognosis}}, m \in M \tag{3}$$

the local controllers will converge to a state for which the voltages in the grid are inside the prescribed voltage range:

$$\begin{gathered} \left[\alpha_n, u_n^{\text{nom}}\ {}_{n=1\dots n_P}\right] = \arg\min Q_{\text{SJ}}, \\ \text{s.t. } u_{\min} < u_m < u_{\max}, m \in M \\ \text{where } \left[u_{m,m\in M}\ , Q_{\text{SJ}}\right] = PF(P,Q) \end{gathered} \tag{4}$$

where PF is the power flow solution given the active and the reactive power sets in the grid (P_m, Q_m $m \in M$) and depending on the grid topology and admittances. The reactive power at the prosumer nodes is given by equation (2), while the one at the rest of the nodes is assumed to be zero or known according to each node type.

The droop proportionality constant α has an important influence on the system oscillations and stability. For large values of α, even small variations of the voltage will result in large variations of the reactive power, which in turn will result in further variations of the voltage, the system showing oscillations of the voltage. For this reason it is important to limit the values of α. The upper limit of the droop coefficients α is introduced in the optimization as constraint and is computed so that the maximum reactive power $Q_{\max}$ is generated at maximum voltage deviation:

$$0 \le \alpha_n \le \alpha_{n,\max} \tag{5}$$

$$\alpha_{n,\max} = Q_n^{\max} / (u_{\max} - u_{\text{nom}}) \tag{6}$$

5. PROCESS OPTIMIZATION APPROACHES

The active power values for the power flow computation are given by the prognosis process. Let us denote a complete set of active powers of all the generators and consumers at a given moment as a "snapshot".

The problem of (4) can be solved using standard constrained optimization solvers, for example interior point or active-set methods. The most difficult part is that the constraints (i.e. voltage constrains) must be satisfied at any time during the forecasted interval.

Depending on how accurate the prognosis process is, two approached presented below can be considered.

5.1. Iterative Approach

If the active power forecast can be assumed quite accurate, then a series of snapshots can be generated, which would characterize the future power flows (PF). This means that the prognosis is able to predict which combinations of active power the users will produce.

The optimization needs in this case to be solved for the given set of snapshots so that a common set of droop parameters satisfy all the snapshots.

The solution for this approach can be achieved in that all the snapshots are added to the constraints, but this would result in a large and slow optimization. A simpler approach is to solve the optimization iteratively starting from one snapshot and then adding those snapshots to the constraints where the voltage boundaries are broken with the highest difference. The first snapshot is found just solving the power flow problem in the case that the inverters do not generate or consume reactive power.

The resulting solution is guaranteeing the voltage boundaries for the given snapshots, while keeping the droop coefficients as low as possible to minimize the used reactive power and maximize system stability.

5.2. Worst Cases Approach

If the accuracy of the prognosis is not that reliable, then the worst cases scenarios for the maximum and the minimum voltage must be considered. In this case the prognosis need only to generate the minimum and the maximum active power forecasted for the given period.

The first worst case is a snapshot where each prosumer generates its maximum active power (instant capacity) and each consumer consumes its minimum active power which is defined by a minimum value during prognosis time.

The second worst case is a snapshot where each prosumer generates no active power and each consumer consumes the maximum amount of active power which is defined by a maximum value during prognosis time.

For satisfying these two worst cases, the needed reactive power will be much higher, so the droop coefficients will need to be higher. In the case that no solution is possible, then also the active power of the controllable devices (prosumers) will need to be also limited.

6. DESCRIPTION OF THE TEST GRID

Simulations are done using a model of a distribution grid with a high penetration of PV power plants.

6.1. Overview of the Test Grid

Fig. 3 shows the structure of the grid, visualized in MATLAB. Each grid joint can be connected to several consumers or producers. Joints with only consumers connected are shown with light grey color and prosumers (generators) are black.

The most of the customers are households which are fed from the main grid via two transformers with rated power of 630 kVA. There are 134 consumers and 26 prosumers in the concerned grid. Generation structure is as follows: 23 PV, 2 batteries and 1 CHP (Combined Heat and Power generator).

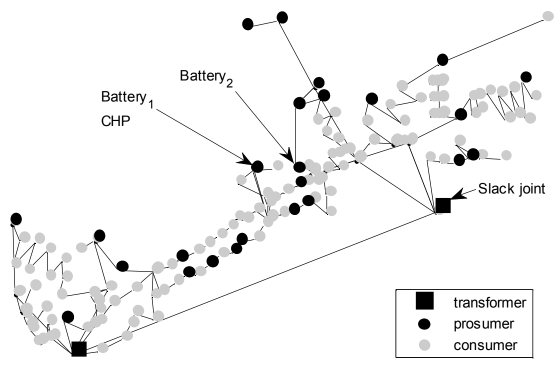


Fig. 3. Test grid

The total installed capacity of PV systems is approximately 500 kW. There are several large PV systems (agricultural buildings with large roof area) which have high influence on the grid. On sunny days due to large capacity of PV systems, reverse of power flow though the transformers can be detected.

6.2. Active Power Prognosis

Typical active power prognosis for the grid described above is shown in Fig. 4. Negative active power values mean generation while positive values indicate consumption. The batteries are charged during the day when PV generation exceeds the consumption, while in the evening the consumption is large and the needed power is generated by CHP and the additionally by the batteries.

For this prognosis grid voltages without reactive power injections are shown in Fig. 5. It can be seen that upper voltage border (420 V) is broken considerably.

For this experiment we have set the voltage limits at +/– 5%, i.e. +/– 20V line to line, to give a security margin of additional voltage variations due to transport grid voltage variations and also to simulate the case when the grid would be even weaker / the renewable penetration even higher.

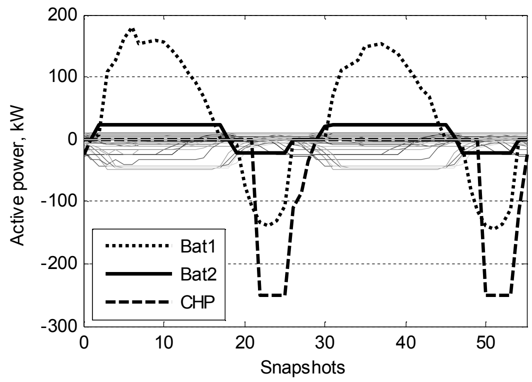


Fig. 4. Active power generation/consumption prognosis.

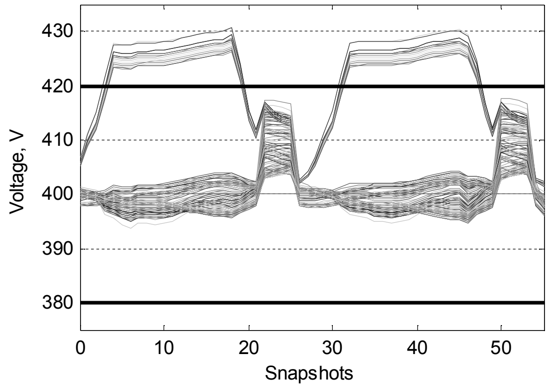


Fig. 5. Nodes' voltages without reactive power control.

7. SIMULATION RESULTS

For this study, taking into account information in Section 2 and a minimum power factor of 0.9, the limits on the reactive power will be $|Q_{min}| = |Q_{max}| = 0.5|P_{max}|$, where P_{max} is maximum active power during prognosis time. According to Section 4 considerations, voltage bounds are set as follows: u_{min} = 380 V, u_{max} = 420 V and nominal voltage is 400 V. Upper border for droop coefficients appeared to be equal to 2500.

7.1. Iterative Approach

The droop coefficients, obtained using iterative approach, are shown in Fig. 6 (a), while the resulting voltage values in the grid for the considered active powers are shown in Fig. 7 (a). The reactive power transfer over the slack joint it is plotted in Fig. 8 (a).

7.2. Worst Cases Approach

The results of the optimization for this case are shown in Fig. 6 (b): optimum droop coefficients found for the two worst power configurations. Using these droop coefficients for the reactive power control and computing the regime for each snapshot in the prognosis time nodes' voltages are obtained and presented in Fig. 7 (b). Slack joint power flow is depicted in Fig. 8 (b).

7.3. Results compasion

Both approaches show their applicability to the specified problem. Though the set of droop coefficients are different for described two approaches the result is very similar.

Comparing to the results in Fig. 6 one can notice that set of droop coefficients for worst cases approach in Fig. 6 (b) is higher in average. Voltages are satisfied in both cases (see Fig. 7). Fig. 8 (a) and (b) show small difference between slack joint reactive power flows for the two approaches.

One reason for the similarity is that actually optimizing over the entire range of snapshots we cover almost the same range of active powers as the worst case approaches. Lower reactive power could be achieved with more often updates of the local controller parameters. Such a case will be less robust against prognosis errors and communication breakdown, but the grid operation will be closer to the optimum. Also the communication requirements will be higher.

In an advanced solution two sets of parameters for the local controller could be computed: one set of parameters computed for a shorter prognosis period which ensures an operation of the grid closer to the optimum and a second backup set which should be used in case of communication breakdown, or when the prognosis period is expired without getting an update of the local controller parameters.

8. CONCLUSIONS

In this work a scheme for controlling PV inverter-generated reactive power for high PV penetration distribution grids is developed. The concept described in this paper provides improved voltage quality and higher line capacities in distribution grids with a high penetration of PV power plants. Approaches for derivation of robust droop parameters in conditions of rapid solar irradiance variations are developed.

Two methods were proposed, depending on how accurate the power generation and consumption forecast is available: iterative and worst cases approaches. Droop coefficients are lower using iterative cases approach which generally provides better system stability.

The technology described above is currently under development and partly being tested with solar inverters in a distribution grid. The technology can be applied to any power electronic inverter which is either permanently or temporarily connected to the grid. Due to the inbuilt data communication and data acquisition facilities the system can be automatically configured after connecting a new inverter to the grid. More tests with grid models are to be performed in order generalize the proposed concept.

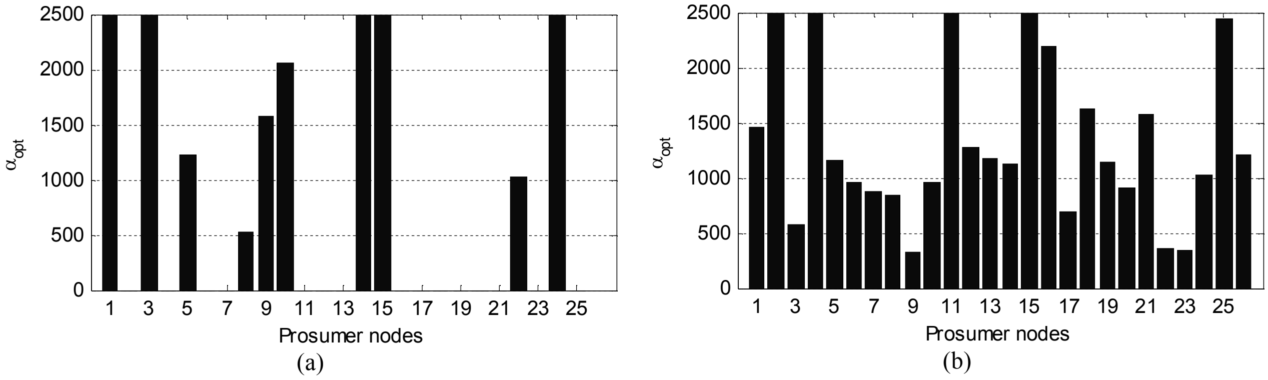
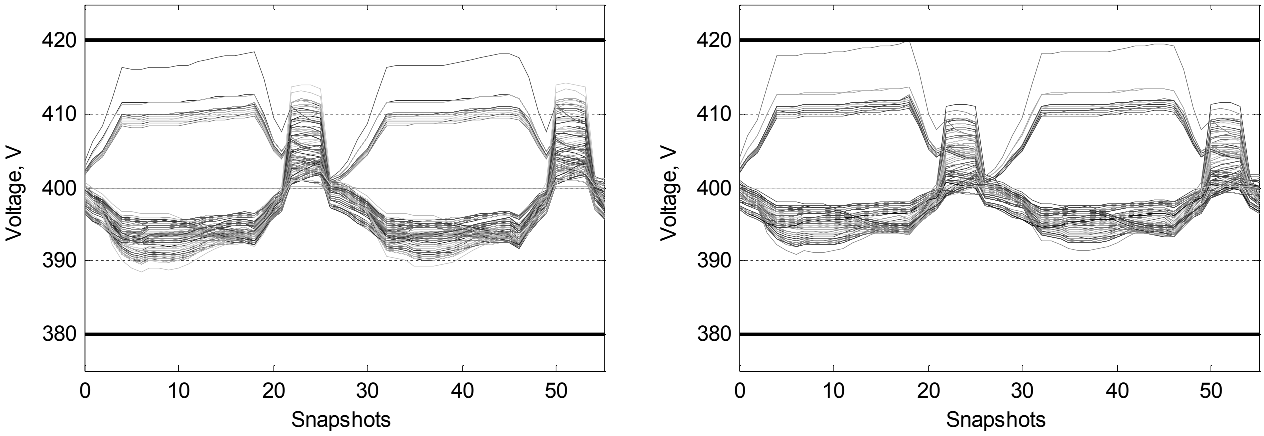
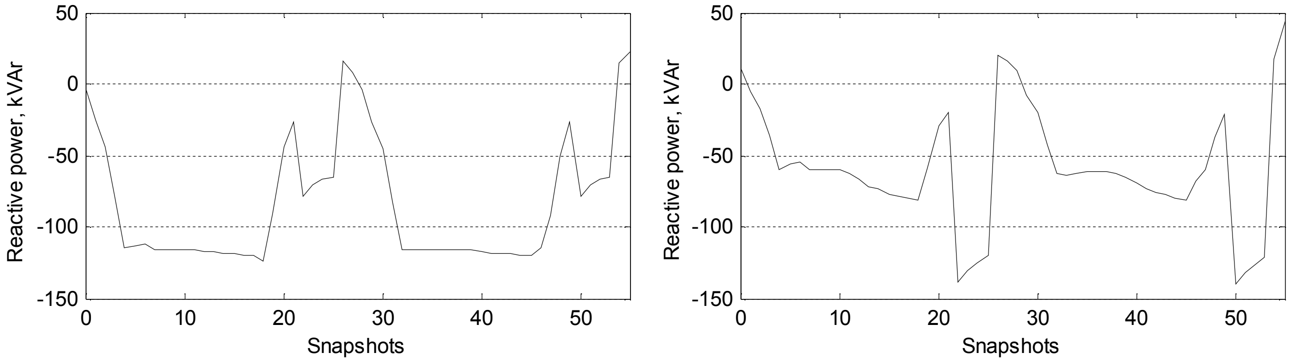


Fig. 6. Prosumers' optimum droop coefficients for the iterative (a) and worst cases (b) approaches



(a) (b)

Fig. 7. Local voltages are satisfied for the iterative (a) and worst cases (b) approaches



(a) (b)

Fig. 8. Slack joint reactive power for the iterative (a) and worst cases (b) approach.

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