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Decentralized Active and Reactive Power Control for PV Generation Plants using Real-time Pricing Strategy

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***Abstract*— PV (photovoltaic) generation may cause voltage rise at the interconnection point due to reverse power flow, which is recognized as a critical issue for keeping power quality. This paper investigates a decentralized management problem of PCSs (Power Conditioning Systems) which are used to interconnect the PV system into the power grid. We consider a real-time pricing strategy of the operator who plays the role of a management office of a PV generation plant. Each PCS determines own set-points of the active and reactive power injections by solving an individual small size optimization problem that includes the conceptual price provided by the operator. This feedback interaction between the operator and PCSs eventually suppresses the voltage deviation. The effectiveness of the proposed methodology is evaluated through the numerical and real physical experiments.**

I. Introduction

PV (photovoltaic) generation has experienced the most growth among the renewable energy sources in the last few years. PV installations are no longer isolated from the power grid but connected to it, and the interconnection capacity may continue to increase [1]. Reverse power flow from a PV generation plant may lead to voltage rise, which is recognized as a critical issue for keeping the power quality [2].

Voltage regulation devices such as LRTs (Load Ratio control Transformers), SVRs (Step Voltage Regulators) and SCs (Shunt Capacitors) can contribute to mitigate the voltage rise [3], [4]. Another possibility is utilizing the capability of inverters or PCSs (Power Conditioning Systems), which are used to interconnect the PV system into the power grid, for reactive power control as well as adjusting the amount of active power produced [5], [6], [7], [8]. Reverse power flow often fluctuates and makes the voltage profile complicated. This necessitates an alternative method to control the amount of active and reactive power injections to compensate the voltage rise. In addition, a decentralized control strategy is implementable, which will be the main theme of this paper.

In [5], a reactive power dispatching scheme has been considered for voltage support through multi-agent based optimization. Voltage regulation by injecting reactive power with uniformly distributed generators has been investigated in [6]. A reactive power control strategy proposed in [7] uses the voltage control mode and the power factor control mode, and it was discussed how distributed control can achieve similar results to centralized control. In [8], a reactive power injection regulation mechanism for distributed generators has been considered, where a necessary amount of reactive power which mitigates voltage rise caused by own active power injection will be injected.

This paper investigates a decentralized control of PCSs. We determine the optimal set-points of active and reactive power of each PCS in a distributed manner. We investigate a real-time pricing strategy and consider distributed decision making by each PCS. This framework will overcome the difficulties with the centralized operation. Although our approach assumes a centralized operator, a duty of the operator is quite small, and it does not need to know anything about operating constraints of each PCS even the number of PCSs connected to the PV generation plant. The only task of the operator is to observe the voltage at the interconnection point and determine the real-time pricing signal according to a very simple updating rule. The pricing signal will be sent to each PCS, and the PCS will determine its optimal set-points as a solution to an individual small size optimization problem, which includes the received pricing signal. This feedback interaction between the centralized operator and the PCSs eventually suppresses the voltage deviation. In our real-time pricing and distributed decision making methodology, the operator does not need to have any model of the PCS, and no-one needs to formulate and solve a large size optimization problem. In addition, it provides a plug-and-play type functionality to cooperatively operate the PCSs.

A theoretical frame work of the real-time pricing and distributed decision making methodology has been investigated in [9]. This paper considers suitable modifications of the problem formulations discussed in [9] to enhance the voltage regulation for the PV system. The effectiveness of the proposed method will be evaluated by the numerical and real physical experiments which assume the PV generation plant having 5 MW total capacity.

Voltage regulation by using the reactive power injection only has been investigated in [10]. The present and recently accepted papers [11] consider adjusting both of the active and reactive power injections. This paper especially investigates the effectiveness of the plug-and-play type functionality to cooperatively operate PCSs through the numerical experiment in Section IV. On the other hand, this paper shows only a single result of the real physical experiment, but other extensive results under practical configurations as well as

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more detailed discussions can be found in [11].

II. Voltage Deviation Problem

We consider a single PV generation plant consisting of n power conditioning systems, PCS_i, $i = 1, \dots, n$. Fig. 1 shows a schematic diagram of the PV system configurations. We denote by V_1 and V_2 the root-mean-square values of the receiving and sending end voltages, respectively. We suppose that the receiving end has a large enough capacity compared to that of a single PV generation plant, and thus we assume V_1 is constant. The purpose of the voltage regulation problem is to suppress the voltage deviation $V_2 - V_1$ at the interconnection point.

We denote by P_i^{r} and Q_i^{r} the set-points for the active and reactive power outputs of PCS_i. According to the inverter dynamics, each PCS_i outputs the active power P_i and reactive power Q_i which will track to the set-points P_i^{r} and Q_i^{r}, respectively.

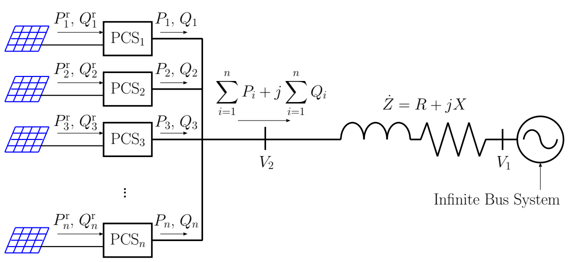


Fig. 1. PV generation plant configurations.

Let R and X denote the resistance and reactance of the power line. We have the power flow equation as

$$\sum_{i=1}^{n} (P_i + jQ_i) = \dot{V}_2 \dot{I}^* = \dot{V}_2 \left(\frac{\dot{V}_2 - \dot{V}_1}{R + jX} \right)^*$$

where $\dot{V}_1$ and $\dot{V}_2$ are the voltage vectors with magnitude V_1 and V_2, respectively. $\dot{I}^*$ denotes the complex conjugate of the current vector. We suppose that the phase shift between $\dot{V}_1$ and $\dot{V}_2$ is small, and this allows us to derive an approximate model of the voltage deviation as

$$V_2 - V_1 \approx \frac{R}{V_2} \sum_{i=1}^{n} P_i + \frac{X}{V_2} \sum_{i=1}^{n} Q_i \tag{1}$$

The approximate voltage deviation in (1) shows that the voltage at the interconnection point is affected by injections of the active power P_is and it may be possible to suppress the voltage deviation by injecting the reactive power Q_is.

Our problem is to determine the set-points P_i^{r} and Q_i^{r}, $i = 1, \dots, n$, which, taken together, suppress the voltage deviation. In addition to this main purpose, we set the following three objectives, which are intended to be attained by the proposed decentralized voltage regulation system.

1) Each PCS_i injects active power P_i as much as possible; in other words, avoids unnecessary reductions in the amount of active power produced.
2) Q_i^{r} determined by each PCS_i should be equal to each other as much as possible.
3) Some PCS_is may not inject enough reactive power or connect due to operating constraints such as over-heating of the hardware equipment or a capacity limitation. In such cases, the other PCS_js adjust Q_j^{r}s and P_j^{r}s to suppress the voltage deviation in a cooperative manner.

III. Decentralized Control of Inverter Networks using Real-time Pricing Strategy

We start with considering a centralized large size optimization problem. Let us suppose that the operator of the PV generation plant wants to determine P_i^{r} and Q_i^{r}, $i = 1, \dots, n$ as the solution to the following optimization problem.

$$\min_{\substack{P_i^{\mathrm{r}}, Q_i^{\mathrm{r}} \\ i=1,\dots,n}} \quad \sum_{i=1}^{n} \left((P_i^{\mathrm{r}} - P_i^{\mathrm{d}})^2 + (Q_i^{\mathrm{r}})^2 \right) \tag{2a}$$

$$\text{subject to} \quad -\gamma_i P_i^{\mathrm{r}} \le Q_i^{\mathrm{r}} \le \gamma_i P_i^{\mathrm{r}} \tag{2b}$$

$$0 \le P_i^{\mathrm{r}} \le P_i^{\mathrm{l}} \tag{2c}$$

$$(P_i^{\mathrm{r}})^2 + (Q_i^{\mathrm{r}})^2 \le (S_i^{\mathrm{d}})^2 \qquad i = 1, \dots, n \tag{2d}$$

$$\frac{R}{V_2} \sum_{i=1}^{n} P_i^{\mathrm{r}} + \frac{X}{V_2} \sum_{i=1}^{n} Q_i^{\mathrm{r}} = 0 \tag{2e}$$

where $\gamma_i = \tan \theta_i^{\mathrm{l}}$ and $\cos \theta_i^{\mathrm{l}}$ is the limit of the power factor which is assigned by the electric grid company, a constant P_i^{l} denotes the rated power of PCS_i, and both of P_i^{d} and S_i^{d} are design parameters, which will be specified by PCS_i as described bellow. The equality constraint in (2e) implies the voltage deviation suppression. The inequality constraint in (2c) specifies a capacity limit of the active power produced, and (2b) represents the power factor constraint. We denote by $(P_i^{\mathrm{r}})^*$ and $(Q_i^{\mathrm{r}})^*$, $i = 1, \dots, n$ the optimal solution to (2).

Let a constant S_i^{l} denote the apparent power capacity of PCS_i, which is determined by the hardware equipment of PCS_i as similar to P_i^{l}. S_i^{d} in (2d) is a design parameter that will be set by each PCS_i as $S_i^{\mathrm{d}} \le S_i^{\mathrm{l}}$. Each PCS_i usually may set $S_i^{\mathrm{d}} = S_i^{\mathrm{l}}$, and this allows PCS_i to inject active or reactive power as much as possible. In addition, PCS_js which share the same apparent power capacity will share the same amount of the reactive power as objective 2) requires. On the other hand, let us suppose that certain PCS_k encounters a faulty operating condition like over-heating and needs to reduce the amount of injecting apparent power to prevent the hardware equipment from being seriously damaged. PCS_k can adjust S_k^{d} by itself, for example $S_k^{\mathrm{d}} = S_k^{\mathrm{l}}/2$, and this implies that PCS_k will reduce the amount of active and reactive power as compared to the other PCS_js in healthy operating condition. Even when certain PCS_k modifies S_k^{d}, the other PCS_js will cooperatively adjust Q_j^{r}s and P_j^{r}s by imposing the equality constraint in (2e) and suppress the voltage deviation as objective 3) requires.

The cost function in (2a) implies minimizing the amount of reactive power injection as well as maximizing the amount of active power injection, where $P_i^{\rm d}$ in the cost function is a design parameter that will be set by each PCS_i. By simply choosing a large enough $P_i^{\rm d}$, as $P_i^{\rm d} > P_i^{\rm l}$, we can emphasize the maximization of amount of active power produced, rather than reactive power injection as objective 1) requires.

By solving the optimization problem (2), we may have the desired solution $(P_i^{\rm r})^*$ and $(Q_i^{\rm r})^*$, $i = 1, \dots, n$. The solution can be sent to each PCS_i as its optimal set-points. However, this is a centralized control law. To formulate the optimization problem (2), the operator needs to know the parameters γ_i, $P_i^{\rm l}$, $P_i^{\rm d}$ and $S_i^{\rm d}$ of every PCS_i, where these parameters except $P_i^{\rm l}$ are possibly time-varying due to the change of the operating constraints. This requires significant bidirectional communication between the operator and each PCS_i. In addition, if the number of PCSs involved in the PV generation plant at the present moment is changed, the operator needs to reformulate the optimization problem itself. This makes it difficult to enhance a plug-and-play type functionality to operate PCSs.

Let us now consider the distributed decision making by each PCS_i. We suppose that each PCS_i solves the following individual small size optimization problem.

$$\min_{P_i^{\rm r}, Q_i^{\rm r}} \quad (P_i^{\rm r} - P_i^{\rm d})^2 + (Q_i^{\rm r})^2 \tag{3a}$$
$$\text{subject to} \quad -\gamma_i P_i^{\rm r} \le Q_i^{\rm r} \le \gamma_i P_i^{\rm r} \tag{3b}$$
$$0 \le P_i^{\rm r} \le P_i^{\rm l} \tag{3c}$$
$$(P_i^{\rm r})^2 + (Q_i^{\rm r})^2 \le (S_i^{\rm d})^2 \tag{3d}$$

We note that PCS_i does not know any decision of the other PCS_js, thus PCS_i cannot incorporate the equality constraint in (2e). We denote by $(P_i^{\rm r})^\sharp$ and $(Q_i^{\rm r})^\sharp$ the optimal solution to (3).

The problem (3) is a decentralized small size optimization, which is not difficult to solve. However, it is unlikely that the individual decision making $(P_i^{\rm r})^\sharp$ and $(Q_i^{\rm r})^\sharp$ of each PCS_i will align with the optimal solution $(P_i^{\rm r})^*$ and $(Q_i^{\rm r})^*$. In order to align the individual decision making of each PCS_i with the optimal solution, we suppose that the operator is allowed to provide additional prices p_{Pi} and p_{Qi} of the active and reactive power injection, respectively. Each PCS_i determines own set-points of the active and reactive power as the solution to the following optimization problem.

$$\min_{P_i^{\rm r}, Q_i^{\rm r}} \quad (P_i^{\rm r} - P_i^{\rm d})^2 + (Q_i^{\rm r})^2 + p_{Pi}(P_i^{\rm r} - P_i^{\rm d}) + p_{Qi} Q_i^{\rm r} \tag{4a}$$
$$\text{s. t.} \quad -\gamma_i P_i^{\rm r} \le Q_i^{\rm r} \le \gamma_i P_i^{\rm r} \tag{4b}$$
$$0 \le P_i^{\rm r} \le P_i^{\rm l} \tag{4c}$$
$$(P_i^{\rm r})^2 + (Q_i^{\rm r})^2 \le (S_i^{\rm d})^2 \tag{4d}$$

We note that $p_{Pi} \times (P_i^{\rm r} - P_i^{\rm d})$ and $p_{Qi} \times Q_i^{\rm r}$ represent additional costs of PCS_i. We denote by $(P_i^{\rm r})^\flat(p_i)$ and $(Q_i^{\rm r})^\flat(p_i)$ the optimal solution to (4), where we set $p_i = [p_{Pi} \quad p_{Qi}]^{\rm T}$.

The optimal price p_i^* that achieves $(P_i^{\rm r})^* = (P_i^{\rm r})^\flat(p_i^*)$ and $(Q_i^{\rm r})^* = (Q_i^{\rm r})^\flat(p_i^*)$ can be determined as the dual optimal of the problem (2), which is known as the concept of shadow price in optimization literature; see for example [12]. Solving the dual problem of (2) is essentially equivalent to solving (2). Instead of solving (2) or its dual, in [9], a feedback interaction between the operator and the multiple agents, which correspond to PCS_is in the problem of this paper, has been investigated, where the operator will determine and provide the price $p_i(t)$ in real-time and each agent will determine its own set-points as $P_i^{\rm r}(t) = (P_i^{\rm r})^\flat(p_i(t))$ and $Q_i^{\rm r}(t) = (Q_i^{\rm r})^\flat(p_i(t))$ in real-time, and this feedback interaction between the operator and PCS_is eventually realizes $P_i^{\rm r}(t) \to (P_i^{\rm r})^*$ and $Q_i^{\rm r}(t) \to (Q_i^{\rm r})^*$.

By applying the real-time pricing strategy of the operator proposed in [9], we have

$$p_i(t) = \left[\frac{R}{V_2(t)}\lambda(t) \quad \frac{X}{V_2(t)}\lambda(t) \right]^{\rm T} \quad i = 1, \dots, n \tag{5a}$$
$$\dot{\lambda}(t) = \epsilon \left(\frac{R}{V_2(t)} \sum_{i=1}^n P_i(t) + \frac{X}{V_2(t)} \sum_{i=1}^n Q_i(t) \right) \tag{5b}$$

where $\epsilon > 0$. The right-hand side of (5b) corresponds to the approximate model of the voltage deviation $V_2 - V_1$ in (1). Thus, in this paper, we consider

$$\dot{\lambda}(t) = \epsilon(V_2(t) - V_1) \qquad \epsilon > 0 \tag{5c}$$

instead of (5b). The feedback interaction between the operator and PCS_is, according to the real-time pricing strategy (5a), (5c) and the distributed decision making in (4), may eventually realize $P_i^{\rm r}(t) \to (P_i^{\rm r})^*$ and $Q_i^{\rm r}(t) \to (Q_i^{\rm r})^*$. Fig. 2 shows a schematic block diagram of the closed-loop system that consists of the real-time pricing strategy (5a), (5c) and the distributed decision making (4) of each PCS_i[1].

We note that, in the proposed closed-loop system in Fig. 2, the operator needs to know nothing about the operating constraints of each PCS_i, and no-one needs to solve a large size optimization problem nor consider iterative calculations to determine the price. The task of the operator is very simple, it just needs to observe the voltage V_2 at the interconnection point and update the price according to (5c). The pricing strategy (5a), (5c) does not depend on even the number of PCS_is involved in the PV generation plant. This enhances a plug-and-play type functionality to operate PCS_is.

In [9], local stability of the resulting closed-loop system has been investigated and theoretical convergence $P_i^{\rm r}(t) \to (P_i^{\rm r})^*$ and $Q_i^{\rm r}(t) \to (Q_i^{\rm r})^*$ has been proved. However, we note that we have replaced the approximate voltage deviation in the right hand side of (5b) by the exact voltage deviation as in (5c). Stability of this system, in a global sense, does not directly concluded from the result in [9].

IV. Numerical Experiments

From the power flow equation in Section II, we can derive the exact mathematical model for V_2 as

$$V_2 = \sqrt{\frac{b + \sqrt{b^2 - 4c}}{2}} \tag{6}$$
$$b = 2(PR + QX) + V_1^2 \quad c = (P^2 + Q^2)(R^2 + X^2)$$

[1]In Fig. 2, $P_i^{\rm c}$ represents the maximum possible active power obtained from the PV panels connected to PCS_i, and the amount of $P_i^{\rm c}$ is determined by the solar radiation at the present moment.

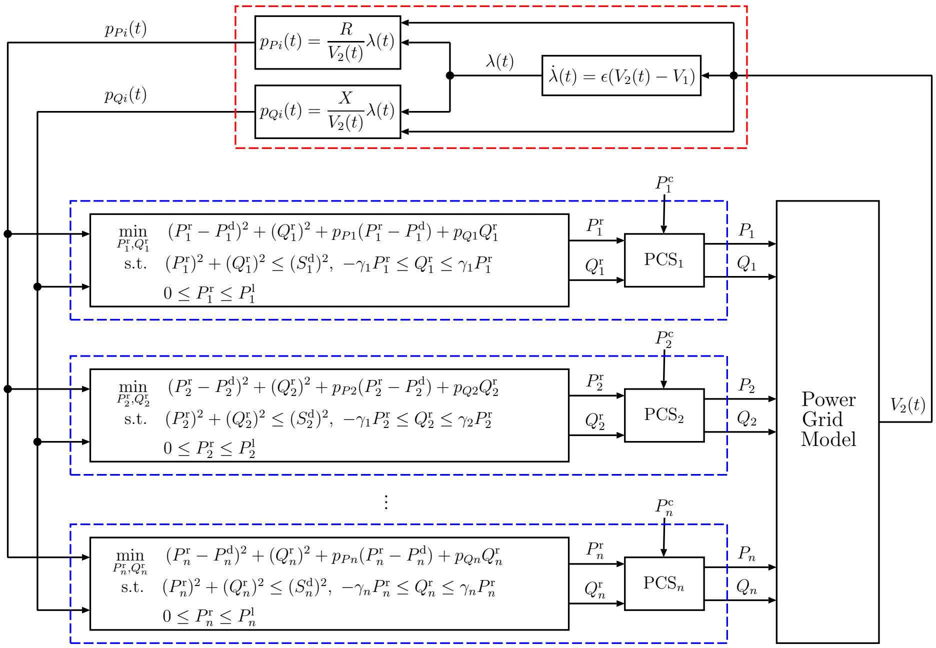


Fig. 2. Real-time pricing and distributed optimization strategy for voltage regulation.

TABLE I
POWER LINE PARAMETERS

Receiving End Voltage	V_1	6600 V
Line Resistance	R_ℓ	0.220 Ω/km
Line Reactance	X_ℓ	0.276 Ω/km
Line Length	ℓ	5 km

where $P = \sum_{i=1}^{n} P_i$ and $Q = \sum_{i=1}^{n} Q_i$, and this will be used as the mathematical model of the power grid (the Power Grid Model block in Fig. 2). Table I shows the parameters of distribution power line, where $R = R_\ell \times \ell$ and $X = X_\ell \times \ell$.

To implement the proposed real-time pricing and distributed decision making methodology, we consider the discretized model of (5a) and (5c) with the sampling period t_s. Each PCS_i also updates P_i^r and Q_i^r in every t_s. In the numerical experiments, we use $t_s = 1$ s and $\epsilon = 8.0 \times 10^5$.

We consider a PV generation plant having $n = 10$ PCSs and suppose that each PCS_i has $S_i^d = S_i^l = 560$ kVA, $P_i^l = 500$ kW, $P_i^d = 2 \times P_i^l$ and $\cos\theta_i^l = 0.10$ for all $i = 1, \ldots, 10$. The proposed pricing mechanism (5a) and (5c) does not depend the number n of PCSs involved in the PV generation plant. This means that the proposed pricing mechanism enhances a plug-and-play type operations of PCSs. This numerical example assumes that eight PCSs are running initially, but PCS_8 will disconnect at $t = 80$ s due to malfunction and the other new PCS_9 and PCS_{10} will connect at $t = 120$ s. Fig. 3 shows the resulting time responses, where we suppose the unknown potential active power generation P_i^c as shown in Fig. 3(g).

Figs. 3(a) and 3(b) show the reference for the active power output P_i^r and the corresponding active power output P_i, respectively. The reference for the reactive power output Q_i^r and the corresponding reactive power output Q_i are shown in Figs. 3(d) and 3(e), respectively. Fig. 3(c) shows the voltage deviation at the interconnection point. Fig. 3(f) shows the prices p_{Pi} and p_{Qi} which are determined and provided by the operator. From Fig. 3(c), it can be confirmed that even if the number of PCSs involved in the PV generation plant is changed the voltage deviation can be suppressed. This confirms effectiveness of the proposed real-time pricing and distributed decision making methodology and it also can realize a plug-and-play type operation of PCSs.

V. EXPERIMENTAL VERIFICATION

We consider a PV generation plant having total capacity 5 MW with $n = 10$ PCSs. Each PCS_i has $S_i^l = 560$ kVA and $P_i^l = 500$ kW physical capacity. However, developing the experimental environment having 5 MW total capacity is unrealistic due to the cost and the safety reasons such as cooling against heat generation. It is also impractical to realize reverse power flow of 5 MW scale into the existing power grid. We have developed a scale-downed inverter, called mini-model (see Fig. 4), of the actual PCS. The mini-model has the same electric circuits, control circuits, processing unit and software with the actual PCS, and it ensures the same conversion characteristics. Only the capacity is scale-downed into 1 kW. The outputs from the mini-models will be multiplied by a constant (500 times in this experiment) and supplied to the real-time power grid simulator that emulates the behavior of the power grid. Thereby, while using the mini-models, we make it possible to evaluate the operation of the PV system having 5 MW total capacity.

The power grid simulator consists of a PC for usual operation, a real-time simulator by Opal-RT Technologies Inc.

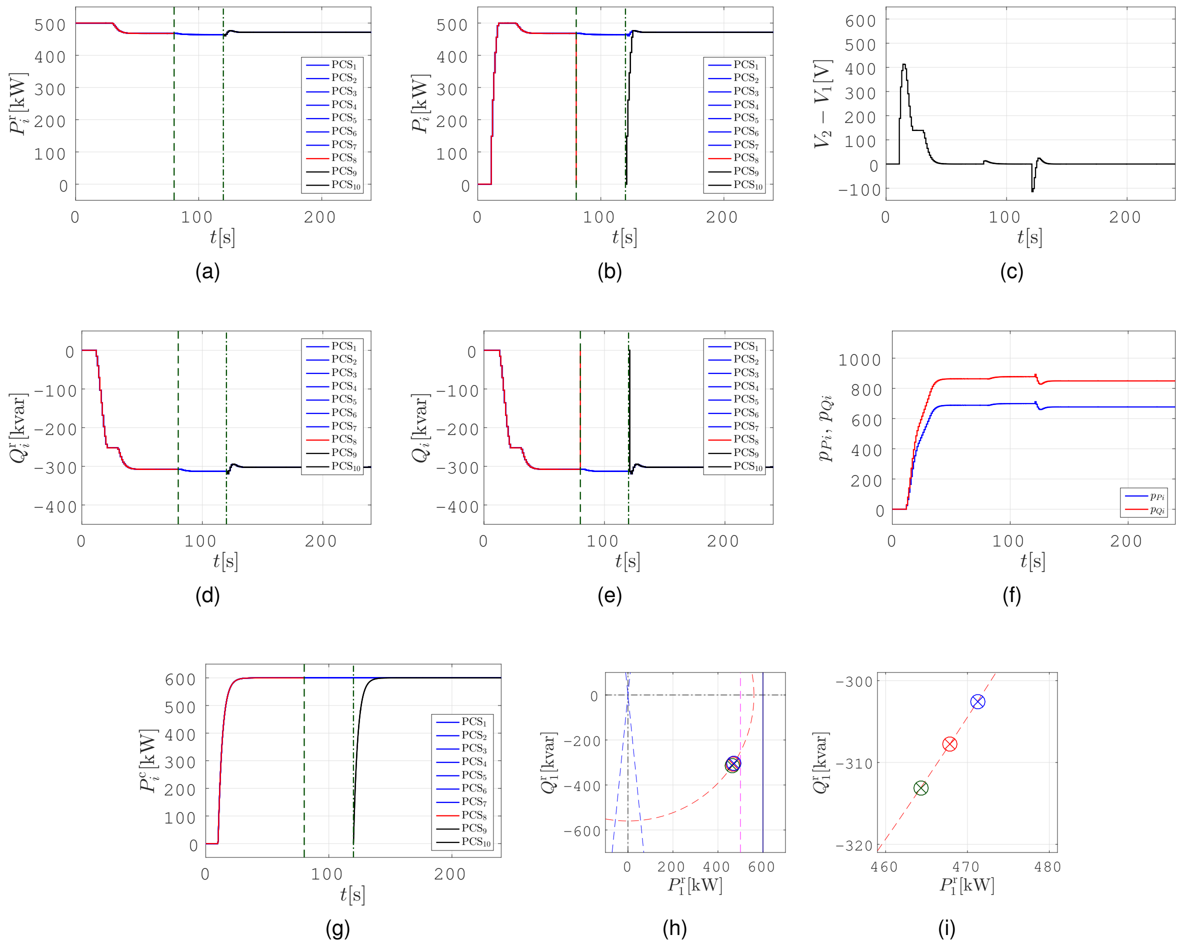


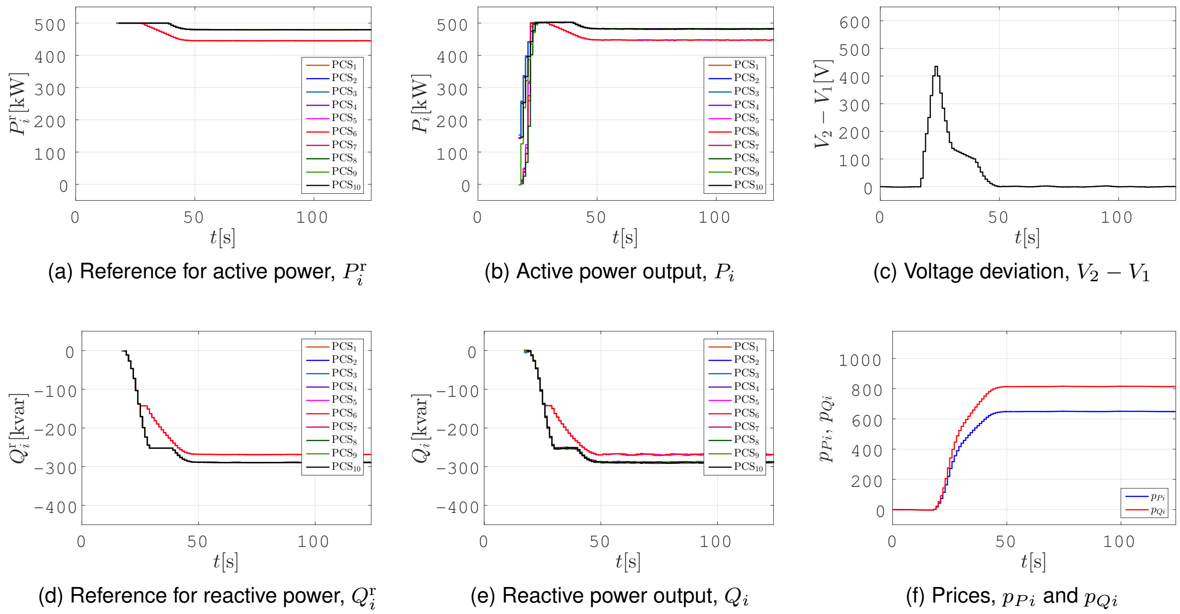
Fig. 3. Time responses of the voltage regulation system where PCS$_8$ disconnect at $t = 80$ s, PCS$_9$ and PCS$_{10}$ connect at $t = 120$ s: (a) reference for active power $P_i^{\rm r}$, (b) active power output P_i, (c) voltage deviation $V_2 - V_1$, (d) reference for reactive power $Q_i^{\rm r}$, (e) reactive power output Q_i, (f) prices p_{Pi} and p_{Qi}, (g) unknown potential power generation $P_i^{\rm c}$, (h) and (i) power circle diagram of PCS$_1$.

Fig. 4. Power conditioning systems (mini-model).

(software: RT-LAB, hardware: OP5600), a programmable AC power source by NF Corp. (ES24000T), voltage and current sensors. We use (6) and the parameters in Table I as a mathematical model for the power grid simulator, where the values of P and Q are calculated from the measuring results by voltage and current sensors. The power grid simulator emulates V_2 in 6600 V system unit and it will be scaled and supplied to the programmable AC power source as the reference signal. The programmable AC power source generates the actual voltage signal according to the supplied reference.

We suppose that the apparent power capacity of PCS$_5$ and PCS$_6$ are smaller than the other eight PCS$_i$s, and we have set $S_5^{\rm l} = S_6^{\rm l} = 520$ kVA and $S_i^{\rm l} = 560$ kVA for the other eight PCS$_i$s. The rated power and power factor constraint are set as $P_i^{\rm l} = 500$ kW and $\cos\theta_i^{\rm l} = 0.10$ for all $i = 1, \ldots, 10$, respectively. Design parameters we have chosen are $S_i^{\rm d} = S_i^{\rm l}$ and $P_i^{\rm d} = 2 \times P_i^{\rm l}$ for all $i = 1, \ldots, 10$. Each PV panel starts power generation around $t = 18$ s and is assumed to have solar radiation that can generate $P_i^{\rm c} = 510$ kW. We set $\epsilon = 8.0 \times 10^5$ for (5c). Fig. 5 shows the experimental result of the voltage deviation suppression using the real-time pricing and distributed decision making methodology.

Figs. 5(a) and 5(b) show the reference for the active power output $P_i^{\rm r}$ and the corresponding active power output P_i, respectively. The reference for the reactive power output $Q_i^{\rm r}$ and the corresponding reactive power output Q_i are shown in Figs. 5(d) and 5(e). Fig. 5(c) shows the voltage deviation at the interconnection point. Fig. 5(f) shows the prices p_{Pi}



(a) Reference for active power, P_i^{r} (b) Active power output, P_i (c) Voltage deviation, $V_2 - V_1$

(d) Reference for reactive power, Q_i^{r} (e) Reactive power output, Q_i (f) Prices, p_{Pi} and p_{Qi}

Fig. 5. Experimental result of the voltage regulation system, where PCS_5 and PCS_6 have a smaller capacity, $S_5^{\mathrm{d}} = S_6^{\mathrm{d}} = 520$ kVA, compared to the other power conditioning systems having $S_i^{\mathrm{d}} = 560$ kVA: (a) reference for active power P_i^{r}, (b) active power output P_i, (c) voltage deviation $V_2 - V_1$, (d) reference for reactive power Q_i^{r}, (e) reactive power output Q_i, and (f) prices p_{Pi} and p_{Qi}.

and p_{Qi} which are determined and provided by the operator. It can be seen that PCS_5 and PCS_6 having the smaller apparent power capacity reduced a more amount of active power compared to the other eight PCS_is. Similarly, PCS_5 and PCS_6 inject a smaller amount of reactive power than the other PCS_is. From Fig. 5(c), we can confirm that the voltage deviation is suppressed. In the steady-state, Q_5, Q_6 and the other eight Q_is converge to respective common values. This means that each PCS_i shares the same amount of the injecting reactive power. Thus, this experimental verification confirms effectiveness of the proposed real-time pricing and distributed decision making methodology.

VI. Conclusions

This paper investigated the decentralized management problem of PCSs which are used to interconnect the PV system into the power grid. The voltage rise due to the reverse power flow can be suppressed by reducing the amount of active power produced, as well as, injecting an appropriate amount of reactive power. We have proposed the real-time pricing strategy of the operator, a management office of the PV generation plant, and each PCS determines own set-points for the active and reactive power flow by solving the individual optimization problem including the provided price. This feedback interaction between the operator and PCSs suppresses the voltage deviation. The effectiveness of the proposed real-time pricing and distributed decision making methodology is evaluated through the real physical experiment.

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