A novel quasi-master-slave control frame for PV-storage independent microgrid

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\begin{abstract}
In microgrid, photovoltaic (PV) and storage are always combined as a droop-controlled ideal source, which is not very practical. Alternatively, this paper introduces a PV-storage independent system via allocating the PV-storage separately. For this structure, a novel quasi-master-slave control frame is proposed without communication. Storages work as master voltage sources, and PVs operate as current controlled voltage sources (CCVS). For the slave PVs, a MPPT-based power droop control and an adaptive reactive power control are proposed. Thus, PVs can simultaneously achieve maximum energy utilization in real-time and the voltage/frequency regulation. Compared with the conventional master-slave frame, this quasi-master-slave frame is more applicable for allowing a high PV penetration and for unifying islanded and grid-connected modes. Furthermore, the small signal stability of entire system is analyzed to design the physical and control parameters, such as, the minimum capacitance value of DC side, droop coefficients. Finally, simulation and experimental results are presented to verify the system effectiveness.
\end{abstract}

1. Introduction

Renewable energy sources are drawing considerable attention because of the cleanliness, environmental protection and sustainability. Among the renewable sources, photovoltaic (PV) has emerged to be one of the major distributed generators (DGs) due to the decreased installation cost in recent years [1,2]. In islanded PV-storage microgrid, the coordination control between PVs and storages and the system voltage/frequency stability are two major tasks. Hence, this paper would focus on the control frame of PV-storage system.

In PV-storage based microgrid, there are two typical configurations shown in Fig. 1 [6–9]: (a) PV-storage integrated system; (b) PV-storage independent system. In the former, storage units are integrated with PVs to form a micro-source which is independent on the power characteristics of solar panels. Due to the power fluctuations of PV, the units would charge or discharge frequently, resulting in low efficiency and short lifespan. To overcome these drawbacks, a centralized storage system should be disposed. As a separate unit, storage is managed according to the voltage/frequency of AC bus. Therefore, the latter is preferable to flexibly dispatch storage and easily optimize storage allocation. For the PV-storage independent system, the two general structures are shown in Fig. 1(b): (b.1) DC/AC coupled architecture. (b.2) AC coupled architecture. In the DC/AC coupled architecture, PVs and storages are connected to the DC bus. The AC bus is connected with the DC bus via a DC/AC inverter. The advantage of this architecture is that it can fed DC loads through the DC bus directly, which avoids the extra power losses [8–10]. Since there is only one inverter, the system is easier to be controlled. Meanwhile, the inverter must be highly reliable because almost all the power needed by ac loads flows through it [11]. This architecture is more suitable for the local energy management which has lots of DC loads, such as loads of the households. In the AC coupled architecture, the loads are connected directly to the AC bus. It would cause the power loss and extra cost with a high proportion of DC load [11]. However, the system has a high flexibility to be controlled and optimized and it is easier to be modularized. It is convenient for utilizing the remote DGs. The investigation in this paper is focused on the AC coupled architecture.

For the PV-storage integrated microgrid, peer-to-peer control frame is often applied to feature the plug-and-play capacity. As a typical control scheme, various droop control methods have been widely adopted [12–16]. In [12], the basic concepts of frequency droop, angle
There are some references about the voltage-controlled PV inverter. In [13], an adaptive droop control is investigated for PV-storage hybrid units. The battery may provide extra power when the available power of the integrated PV is insufficient. In [14], a V-I droop mechanism is utilized in the primary controller to share load power among DGs. These peer-to-peer strategies [12–16] do not require communication, which reduce the system cost and improve the reliability. However, this peer-to-peer frame is only applicable for the ideal sources [17,18]. It needs considerable storages to fill the fluctuation of renewable energy generation, which is expensive and impractical.

For the PV-storage independent system, the master-slave frame has been a common control structure [19–23]. In [19], an auto-master-slave control technique is presented to ensure a fast dynamic response and precise load power sharing. In [20], a utility interface (UI) installed at the PCC is controlled as the master source. The UI works in grid-supporting mode under grid-connected operation and grid-forming mode under islanded operation. To eliminate the limitation of physical connection among DGs, a master-slave control with analog wireless communication is demonstrate in [21]. This master-slave frame in [19–23] enables PVs as slave current sources to inject maximum energy to Microgrid. Storages operate as master voltage sources to support system voltage and frequency. However, there are some limitations: (a) Real-time communication reduces system reliability and increases cost; (b) It needs a considerable master source to avoid a single point of failure [24]; (c) High-output voltage/frequency overshoot may occur during transients since only master sources support the system voltage.

In a word, the existing master-slave frame is operational for the microgrid with a low PV penetration. With the penetration level increasing, PVs should participate in the system voltage/frequency regulation. These challenges would be addressed in this paper.

There are some references about the voltage-controlled PV inverter. Ref. [26] proposes a voltage-source control strategy based on droop control concept for PV inverter. This controller can maintain the dc bus stability even during load transient and automatically reduce generation of PVs with low load demand. This controller is only applicable to single-stage inverter. Focusing on the specific characteristic of PV, the \( V_{dc}/V_{g}\)-droop and \( P/V_{g}\)-droop are combined to obtain the proper power sharing in [27]. But each inverter requires a multistage controller to implement this control strategy, which may reduce the system efficiency. In [28], a universal controller is proposed to combine the maximum power point tracking (MPPT), droop control and dc side voltage regulation. However, the range of load variation is limited by the capacity of the storage in microgrid. In a word, each of [26–28] just proposes a single modified droop control for voltage-controlled PV inverter, while they do not give a comprehensive point from a level of the system operation mode.

Considering the characteristics of PVs and storages, a novel control frame should be developed, which can ensure the MPPT of PVs and efficient operation of storages. In this paper, a novel quasi-master-slave control frame is proposed by combining features of peer-to-peer and master-slave frame. As shown in Fig. 2, the control frame is a compromised choice, whose features are given as follows:

- **Non-communication.** This control frame allows DGs to regulate the voltage and frequency without communication, so physical connection constraint and high cost are avoided. In addition, a high reliability and plug-and-play capability of the system are obtained.

- **Multiple master and multiple CCVS-based slave sources.** All of the dispatchable energy sources are controlled as master sources to avoid the single point of failure. The PV sources function as current controlled voltage sources (CCVS) to participate in the voltage/frequency regulation, especially for a high PV penetration.
2. Conventional control frames

2.1. Peer-to-peer control frame

In peer-to-peer control frame, each DG supports the system voltage/frequency regulation and shares the load demand. This frame has the plug-and-play capacity and the high system redundancy [12-15]. As a typical peer-to-peer control, the conventional droop control is commonly used for the microgrid without any communication [29].

\[
\omega = \omega^* - mP, \quad m = (\omega_{\text{max}} - \omega_{\text{min}}) / P_{\text{rating}} \tag{1}
\]

\[
V = V^* - nQ, \quad n = (V_{\text{max}} - V_{\text{min}}) / Q_{\text{rating}} \tag{2}
\]

where \(\omega\) and \(V\) are the angular frequency and voltage amplitude of an inverter; \(P, Q, P_{\text{rating}}, Q_{\text{rating}}\) are output active/reactive power and rated active/reactive power; \(\omega^*\) and \(V^*\) represent values of \(\omega\) and \(V\) at no load; \(m\) and \(n\) are droop coefficients of \(P-\omega\) and \(Q-V\), respectively. \(\omega_{\text{max}}\) and \(\omega_{\text{min}}\) are maximum and minimum values of the allowable angular frequency; \(V_{\text{max}}\) and \(V_{\text{min}}\) are maximum and minimum values of the allowable voltage amplitude, respectively.

For a system with two DGs, since \(\omega_1 = \omega_2\) in steady state [24], Eq. (3) is obtained from (1)

\[
P_1 / P_2 \approx m_2 / m_1 \approx P_{\text{rating}1} / P_{\text{rating}2} \tag{3}
\]

Eq. (3) reveals that the conventional droop scheme ensures the proportional output power sharing based on the DG’s rating. However, since the droop coefficients are constants, it is not sensible to the power fluctuation of PVs caused by irradiance level and temperature.

2.2. Master-slave control frame

In the master-slave control frame, there is one considerable DG acting as a master voltage source to support the system voltage. The others function as slave current sources to follow the active/reactive power varying.

\[
I = \sqrt{\frac{P_{\text{ref}} + Q_{\text{ref}}}{V_p}} \tag{4}
\]

\[
\delta = \delta_p - \text{arctan} \frac{Q_{\text{ref}}}{P_{\text{ref}}} \tag{5}
\]

where \(P_{\text{ref}}\) and \(Q_{\text{ref}}\) are the active and reactive power given by the front-end MPPT controller, respectively. \(V_p\) and \(\delta_p\) are the voltage amplitude and phase angle of the PCC obtained from a phase-locked loop (PLL). P/Q control enables each PV to output its maximum available power at the price of abandoning the voltage/frequency support ability. Therefore, in the islanded mode, there should be at least one DG being controlled as a master VSI to regulate voltage and frequency at the PCC.

In summary, master-slave control frame is very applicable for energy management and generation maximum utilization. However, the
system is not redundant and has a high cost in communication links. Moreover, the existence of PLL has a serious effect on the dynamic stability of system [31].

3. Quasi-master-slave control frame

For the PV-storage independent microgrid in Fig. 1(b.1), a novel quasi-master-slave control frame is proposed by combining the peer-to-peer and master-slave control frame. Compared with the peer-to-peer frame, this frame takes the power fluctuation of PVs into account so that the MPPT can be ensured. Compared with the master-slave frame, the slave sources serve as CCVS to participate in the voltage/frequency regulation, and the communication links and PLLs are removed. Thus, the higher reliability, less cost and better dynamic response of system are ensured.

To implement the proposed control frame, a MPPT-based power droop control and an adaptive reactive power control are proposed, whose principle is shown in Fig. 3. In the same case as described in Section 2.1, when the available output power of PV#1 reduces, the droop curve upward to increase the output power. The key is to de

\[
\omega_i = \omega_{\text{ref}} - \frac{m_i (P_i - P_{\text{ref}})}{K_p + K_i \frac{u_{\text{ref}} - u_{\text{ref}}^*}{P_{\text{ref}}}}
\]

where \(P_{\text{ref}}\) is the available active power of the i-th PV given by the

feedforward controller. \(K_p\) and \(K_i\) are the proportional and integral coefficients of the PI controller of the i-th PV, respectively. Compared with the conventional droop, \(P_i = V_{\text{ref}}I_{\text{ref}}\) is added in the first term, which is obtained from the front-end MPPT controller. By considering the fluctuation of PVs, the dynamic response is improved. The second term is the PI controller for DC bus voltage regulation. The PI controller ensures the balance between the power extracted by DC/AC inverter and the one supplied by DC/DC converter. Thus, the maximum utilization of energy is guaranteed. The block diagram is shown in Fig. 4(c).

The amount of reactive power supplied by inverter is an important factor that limits the active power capability of PV. Supplying reactive power excessively would impose extra stress on the inverter, which could lead to the ripple in the dc bus voltage and affect the effectiveness of the MPPT. Therefore, an adaptive reactive power control strategy is proposed.

\[
V_i = V_{\text{ref}} - n_i Q_i
\]

where \(n_i\) is the adaptive droop coefficient

\[
n_i = \frac{V_{\text{max}} - V_{\text{min}}}{Q_{\text{ref}}}\]

where \(Q_{\text{ref}}\) is the available reactive power of the i-th DG. It is calculated according to the rated apparent power and available active power. The droop coefficient \(n_i\) is inversely proportional to the \(Q_{\text{ref}}\). The principle of the proposed reactive power control strategy is shown in Fig. 5. When the available active power of PV#1 reduces, the Q-V curve would shift to the right green one. It makes PV#1 supply more reactive power, and vice versa. Specially, the PV with a low ability of active power supplying can provide the reactive power for the system.

To match the power balance between generation and demand, the ESS is controlled by conventional active power droop and proposed adaptive reactive power droop.
4. Stability analysis

In this section, small signal stability is carried out to perform the system stability and sensibility analysis of control parameters. The equivalent circuit of the microgrid is shown in Fig. 6, which consists of m PV units and n-m separate storage units.

4.1. Small signal modeling

4.1.1. Network modeling

The power generation of the i-th DG is presented as

\[
\begin{align*}
 p_i &= G_i V_i (V_i - V_j \cos \delta_j) - B_i V_i V_j \sin \delta_j \\
 q_i &= -B_i V_i (V_j - V_i \cos \delta_j) - G_i V_i V_j \sin \delta_j
\end{align*}
\]

where \( \delta_j = \delta - \delta_j \) and \( G_i \) and \( B_i \) are the conductance and susceptance of line admittance, respectively. According to kirchhoff laws, the voltage of PCC is obtained

\[
V_{PCC} = \sum_{i=1}^{n} Y_i^* V_i e^{j\delta_i}
\]

Define \( \tilde{\delta}_i = \delta_i - \delta_0 \), where \( \omega_0 \) is the frequency of steady state. Then, combining (10)–(12) yields

\[
\begin{align*}
 p_i &= G_i V_i^2 - G_i V_i \sum_{j=1}^{n} V_j (V_j \cos (\tilde{\delta}_j - \tilde{\delta}_i) - B_i V_i \sum_{j=1}^{n} V_j (V_j \sin (\tilde{\delta}_j - \tilde{\delta}_i)) \\
 &= F(V_i, V_j, \ldots, V_n, \tilde{\delta}_j, \ldots, \tilde{\delta}_n)
\end{align*}
\]

Rewrite (15), (16) in matrix form as

\[
\begin{align*}
 \Delta p &= K_Q \Delta Q + K_{\Delta \delta} \Delta \tilde{\delta} \\
 \Delta q &= K_Q \Delta Q + K_{\Delta \delta} \Delta \tilde{\delta}
\end{align*}
\]

where the variable vectors \( (\Delta p, \Delta q, \Delta Q, \Delta \tilde{\delta}) \) and the parameter matrices \( (K_Q, K_{\Delta \delta}, K_{\Delta \tilde{\delta}}, K_{\Delta \hat{\delta}}) \) are shown in the Appendix.

4.1.2. PV units modeling

The PV units with MPPT-based power droop control scheme are modeled as

\[
\begin{align*}
 u_{dak} &= \frac{1}{C_{ak}} (u_{yak} - p_k) \\
 \dot{p}_k &= \omega_0 (-p_k + p_k) \\
 \dot{Q}_k &= \omega_0 (-Q_k + q_k) \\
 \omega_k &= -m_k \dot{p}_k + K_{P_k} u_{dak} + K_{Q_k} (u_{dak} - u^*_{dak}) \\
 \dot{\delta}_k &= \delta_k - \tilde{\delta}_k + \omega_k - \omega_0
\end{align*}
\]

where \( C_{ak} \) is the capacitance value of DC bus in Fig. 4(c), \( P_k \) and \( Q_k \) are active and reactive power of the \( k \)-th PV by a low-pass filter with cutoff frequency \( \omega_0 \). Combining (18)–(20), the small signal models of PV units are written as
4.1.4. Entire system modeling

Combining the small signal models of PV part and storage part, the small signal dynamic model of the entire system is constructed as follows

$$\Delta \dot{x} = A \Delta x$$

(26)

where the state variable vector $\Delta x$ and the system matrix $A$ are shown in the Appendix.

4.2. Eigenvalue analysis

The eigenvalues of matrix $A$ can be used to study the stability of the system around the operating point. According to the simulation described in Section V, the dominant poles of system (26) are analyzed while varying the capacitance $C_i$, control parameters $m_i$, $n_i$, $K_{Pi}$, and $K_{Ki}$.

The matrix $A$ has one zero eigenvalue and twelve nonzero eigenvalues. The one zero eigenvalue is corresponding to rotational symmetry and only the nonzero eigenvalues are valid for the system dynamic stability [32,33].

When the capacitance $C_i$ changes from 2000 $\mu$F to 10$^5$ $\mu$F, the root locus of eigenvalues are shown in Fig. 7. When $C_i$ is small, $\lambda_1 \sim \lambda_4$ lie on the right half-plane, which means that system is unstable. These poles lie on the left of the imaginary axis when $C_i$ increases to 3500 $\mu$F and move away from it with further increasing $C_i$. Meanwhile, $\lambda_5 \sim \lambda_8$ become dominate poles while $C_i$ increasing, and they always stay at the right half-plane. In this case, the system is stable during $C_i (3500 \mu F, + \infty)$.

The droop coefficients $m_i$ and $n_i$ have a significant influence on the system stability. According to the requirement of steady state in (7) and (9), the range of $m_i$ and $n_i$ are (0, 4 × 10$^{-3}$) and (0, 6 × 10$^{-3}$), respectively. The root locus are shown in Figs. 8 and 9. In Fig. 8, $\lambda_1 \sim \lambda_4$ move to the left of imaginary axis when $m_i$ increases to 2.8 × 10$^{-4}$. With increasing $m_i$, $\lambda_5 \sim \lambda_8$ move away from the imaginary axis keeping system stable. Meanwhile, $\lambda_5 \sim \lambda_8$ move close to the imaginary axis decreasing the damping ratio of system. When $m_i$ is chosen in the range of (5 × 10$^{-5}$, 4 × 10$^{-3}$), the system is stable. Fig. 9 shows that $n_i$ has little influence on the system dynamic performance and the system keep stable during $n_i (0, 6 \times 10^{-3})$.

PI control coefficients of (6) should be designed properly to ensure the system stable. The root locus with $K_{Pi}$ and $K_{Ki}$ varying are shown in Figs. 10 and 11. When $K_{Pi}$ is small, the dominated poles $\lambda_5 \sim \lambda_8$ stay at the right half-plane. As $K_{Pi}$ increases, $\lambda_5 \sim \lambda_8$ move to the left half-plane and $\lambda_1 \sim \lambda_4$ become the dominated poles. When $K_{Pi}$ increases to 3.5, $\lambda_1 \sim \lambda_4$ move to the unstable region. Moreover, Fig. 11 shows that increasing $K_{Ki}$ attracts the conjugate poles $\lambda_1$ and $\lambda_2$ to the imaginary axis, which would make the system stable. The stable regions of $K_{Pi}$ and $K_{Ki}$ are $K_{Pi} \epsilon(0.05, 3.5)$ and $K_{Ki} \epsilon(0, 18)$, respectively.

When the ratio of line impedance $r_1 = X_1 / R_1$ changes from 0.01 to

![Figure 7. Eigenvalues of (26) for different capacitance $C_i$.](image)

![Figure 8. Eigenvalues of (26) for different droop coefficient $m_i$.](image)
To study the dynamic performance of the system, the load power changes at 0.6 s and recovers at 1.2 s. The available power of PVs are set as $P_{1,a} = 1.5$ kW and $P_{2,a} = 1$ kW. The results shown in Fig. 14 reveal that the system has a fast response for the load change. From Fig. 14(a), 350 V to avoid over-modulation.

### 5. Simulation results

To investigate the validity of the proposed quasi-master-slave control frame, a single-phase AC microgrid with two PVs and one storage is built. The simulation parameters are listed in Table 1 [34]. The normal voltage reference is 50 Hz/311 V. The DC bus voltage is controlled at 350 V to avoid over-modulation.

### 5.1. Case I: Simulation with PV power fluctuation

In this case, a random disturbance is imposed on PV output current $i_{PV}$ to simulate the power fluctuation of PV. Fig. 13 shows the output active/reactive power and load demand, random PV output current, the DC bus voltage and the frequency of three DGs. From Fig. 13(a), (c) and (d), two PVs output their available power all the time and the storage unit supplies power when load demand exceeds the total available power of PVs. The reactive power results are shown in Fig. 13(b). The reactive power of PV is decreased/increased when the active power is increased/decreased so that the burden of power supply among DGs are shared. The remaining reactive power is supplied by the storage unit. Fig. 13(d) shows that DC bus voltages of two PVs are kept at 350 V even with available power varying, which indicates the maximum utilization of renewable energy is always achieved. Fig. 13(e) reveals the system frequency is approximated to 50 Hz under the fluctuation of PVs.

### 5.2. Case II: Simulation with load change

To study the dynamic performance of the system, the load power changes at 0.6 s and recovers at 1.2 s. The available power of PVs are set as $P_{1,a} = 1.5$ kW and $P_{2,a} = 1$ kW. The results shown in Fig. 14 reveal that the system has a fast response for the load change. From Fig. 14(a), 350 V to avoid over-modulation.

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the output active power of two PVs are remained to the available power. When the load power is changed, the supply-demand power balance is maintained by storage unit. Fig. 14(a) and (c) show that the MPPT of PVs are achieved within 0.2 s when the load is changed. Fig. 14(d) shows the system has a fast response with the load change due to an auxiliary service for frequency regulation of PVs.

5.3. Case III: Simulation with line impedance ratio change

To verify the system stability with the line impedance ratio change, the ratio of line impedance $r_1$ is changed from 2 to 1 at 1 s and to 1/2 at 2 s. The available power of PVs are still set as $P_{1,a} = 1.5$ kW and $P_{2,a} = 1$ kW. The results in Fig. 15 shows that the system remains stable when the ratio of line impedance changes in a certain region. From Fig. 15, though the system needs longer time to go to steady state when the line impedance ratio is equal to 2, the microgrid remains stable with line impedance ratio variations within a large region.

6. Experimental results

A laboratory microgrid prototype is built as shown in Fig. 16. The microgrid consists of two micro-sources based on the single-phase inverters. One is supplied by photovoltaic simulator to simulate the PV source and the other is supplied by storage. The main circuit of the setup is shown in Fig. 17, which includes the experiment parameters of output filter, line, and load. The sample frequency is 12.8 kHz. The referent voltage frequency $f^*$ and amplitude $V^*$ are 50 Hz and 48 V, respectively. The DC bus voltage is controlled at 60 V to avoid over-modulation.
are shown in Fig. 19. A t

0.7

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The waveforms from top to down are the output voltage of based power droop control and the adaptive reactive power control during 0.7

0.25

rent amplitudes of inverter#1 are 1.2 A during 0

verter#1 and inverter#2 are 45.3 V and 45.8 V, respectively. The cur-

6.1. Case I: Experiment with PV power fluctuation

To simulate the power fluctuation of PV caused by atmospheric conditions, the output current of PV simulator at maximum power point is set as \(i_{PV} = 0.27\) A during 0–0.25 s, 0.4 A during 0.25–0.7 s, 0.47 A during 0.7–1 s. Fig. 18 shows the measured waveforms with the MPPT-based power droop control and the adaptive reactive power control strategy. The waveforms from top to down are the output voltage of inverter#1 \(u_1\) and inverter#2 \(u_2\), the output current of inverter#1 \(i_1\) and inverter#2 \(i_2\), respectively. The voltage amplitudes of inverter#1 and inverter#2 are 45.3 V and 45.8 V, respectively. The cur-

2.15 A during 1.3

2.7 s, 1.28 A during

1.3 s, 1.72 A during 1.3–2.7 s, 1.28 A during 2.7–4 s. The current amplitudes of inverter#2 are 1.66 A during 0–1.3 s, 2.15 A during 1.3–2.7 s, 1.66 A during 2.7–4 s.

From Fig. 21, the steady-state output active power of inverter#1 is kept at 30 W, which means the maximum energy utilization of PV is achieved all the time. The increased power caused by load change is supplied by the inverter#2. Although there is a rush to the output active power of inverter#1 with load change, it is recovered to 30 W within 0.2 s, which indicates that the system has a fast response for the load change.

6.2. Case II: Experiment with load change

To investigate the dynamic response of the system with load change, a 25 \(\Omega\) resistance is switched on at 1.3 s and is shed at 2.7 s. The output current of PV simulator at maximum power point is set as \(i_{PV} = 0.5\) A.

Figs. 20 and 21 show the measured waveforms and output power, respectively. The voltage amplitudes of inverter#1 and inverter#2 are 45.1 V and 46.2 V, respectively. The current amplitudes of inverter#1 are 1.28 A during 0–1.3 s, 1.72 A during 1.3–2.7 s, 1.28 A during 2.7–4 s. The current amplitudes of inverter#2 are 1.66 A during 0–1.3 s, 2.15 A during 1.3–2.7 s, 1.66 A during 2.7–4 s.

7. Conclusions

Taking the characteristic of PVs into account, the PV-storage independent system is adopted to improve system efficiency. Beyond the peer-to-peer frame and master-slave frame, a novel quasi-master-slave control frame is proposed. PVs operate as slave CCVS and storages act as master sources. A MPPT-based power droop control and an adaptive reactive power control is proposed to implement this control frame. Compared with the peer-to-peer control, this frame enables PVs to inject the maximum energy to the microgrid. Compared with the master-slave control, the slave sources behave as voltage sources to provide the...
auxiliary voltage/frequency regulation, which improves the system reliability and dynamic response. No-communication feature makes system more flexible and ensures the plug-and-play capability of DGs. According to the small signal stability of entire system, the minimum capacitance $C_i$ of system critical stability is given, and the feasible regions of control parameters ($m_i$, $n_i$, $K_{Pi}$, $K_{Ii}$) are provided. Finally, simulation and experimental results have verified that PVs can achieve the maximum energy utilization in real-time and the satisfied dynamic performance with load change.

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Appendix A

The variable vectors ($\Delta p, \Delta q, \Delta Q$ and $\Delta \delta$) and the parameter matrices ($K_{pQ}, K_{qQ}, K_{p\delta}, K_{q\delta}$) in (18) and (19) are shown as:

\[
\begin{align*}
\Delta p &= \begin{bmatrix} \Delta p^p \ \\ \Delta p^q \end{bmatrix} = \begin{bmatrix} \Delta p_1 & \cdots & \Delta p_m & \Delta p_{m+1} & \cdots & \Delta p_n \end{bmatrix}^T \\
\Delta q &= \begin{bmatrix} \Delta q^p \ \\ \Delta q^q \end{bmatrix} = \begin{bmatrix} \Delta q_1 & \cdots & \Delta q_m & \Delta q_{m+1} & \cdots & \Delta q_n \end{bmatrix}^T \\
\Delta Q &= \begin{bmatrix} \Delta Q^p \ \\ \Delta Q^q \end{bmatrix} = \begin{bmatrix} \Delta Q_1 & \cdots & \Delta Q_m & \Delta Q_{m+1} & \cdots & \Delta Q_n \end{bmatrix}^T \\
\Delta \delta &= \begin{bmatrix} \Delta \delta^p \ \\ \Delta \delta^q \end{bmatrix} = \begin{bmatrix} \Delta \delta_1 & \cdots & \Delta \delta_m & \Delta \delta_{m+1} & \cdots & \Delta \delta_n \end{bmatrix}^T
\end{align*}
\]

\[
K_{pQ} = \begin{bmatrix} K_{pQ}^p \\ K_{pQ}^q \end{bmatrix} = \begin{bmatrix} -n_i k_{p_i V_i} & \cdots & -n_n k_{p_n V_n} \\ \vdots & \ddots & \vdots \\ -n_i k_{p_m V_m} & \cdots & -n_n k_{p_n V_n} \end{bmatrix} ;
K_{p\delta} = \begin{bmatrix} K_{p\delta}^p \\ K_{p\delta}^q \end{bmatrix} = \begin{bmatrix} k_{p_i \delta_i} & \cdots & k_{p_n \delta_n} \\ \vdots & \ddots & \vdots \\ k_{p_m \delta_m} & \cdots & k_{p_n \delta_n} \end{bmatrix}
\]

\[
K_{qQ} = \begin{bmatrix} K_{qQ}^p \\ K_{qQ}^q \end{bmatrix} = \begin{bmatrix} -n_i k_{q_i V_i} & \cdots & -n_n k_{q_n V_n} \\ \vdots & \ddots & \vdots \\ -n_i k_{q_m V_m} & \cdots & -n_n k_{q_n V_n} \end{bmatrix} ;
K_{q\delta} = \begin{bmatrix} K_{q\delta}^p \\ K_{q\delta}^q \end{bmatrix} = \begin{bmatrix} k_{q_i \delta_i} & \cdots & k_{q_n \delta_n} \\ \vdots & \ddots & \vdots \\ k_{q_m \delta_m} & \cdots & k_{q_n \delta_n} \end{bmatrix}
\]

(A.1)

The state variable vector $\Delta x$ and the system matrix $A$ in (26) are shown as
where $I_n$ is the n-th order identity matrix and $I_m$ is the m-th order identity matrix.

**References**


