Mechanism Analysis of PV Generation System for Damping Electromechanical Oscillations

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Abstract. For physically understanding the dynamic response of a photovoltaic (PV)-based integrated power system for electromechanical oscillation damping, firstly, this paper develops the linear mathematical model of a single machine infinite bus system integrated with PV in the electromechanical time scale. Then, based on the electric torque analysis method and the functional route of active power control (P-control) and reactive power control (Q-control), the key factors and influence laws of the power system inertial effect, damping level and synchronization capability are analyzed. The results show that when the PV operating mode utilizes the rotor speed as feedback signal, the PID controller parameters of P or Q-control loop can affect the damping level, synchronization capability and inertial effect of the power system, respectively. The accuracy of the physical mechanism analysis is verified by MATLAB.

1. Introduction

Low frequency electromechanical oscillations (typically 0.1–2.5 Hz) are regarded as one of the major limiting factors in power transfer over long transmission lines [1]. To this end, previous works have developed different measures to damp electromechanical oscillations. Power system stabilizer (PSS) integrated with synchronous generator (SG) is often the most common measure for electromechanical oscillations damping [2], however, for the large interconnected power systems, a complexed and coordinated PSS parameters tuning scheme for each involved generator must be required.

Flexible AC transmission system (FACTS) devices can be used to offer extra damping effect support by controlling reactive power output [3]. Energy storage system equipped with oscillation damping controllers are also developed to enhance the power system stability [4], however, high battery hardware cost limits its large-scale installation and operation. Analogously, for interarea oscillation damping, a combining active and reactive power modulation mode of wind generation is developed in [5].

Photovoltaic (PV) generation system has been widely developed to alleviate the energy crisis and brought a series of new challenges and solutions on the power system stability [6]. Adverse effects of high penetration PV generation system on the power system dynamic stability have been studied by some researchers. The potential of reduction in power system stability is more with significant amount of inertia-less power injection from PV into the grid [7-9]. The large-scale PV plant equipped with a
A robust PID controller is developed in [10], which provides the PV with the oscillation damping ability. A novel control mode of PV solar farm is suggested in [11] by working PV as FACTS devices with discontinuing its real power generation function briefly. Moreover, an energy function-based design of damping controller was presented in [12], however, which are relatively complex in design.

The existing work mainly focuses on the PV out power control strategies for electromechanical oscillations damping [13-16], however, few literatures have investigated the physical mechanisms of PV generation system for oscillations damping, especially the influence of power control strategies, control parameters and installation location on the power system dynamic characteristics.

The paper is organized as follows: Section 2 introduces background on PV system to damp oscillation. Section 3 develops the linear mathematical model of an integrated single machine infinite bus (SMIB) system for interaction process modeling. Section 4 describes the physical mechanism of PV system to damp oscillation. MATLAB simulation verification for the correctness of mechanism analysis are presented in Sections 5. The conclusions are drawn in Section 6.

2. Background on PV Damping Oscillation

The grid imbalance active power, as the endogenous driving force, leads to the electromechanical oscillations. Hence, by injecting controlled active or reactive power into the grid according to the current rotor speed ($\omega$), the imbalanced power can effectively be suppressed. The PV output power control mode could be divided into active and reactive power control ($P$ & $Q$-control). $P$-control mode can directly affect the electromagnetic power distribution and rotor speed dynamics, and $Q$-control mode could change the grid voltage distribution to indirectly affect the electromagnetic power.

From Fig. 1, the PV output power $P_{PV}$ is affected by the change of output voltage $U_{dc}$. $U_{MPPT}$ represents the corresponding output voltage of the maximum power $P_{PV-max}$. To utilize the controlled active and reactive power to damp oscillation, the steady-state power $P_{PV0}$ is set as smaller than $P_{PV-max}$. The allowable $U_{dc}$ operation range is set between $U_{MPPT}$ and $U_{oc}$, since compared with $U_{dc} \in [0, U_{MPPT}]$, $P_{pv}$ could be proportionally tuned from 0 to $P_{PV-max}$ with higher sensitivity.

![Figure 1. PV operation characteristic](image1.png)

From Fig. 2, $C_{dc}$ and $P_{C}$ represent the DC side capacitor and the capacitor power, respectively. $P$ and $Q$ are the controlled output active and reactive power injected into the grid. The relationship between the $P_{PV}$, $P_{C}$ and $P$ can be expressed as

$$P_{PV} = P + P_{C}$$

Hence, the $P_{PV}$ can be tuned by the change of $P$ during the grid oscillation condition. Moreover, the reactive power output is limited by the designed PV inverter capacity $S$, the range of $Q$ are shown as

$$-\sqrt{S-P^2} \leq Q \leq \sqrt{S-P^2}$$

To demonstrate the inertia, damping and synchronization characteristics of the SG-dominated power system integrated with the PV grid-tied inverter effectively, as seen in Fig. 3, a SMIB composed of a SG and a DC/AC inverter, is taken as an example to explain the dynamic interaction mechanism among the SG, the grid-tied inverter and the infinite grid.
The infinite grid

**Figure 3.** Model of the integrated SMIB for electromechanical oscillation damping

In Fig. 3, $P_m$ and $P_e$ are the mechanical input power and the electromagnetic power, respectively. $\omega$ represents the rotor speed. $\omega_0$ represents the rated value. $E$, $U$, $V$, $Z_1$, $Z_2$ and $Z_0$ respectively represent the voltage vector and the equivalent line reactance between i) the SG, ii) the infinite grid, iii) the PV grid-tied inverter and the point of common coupling (PCC). $I_d$ and $I_q$ are the inverter output active and reactive current in the dq frame, $I_d^*$ and $I_q^*$ represent the output current reference, respectively.

Moreover, the output dynamics of the integrated power system during oscillation process could be divided into the electromechanical time scale (seconds-level response) and the electromagnetic time scale (milliseconds-level response). The former includes rotor speed control loop, the latter includes the DC voltage control (i.e., phase locked loop, PLL), about 100 ms) and AC current control loop (about 10 ms). Due to their relatively separated response, the DC voltage control and AC current control process of the PV grid-tied inverter could thus be omitted, viz, assuming $I_d = I_d^*$ and $I_q = I_q^*$.

The electric torque analysis method is utilized to analyze how PV generation system affecting the inertia characteristics and rotor speed dynamics response of the SG-dominated power system. The SG mechanical dynamics using the standard rotor motion equation can be expressed as

$$
\frac{d\delta}{dt} = \omega - 1
$$

$$
2H \left( \frac{d\omega}{dt} \right) = P_m - P_e - D(\omega - \omega_0)
$$

Where, $H$ and $D$ (per unit) represents the generator internal inertia and damping constants, respectively.

Assuming the mechanical power $P_m$ constant and linearizing of (3), the dynamic process of the rotor speed and the power angle can be described as

$$
\frac{d\Delta\delta}{dt} = \Delta\omega
$$

$$
T_j \left( \frac{d\Delta\omega}{dt} \right) = -T_D \Delta\omega - T_S \Delta\delta
$$

Where $T_j$, $T_D$ and $T_S$ represent the equivalent inertia, damping and synchronization coefficient of the generator rotor speed, respectively.

3. Interaction Process Modeling

Based on the classification of control timescales, the PV inverter can thus be simplified into a controlled active current source and a controlled reactive current source, which correspond to P-control and Q-control mode, respectively. Consequently, the integrated SMIB system model in the Fig. 3 can be simplified into the circuit model in the Fig. 4, and the corresponding voltage vector diagram of the simplified model are shown in the Fig. 5.

**Figure 4.** Simplified model of integrated power system

In Fig. 4, the SG can be equivalent to $E \angle \delta$ and the series reactance $X$. Moreover, $X_T$ are the equivalent reactance between the PCC and the grid, and $X_T$ equals to $kX$. Where, the parameter $k$ is
defined for describing the inverter location: when \( k \) approaches 0, the PV inverter is close to the grid, and vice versa. \( I_g \) and \( I_b \) represent the current of equivalent line reactance \( Z_1 \) and \( Z_2 \) in the Fig. 3. (presuming \( E \) and \( U \) are equal and constant).

Using Kirchhoff’s current law, it holds that

\[
\left( E \angle \delta - V \angle \theta \right) / jX + I_4 \angle \theta = (V \angle \theta - U \angle \theta) / jkX
\]

(6) can be rewritten as

\[
\left(kE \sin \delta + kX I_d \right)^2 + \left[ V + k \left( V - E \cos \delta + X I_q \right) \right]^2 = U^2
\]

(7)

Linearization of (7) yields

\[
k^2 \left( E \sin \delta + X I_{d0} \right) (E \cos \delta \Delta \delta + X \Delta I_d) = \left[ V_0 - k \left( E \cos \delta_0 + X I_{q0} \right) \right] \Delta V + k \left( V + E \sin \delta + X \Delta I_q \right)
\]

According to (8) and Fig. 5, it can be noticed that the PCC voltage \( V \) is affected simultaneously by the power angle \( \delta \), the inverter output current \( I_d \) and \( I_q \). Hence, we choose \( \delta \), \( I_d \) and \( I_q \) as independent variables and \( V \) as the dependent variable, (8) can thus be described as

\[
\Delta V = \frac{k^2 (E \sin \delta + X I_{d0}) \cos \delta_0 - \sin \delta_0}{1+k} \Delta \delta + \frac{k^2 (E \sin \delta + X I_{d0}) X}{1+k (E \cos \delta_0 - V_0 (1+k) - kX I_{q0})} \Delta I_d - \frac{kX}{1+k} \Delta I_q
\]

(9)

Linearization of the electromagnetic power \( P_e \) yields

\[
\Delta P_e = E \left( \sin \delta_0 \Delta V + V \cos \delta_0 \Delta \delta \right) / X
\]

(10)

Substituting (9) into (10), one obtains

\[
\Delta P_e = K_g \Delta \delta - K_e \Delta I_d - K_f \Delta I_q = \frac{E V_0}{X} \left[ \frac{kE \sin \delta_0}{1+k} \left( \frac{k \left( E \sin \delta_0 + X I_{d0} \right) \cos \delta_0 - \sin \delta_0 + \cos \delta_0 \right) \Delta \delta \right]
\]

\[
- \frac{k^2 E V_0 \sin \delta_0 \left( E \sin \delta_0 + X I_{d0} \right)}{(1+k) \left( E \cos \delta_0 - V_0 (1+k) - kX I_{q0} \right)} \Delta I_d - \frac{\sin \delta_0 kEV_0}{1+k} \Delta I_q
\]

(11)

where \( K_g \) is the inherent synchronization coefficient of the integrated power system, which corresponds to the system intrinsic synchronous operation stability; \( K_e \) and \( K_f \) are corresponding to the PV grid-tied inverter control coefficients, which represent the influence of the rotor speed dynamics.

4. Physical Mechanism Analysis of the Integrated System to Damp Oscillation

Based on the linear mathematical model in Section 3, the interaction process of the PV generation system in damping electromechanical oscillation will be demonstrated in detail from the perspective of physical mechanism. Moreover, in a typical \( P-Q \) decoupled control scheme of the PV inverter, the active and reactive output power can be independently regulated to their reference values.

When the rotor speed \( \omega \) is greater than the rated speed \( \omega_0 \) (i.e., \( \omega_\omega_0 \)), in this case, to restrain the rotor speed from increasing, PV should reduce the active or increase reactive output power. Counter, PV should increase the active output power or reduce active output power to damp electromechanical oscillation, which can effectively shorten the rotor oscillation time. The controlled active and reactive output current could be described as

\[
\begin{align*}
I_d & = (\omega_0 - \omega) \left( K_{p1} + K_{i1} / s + sK_{d1} \right) + I_{d0} \\
I_q & = (\omega_0 - \omega) \left( K_{p2} + K_{i2} / s + sK_{d2} \right)
\end{align*}
\]

(12)

Considering \( s \Delta \delta = \Delta \omega \) and respectively linearizing (12), respectively, we have
\[ \begin{align*}
\Delta I_d &= -K_p \Delta \omega - K_i \Delta \delta - sK_d \Delta \omega \\
\Delta I_q &= -K_p \Delta \omega - K_i \Delta \delta - sK_d \Delta \omega
\end{align*} \tag{13} \]

Substituting (13) into (11), one obtains
\[ \Delta P_e = \left( K_g + K_e K_i + K_f K_d \right) \Delta \delta + \left( K_e K_p + sK_p K_d + K_f K_p \right) \Delta \omega \tag{14} \]

From (14), (4) can thus be rewritten as
\[ \frac{2H + K_e K_k + K_d K_k}{T_f} \frac{d\Delta \omega}{dt} = -\left( K_e + K_e K_i + K_f K_d \right) \Delta \delta + \left( K_e K_p + K_f K_p + D \right) \Delta \omega \tag{15} \]

From (15), it is concluded that adjusting the PID controller parameters \( K_d, K_i, \) and \( K_p \) of the \( P \) or \( Q \)-control loop, can equivalently affect the inertia effect, synchronous ability, and oscillation damping level of the SG-dominated power system.

5. Experimental Verification

In this paper, MATLAB/Simulink-based simulations are utilized to verify the correctness of physical mechanism analysis in this paper. Assuming that the grid is disturbed at \( t = 19 \) s, the mechanical input power suddenly decreases. The experimental circuit topology is shown in Fig. 3, with the main parameters listed in Tab. I.

| Parameter                        | Value          |
|-----------------------------------|----------------|
| Line-to-line voltage \( U \)      | 380 V          |
| Line-to-line voltage \( E \)      | 380 V          |
| Switching frequency              | 15 kHz         |
| Line-to-line voltage \( V \)      | 400 V          |
| Grid frequency                    | 50 Hz          |
| \( I_{d0} \)                      | 10 A           |
| \( I_{q0} \)                      | 0.5 p.u.       |

When the PV generation system only operates in \( P(Q) \)-control mode, the reactive current \( I_q (I_d) \) needs to be set to 0. The experimental results dominated by different controller are shown in Fig. 7-9.

![Figure 6](image1)
![Figure 7](image2)
Figure 8. Experimental results for P controller dominated scenario

With the parameters $K_d1$ increasing, the D controller further enhances the inertia effect [see Fig. 6(a)]. As shown in Fig. 6(b), obviously, the notable increase of $K_d1$ also amplify the PV output active power. It can be noticed that the essence of inertia effect enhancing is energy, therefore, the more active output power released by the PV grid-tied inverter, the larger the inertia effect. The experimental results based on the I and D controller are shown in Fig. 7 and 8, respectively. While the parameters $K_i1$ and $K_p1$ increasing, the I and P controller can further enhance the synchronous capability and the damping level.

6. Conclusion

To demonstrate the mechanism of PV generation system in damping the electromechanical oscillation, this paper develops a linear mathematical model of a SMIB integrated PV in the electromechanical time scale. The proposed model reveals the relationship between the active/reactive powers injected by the PV inverter, and the synchronization capability and damping level of the power system. Based on the PID controller embedded schemes with rotor speed feedback, the P, I and D parameters of the power control loop can proportionally affect the damping level, synchronization capability and inertia effect of the integrated SG-based power system, respectively.

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