Transient Synchronization Stability Mechanism of PMSG With Additional Inertia Control

Yayao Zhang ¹ and Meng Zhan ²

¹State Key Laboratory of Advanced Electromagnetic Engineering and Technology
²Affiliation not available

December 7, 2023

Abstract

Synchronous stability is crucial for the safety and operation of AC power systems. However, most of the current researches focused on the stability of grid-connected converters, and that of renewable equipment still lacked. In this paper, the impact of the additional inertia control (AIC) on the permanent magnet synchronous generator (PMSG) is studied. It is found that with the AIC, the system dominant dynamics shifts from the electromagnetic to electromechanical timescales. This paper develops a simplified model for the single-PMSG infinite-bus system with the AIC within the electromechanical timescale, and reveals the transient synchronization stability mechanism from three aspects: the machine-network interface, transient dominant variable, and interaction between the synchronous loop and the power imbalance loop. Finally, this paper analyzes the swing characteristics of the PMSG system, and uncovers the relationship between the energy transmission and synchronization. These findings could provide improved insights into the synchronous stability mechanism of renewable-dominated new-type power systems.
Transient Synchronization Stability Mechanism of PMSG With Additional Inertia Control

Yayao Zhang, Meng Zhan, Senior Member, IEEE

Abstract—Synchronous stability is crucial for the safety and operation of AC power systems. However, most of the current researches focused on the stability of grid-connected converters, and that of renewable equipment still lacked. In this paper, the impact of the additional inertia control (AIC) on the permanent magnet synchronous generator (PMSG) is studied. It is found that with the AIC, the system dominant dynamics shifts from the electromagnetic to electromechanical timescales. This paper develops a simplified model for the single-PMSG infinite-bus system with the AIC within the electromechanical timescale, and reveals the transient synchronization stability mechanism from three aspects: the machine-network interface, transient dominant variable, and interaction between the synchronous loop and the power imbalance loop. Finally, this paper analyzes the swing variable, and interaction between the synchronous loop and the three aspects: the machine-network interface, transient dominant variable, and interaction between the synchronous loop and the power imbalance loop. These findings could provide improved insights into the synchronous stability mechanism of renewable-dominated new-type power systems.

Index Terms—Transient synchronization stability mechanism, Permanent magnet synchronous generator, Additional inertia control, Electromechanical timescale, Phase-locked loop.

NOMENCLATURE

$\theta_{pll}$ Phase-locked loop (PLL) output angle in the three-phase stationary abc reference frame
$\varphi_{pll}$ PLL output angle in the $xy$ common reference frame
$\theta_t$ Terminal voltage angle in the $xy$ common reference frame
$\Delta \theta$ Phase difference between the terminal voltage angle and the PLL output angle
$P_{in}$ Input mechanical power of permanent magnet synchronous generator (PMSG)
$P_m, P_e$ Machine-side converter (MSC) and grid-side converter (GSC) output electromagnetic powers
$\omega_g, \omega_{pll}, \omega_r$ The $xy$ common reference frame frequency, PLL output frequency, and PMSG rotor speed, respectively
$i_{sq}$ MSC output current in the $q$ coordinate
$i_{int}, i_{rsc}$ Output currents of additional inertia control and rotor speed control, respectively
$U_t, U_g$ Terminal voltage and infinite-bus voltage
$u_{tg}$ Terminal voltage in the $q$ coordinate

$I_y, L_f$ Line and filter inductances
$k_{p,pll}, k_{i,pll}$ Proportional and integral parameters of the PLL

I. INTRODUCTION

WITH growing shortage of fossil fuels and continuous problems of environmental pollution, it is imperative to accelerate construction of renewable-dominated new-type power systems [1], [2]. In recent years, a large number of renewable equipment, including permanent magnet synchronous generators (PMSGs), doubly fed induction generators, and photovoltaics, have been integrated into the power grids through power electronic inverters [3]. These primary-device replacements and revolutions fundamentally change the power system dynamics and bring significant variations to all aspects of the system, including analysis, relaying, control, and operation.

As the alternating current transmission technique is unchanged, synchronous stability still plays an essential role in the system safety and reliability [4]. For the synchronous generators (SGs) in the traditional power systems, their transient synchronization mechanism is well understood and described by the rotor’s motion equations. Therefore, the synchronization stability of traditional power systems is considered as whether the rotor speed of the SG is identical or keeps synchronous, or the rotor angle mismatch of the SG remains finite [5], [6]. However, the transient synchronization stability mechanism of renewable equipment has been significantly changed. Taking the PMSG as an example, it is connected to the grid through full-scale converters and synchronized with the grid by the phase-locked loop (PLL) technique. Its synchronization mechanism is determined by its complex control strategies, exhibiting the characteristics of control-dominated synchronization [7]. The diversity and nonlinearity of control structures bring great obstacles to the transient synchronous stability analysis of the new-type power system.

With rapid development of wind power generation technology, PMSG has shown significant advantages with its high efficiency, low noise, and low failure rate, and gradually become a mainstream generator of variable frequency wind turbines [8]. Indeed, the transient synchronous stability of the PMSG system is an important problem [9], [10]. Modeling PMSG appropriately is fundamental for our understanding and analyzing. The earliest PMSG model was established by several wind turbine manufacturers [11]. However, due to inconsistent control schemes, the model generality is poor. General Electric and the Western Electricity Coordinating Council in the United States synthesized the actual wind turbine structures...
and control strategies of various wind turbine manufacturers and constructed a universal electromechanical timescale model for the PMSG [12], [13]. However, these models are mainly used for simulations, rather than for mechanism analysis. At the same time, early studies largely focused on the impact of wind turbine on the transient stability of the SG, rather than the salient properties of the wind turbine itself. The effects of wind turbine permeability, grid connection location, etc. on the transient synchronous stability of the SG have also been widely investigated by simulations under typical environments [14], [15].

As the wind power has become the dominant power source in certain regions, the transient synchronous stability of the PMSG have gradually attracted widespread attention [16]–[27]. Due to the certain isolation effect of full-scale converters under grid-side faults [16], researchers have simplified the machine-side converter (MSC) of the PMSG as a constant power source, and focused on the dynamics of the grid-side converter (GSC) only [17], [18]. By nonlinear methods, the single voltage source converter (VSC) system connected to an infinite bus were analyzed and its basin of attraction was calculated [19], [20]. In [21], its dominant transient unstable characteristics was studied. For some other theoretical studies, the GSC was further simplified as a PLL, and the transient synchronous stability of the PLL second-order system was extensively studied by using Lyapunov function [22], equal area rule [23]–[25], phase portrait approach [26], etc. In addition, a variety of transient synchronous stability enhancement methods have also been proposed very recently [25]–[27].

However, due to the recent requirements for frequency response of wind turbines in several national grid-connection guidelines [28], additional inertia control (AIC) has become obligatory. Under the action of AIC, the wind turbines need to improve its ability to support system frequency by releasing rotor kinetic energy for a short time [29]. At this point, the MSC dynamics of the PMSG may naturally incorporate into the system transients and cannot be simply neglected again [30]. In [31], [32], the detailed mathematical models of the PMSG with the AIC were established, but any possible transient synchronization stability mechanism remained obscure.

Therefore, this paper focuses on the single-PMSG infinite-bus system with the AIC, aiming at clarifying its transient synchronization stability mechanism. The remainder of the paper is structured as follows. Section II studies the influence of the AIC on the transient characteristics of the PMSG. In Section III, a simplified electromechanical timescale model is proposed. Section IV investigates the transient synchronization mechanism from three aspects: the machine-network interface, the dominant transient variable, and the interaction analysis. Section V is devoted to the swing characteristics of PMSG. Finally, our conclusions are given in Section VI.

II. IMPACT OF ADDITIONAL INERTIA CONTROL

A. Single-PMSG Infinite-Bus System

Fig. 1 shows the topology structure of the single-PMSG infinite-bus system. The MSC is connected to the GSC by a DC capacitor $C$, and the GSC is connected to the infinite-bus by a filter inductance $L_f$ and a line inductance $L_g$. Typical vector controls for the MSC and the GSC are composed of active and reactive powers decoupling control.

For the MSC, it adopts zero $d$-axis current control, the maximum power point tracking (MPPT), the pitch control, the rotor speed control (RSC), the AIC, and the AC current control (ACC). At different wind speeds, the PMSG adjusts the rotor speed and the pitch angle through the MPPT and the pitch control, respectively, in order to capture the maximum wind energy and ensure its safe stable operation. Since this paper focuses on the transient synchronous characteristics of the PMSG within the electromechanical timescale, the much slower MPPT and pitch control are ignored. The $q$-axis current reference of the stator $i_{sqref}$ is given by both the RSC and AIC, and the $d$-axis current reference of the stator $i_{dqref}$ is set to zero. The ACC generates the modulation voltage $e_{sd}$ and $e_{sq}$ based on the current references. After the coordinate transformation, the trigger signals are generated by the pulse width modulation (PWM). Fig. 2 shows the relationship between the $dq$ reference frame of the MSC and GSC and the $xy$ common reference frame, associated with several major angles used in the paper.

For the GSC, it consists of the DC-link voltage control (DVC), terminal voltage control (TVC), ACC, and PLL. The DVC gives the $d$-axis current reference $i_{dref}$ by controlling the capacitor voltage $U_{dc}$, and the TVC gives the $q$-axis current reference $i_{qref}$ by controlling the terminal voltage $U_t$. Similarly, according to the current references, the ACC generates the modulation voltages $e_d$ and $e_q$, and the trigger signals are generated by the PWM. The PLL provides the basis for the angle transformation between the $dq$ reference frame of the GSC and the $abc$ reference frame, as shown in Fig. 2. To be simple, the PLL is converted into the phase model within the $xy$ common reference frame, as shown in Fig. 3. In this respect, the input and output signals are the terminal voltage angle $\theta$ and the PLL output angle $\varphi_{pll}$, respectively, and $\Delta \theta = \theta - \varphi_{pll}$.

B. PMSG Without AIC

In the absence of the AIC, the MSC is connected to the GSC by the DC capacitor. The input mechanical power of PMSG, $P_m$, is transmitted from the MSC to the grid, and the PLL ensures synchronization between the PMSG and the grid. Fig. 4 shows the transient response of the PMSG when the infinite-bus voltage $U_g$ dips to 0.7 p.u. For the MSC, the rotor frequency $\omega_r$ [in Fig. 4(f)] and the output electromagnetic power $P_m$ [the dashed line in Fig. 4(e)] remain unchanged. These indicate that the MSC does not respond to any grid-side disturbances. For the GSC, the PLL output angle $\varphi_{pll}$ and frequency $\omega_{pll}$, terminal voltage $U_t$, DC-link capacitor voltage $U_{dc}$, and output electromagnetic power $P_e$ all show electromagnetic timescale dynamics, and their oscillation frequencies are identical and approximately equal 5.88 Hz $(1/0.17 s \approx 5.88$ Hz).

Clearly due to the back-to-back connection between the MSC and the GSC, they are separated and the MSC does not respond grid-side disturbances. Therefore, it is easy to
understand that in most of previous works on the synchronous stability of PMSG, the dynamics of the MSC has been completely ignored and the whole PMSG system has been reduced to a single-VSC infinite-bus system. Under this situation, the PMSG dynamics is within the electromagnetic timescale, and its transient synchronization characteristics has been extensively studied [19], [21].

C. PMSG With AIC

When the AIC is considered, the MSC and the GSC are coupled by the AIC. Figs. 5 and 6 show the transient responses of the PMSG when the infinite-bus voltage $U_g$ dips to 0.45 p.u. for the machine-side and grid-side variables, respectively. For the MSC in Fig. 5, now $\omega_r$, $P_m$, and the AIC output current $i_{int}$ all exhibit electromechanical timescale dynamics, that is, the MSC can respond to grid-side disturbances. Meanwhile, the output electromagnetic power $P_e$ of the GSC rapidly tracks the output electromagnetic power $P_m$ of the MSC in Fig. 5(a). For the GSC in Fig. 6, there are high-frequency oscillations in the $U_t$ and $U_{dc}$ during the preliminary stage of the faults, and they decay quickly. The oscillation frequencies of $P_m$, $P_e$, $\omega_r$, $i_{int}$, and $i_{tsc}$ in Fig. 5 and $\omega_{pll}$ and $\omega_{pll}$ in Fig. 6 are all identical and approximately equal 0.36 Hz ($1/2.76$ s $\approx 0.36$ Hz), indicating a whole-system-level electromechanical timescale dynamics.

Based on these comparisons, it is well understood that when the AIC is considered, the coupling between the MSC and the GSC deepens, and the MSC begins to respond to grid-side disturbances. Therefore, the electromechanical dynamics of the rotor can affect the dynamics of the PLL, which is originally believed as an electromagnetic timescale dynamics.
Their interaction between the GSC and MSC will become a clue for the organization rule for how the PMSG works.

D. Multi-timescale Characteristics

Figs. 5 and 6 for the PMSG dynamics show a clear multi-timescale characteristics. For the GSC, during the preliminary stage of the faults, $U_i$, $U_{dc}$, $P_c$, and $\omega_{plt}$ all exhibit high-frequency oscillations, approximately sustaining for only about 0.1 s. This indicates that the rotor with the electromechanical timescale controls of the PMSG have not yet responded to the faults during the fault-on stage, whereas the electromagnetic timescale controls have already started to act. At this short period, the PMSG exhibits electromagnetic timescale dynamics. After that, the rotor frequency $\omega_r$ begins to alter, triggering the action of the electromechanical timescale controls, and then adjusting $P_m$ and $P_e$ accordingly. Hence the PMSG starts to exhibit electromechanical timescale dynamics.

E. Influence of AIC parameter $K_f$

The high frequency oscillation of $P_m$ is related to the differential coefficients of the AIC $K_f$. When $K_f$ is 5 and 20, the amplitude-frequency characteristics of the AIC are shown in Figs. 7(a) and 7(b), respectively. Fig. 7 illustrates that as $K_f$ increases, the gain of the AIC for the high-frequency signals gradually increases, indicating that the AIC is more sensitive to noise. Therefore, as the input signal of AIC $\omega_{plt}$ changes significantly in the early stage of faults, $i_{int}$ will exhibit high-frequency oscillation, resulting in a significant change of $P_m$.

Fig. 8 shows the dynamic responses of $P_m$ under different values of $K_f$ after large disturbances. It is found that as $K_f$ decreases, the oscillations of $P_m$ within the electromagnetic timescale gradually decreases and decays rapidly, which is consistent with the theoretical analysis in Fig. 7. However, when $K_f$ is smaller, the frequency support effect of the AIC also becomes weaker. Therefore, it is necessary to choose $K_f$ appropriately [33].

III. MODELING AND VERIFICATION

A. Electromechanical Timescale Nonlinear Modeling

Based on the previous analysis, within the electromechanical timescale, the electromagnetic timescale controls of the PMSG and the DC capacitor dynamics can be ignored, and only the rotor dynamics, RSC, AIC, and PLL should be considered. The nonlinear modeling of the single-PMSG
infinite-bus system with the AIC within the electromechanical timescale will be established as follows.

The differential equation for the rotor of the PMSG is

\[ 2H \dot{\omega}_r = P_{in} - P_m, \tag{1} \]

where \( H \) represents the inertial time constant of the rotor, \( P_{in} \) denotes the input mechanical power of the PMSG, and \( P_m \) is the output electromagnetic power of the MSC. Without losing generality, \( P_{in} \) = constant is always chosen.

The dynamical equation for the RSC is

\[ i_{sq} = k_{p,rsc}\dot{\omega}_r + k_{i,rsc}(\omega_r - \omega_{ref}) - i_{int}. \tag{2} \]

The differential equation for the AIC is

\[ T_f \dot{i}_{int} = -i_{int} + K_f \dot{\omega}_{pll}. \tag{3} \]

The differential and algebraic equations for the PLL are

\[
\begin{align*}
\dot{\varphi}_{pll} &= \omega_{pll} \\
\omega_{pll} &= k_{p,pll}u_{tq} + k_{i,pll}u_{tq},
\end{align*}
\]

and

\[ u_{sq} = U_t \sin (\theta_t - \varphi_{pll}), \tag{5} \]

respectively. The TVC is ignored; \( U_t = U_{tref}. \)

The output electromagnetic power \( P_m \) of the MSC is

\[ P_m = \omega_r T_m = \omega_r [i_{sq}\psi_r - (L_d - L_q)i_{sd}i_{sq}], \tag{6} \]

where \( \psi_r \) is the constant rotor flux of the PMSG. \( T_m \) is the electromagnetic torque of the PMSG. \( L_d \) and \( L_q \) are the \( d \)-axis and \( q \)-axis stator inductances of the PMSG, respectively.

Due to the zero \( d \)-axis current control (i.e., \( i_{sd} = 0 \)) and neglect of the electromagnetic timescale controls, \( P_m \) and \( P_e \) satisfy the following constraints:

\[ P_m = P_e = \omega_r i_{sq}\psi_r. \tag{7} \]

Within the electromechanical timescale, the network adopts the static model, so that \( P_e \) is written as

\[ P_e = \frac{U_tU_g}{\omega_2L_g} \sin \theta_t, \tag{8} \]

or,

\[ \theta_t = \arcsin \frac{P_e\omega_2L_g}{U_tU_g}. \tag{9} \]

Taking \( [\omega_r, i_{sq}, i_{int}, \varphi_{pll}, \omega_{pll}]^T \) as the state variables and combining the above equations from (1) to (9), the system differential-algebraic equations can be obtained as follows:

\[
\begin{align*}
2H\dot{\omega}_r &= P_{in} - P_m \\
\dot{i}_{sq} &= k_{p,rsc}\dot{\omega}_r + k_{i,rsc}(\omega_r - \omega_{ref}) - i_{int} \\
T_f \dot{i}_{int} &= -i_{int} + K_f \dot{\omega}_{pll} \\
\dot{\varphi}_{pll} &= \omega_{pll} \\
\omega_{pll} &= k_{p,pll}u_{tq} + k_{i,pll}u_{tq}
\end{align*}
\]

\[
\begin{align*}
P_m &= \omega_r i_{sq}\psi_r = P_e \\
u_{tq} &= U_t \sin (\theta_t - \varphi_{pll}) \\
U_t &= U_{tref} \\
\theta_t &= \arcsin \frac{P_e\omega_2L_g}{U_tU_g}
\end{align*}
\]  \tag{11}
These relations can also be easily extended to multiple PMSG systems.

Fig. 10(b) shows the interface between multiple PMSGs and the network, where \( S, U, \) and \( \mathbf{Y} \) represent the node injection power matrix, node voltage matrix, and node admittance matrix, respectively. The subscript \( i \) represents the \( i \)-th PMSG. The network for the interaction of PMSGs becomes a little bit more complicated, but the input-output form for each PMSG is the same. Similarly \( P_m \) and \( U_t \) represent the output of the PMSG and the input of the network, and the terminal voltage angle \( \theta_t \) represents the output of the network and the input of the PMSG. Clearly the only difference from the single-PMSG system is that now the network description becomes more complicated. Therefore, the physical picture is that the PMSG injects the electromagnetic power \( P_m \) into the network, and the network acts as the bridge to obtain \( \theta_t \) as an input to the PLL. Obviously, it is similar to the machine-network interface between the SG and the network in the traditional power systems.

B. Transient Dominant Variable Analysis

Although the simplified electromechanical timescale model has been obtained, it is still difficult to identify possible dominant unstable variable, which might pose certain difficulties for further analysis of synchronous stability. Therefore, this paper uses the participation factor analyses of controlling-unstable-equilibrium-point (CUEP) to extract the dominant unstable variable of the PMSG, which has been developed recently in our research group [34], [35]. Basically, the unstable manifold of the CUEP largely determines the system transient behavior. Therefore, the participation factor for the unstable manifold (eigenvector) of the CUEP could uncover the participation degree for each state variable. Without loss of generality, the results under four distinctive cases are shown in Table I, and the associated parameters are presented in Appendix.

Based on these broad studies, it can be found that the proportions of the participation factors of the synchronization loop variables \((\varphi_{\text{pll}} \text{ and } \omega_{\text{pll}})\) are dominant: 83.84\%, 95.26\%, 86.68\%, and 89.65\%, respectively. Comparatively, the proportions of participation factors of the active power loop variables \((\omega_r, i_{sq}, \text{ and } i_{int})\) are small: 16.16\%, 4.71\%, 13.32\%, and 10.35\%, respectively. These indicate that both the synchronization loop and the active power loop contribute to the transient synchronous stability, but the synchronization loop is dominant. Therefore, the PLL output angle in the \(xy\) common reference frame, \(\varphi_{\text{pll}}\), plays a similar significant role with the rotor-angle of the SG in the traditional power systems.

C. Interaction analysis

Based on the simplified electromechanical timescale model, the original control diagram in Fig. 1 can be restructured. Fig. 11 shows the corresponding control diagram for the simplified model, in which the coupling among the MSC, network, and GSC are clear. The red box is for the electromechanical timescale dynamics, the green box is for the electromagnetic timescale dynamics, and the black box is for the algebraic equation. In particular, the algebraic expressions for \(f_1(x), f_2(x), \text{ and } f_3(x)\) are as follows

\[
\begin{align*}
  f_1(x) &= (\cdot)(\cdot)\psi_r \\
  f_2(x) &= \arcsin (\cdot) \frac{\omega_g L_g}{U_t U_g} \\
  f_3(x) &= U_t \sin (\cdot)
\end{align*}
\]

which correspond to (7), (9), and (5), respectively.

Based on this simplified control diagram, the dynamical process between the PMSG and the grid can be easily understood: after a sudden large disturbance, e.g., a grid voltage dips, \(\theta_t\) may show a significant jump, and then the PLL frequency \(\omega_{\text{pll}}\) changes rapidly. Owing to the presence of AIC, \(\omega_{\text{pll}}\) can change the output electromagnetic power \(P_m\) of the MSC by the action of \(i_{int}\). Meantime, as the rotor is driven by the imbalanced power between the input mechanical power \(P_r\) and the output electromagnetic power \(P_m\), the rotor speed \(\omega_r\) also changes. Then the RSC could adjust \(i_{rsc}\) to change the \(q\)-axis current \(i_{sq}\), and thereby change \(P_m\) to achieve a new power balance. From \(f_2(x), \theta_t\) changes with the variation of the \(P_m\), which may further cause those of \(\varphi_{\text{pll}}\) and \(\omega_{\text{pll}}\). Finally, the power on the rotor may tend to rebalance, and \(\omega_{\text{pll}}\) may become synchronous with the grid again. Or the system becomes unstable otherwise. Since with the AIC, the rotor dynamics, the RSC, and the \(P_m\) all belong to electromechanical timescale, and the dynamics of \(\varphi_{\text{pll}}\), which originally belongs to electromagnetic timescale, now also becomes electromechanical timescale. Therefore, in the transient process, the angle difference \(\Delta \theta\) causes the changes of the PLL output angle \(\varphi_{\text{pll}}\) and frequency \(\omega_{\text{pll}}\), and further
results in an imbalanced active power on the rotor, thereby driving the machine-side controls to rebalance the active power and resynchronize $\omega_{pll}$ with the grid frequency. Due to the coupling between the synchronization loop (grid-side) and the active power loop (machine-side), which is possible with the aid of the AIC, the dynamics of $\varphi_{pll}$ have shifted from electromagnetic timescale to electromechanical timescale. In a sharp contrast, in the absence of the AIC, clearly in Fig. 11 there is only one-way action from the machine side to the grid side and, therefore, the PMSG cannot respond to the grid-side disturbances.

V. Swing Characteristics Analysis

In this section, we will study the important swing characteristics of the PMSG. Similar to the straight-line or rotational motion by Newton’s second law, both the synchronization and active power loops should be separately dealt with, and their variables can be defined as acceleration, speed, and displacement. Further, whether the acceleration or speed cross zero can be used as the basis for the criterion of different swing stages. For example, for the synchronization loop on the grid-side, $\Delta \theta$ is defined as acceleration, $\omega_{pll}$ is defined as speed, and $\varphi_{pll}$ is defined as displacement. $\omega_{pll}$ increases (decreases) when $\Delta \theta$ is greater (smaller) than 0. Similarly, $\varphi_{pll}$ increases (decreases) when $\omega_{pll}$ is greater (smaller) than 0. Correspondingly, for the active power loop on the machine-side, the active power imbalance $P_{in} - P_m$ is defined as acceleration, $\omega_r - 1$ is defined as speed, and $i_{rsc}$ is defined as displacement. Thus, $\omega_r$ increases (decreases) when $P_{in} - P_m$ is greater (smaller) than 0, and $i_{rsc}$ increases (decreases) when $\omega_r - 1$ is greater (smaller) than 0. However, due to the influence of AIC and $i_{sq} = i_{rsc} - i_{int}$, the swing characteristics of $i_{sq}$ and $i_{int}$ should also be studied.

Two simulation cases for stable and unstable systems are listed below.

Case I: set the fault as the voltage $U_g$ dips 0.55 p.u. at $t = 0.1$ s. The system eventually becomes stable. The simulation results of the PMSG for the grid-side and machine-side variables are shown in Figs. 12 and 13, respectively.

In Fig. 12, based on the classification for different stages, the transient process can be divided into five stages:

- **Stage I:** $U_g \downarrow \Rightarrow \theta_1 \uparrow \Rightarrow \Delta \theta > 0 \Rightarrow \omega_{pll} \uparrow \Rightarrow 0 \Rightarrow \varphi_{pll} \uparrow$;
- **Stage II:** $\varphi_{pll} \uparrow \Rightarrow \Delta \theta < 0 \Rightarrow \omega_{pll} \downarrow \Rightarrow 0 \Rightarrow \varphi_{pll} \uparrow$;
- **Stage III:** $\varphi_{pll} \uparrow \Rightarrow \Delta \theta < 0 \Rightarrow \omega_{ pll} \downarrow \Rightarrow 0 \Rightarrow \varphi_{pll} \downarrow$;
- **Stage IV:** $\varphi_{pll} \downarrow \Rightarrow \Delta \theta > 0 \Rightarrow \omega_{pll} \uparrow \Rightarrow 0 \Rightarrow \varphi_{pll} \downarrow$;

After that, when $\Delta \theta$ is less than 0 again, the second, third, fourth, and fifth stages repeat. The oscillations of $\varphi_{pll}$ and $\omega_{pll}$ gradually decay, and they return to be stable eventually.

In Fig. 13, similarly based on the classification for different stages for the machine variables, the transient process can be divided into five stages. There is no one-to-one strict correspondence with Fig. 12.

- **Stage I:** $\omega_{PLL} \uparrow \Rightarrow i_{int} \uparrow \Rightarrow i_{sq} \downarrow \Rightarrow P_m \downarrow$;
- **Stage II:** $P_m \downarrow < P_{in} \Rightarrow \omega_r \uparrow \Rightarrow 0 \Rightarrow i_{sq} \uparrow \Rightarrow P_m \uparrow$;
- **Stage III:** $P_m \Rightarrow P_{in} \Rightarrow \omega_r \downarrow \Rightarrow 0 \Rightarrow i_{sq} \uparrow \Rightarrow P_m \Rightarrow \omega_r \downarrow$;
- **Stage IV:** $\omega_r \downarrow < 0 \Rightarrow i_{sq} \downarrow \Rightarrow P_m \downarrow \Rightarrow P_{in} \Rightarrow \omega_r \downarrow < 1 \Rightarrow i_{sq} \downarrow \Rightarrow P_m \downarrow$;
- **Stage V:** $P_m \downarrow < P_{in} \Rightarrow \omega_r \uparrow \Rightarrow 0 \Rightarrow i_{sq} \downarrow \Rightarrow P_m \downarrow$.

After that, when $\omega_r$ is greater than 1 again, the second, third, fourth, and fifth stages repeat, and the oscillations of $P_m$ and $\omega_r$ gradually decay and return to be stable eventually. It is clear that they reflect the output electromagnetic power dynamics of the PMSG, namely, the energy transmission process between the PMSG and the grid.
Case II: set the fault as the voltage $U_g$ dips 0.59 p.u. at $t = 0.1$ s, and the system becomes unstable eventually. The simulation results of the PMSG are shown in Figs. 14 and 15. Fig. 14 shows the swing characteristics of the synchronization loop, and now the transient can be divided into three stages.

Stage I: $U_g ↓⇒ \theta_l ↑⇒ \Delta \theta > 0 ⇒ \omega_{\text{plll}} ↑⇒ \varphi_{\text{plll}} ↑$;
Stage II: $\varphi_{\text{plll}} ↑⇒ \Delta \theta < 0 ⇒ \omega_{\text{plll}} ↓⇒ \varphi_{\text{plll}} ↑$;
Stage III: $\theta_l ↑⇒ \Delta \theta > 0 ⇒ \omega_{\text{plll}} ↑⇒ \varphi_{\text{plll}} ↑$.

Since then, as $\omega_{\text{plll}}$ is always greater than 0, $\varphi_{\text{plll}}$ diverges monotonically, and the system becomes unstable.

Fig. 15 shows the swing characteristics of the active power loop. Similarly, the energy transmission process can be divided into three stages.

Stage I: $\omega_{\text{plll}} ↑⇒ i_{\text{int}} ↑⇒ i_{\text{sq}} ↓⇒ P_m ↓$;
Stage II: $P_m ↓< P_m ⇒ \omega_r ↑⇒ i_{\text{sq}} ↑⇒ P_m ↑$;
Stage III: $\omega_{\text{plll}} ↑⇒ i_{\text{int}} ↑⇒ i_{\text{sq}} ↓⇒ P_m ↓< P_m ⇒ \omega_r ↑$.

After that, $\omega_r$ also diverges monotonically, and the system becomes unstable.

Based on these comparisons for stable and unstable cases for all major variables of the synchronization and active power loops, it can be seen that the system can show either oscillatory multi-swing stability or monotonic single-swing divergence, for most of transient behaviors. This is quite similar to the rotor-angle swing characteristics for a single-SG infinite bus system [5], [6]. In fact, we also find an atypical phenomenon, multi-swing instability, exists in a very tiny range of $U_g$ dip between 0.58 p.u. and 0.59 p.u.

On the other hand, comparing Figs. 13 and 15, it can be found that the swings of $i_{\text{sq}}$ are different. When the system is stable in Fig. 13, $i_{\text{sq}}$ is mainly dominated by the current $i_{\text{rsc}}$, and $i_{\text{int}}$ quickly decays to zero. At this time, the rotor on the machine-side can provide a sufficient support for $\omega_{\text{plll}}$, and the $\varphi_{\text{plll}}$’s swing converges. However, when the system is unstable in Fig. 15, $i_{\text{sq}}$ is gradually dominated by $i_{\text{int}}$ on Stage III, and the increase of $i_{\text{rsc}}$ cannot offset the influence of $i_{\text{int}}$ on $i_{\text{sq}}$. At this time, due to the rapid increase of $\omega_{\text{plll}}$, the rotor is unable to provide a sufficient support for $\omega_{\text{plll}}$. Meanwhile, the AIC makes $P_m$ dip, which further increases the imbalanced power on the rotor and leads to the system instability. At the same time, $\varphi_{\text{plll}}$ monotonically diverges. Therefore, the interaction between the synchronization and active power loops indeed plays a key role in the system transient dynamics.

Finally, to be compared with the SG, although the PMSG show more complicated swing stages and characteristics due to the PMSG’s intrinsic properties: nonlinear and high-dimensional state space, from the perspective of energy conversion, the synchronization between the PMSG and the grid is still driven by the imbalanced active power. In addition, the power imbalance and synchronization loops are now physically separated and dominated by the machine-side and the grid-side controls, respectively. The AIC establishes a bridge for them. Therefore, for the SG, its rotor-angle synchronization variable is on the rotor, and its imbalanced active power is also on the rotor. They are naturally coupled. A simple second-order swing equation can catch the rotor synchronization...
motion under the action of imbalanced power [5], [6]. Distinctively, for the PMSG, the synchronization and the active power loops are physically separated, but functionally connected by the AIC. Therefore, their synchronization mechanisms are similar.

VI. CONCLUSIONS

In conclusion, under the recent urgent requirement of grid codes of PMSG, the AIC becomes necessary. The impact of the AIC on the transient synchronization stability characteristics of the PMSG has been systematically studied. For this target, this paper establishes a simplified model of the single-PMSG infinite-bus system with the AIC within the electromechanical timescale, and analyzes its transient synchronization mechanism and swing characteristics. It is found that the AIC can change the synchronous dynamics of the PMSG from electromagnetic timescale to electromechanical timescale. Within the electromechanical timescale, this paper uncovers the transient synchronization stability mechanism from the three aspects, including the machine-network interface, transient dominant variables, and interaction analysis.

By analyzing the swing characteristics of the active power loop on the machine-side and the synchronization loop on the grid-side, it is discovered that the system can show either oscillatory multi-swing stability or monotonic single-swing instability, similar to the rotor-angle swing characteristics in a single-SG infinite bus system. In addition, it is found that the synchronization between the PMSG and the grid is still driven by the imbalanced power on the rotor motion, although the power imbalance and synchronization loops are physically separated. Different from the most recent studies on the wide simulations of the PMSG integration and the transient synchronization stability analyses of the grid-tied PLL-based VSCs, this paper provides a clear physical picture for how the PMSG works. All these findings are helpful for transient synchronous stability problems of renewable-dominated new-type power systems.

APPENDIX

Parameters used in the paper: \( S_b = 2 \text{ MW}, U_b = 690 \text{ V (line rms value)}, f_g = 50 \text{ Hz}, \omega_g = 2\pi f_g, L_g = 0.5/\omega_g \text{ H}, U_g = 1.0 \text{ p.u.}, H = 4 \text{ p.u.}, P_{in} = 0.8 \text{ p.u.}, \psi_r = 0.9 \text{ p.u.}, U_{tr-ref} = 1 \text{ p.u.}, \text{ and } U_{rr-ref} = 1 \text{ p.u.}.

Controller parameters of Case 1: (1) RSC: \( k_{p,rsc} = 10, k_{i,rsc} = 40 \). (2) AIC: \( K_f = 10, T_f = 1 \). (3) PLL: \( k_{p,pll} = 50/\omega_g, k_{i,pll} = 2000/\omega_g \).

The changing parameters for other cases are as follows. Case 2: \( L_g = 0.1/\omega_g \text{ H} \); Case 3: \( k_{p,pll} = 60/\omega_g, k_{i,pll} = 1400/\omega_g \); Case 4: \( K_f = 5 \).

REFERENCES


