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Sub-synchronous interactions caused by the PLL in the grid-connected PMSG for the wind power generation

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ABSTRACT

A phase locked loop (PLL) functions to connect a grid-connected permanent magnet synchronous generator (PMSG) for wind power generation to a power system. This paper investigates the sub-synchronous interactions (SSIs) caused by a PLL. A closed-loop interconnected model for the power system with the PMSG is established, wherein, the PLL and the rest of power system are modelled as two open-loop subsystems. Analysis in the paper indicates that when an open-loop complex pole of the PLL subsystem is close to an open-loop sub-synchronous oscillation (SSO) mode of the rest of power system, this open-loop modal resonance may cause strong SSIs between the PLL and power system. It is very likely that the strong SSIs may degrade the damping of power system SSOs. Hence, the mechanism that the grid connection of the PMSG may cause the SSO instability of the power system is revealed from the perspective of open-loop modal resonance introduced by the PLL. In the paper, a method of open-loop modal analysis is proposed to identify the instability risk of open-loop modal resonance brought about by the PLL. Study cases are presented in the paper to demonstrate and evaluate the analysis and conclusions.

1. Introduction

Grid connection of a permanent magnet synchronous generator (PMSG) for wind power generation relies on the function of a phase locked loop (PLL) to provide instantaneous estimation of the phase of its terminal voltage. The estimation is used by the vector control of the grid side converter (GSC) to connect the PMSG to a power system.

Recently, risk of growing sub-synchronous oscillations (SSOs) brought about by the grid connection of the PMSG is examined in [1–6] by using the impedance model analysis. Harmful effect of the PMSG is attributed to the contribution of negative resistance. By varying the gains of the PLL, it is found that the PLL may play a role to contribute the negative resistance [7]. Merits of impedance model analysis used in [5–7] are in two folds. First, the analysis is applied on a closed-loop model of the power system with the PMSG. The sub-synchronous interactions (SSIs) between the open-loop subsystems are linked with the stability of the closed-loop system. Thus, degradation of system SSO stability is endorsed with physical explanation. Second, the mechanism that the PMSG degrades system SSO stability is revealed to be the contribution of negative resistance from the PMSG. This helps considerably the understanding about why the undesired SSOs may be caused by the PMSG under certain circumstances [5–7]. However, the impedance model analysis is applied to a single dynamic component, such as the PMSG or the PLL, in the power system, which is modelled as an open-loop subsystem. At the same time, all other dynamic components are included in the other open-loop subsystem. Hence, it would be difficult to examine the SSIs among multiple dynamic components, such as the PMSGs, the PLLs and the synchronous generators (SGs) such that the trouble-making dynamic components can be identified. In addition, the impedance model analysis often cannot produce the estimation on how much the damping degradation may be caused by the PMSG when the negative resistance contribution is found.

For studying power system SSOs, modal analysis has been an extensively-used method, comparable to the impedance model analysis [8]. Advantages of modal analysis include its accuracy in assessing the damping of the SSOs and the indication on the level of dynamic interactions among different dynamic components in the power system by computing the participation factors (PFs). However, the results of modal analysis are not directly linked with the SSIs between various dynamic components because the modal analysis is normally applied to the state-space model of entire system. Whether the role played by a dynamic component is beneficial or detrimental to system SSO stability cannot be identified by computing the PFs.

This paper proposes a method of open-loop modal analysis to examine the SSIs between a grid-connected PMSG and the power system. The examination focuses on the impact of the PLL employed by the

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PMSG and is carried out for the open-loop subsystems on the basis of a closed-loop interconnected model, wherein, the PLL and the rest of power system are modelled as two open-loop subsystems. Thus, the results of proposed open-loop modal analysis are linked with the SSIs between the open-loop subsystems. Merits of impedance model analysis demonstrated in [5–7] are extended to the proposed open-loop modal analysis.

Theoretical analysis in the paper indicates that under the condition of open-loop modal resonance, i.e., an open-loop complex pole of the PLL is in the proximity to an open-loop SSO mode of the power system on the complex plane, strong SSIs occur between the PLL and power system which may degrade the damping of power system SSOs. Estimation on the damping degradation caused by the PLL under the condition of open-loop modal resonance is proposed in the paper. Hence, the mechanism that the PLL may affect power system SSO stability is revealed from the perspective of open-loop modal resonance.

In the paper, two example power systems with the PMSGs are used to validate the proposed open-loop modal analysis and conclusions made. The applicability of the proposed open-loop modal analysis to examine the impact of the SSIs between multiple PMSGs and torsional dynamics of the SG is demonstrated.

2. Open-loop modal analysis to examine the impact of the SSIs introduced by the PLL

2.1. Closed-loop interconnected model

Consider a power system with k PMSGs for the wind power generation. Fig. 1a shows the configuration of the power system; Fig. 1b is the configuration of the vector control system of the GSC employed by the kth PMSG [9]; Fig. 1c shows the relative position of coordinates of the kth PMSG and the power system. A closed-loop interconnected linearized model is derived in this sub-section for the power system shown by Fig. 1b, where the PLL for the kth PMSG and the rest of power system are modelled as two separate open-loop subsystems.

Function of the PLL is to estimate the phase of terminal voltage of the kth PMSG, θ_p. The estimation is used to determine the position of $d-q$ coordinate of the GSC of the kth PMSG in respect to the common $x-y$ coordinate of the power system in order to implement the vector control. Denote $\widetilde{\theta}_p$ as the estimation of θ_p by the PLL. The direction of d axis of the $d-q$ coordinate of the GSC is determined by $\widetilde{\theta}_p$ as shown in Fig. 1c. Fig. 1d shows the configuration of synchronous reference frame (SRF) PLL, which is the simplest and most commonly-used PLL.

From Fig. 1c, it can have

$$V_d = V_p\cos\theta_e, \quad V_q = V_p\sin\theta_e \tag{1}$$

where $\theta_e = \theta_p - \widetilde{\theta}_p$ is the phase-tracking error of the PLL.

At steady state, $\theta_{e0} = 0$; linearization of (1) is

$$\Delta V_d = \Delta V_p, \quad \Delta V_q = V_{p0}\Delta\theta_e = V_{d0}\Delta\theta_e \tag{2}$$

There are many different schemes to build and design a control system to fulfill the function for $\widetilde{\theta}_p$ to track θ_p. Those schemes are often referred to as different PLLs [10–12]. However, the core of majority of the PLLs is a closed-loop control system with input-output pair of signals being $\theta_p - \widetilde{\theta}_p$. Hence, the linearized model of the PLL can be generally expressed by the transfer function as $\Delta\widetilde{\theta}_p = H_{pll}(s)\Delta\theta_p$. Thus,

$$\Delta\theta_e = \Delta\theta_p - \Delta\widetilde{\theta}_p = [1 - H_{pll}(s)]\Delta\theta_p = H(s)\Delta\theta_p \tag{3}$$

From Fig. 1c, it can be seen that in fact θ_e is the phase of terminal voltage of the kth PMSG expressed in the $d-q$ coordinate. The above equation just transforms the input-output pair of the PLL from $\theta_p - \widetilde{\theta}_p$ to $\theta_p - \theta_e$. Let the state-space realization of $H(s)$ be

$$\begin{aligned} \frac{d}{dt}\boldsymbol{\Delta X_p} &= \boldsymbol{A_p \Delta X_p} + \boldsymbol{b_p}\Delta\theta_p \\ \theta_e &= \boldsymbol{c_p^T \Delta X_p} + d_p\Delta\theta_p \end{aligned} \tag{4}$$

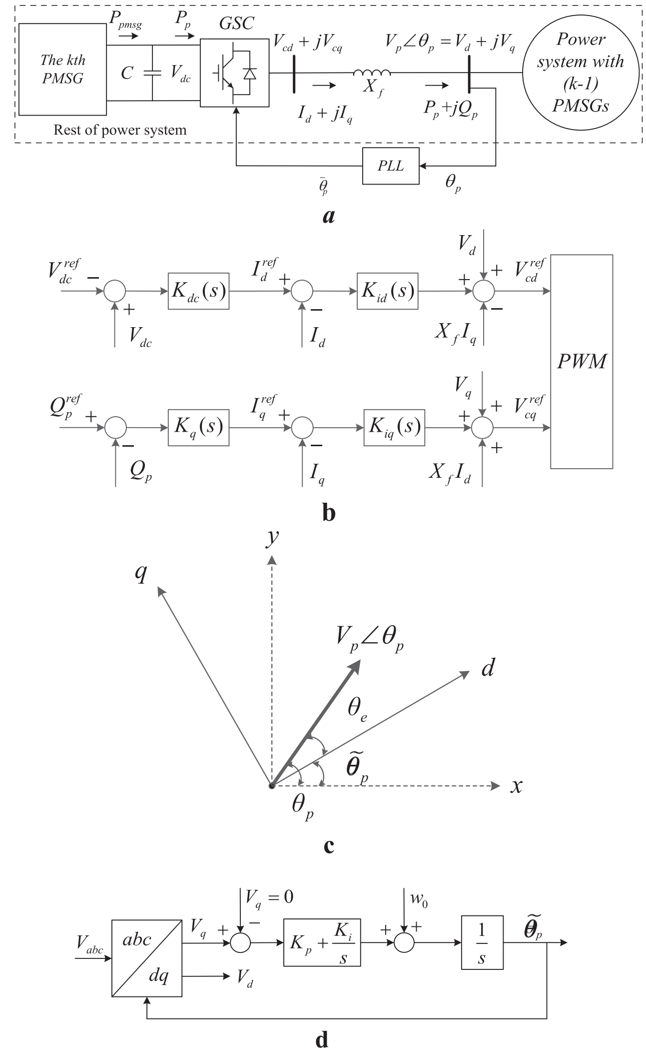

Fig. 1. The power system with the PMSGs. **a.** Configuration of a power system with the PMSGs. **b.** Configuration of vector control system the GSC. **c.** Position of the GSC's coordinate determined by the PLL. **d.** The SRF-PLL.

where $\boldsymbol{\Delta X_p}$ is the vector of all the state variables of the PLL and $H(s) = \boldsymbol{c_p^T}(sI - \boldsymbol{A_p})^{-1}\boldsymbol{b_p} + d_p$.

The state-space model of the rest of power system with the PLL being excluded can be written as

$$\begin{aligned} \frac{d}{dt}\boldsymbol{\Delta X_g} &= \boldsymbol{A_g \Delta X_g} + \boldsymbol{b_g}\Delta\theta_e \\ \Delta\theta_p &= \boldsymbol{c_g^T \Delta X_g} \end{aligned} \tag{5}$$

where $\boldsymbol{\Delta X_g}$ is the vector of all the state variables of the rest of power system, excluding all the state variables of the PLL for the kth PMSG.

From (3) and (5), following state-space model of the closed-loop interconnected system is obtained

$$\frac{d}{dt}\boldsymbol{\Delta X} = \boldsymbol{A\Delta X} \tag{6}$$

where

$$\boldsymbol{\Delta X} = [\boldsymbol{\Delta X_g^T} \quad \boldsymbol{\Delta X_p^T}]^T, \quad \boldsymbol{A} = \begin{bmatrix} \boldsymbol{A_g} + d_p\boldsymbol{b_g c_g^T} & \boldsymbol{b_g c_p^T} \\ \boldsymbol{b_p c_g^T} & \boldsymbol{A_p} \end{bmatrix}.$$

The closed-loop interconnected model is shown by Fig. 2, where $G(s) = \boldsymbol{c_g^T}(s\boldsymbol{I} - \boldsymbol{A_g})^{-1}\boldsymbol{b_g}$.