Calculation of Stable Domain of DFIG-Based Wind Farm in Series Compensated Power Systems

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ABSTRACT Subsynchronous oscillation (SSO) has concerned scholars who work with doubly-fed induction generator (DFIG)-based wind farms which are interfaced with series compensated power systems. The critical factors impacting SSO are compensation level $K_C$, proportional gain of rotor side controller (RSC) current tracking control $K_P$, number of DFIGs, and wind speed. In this paper, we analyze the stable domain of $K_C$ and $K_P$ as it is impacted by variable and uncontrollable wind speeds. Eigenvalues are used to conduct comprehensive stability analyses of the power systems, in which participation factors are employed to identify oscillation modes, and the trajectories of all the oscillation modes versus $K_C$ and $K_P$ are presented to support the identification results, time domain simulation based on Simulink is also applied to verify the conclusions. Monte Carlo simulation is conducted to simulate the variable characteristic of wind speed by sampling the Weibull distribution. The impacts of the number of DFIGs and transmission distance on the stable domain are analyzed, the stable and SSO probabilities are employed in the stable domain under a variable wind speed. The constant stable domain of $K_C$ and $K_P$ is presented, the power system will remain stable under a variable wind speed in this area.

INDEX TERMS Stable domain analyses, subsynchronous oscillation, series compensation, variable wind speed, doubly-fed induction generator.

I. INTRODUCTION

With the rapid proliferation of wind power, series compensation capacitors have been introduced to extend the power transmission capacity and deliver bulk wind power to remote load centers efficiently. However, extensive applications of series compensation capacitors increase the risk of subsynchronous oscillation (SSO) in large power systems. Numerous SSO cases have emerged in recent years in doubly-fed induction generators (DFIGs) interfaced with series compensated power systems [1]–[6]. As the number of SSOs is on the rise, many researchers have conducted several studies to learn more about participation factors and mitigate the impacts on large power systems. In [7]–[10], eigenvalue and participation factor analyses are applied to DFIG-based wind farm interfaced with series compensated power system. SSO is identified as the dominant mode [7], [8], which can make the system unstable. The research results in [7] demonstrated that the rotor side current control scheme has most significant impacts on system stability, and noted that appropriate controller parameters must be chosen in power system operations. The dominant mode is revealed to change with the operating conditions [9]. Hence, the rational selection of parameters for avoiding SSO may cause other oscillation modes.

To analyze the mechanism and factors impacting the SSO, the effects of rotor resistance and generator inertia on system modes are analyzed in [7], [10]. The papers conclude that induction generator effect (IGE) instead of torsional interaction (TI) is the major cause of SSO in DFIG-based wind farm, which is verified by the application of an impedance-based Nyquist stability criterion in [11]. Frequency scan determines the presence of resonant frequencies in [12], and eigenvalue analysis is performed to conclude that SSO is not a result of the TI. Reference [13] explains the SSO mechanism caused by the interaction between DFIG and series compensation.
capacitor based on the actual SSO events that occurred in North China. The paper concludes that the DFIG-associated SSO is a type of IGE with DFIG controller. According to the references above, SSO is an electrical oscillation associated closely with wind speed, number of DFIGs, series compensation level $K_C$, and proportional gain of rotor side controller (RSC) current tracking control $K_{P3}$. To avoid SSO, the compensation level and controller parameters must be set appropriately in power system planning and operation.

The main work of this paper is to analyze and measure the stable domain of DFIG-based wind farm interfaced with series compensated power system considering a variable wind speed. The Weibull distribution [14] is employed in this paper to fit the probability density of wind speed, and Monte Carlo simulation [15] is performed to study the stochastic stability of the power system. During the Monte Carlo simulation, the variable wind speed is determined by random sampling of the Weibull distribution, and eigenvalue analysis is applied to study the comprehensive stability using the sampled wind speed. The constant stable domain of series compensation level $K_C$ and the proportional gain of RSC current control $K_{P3}$ is determined.

The rest of the paper is organized as follows. Section II introduces the model of the studied system, the wind speed model and the DFIG output power model. In Section III, the procedure for solving the stable domain of $K_C$ and $K_{P3}$ with a stochastic wind speed is presented. In Section IV, the stable domain of $K_C$ and $K_{P3}$ with a fixed wind speed is presented, eigenvalue analysis of the studied system is conducted to identify the modes, the eigenvalue trajectories versus $K_C$ and $K_{P3}$ are presented to study the mechanism of oscillation modes, time domain simulation based on Simulink is also applied to support the results. In Section V, the impacts of the number of DFIGs and transmission distance on stable domain are analyzed. The stable domain with a variable wind speed is calculated in Section VI. The stable probability and SSO probability are presented, and a constant stable domain under a variable wind speed is obtained. The stable domain with a fixed wind speed is the RSC current controller decoupling gain. The values of $K_{P1}$ and $K_{P3}$ are presented to study the mechanism of oscillation modes, time domain simulation based on Simulink is also applied to support the results. In Section V, the impacts of the number of DFIGs and transmission distance on stable domain are analyzed. The stable domain with a variable wind speed is calculated in Section VI. The stable probability and SSO probability are presented, and a constant stable domain under a variable wind speed is obtained. The conclusions of this paper are summarized in Section VII.

II. MODELING OF THE STUDIED SYSTEM

A. SYSTEM DESCRIPTION

The power system shown in Fig. 1 is derived from the IEEE first benchmark model [16]. A DFIG-based wind farm represented by an aggregated model [17] is connected to the infinite bus via a 220 kV transmission line $L1$ and a 500 kV series compensated transmission line $L2$. In Fig. 1, $R_L$ and $X_L$ are the resistances and reactance of the transmission line, respectively, $X_T$ and $X_{tg}$ are the reactance of transformer and induction filter, respectively, and $X_C$ is the reactance of capacitor. The main parameters of a single DFIG and transmission system can be found in [13].

As the effect of DFIG controller on SSO cannot be neglected, the control schemes of RSC and GSC with respect to Fig. 1 are shown in Fig. 2. The outer loop controller of RSC regulates the stator active power $P_s$ and reactive power $Q_s$, while the inner loop controller regulates the dq components of rotor current $i_d$ and $i_q$. The GSC maintains a constant DC bus voltage $U_{dc}$ and regulates the dq components of GSC current $i_{gd}$ and $i_{gq}$. The reference value is distinguished by subscript ref. $P_{ref}$ is obtained using the relationship between wind speed and DFIG output power. In this paper, $Q_{ref}$ is set to be zero as the power factor is set at 1.0, the reference values for the currents can be determined by $P_{ref}$ and $Q_{ref}$. $u_{gd}$ and $u_{gq}$ are the dq components of rotor voltage, while $u_{gd}$ and $u_{gq}$ are the dq components of GSC voltages. $H(s) = K_p + K_i/s$ is transfer function of PI controller, where $s$ is the Laplace transform. $K_d$ is the RSC current controller decoupling gain. The values of controller parameters are shown in Table 1.

B. LINEAR MODEL OF THE POWER SYSTEM

Eigenvalue analysis is applied to study the stability of the power system. The 16 state variables shown in Table 2 are chosen to build the power system state equations. The power

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**FIGURE 1.** One-line diagram of the power system.

**FIGURE 2.** Control loops of DFIG controller.

**TABLE 1.** Controller parameters.

| Symbols | Value(p.u.) | Symbols | Value(p.u.) |
|---------|-------------|---------|-------------|
| $K_{P1}$ | 0.5         | $K_{P2}$ | 30          |
| $K_{i1}$ | 25          | $K_{P3}$ | 500         |
| $K_{P3}$ | 0.3         | $K_{P4}$ | 1.2         |
| $K_i$   | 15          | $K_a$   | 20          |
| $K_d$   | 0.025       |         |             |
system state and algebraic equations are denoted as
\[
\Delta \dot{X} = A_{sys} \Delta X + B \Delta Y 
\]
(1)
\[
0 = C \Delta X + D \Delta Y 
\]
(2)
where \(X\) is the state variable vector, \(\dot{X}\) is the derivative of \(X\), \(Y\) is the algebraic vector, \(\Delta\) is deviation operation. \(A\), \(B\), \(C\) and \(D\) are coefficient matrices. According to (1) and (2), we have
\[
\Delta \dot{X} = A_{sys} \Delta X 
\]
(3)
where \(A_{sys}=A-BD^{-1}C\), is the state space matrix of the power system, the system stability is determined from the \(A_{sys}\) eigenvalues. For a given eigenvalue \(\lambda = \alpha \pm j\omega\), \(\alpha > 0\) indicates an unstable system, and \(\alpha < 0\) represents a stable system. In addition, strong unstable oscillation is identified by large positive values of \(\alpha\). A normalized participation factor is used to measure the effect of each variable on each mode. The effect of the \(i\)th state variable on the \(j\)th eigenvalue \(p_{ji}\) [8], [10] is calculated as
\[
p_{ji} = \frac{|V_{ij}| |W_{ji}|}{\sum_{j=1}^{n} |V_{ij}| |W_{ji}|} 
\]
(4)
where \(V_{ij}\) is the element in the \(i\)th row and the \(j\)th column of left eigenvector matrix, \(W_{ji}\) is the element in the \(j\)th row and the \(i\)th column of right eigenvector matrix.

Participation factor is applied to screen the SSOs and super-synchronous oscillations in this paper. The SSO and super-synchronous oscillations have a comparatively closer relationship with \(u_{cd}\) and \(u_{cq}\) [9]. When the two modes most relevant to \(u_{cd}\) and \(u_{cq}\) are determined, the mode with a frequency lower than 50 Hz is considered to be SSO mode, while the mode with a frequency higher than 50 Hz is considered to be super-synchronous oscillation.

### C. WIND SPEED MODEL

The Weibull distribution [14] is employed to fit the probability distribution of wind speed. The probability density and probability distribution function of Weibull distribution with two parameters are shown in (5) and (6):
\[
f (V_w) = \left(\frac{k}{c}\right) \left(\frac{V_w}{c}\right)^{k-1} \exp \left[\left(-\frac{V_w}{c}\right)^k\right] 
\]
(5)
\[
F (V_w) = P(v \leq V_w) = \int_{0}^{V_w} f (v) dv = 1 - \exp \left[-\left(\frac{V_w}{c}\right)^k\right] 
\]
(6)

**TABLE 2. State variables of the studied system.**

| Symbols | Meaning | Symbols | Meaning |
|---------|---------|---------|---------|
| \(i_{d1}l_{eq}\) | Stator current in dq axis | \(x_{11}\) | State variables of RSC |
| \(i_{d2}l_{eq}\) | Rotor current in dq axis | \(x_{21}\) | State variables of GSC |
| \(U_{dc}\) | Voltage of DC link capacitor | \(u_{dc}\) | Series capacitor voltage in dq axis |
| \(i_{d3}l_{eq}\) | Transmission line current in dq axis | \(u_{eq}\) | |

**FIGURE 3. Probability density and distribution of wind speed: (a) probability density curve; (b) probability distribution curve.**

**FIGURE 4. Rotor speed and output power curves of the DFIG.**

where \(k\) and \(c\) are the shape and scale parameters of Weibull distribution, respectively, which are calculated by the wind speed mean \(\mu\) and standard deviation \(\delta\) shown in (7) and (8).
\[
k = \left(\frac{\delta}{\mu}\right)^{-1.086} 
\]
(7)
\[
c = \mu / \Gamma \left(1 + 1/k\right) 
\]
(8)

The mean and the variance of wind speeds used in this paper are \(\mu = 6.42812\) and \(\delta^2 = 9.30032\) [18]. Using (7) and (8), we conclude that \(k = 2.2474\) and \(c = 7.2575\), and the wind speed for the Monte Carlo simulation is determined by random sampling of Weibull distribution. The probability density and distribution curves of wind speed are shown in Fig. 3, where probability density reaches its maximum of 12.82% at a wind speed \(V_w = 5.59\text{m/s}\).

**D. ROTOR SPEED AND OUTPUT POWER OF THE DFIG**

The relationships among \(V_w\), \(\omega_r\) and \(P_w\) are derived in [18]. The DFIG operation region is divided into four sections, we linearize sections A-B, B-C and C-D sections as shown in Fig. 4 to relate the rotor speed to the wind speed (Fig. 4(a)) and the DFIG output power to rotor speed (Fig. 4(b)). The corresponding relationships are presented in (9) and (10).

The value of \(V_w\) in the DFIG operation region is between 3 m/s and 25 m/s, as shown by the two red lines in Fig. 3, with a probability that is nearly 87%. \(\omega_r\) and \(P_w\) are fixed after \(V_w\) is sampled and are applied in the following analyses.

\[
\omega_r = \begin{cases} 
0 & V_w < 3 \text{ m/s}, V_w > 25 \text{ m/s} \\
0.667 & 3 \text{ m/s} \leq V_w < 5 \text{ m/s} \\
0.1777V_w - 0.2215 & 5 \text{ m/s} \leq V_w < 8 \text{ m/s} \\
1.200 & 8 \text{ m/s} \leq V_w \leq 25 \text{ m/s} 
\end{cases} 
\]
(9)
FIGURE 5. Flow chart of stable domain calculation.

III. CALCULATION OF THE STABLE DOMAIN UNDER A VARIABLE WIND SPEED

The wind speed $V_w$, numbers of DFIGs $N$, compensation level $K_C$ and proportional gain $K_P$ greatly impact the SSO mode. Among these variables, $V_w$ is uncontrollable, and the stable domain of $K_C$ and $K_P$ is configured when the variable wind speed. The corresponding flow chart is shown in Fig. 5 and is explained in the following:

1) Provide the power system parameters including the wind speed data, ranges of $K_C$ and $K_P$, and numbers of Monte Carlo simulations $N_M$. In this paper, the range of $K_C$ is 0.05-0.5, that of $K_P$ is 0.01-0.5, and $N_M$ is 5000.

2) Conduct $K_C$ and $K_P$ within the given range.

3) Conduct the Monte Carlo simulation. Determine $V_w$ by random sampling; calculate the corresponding $\omega_t$ and $P_w$ by (9) and (10); and calculate the eigenvalues of the power system. If the system is unstable, use participation factors to determine whether it is a result of SSO.

4) When Monte Carlo simulations are completed, calculate the stable probability $P_{stable}$, SSO probability $P_{SSO}$, the probability of other unstable modes $P_{NSSO}$ as follows:

$$P_{stable} = N_{stable} / N_W$$

$$P_{SSO} = N_{SSO} / N_W$$

$$P_{NSSO} = N_{NSSO} / N_W$$

where $N_W$ is the number of times that the variable wind speed lies between 3 m/s to 25 m/s during the Monte Carlo simulations. $N_{stable}$, $N_{SSO}$ and $N_{NSSO}$ are the numbers of system stable, unstable SSO mode and other unstable modes, respectively.

5) If $K_C$ and $K_P$ are enumerated within their respective ranges, terminate the iteration, or return to step 2.

IV. STABLE DOMAIN OF DFIG-BASED WIND FARM INTERFACED WITH SERIES COMPENSATED SYSTEM

A. STABLE DOMAIN WITH A FIXED WIND SPEED AND DFIG NUMBER

The stable ranges of $K_C$ and $K_P$ are analyzed in this part. We increase the value of $K_C$ from 0.05 to 0.5, and that of $K_P$ from 0.01 to 0.5. The wind speed $V_w$ is set to be 8 m/s, numbers of DFIGs $N$ is 600, and the stable domain of $K_C$ and $K_P$ is shown in Fig. 6. Here, the stable domain is located in the green part, while the two separate unstable domains are shown in red and blue. As illustrated, when $K_C$ is 0.3 and $K_P$ is 0.05 (point A), the unstable oscillation mode is $5.83 \pm j48.27$ (7.68 Hz). To determine the characteristic of the oscillation in blue area, eigenvalue analysis is conducted at point A, the oscillation modes and the corresponding participation factors are shown in Table 3, and the negative real eigenvalues are neglected. Modes 2 and 3 are primarily associated with the stator, rotor, and line currents and the compensation capacitor voltage, with frequencies of 55.69 Hz and 44.12 Hz, respectively. Accordingly, modes 2 and 3 are
TABLE 3. Eigenvalues with $K_C = 0.3$ and $K_{P3} = 0.05$.

| Mode | 1       | 2       | 3       | 4       | 5       | 6       | 7       |
|------|---------|---------|---------|---------|---------|---------|---------|
| eigenvalue | -283.85±j971.98 | -10.51±j349.92 | -7.54±j277.23 | -20.11±j110.23 | 5.83±j48.27 | -13.93±j2.09 | -17.03±j0.57 |
| frequency | 154.69Hz | 35.69Hz | 44.12Hz | 17.54Hz | 7.68Hz | 0.33Hz | 0.09Hz |

concluded to be super-synchronous and SSO modes. Mode 5 has a strong correlation with the state variables of RSC, and it is referred to as the RSC mode in this paper. The blue part is unstable owing to the small value of $K_{P3}$, because when $K_{P3}$ is small the function of RSC will be weakened, which degrades the system stability.

For point B, the unstable oscillation mode is $1.45±j267.29$ (42.54 Hz) and is confirmed to be the SSO mode by the participation factors. For point C, the SSO mode is $-0.77±j272.42$ (43.36 Hz) and stable. Therefore, the unstable red and blue domain can be confirmed to be the SSO domain and RSC oscillation domain respectively. It should be noticed that the oscillation frequencies at the specified points (A, B and C) in Fig. 6 are in dq frame, converting oscillation frequencies to stationary $\alpha\beta$ frame as $f_{\alpha\beta}=f_{dq}$ [19], [20], the oscillation frequencies at A, B and C are 42.32 Hz, 7.46 Hz and 6.64 Hz respectively.

B. EIGENVALUE TRAJECTORIES VERSUS $K_C$ AND $K_{P3}$

To verify the correctness of the stable domain shown in Fig. 6, the eigenvalue trajectories versus $K_C$ and $K_{P3}$ are presented in this part to study the impacts of $K_C$ and $K_{P3}$ on oscillations modes. In this part, modes 1 and 4 have comparatively large negative real parts, and they remain stable with varying $K_C$ and $K_{P3}$ in this paper; hence, they are not discussed further.

The impacts of the variation in $K_C$ from 0.05 to 0.5 on the system models are presented in Fig. 7 when $V_w$ is 8 m/s, $N$ is 600, and $K_{P3}$ is 0.45 (Direction 1 shown in Fig. 6). With increasing $K_C$, super-synchronous mode 2 is shifted to the left plane and remains stable, and SSO mode 3 is shifted to the right plane and experiences a decrease in its corresponding frequency. When $K_C$ is set to 0.4, the SSO mode is $0.82±j269.79$ with a frequency of 42.94 Hz, and the system is unstable. The other modes change slightly and remain stable as we increase $K_C$. Clearly, $K_C$ is associated only with the super-synchronous and SSO modes.

The impacts of the variation in $K_{P3}$ from 0.01 to 0.5 on the system models are presented in Fig. 8 when $V_w$ is 8 m/s, $N$ is 600, and $K_C$ is 0.3 (direction shown in Fig. 6). With increasing $K_{P3}$, super-synchronous mode 2 is shifted to the left plane and remains stable, and SSO mode 3 is shifted to the right plane. When $K_{P3}$ is set to 0.5, the SSO mode is
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FIGURE 9. Time domain simulation for RSC oscillation.

0.24±j275.46 with a frequency of 43.84 Hz, and the system is unstable. RSC mode 5 is shifted to the left plane with increasing $K_{P3}$, and RSC mode 5 is shown to be unstable at point A. Hence, $K_{P3}$ is associated with the super-synchronous, SSO and RSC modes, a decrease in $K_{P3}$ will increase the severity of the RSC oscillation.

C. VERIFICATION BY TIME DOMAIN SIMULATION

Time domain simulation based on Simulink is conducted at the specified points A, B and C in Fig. 6. For point A, the compensation capacitor is added to the 500 kV transmission line at 2 s, and the initial value of $K_{P3}$ is 0.3, we set $K_{P3} = 0.05$ at 3 s, and the oscillation occurs. Fast Fourier Transformation (FFT) analysis is applied to the oscillation current, the result of which is shown in Fig. 9. The main current component is 42.86 Hz. When we reset $K_{P3} = 0.3$ at 10 s, the oscillation is attenuated; thus, the unstable oscillation is the result of the small value of $K_{P3}$. For point B, the compensation capacitor is added to the transmission line at 2 s, SSO occurs as shown in Fig. 10(a), and the FFT analysis result is shown in Fig. 10(b); the main current component is 7.45 Hz. For point C, SSO occurs, although currents will be attenuated, as shown in Fig. 11; the main current component is 6.67 Hz. The oscillation frequencies obtained by time domain simulation in this section are nearly the same as those obtained in eigenvalue analysis. From the above verifications, the other unstable modes except the SSO can be confirmed to be the RSC mode in this paper.

V. STABLE DOMAIN ANALYSIS WITH DFIG NUMBERS AND TRANSMISSION DISTANCES

A. IMPACT OF DFIG NUMBER ON THE STABLE DOMAIN

The number of DFIGs corresponds to the maximum power transmitted, and the impact of the number of DFIGs on the stable domain is analyzed in this part. The value of $V_w$ is fixed at 8 m/s, and $N$ is increased from 200 to 1000. The stable domain surfaces for the power system are shown in Fig. 12. Here, when $K_C$ and $K_{P3}$ lie on the red surface, the SSO mode is unstable. When $K_C$ and $K_{P3}$ lie below the blue surface, the RSC mode becomes unstable. The stable domain lies between the blue and red surfaces.

For $N$ fixed at 400, 500, 800 and 1000, and the cross sections of Fig. 12 are as depicted in Fig. 13. Here, the blue unstable area is decreased, and the red unstable area is increased. In other words, with the increase in $N$, the SSO risk increases and the risk of an unstable RSC mode decreases, which is consistent with the conclusion that an increase in $N$ in certain ranges will have a negative impact on the SSO mode.
To obtain the maximum stable domain of $K_C$ and $K_{P3}$, we calculate the percentage of the red, blue, and green areas shown in Fig. 14, which shows that as we increase $N$, the percentage of unstable SSO area will increase, and the percentage of unstable RSC area will decrease. The stable domain percentage will reach its maximum value of 0.81 when the $N$ is approximately 500.

**B. IMPACT OF THE TRANSMISSION DISTANCE ON THE STABLE DOMAIN**

The impact of the transmission distance on the stable domain is studied in this part. Transmission distance $T_{L2}$ is extended from 0.5 to 3 times its base value as we increase the impedance of transmission line 2. The stable domain surfaces for the power system are shown in Fig. 15, and the cross section of Fig. 15 is shown in Fig. 16 for $V_w$ at 8 m/s and $N$ at 600. Here, the stable domain decreases with increasing the transmission distance, and the unstable domain for RSC and SSO modes increase, consistent with the actual situation that SSO occurs more easily over long distance lines with a series compensated system [13].

**VI. STABLE DOMAIN UNDER A VARIABLE WIND SPEED**

We study the stable ranges of $K_{P3}$ and $K_C$ under a variable wind speed in this section. The procedure presented in Section III is conducted, the ranges of $K_C$ and $K_{P3}$ are set at 0.05-0.5 and 0.01-0.5, respectively, and $N$ is 600. Fig. 17 shows $P_{stable}$ under a variable wind speed; the stable domain is impacted by SSO on the left part and by RSC oscillation on the right part. As we increase $K_C$ and $K_{P3}$,
**FIGURE 17.** $P_{\text{stable}}$ with a variable wind speed.

$P_{\text{stable}}$ decreases on the left part of Fig. 17, the reason is that both $K_C$ and $K_{P3}$ have great impacts on SSO. $P_{\text{stable}}$ is related only to $K_{P3}$ on the right part of Fig. 17, as $K_C$ has slight impact on the RSC oscillation.

The SSO probability $P_{\text{SSO}}$ related to the left part of Fig. 17 is presented in Fig. 18. Fig. 17 and 18 show that as we increase $K_C$ and $K_{P3}$, the probability of SSO increases. The probability of the other unstable modes which is confirmed to be RSC oscillation is shown in Fig. 19 as $P_{\text{NSSO}}$; Fig. 19 corresponds to the right part of Fig. 17. As shown, $P_{\text{NSSO}}$ will decrease with increasing $K_{P3}$.

The constant stable domain, obtained by the roof of Fig. 17, is shown in Fig. 20. The power system will always be stable in this area under a variable wind speed, as $P_{\text{stable}}$ is 1 here.

Although wind speed has a large impact on the system stability, it cannot make the system unstable when the system is in the constant stable domain.

**VII. CONCLUSION**

In this paper, under a variable wind speed, the stable domain of $K_C$ and $K_{P3}$ for DFIG-based wind farm interfaced with series compensated power system is studied. Eigenvalue analysis is applied to the studied system, and the obtained oscillation modes are identified by the participation factors. The eigenvalue trajectories of the oscillation modes and time domain simulations based on Simulink are presented to verify the identification results.

We find an unstable mode caused by the RSC when $K_{P3}$ is small enough; hence, in the setting procedure of $K_{P3}$ to avoid SSO, the unstable RSC mode should be considered carefully. The stable domain of $K_C$ and $K_{P3}$ is calculated relative to the RSC and SSO modes. The stable domain increases and then decreases as the number of DFIGs increases, while it decreases with increasing transmission distance.

Finally, the stable probability, SSO probability and other unstable probability on the variable domain of $K_C$ and $K_{P3}$ under a variable wind speed are discussed. An increase in $K_C$ and $K_{P3}$ is found to increase the occurrence of SSO, and a decrease in $K_{P3}$ aggravates the unstable oscillation caused by the RSC mode. A constant stable domain under a variable wind speed is presented, where the power system will always be stable under various wind speeds.

This paper studies the comprehensive stability of the power system after we set $K_C$ and $K_{P3}$. Optimization strategies for setting $K_C$ and $K_{P3}$ such that SSO can be mitigated will be presented in our future work.

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