Research on sub/super-synchronous oscillation suppression method for direct-drive wind turbine based on energy compensation

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Abstract
A method to suppress sub/super-synchronous oscillation of direct-drive wind turbines based on energy compensation is proposed. First, the transient energy model of direct-drive wind turbine is built, and the negative damping energy terms that lead the oscillation of direct-drive wind turbine are extracted. On this basis, the expressions of voltage compensation terms corresponding to negative damping energy terms are derived by backward deduction, thus supplementary energy branches are constructed, and their impact on fundamental frequency characteristics of wind turbine is analyzed. And then, with the compensation energy of supplementary branches reaching the maximum and the increment of fundamental-frequency voltage being the minimum as the objective, and with the frequency-domain characteristic and fundamental-frequency voltage characteristic of control links being satisfied as constraints, a scheme to optimize the compensation coefficients of multiple branches is established. Finally, the model of direct-drive wind turbine is built in RT-LAB for hardware-in-the-loop tests. Simulation results verify that, the method can realize fast frequency-dependent suppression of sub/super-synchronous oscillation in different frequency bands concerning different grid strengths.

1 | INTRODUCTION

As the percentage of permanent magnet synchronous generators (PMSG) in the installed capacity of local areas rapidly increases, sub/super-synchronous oscillation caused by the integration of PMSG to weak power grid via inverter occurs ever more frequently [1–4], greatly intimidating the safe and stable operation of power grid. Currently, due to lack of effective control measures to suppress sub/super-synchronous oscillation of wind turbines, passive measures such as generator tripping are often taken, which sacrifices a large amount of wind power output and causes huge economic loss. Therefore, it is urgent to study active control method to suppress sub/super-synchronous oscillation of direct-drive wind turbine.

In recent years, scholars worldwide have conducted extensive research on measures to suppress sub/super-synchronous oscillation, and there are mainly three methods used—adjusting controller structure, adding damping device and optimizing controller parameters. The method of adjusting controller structure [5–9] is based on the existing inverter control links, and the dynamic characteristics of wind turbines are changed by improving the control link structure of the wind turbine inner loop controller, DC voltage outer loop controller, and PLL controller. This method can achieve online oscillation suppression and has a good suppression effect for different types of oscillations. However, this method needs to modify the control system of the existing equipment, and the implementation process is more complicated. The method of adding damping device [10–14] is to add an independent damping device to the wind power grid-connected system, and design the damping control branch based on the system's observable/controllable comprehensive geometric indicators to realize the online stable oscillation suppression.
control of the wind power system. This method has already achieved a certain degree of engineering application, but it needs to design and optimize damping parameters according to the actual grid characteristics. When the system oscillation frequency drifts or the grid operation conditions change significantly, it is difficult to guarantee the suppression effect of the damping device. The method of optimizing controller parameters [15–19] is to maximize the damping ratio of the interconnected system by coordinating and optimizing the control parameters of the wind turbine generator-side controller (MSC) and the grid-side controller (GSC), thereby changing the resonance point of the oscillation of the wind power system and the grid interaction. This method can fundamentally reduce the risk of system instability. At present, it is only suitable for offline stability analysis and research, and cannot realize online active suppression of oscillation.

The above methods are mostly concerning single oscillation frequency and do not consider the suppression effect at other oscillation frequencies. Besides, the impact of variation of controller parameters on fundamental frequency characteristic and dynamic response characteristic of wind turbine is neglected. Compared with the existing sub/super-synchronous oscillation suppression measures, the main contributions of the method proposed in this paper are as follows. (1) It does not affect the dynamic characteristics of wind turbine during LVRT and can be effectively compatible with fundamental-frequency response capability of wind turbine. (2) It can suppress sub/super-synchronous oscillation in power grid with different strengths within 0.2 s and has a good suppression effect. (3) It can adapt to multi-band sub/super-synchronous oscillation scenarios, and effectively suppress sub/super-synchronous oscillation in frequency bands of 5–40 Hz and 60–95 Hz.

The method to suppress sub/super-synchronous oscillation of direct-drive wind turbine based on energy compensation is put forward in this paper. First, the transient energy model of direct-drive wind turbine with grid-side converter control links is built, and the transient energy characteristics of different control links are analysed, thus the negative damping energy terms that lead the oscillation of wind turbine are determined. On this basis, with the negative damping energy terms as compensation energy terms, the corresponding voltage compensation terms are derived by backward deduction, and the supplementary energy branches are constructed. Further, the expressions of compensation energy and increment of fundamental-frequency voltage brought by each supplementary branch are derived. And then, define the ratio of compensation energy to increment of fundamental-frequency voltage as the objective of optimization, and with the frequency-domain characteristic and fundamental-frequency voltage characteristic of control links being satisfied as the constraints, a scheme to optimize the compensation coefficients of multiple branches is established. The pattern search method is used to determine the optimal compensation coefficients of supplementary branches. Finally, the model of system is built in RT-LAB for simulation tests, and simulation results verify the correctness and effectiveness of the proposed method.

### 2 TRANSIENT ENERGY MODEL OF DIRECT-DRIVE WIND TURBINE

#### 2.1 Transient energy model with grid-side converter control links

According to transient energy construction method based on node voltage equation [20], the expression of transient energy can be obtained using the terminal and node information of direct-drive wind turbine:

$$W_{\text{PMSG}} = \int \text{Im}(-I^*_G dU_G)$$  \hspace{1cm} (1)

where $U_G$ is the bus voltage vector of direct-drive wind turbine. $I_G$ is the node injection current of direct-drive wind turbine. Im means extracting the imaginary part of a complex.

Transform Equation (1) to $dq$ coordinate system of direct-drive wind turbine control system, so that the transient energy of direct-drive wind turbine can be expressed as:

$$W_{\text{PMSG}} = \int (i_d^* u_d + i_q u_q) d\Delta \delta_{\text{PLL}} + \int i_{dq} d\theta_{\text{PLL}} - \int i_{dq}^* d\delta_{\text{PLL}}$$  \hspace{1cm} (2)

where $i_d$, $i_q$, $u_d$ and $u_q$ are respectively $d$-axis and $q$-axis components of current and voltage at the terminal of direct-drive wind turbine. $\Delta \delta_{\text{PLL}}$ represents the dynamic angle of PLL generated during sub/super-synchronous oscillation.

Since the machine end portion of direct-drive wind turbine is electrically decoupled from the grid, and the time scale of wind speed variation is much larger than the time scale of converter control, when studying the transient energy at the machine end portion of direct-drive wind turbine during sub/super-synchronous oscillation, the impact of grid-side converter is emphasized. Besides, consider that in grid-side converter cascade control, voltage outer loop is dynamically decoupled from current inner loop, and the band width of voltage outer loop is smaller than the band width of current inner loop, thus the dynamic response of voltage outer loop is slow in sub/super-synchronous frequency band. Therefore, this paper is focused on the impact of current inner loop and PLL on the transient energy of direct-drive wind turbine grid-side converter.

The control system structure of the direct drive wind turbine as shown in Figure 1. In $dq$ coordinate system of direct-drive wind turbine control system, the control equations of grid-side converter are:

$$
\begin{align*}
  i_d &= \left( k_{p2} + \frac{k_{i2}}{s} \right) (i_d^* - i_d) - w_2 L_2 i_q + \epsilon_d \\
  i_q &= \left( k_{p2} + \frac{k_{i2}}{s} \right) (i_q^* - i_q) + w_2 L_2 i_d + \epsilon_q
\end{align*}
$$  \hspace{1cm} (3)

where $k_{p2}$ and $k_{i2}$ are proportion and integration coefficients of current inner loop. $i_d^*$ and $i_q^*$ are $d$-axis and $q$-axis reference
values of current. \( w_s \) is the angular frequency of power grid. \( L_2 \)
the reactance of outlet line. \( e_d \) and \( e_q \) are \( d \)-axis and \( q \)-axis
components of grid voltage in \( dq \) coordinate system.

Combine Equations (2) and (3), and transform them to
\( dq \) coordinate system of wind farm, so that the transient
energy of different control links in grid-side converter can be
obtained:

\[
W_p = k_{p2} \int \left( i_d^2 + i_q^2 \right) d\theta_{p ll} dt
- k_{p2} \int \left( i_d^2 + i_q^2 \right) d\theta_{p ll} dt
= W_{p1} + W_{p2} + W_{p3} \tag{4}
\]

\[
W_q = k_{q2} \int \left( i_d^2 + i_q^2 \right) d\theta_{p ll} dt
- k_{q2} \int \left( i_d^2 + i_q^2 \right) d\theta_{p ll} dt
= W_{q1} + W_{q2} + W_{q3} \tag{5}
\]

\[
W_L = k_{L2} \int \left( i_d^2 + i_q^2 \right) d\theta_{p ll} dt
- k_{L2} \int \left( i_d^2 + i_q^2 \right) d\theta_{p ll} dt
= W_{L1} + W_{L2} + W_{L3} \tag{6}
\]

where \( W_p \) is the transient energy led by current-loop proportion
link. \( W_q \) is the transient energy led by current-loop integration
link. \( W_L \) is the transient energy caused by the coupling between
\( d \)-axis and \( q \)-axis. \( i_d \) and \( i_q \) are \( d \)-axis and \( q \)-axis measured cur-
rents at the terminal of grid-side converter.

## 2.2 Transient energy characteristics of different control links in grid-side converter

According to Lyapunov's second stability theorem, for a free
dynamic system, if the variation rate of system overall energy
\( W' (W > 0) \) with time \( W'(x) \) is constantly negative, system over-
all energy will keep decreasing until it reaches the minimum
value, when the system will be stable in an equilibrium state.
Therefore, by analysing the accumulation and consumption
trends of the overall energy of direct-drive wind turbine \( W_{PMG} \)
the stability of system can be identified. If \( \Delta W_{PMG} \) keeps
decreasing, i.e. if \( \Delta W_{PMG} \) is constantly negative, direct-drive
wind turbine will absorb transient energy during sub/super-
synchronous oscillation and exhibit positive damping character-
istic. In this case, system oscillation will gradually converge and
the system will go stable. Otherwise, if \( \Delta W_{PMG} \) is constantly
positive, direct-drive wind turbine will continuously generate
transient energy during oscillation and exhibit negative damping
characteristic, causing the system to become unstable.

In the transient energy model of direct-drive wind turbine,
the damping characteristic of transient energy of different
control links is the key factor that determines whether the
oscillation of direct-drive wind turbine converges or not. Thus,
screening out the control links that generate negative energy
is key to suppressing oscillation and guaranteeing the
stable operation of system. The transient energy characteristics
of different control links in grid-side converter are analysed as
follows.

During sub/super-synchronous oscillation, sub/super-
synchronous frequency \( (w_-/w_+) \) current components can be
expressed as:

\[
\begin{align*}
\Delta i_d &= I_d \dot{\lambda} \cos (w_s t + \varphi_d) \\
\Delta i_q &= I_q \dot{\lambda} \sin (w_s t + \varphi_q)
\end{align*}
\tag{7}
\]

where \( I_d, I_q, \varphi_d \) and \( \varphi_q \) are the amplitudes and initial phase angles
of \( d \)-axis and \( q \)-axis components of oscillation current. \( \dot{\lambda} \) is the
oscillation attenuation coefficient. \( w_s \) is the frequency of oscillation
current, \( w_s = w_1 - w_2 = w_s - w_- \).

Due to sub/super-synchronous frequency voltage compo-
nents, PLL dynamic angle will be generated, which can be
expressed as:

\[
\Delta \theta_{p ll} = -k_{q2} \int \Delta u_{q1} dt - k_{q2} \int \Delta u_{q2} dt
\tag{8}
\]

where \( k_{q2} \) and \( k_{q2} \) are proportion and integration coefficients
of PLL. \( \theta_0 \) is the phase angle caused by outlet line reactance.
\( \Delta \dot{\theta}_{q1} \) and \( \beta \) are the oscillation amplitude and initial phase angle
of PLL dynamic angle.

Apply Equations (7) and (8) to Equations (4), (5) and (6), so
that the variation rate of transient energy of each control link in
grid-side converter can be obtained:

\[
\Delta \dot{W}_{p1} = -k_{p2} W_p \dot{I}_d I_q e^{2\lambda t} \cos (\varphi_d - \varphi_q) \tag{9}
\]
\[ \Delta W_{P2} = \frac{1}{2} k_p \frac{I_{d}}{I_{q}} i_{d} \Delta \theta_1 e^{2 \lambda t} \cos(\varphi_d - \beta) \] (10)

\[ \Delta W_{P3} = -k_p \frac{I_{q}}{I_{d}} i_{q} \Delta \theta_1 e^{2 \lambda t} \cos(\varphi_d - \beta) \] (11)

\[ \Delta W_{I1} = \frac{1}{2} k_i \frac{I_{d}}{I_{q}} i_{d} \Delta \theta_1 e^{2 \lambda t} \cos(\varphi_d - \beta) \int i_{d}^2 dt \] (12)

\[ \Delta W_{I2} = \frac{1}{2} k_i \frac{I_{q}}{I_{d}} i_{q} \Delta \theta_1 e^{2 \lambda t} \cos(\varphi_d - \beta) \] (13)

\[ \Delta W_{I3} = \frac{1}{2} k_i \frac{I_{d}}{I_{q}} i_{d} \Delta \theta_1 e^{2 \lambda t} \cos(\varphi_d - \beta) \] (14)

\[ \Delta W_{I4} = -\frac{1}{2} k_i \frac{I_{d}}{I_{q}} \] (15)

\[ \Delta W_{I1,1} = w_2 \Delta W_{Id} \Delta \theta_1 \Delta \theta_1 e^{2 \lambda t} \cos(\varphi_d - \beta) \] (16)

\[ \Delta W_{I2,2} = \frac{1}{2} \lambda (I_{d}^2 + I_{q}^2) e^{2 \lambda t} \approx 0 \] (17)

where \( i_{d0} \) and \( i_{q0} \) are \( d \)-axis and \( q \)-axis components of steady-state current at the terminal of grid-side converter.

The variation rates of transient energy of different control links \( \Delta W_{PMSG} \) characterize the accumulation and consumption trends of the overall energy of direct-drive wind turbine, and the sign of \( \Delta W_{PMSG} \) (being positive or negative) directly determines the stability of system. It can be seen from Equations (9)–(16) that, the sign of \( \Delta W_{P1} \) is determined by \( \cos(\varphi_d - \varphi_q) \), and the signs of Equations (10)–(16) are determined by \( \cos(\varphi_d - \beta) \). Angular differences \( \varphi_d - \varphi_q \) and \( \varphi_d - \beta \) have to do with the initial phase angles of sub/super-synchronous frequency current and voltage and PLL dynamic angle, which are analysed in detail below.

a. Initial phase angle of sub/super-synchronous frequency current and voltage

The initial phase angle of sub/super-synchronous frequency current and voltage can be obtained by extending sub/super-synchronous frequency components:

\[ \cos(\varphi_d - \varphi_q) = \frac{1}{I_{d}} \left( I_{d} + I_{q}^2 \right) \] (18)

\[ \cos(\varphi_d - \beta) = \frac{1}{I_{d}} \left[ I_{d} U_{+} \cos(\alpha_+ - \varepsilon_+) + L \ U_{+} \cos(\alpha_- - \varepsilon_-) \right] \] (19)

\[ \sin(\varphi_d - \varphi_q) = \frac{1}{I_{q}} \left[ I_{q} U_{+} \sin(\alpha_+ - \varepsilon_+) + L \ U_{+} \sin(\alpha_- - \varepsilon_-) \right] \] (20)

where \( L, I_{+}, \alpha_- \) and \( \alpha_+ \) are the amplitudes and initial phase angles of sub/super-synchronous frequency phase-A current, \( U_-, U_+, \varepsilon_- \) and \( \varepsilon_+ \) are the amplitudes and initial phase angles of sub/super-synchronous frequency phase-A voltage. \( U_q \) and \( \phi_q \) are the amplitude and initial phase angle of the \( q \)-axis oscillation voltage.

When oscillation occurs in direct-drive wind turbine, super-synchronous frequency components are usually larger than sub-synchronous frequency components, thus Equation (18)\( > 0 \), i.e. \( \cos(\varphi_d - \varphi_q) > 0 \). Meanwhile, \( \varphi_d - \beta \) in Equations (19) and (20) can be approximated to the difference between initial phase angles of sub/super-synchronous frequency current and super-synchronous frequency voltage. Since the reference value of reactive power of outer-loop control is set to be 0, and the reference value of active power is rated value, the output power is mainly active power. Thus, the difference between initial phase angles of super-synchronous frequency current and super-synchronous frequency voltage is approximately 0, i.e. \( \varphi_d - \beta \approx 0 \). Therefore, the value of \( \cos(\varphi_d - \beta) \) in Equations (19) is positive and much larger than \( \sin(\varphi_d - \beta) \) in Equation (20).

b. Initial phase angle of PLL dynamic angle

Detailed derivation of Equation (8) reveals that, the initial phase angle of PLL dynamic angle \( \beta \) has to do with the initial phase angle of \( q \)-axis sub/super-synchronous frequency voltage \( \phi_q \), i.e. \( \beta = \phi_q + \phi \), where \( \phi \) satisfies the following equations:

\[ \sin \phi = \frac{k_{d} \left( w_{d}^{2} + \lambda^{2} \right)}{\sqrt{k_{d}^{2} \left( w_{d}^{2} + \lambda^{2} \right)^{2} + k_{q}^{2} w_{q}^{2}}} \] (21)

\[ \cos \phi = \frac{k_{q} w_{q}}{\sqrt{k_{d}^{2} \left( w_{d}^{2} + \lambda^{2} \right)^{2} + k_{q}^{2} w_{q}^{2}}} \]

where \( \cos \phi \) and \( \sin \phi \) are both positive, and \( \sin \phi \) is slightly larger than \( \cos \phi \).

Apply \( \beta = \phi_q + \phi \) to \( \cos(\varphi_d - \beta) \), so that

\[ \cos(\varphi_d - \beta) = \cos(\varphi_d - \phi_q) \cos \phi + \sin(\varphi_d - \phi_q) \sin \phi \] (22)

Consider that the value of \( \cos(\varphi_d - \phi_q) \) in Equation (19) is positive and much larger than \( \sin(\varphi_d - \phi_q) \). In Equation (22) is constantly positive, i.e. \( \cos(\varphi_d - \beta) > 0 \).

Therefore, Equations (9), (11), (13) and (15) are constantly negative, Equation (17) is approximately 0, \( \Delta W_{P1}, \Delta W_{P3}, \Delta W_{12}, \Delta W_{14} \) and \( \Delta W_{12} \) have positive damping effect on system oscillation and make for the converging of oscillation. Equations (10), (12), (14) and (16) are constantly positive, i.e. \( \Delta W_{P2}, \Delta W_{11}, \Delta W_{13} \) and \( \Delta W_{11} \) are positive, thus they have negative damping effect on system oscillation and make against the stability of system. The amplitude of \( \Delta W_{13} \) is much smaller than the amplitudes of the other three terms, thus \( \Delta W_{13} \) can be neglected. The energy flow diagram of the direct-drive wind turbines is shown in Figure 2. The oscillation component is introduced through the PLL and the current loop. The \( d \)-axis current loop control
3.1  Design of supplementary energy branches

Backward deduction method is used to construct supplementary energy branches. First, search for transient energy terms in Equation (2), which are similar to negative damping energy terms. And then, eliminate the current terms in negative damping energy terms which are the same as the similar terms, and the rest part in negative damping energy terms are voltage compensation terms. Energy compensation can be converted to voltage compensation, thus the voltage compensation terms can be used to design supplementary energy branches.

Take negative damping energy \( W_{p2} \) for example, the detailed process of obtaining the corresponding voltage compensation term is illustrated. First, transform \( W_{p2} \) in Equation (4) to \( dq \) coordinate system of direct-drive wind turbine control system:

\[
W_{p2} = k_{p2} \int i_{dq}^* i_{dc} d\Delta \theta_{pll} \quad (23)
\]

Compared with the expression of transient energy in Equation (2), it can be seen that the expression of \( W_{p2} \) in Equation (23) is similar to the first term in Equation (2), i.e. \( \int i_{dc} u_{dc} d\Delta \theta_{pll} \), both containing current term \( i_{dc} \). Eliminate current term \( i_{dc} \) in \( W_{p2} \), so that the voltage compensation term can be obtained:

\[
\Delta u_{d1} = -k_{p2} i_{dc}^* \quad (24)
\]

Similarly, compare \( W_{l1} \) in Equation (5) and \( W_{l1} \) in Equation (6) with Equation (2), so that the corresponding voltage compensation terms can be extracted:

\[
\begin{align*}
\Delta u_{d2} &= -k_{l2} \int i_{dq}^* dt \\
\Delta u_{d3} &= -w_{l2} i_{dq}^* \Delta \theta_{pll} \\
\Delta u_{d4} &= -w_{l2} i_{dq}^* \Delta \theta_{pll} \\
\end{align*}
\quad (25)
\]

For Equations (24) and (25), the input term is \( i_{dc}^* \), and the output terms are \( \Delta u_{d1} \) and \( \Delta u_{d2} \), which respectively represent proportion and integration control links, thus Equations (24) and (25) can form a PI controller. For Equation (26), the input terms are \( i_{dc}^* \) and \( i_{dq}^* \), and the output terms are \( \Delta u_{d3} \) and \( \Delta u_{d4} \), which represent proportion control links with equal \( d \)-axis and \( q \)-axis proportion coefficients. According to voltage compensation terms in Equations (24)–(26), supplementary energy branches \( V_{p2}, V_{l1} \) and \( V_{l1} \) are constructed, as shown in Figure 3.

Apply Equations (24)–(26) to Equation (2), so that the energy increments brought by supplementary energy branches can be obtained:

\[
\begin{align*}
W_{p2} &= 2k_{p2} i_{dc}^* \int i_{dq} \Delta \theta_{pll} d\Delta \theta_{pll} - k_{p2} \int i_{dq}^* i_{dc} d\Delta \theta_{pll} \\
&= W_{e1} - W_{e1} \quad (27)
\end{align*}
\]

\[
\begin{align*}
W_{p2} &= k_{l2} \int i_{dq}^* dt + 2k_{l2} \int i_{dq}^* i_{dq} \Delta \theta_{pll} d\Delta \theta_{pll} \\
&- k_{l2} \int i_{dq}^* i_{dc} d\Delta \theta_{pll} \\
&= W_{e2} - W_{e2} \quad (28)
\end{align*}
\]
**Objective function**

Optimization of supplementary energy

Thus extra introduced energy

and fundamental frequency, when energy branches $V_{\rho 2}$, $V_{\rho 1}$ and $V_{I,1}$ are added, the increment of fundamental-frequency voltage are:

$$
\Delta u^*_{\rho 1} = -k_{\rho 2}i^*_{\rho 2} \\
\Delta u^*_{\rho 2} = -k_{\rho 3} \int i^*_{\rho 3} dt \\
\Delta u^*_{\rho 7} = 0 \\
\Delta u^*_{q 5} = 0
$$

It can be seen from Equations (30)–(32) that, in fundamental frequency, supplementary branches $V_{\rho 2}$ and $V_{\rho 1}$ mainly affect $d$-axis current inner-loop control, weakening PI steady-state error control of current inner loop, thus they will affect the fundamental-frequency voltage of wind turbine. The output of supplementary branch $V_{I,1}$ in fundamental frequency is 0, thus it does not affect the fundamental-frequency voltage of wind turbine. In view of the compensation capability of different supplementary branches and their impact on the fundamental-frequency voltage, the control parameter of each supplementary energy branch should be appropriately set in order to realize effective suppression of oscillation.

3.2 | Optimization of supplementary energy branches

In order to improve the compensation capability of supplementary energy branches without affecting the fundamental frequency characteristic of direct-drive wind turbine, a scheme to optimize the supplementary energy branches is proposed. With the compensation energy of each branch being the maximum and the increment of fundamental-frequency voltage being the minimum as the objective, the compensation coefficient of each supplementary energy branch is optimized.

3.2.1 | Objective function

The ratio of compensation energy to increment of fundamental-frequency voltage is defined as the objective of optimization, i.e.

$$
\max f = \frac{\sum_{i=1}^{\omega} k_{i,1} W_{i,1}^*}{\sum_{i=1}^{\omega} k_{1,i} \Delta u^*_{d(q)l_i}}
$$

where $k_{i,1}$ is the compensation coefficient of the $i$th supplementary energy branch, $W_{i,1}$ is the compensation energy of the $i$th supplementary energy branch. $\Delta u^*_{d(q)l_i}$ is the increment of $d/q$-axis fundamental-frequency voltage of the $i$th supplementary branch.

**FIGURE 3** Supplementary energy branches

\[ W_{1,1} = w_2L_2 \int \Delta \theta_{PLL} (i_q^* d_{id} - i_d^* d_{iq}) \\
- w_2L_2 \int (i_{d}^2 + i_{q}^2) \Delta \theta_{PLL} d \Delta \theta_{PLL} \\
= W_{c3} - W_{V/3} \] (29)
3.2.2 Constraints

Value range of compensation coefficients

Consider that supplementary branches \( V_{l2}, V_{l1} \) and \( V_{l1.1} \) all affect the control structure of current loop, to guarantee the stable operation of control links after supplementary branches are added, the parameter interval of compensation coefficient of each supplementary branch is designed referring to the stability characteristics of closed-loop system in the frequency domain.

Convert Equations (24)–(26) to the frequency domain and apply them to Equation (3), so that the transfer functions of closed-loop systems with supplementary energy branches can be obtained:

\[
T_{ljy}(s) = \frac{1 - k_{lj1}}{s^2 + 1 - k_{lj1}} \frac{k_{l2}^2}{L_2} + \frac{1 - k_{lj2}}{s^2 + 1 - k_{lj2}} \frac{k_{l2}^2}{L_2} \tag{34}
\]

\[
T_{l1.1}(s) = \frac{k_{l3}w_2\Delta\theta_{pll}}{s + k_{l3}w_2\Delta\theta_{pll}} \tag{35}
\]

where Equation (34) is a typical second-order system with supplementary branches \( V_{l2} \) and \( V_{l1} \). Equation (35) is a typical first-order system with \( q \)-axis branch of \( V_{l1.1} \). The system with \( q \)-axis branch of \( V_{l1.1} \) is similar to Equation (35) and is not repeated here.

According to frequency-domain characteristics of closed-loop system, the compensation coefficient of each supplementary branch can be calculated:

\[
\begin{align*}
k_{l1} &= \frac{1 - L_{l2}\omega_{pl}^2}{k_{l2}} \left( \sqrt{1 + 4\xi_f^2 - 2\xi_f} \right) \\
k_{l2} &= \frac{1 - 2L_{l2}\omega_{pl}^2}{k_{l2}} \left( \sqrt{1 + 4\xi_f^2 - 2\xi_f} \right) \\
k_{l3} &= \frac{\omega_{ll}}{w_2\Delta\theta_{pl}}
\end{align*} \tag{36}
\]

where \( \xi_f \) is the damping ratio of supplementary branches \( V_{l2} \) and \( V_{l1} \). \( \omega_{pl} = 2\pi f_{pl}, \) where \( f_{pl} \) is the control bandwidth of supplementary branches \( V_{l2} \) and \( V_{l1} \). \( \omega_{ll} = 2\pi f_{ll}, \) where \( f_{ll} \) is the control bandwidth of supplementary branch \( V_{l1.1} \).

It can be seen from Equation (36) that, the compensation coefficient of each supplementary branch is determined by the damping ratio or control bandwidth. To ensure the speed and smoothness of supplementary branches, the damping ratio usually satisfies: \( 0.4 \leq \xi_f \leq 0.8 \). Meanwhile, consider that the dangerous frequency bands where sub/super-synchronous oscillation may occur when direct-drive wind turbine is integrated to weak power grid are 20–30 Hz and 70–80 Hz [21], \( f_{pl} \) and \( f_{ll} \) can be set as: \( 20 \leq f_{pl}, f_{ll} \leq 30, \) \( 70 \leq f_{pl}, f_{ll} \leq 80 \). According to the value ranges of damping ratio and control bandwidth, the parameter intervals of compensation coefficients can be determined:

\[
\begin{align*}
k_{l1} &= \frac{k_{l1}}{\xi_f^1} \in \left[ k_{l1\min}, k_{l1\max} \right] \\
k_{l2} &= \frac{k_{l2}}{\xi_f^2} \in \left[ k_{l2\min}, k_{l2\max} \right] \\
k_{l3} &= \frac{k_{l3}}{\xi_f^3} \in \left[ k_{l3\min}, k_{l3\max} \right]
\end{align*} \tag{37}
\]

where \( k_{l1\min}, k_{l1\max}, k_{l2\min}, k_{l2\max}, k_{l3\min}, \) and \( k_{l3\max} \) can be calculated according to Equation (36).

Constraints of fundamental-frequency voltage

To ensure the normal operation of direct-drive wind turbine after supplementary energy branches are added, the increment of fundamental-frequency voltage brought by supplementary branches must not exceed the allowed range. According to general requirement on grid connection of wind turbine, the allowed voltage deviation in normal operation state is \( -10–10\% \), but consider the requirement of output and stability margin, the voltage deviation is set to be between \( -5–5\% \), i.e. the increment of fundamental-frequency voltage brought by supplementary branches should satisfy:

\[
\sqrt{\sum_{i=1}^{n} \left( k_{l1}\Delta u_i^a \right)^2} \leq 5\%U_u \tag{38}
\]

where \( U_u \) is the rated voltage at the terminal of direct-drive wind turbine, the per unit value of which is 1.

3.2.3 Optimization scheme

Concerning the above model to optimize the compensation coefficients of supplementary energy branches, the pattern search method is used to determine the optimal compensation coefficients.

Step 1: Measure the data of voltage and current at the terminal of direct-drive wind turbine online, and calculate the compensation energy of each supplementary branch according to Equations (27)–(29); calculate the increment of fundamental-frequency voltage brought by each supplementary branch according to Equations (30)–(32). And determine the parameter interval of each compensation coefficient according to Equations (36) and (37).

Step 2: Set the initial values of compensation coefficients \( k_{l1}, k_{l2}, \) and \( k_{l3} \). If a certain group of compensation coefficients \( x_1 \) satisfies the constraints in Equation (38), \( x_1 \) is a feasible solution, i.e. the current optimal solution. Otherwise, set new initial values until any feasible solution is found.
**TABLE 1** Parameters of direct-drive wind turbine

| Symbol | Parameter       | Value             |
|--------|-----------------|-------------------|
| $U_a$  | Rated line voltage | 0.69 kV          |
| $f_a$  | Rated frequency  | 50 Hz             |
| $U_{dc}$ | DC voltage      | 1.2 kV            |
| $L_2$  | Filter inductance | 2 mH              |
| $L_g$  | Grid inductance  | 7 mH              |
| $f_c$  | Switching frequency | 6 kHz             |
| $f_s$  | Sampling frequency | 6 kHz             |
| $k_{p1}, k_{i1}$ | Parameters of current loop | 0.0005, 0.1238 |
| $k_{p4}, k_{i4}$ | Parameters of PLL | 0.67, 38.2       |

Step 3: Based on the current optimal solution $x_i$ ($i = 1, 2, 3...$), use the pattern search method to update the compensation coefficients. For new feasible solution $x_{i+1}$ that satisfies Equation (38), calculate the objective function in Equation (33). If $f_{i+1} > f_i$, $x_{i+1}$ is the current optimal solution; otherwise, repeat Step 3.

Step 4: Repeat the search process until the number of iterations is satisfied. The current optimal solution is the optimal compensation coefficient.

**4 | SIMULATION ANALYSIS**

**4.1 | Test system**

A model of power system integrated with direct-drive wind turbines is built in RTLAB for simulation tests, as shown in Figure 4. Direct-drive wind turbines are connected to the bus via a 0.69/20kV field transformer and then connected to PCC (point of common coupling) via a 20/230kV transformer. The main parameters of direct-drive wind turbine are shown in Table 1.

To verify the correctness and effectiveness of the proposed method, different sub/super-synchronous oscillation cases with different power grid strengths are set in this paper, i.e. diverging oscillation (Case 1), constant-amplitude oscillation (Case 2) and converging oscillation (Case 3). Concerning the three cases, the variation of transient energy of different control links in grid-side converter and the suppression effect of supplementary energy branches are analysed.

**4.2 | Transient energy of different control links in grid-side converter**

According to Equations (4)–(6), the transient energy of different control links in grid-side converter in Case 1, Case 2 and Case 3 is calculated (per unit values of variables are used in the calculation and with 0 s as the oscillation start time). The simulation curves of transient energy are shown in Figure 5.

It can be seen from Figure 5(a,b,c) that, in Case 1, Case 2 and Case 3, $W_{P1}$, $W_{P3}$, $W_{L2}$ and $W_{L2}$ are all negative, so are their variation rates, thus the corresponding control links exhibit positive damping characteristic, they keep absorbing transient energy, which makes for the stability of system. $W_{P4}$ and its variation rate is approximately 0, which basically has no effect on system stability. $W_{P3}$, $W_{P1}$, $W_{L1}$ and $W_{L2}$ are all positive, so are their variation rates, thus the corresponding control links exhibit negative damping characteristic, they keep generating transient energy, causing the system to go unstable. The amplitude of $W_{P4}$ is the largest, the amplitudes of $W_{P3}$, $W_{P1}$ and $W_{L2}$...
are relatively large, while the amplitudes of $W_{L3}$, $W_{L4}$, $W_{L, 1}$ and $W_{L, 2}$ are relatively small, and the amplitude of $W_{L3}$ and $W_{L, 2}$ are next to 0. The above simulation results verify the damping characteristics of different control links in grid-side converter analysed in Section 2.2. During sub/super-synchronous oscillation, $W_{P2}$, $W_{I1}$ and $W_{P, 1}$ are the negative damping energy terms that lead the oscillation of direct-drive wind turbine. Thus, the corresponding $d$-axis current loop control link and $d$-axis and $q$-axis cross-coupled control links have leading effect on system oscillation, while $q$-axis current loop control link scarcely affects the oscillation.

### 4.3 Suppression effect of supplementary energy branches

Construct supplementary energy branches according to the method proposed in Section 3.1, and combining the simulation data of Case 1, the model to optimize the compensation coefficients of multiple branches is built according to Equations (33)–(38). And then the pattern search method is used to determine the optimal compensation coefficients. Since supplementary branch $V_{L, 1}$ does not generate any increment of fundamental-frequency voltage, its compensation coefficient $k_{1/3}$ is set to render its compensation energy the maximum. $k_{1/3}$ applies the maximum value in the parameter interval. Optimization of compensation coefficients of supplementary branches $V_{P2}$ and $V_{I1}$ is shown in Figure 6. It can be seen that, the bigger $k_{1/1}$ is and the smaller $k_{1/2}$ is, the bigger the ratio of compensation energy to increment of fundamental-frequency voltage is, and the better compatible supplementary energy branches are with compensation capability and impact on fundamental frequency characteristic. Therefore, the optimal compensation coefficients are designed as: $k_{1/1} = 3.358$, $k_{1/2} = 7.109$ and $k_{1/3} = 0.0769$.

To verify the effectiveness of the proposed supplementary energy branches, the suppression effects of supplementary energy branches corresponding to different grid strengths and different oscillation frequencies are analysed. Besides, the impact of supplementary energy branches on the fundamental frequency characteristic of wind turbine is verified.

#### 4.3.1 Suppression effects of supplementary energy branches corresponding to different grid strengths

Suppose the optimal supplementary energy branches are added in Case 1, Case 2 and Case 3, and the variation curves of output power of direct-drive wind turbine are shown in Figure 7(a,c). By regulating the parameters of power grid, the suppression effects of supplementary energy branches corresponding to different grid strengths can be obtained, shown in Figure 7(d).

It can be seen from Figure 7(a,c) that, after supplementary energy branches are added in Case 1, Case 2 and Case 3, the oscillation amplitude of output power of direct-drive wind turbine immediately drops, and the oscillation converges to stable state within 0.2 s. According to Figure 7(d), for different grid strengths, the dropping degree and converging trend of oscillation amplitude are almost the same, and the oscillation can all be effectively suppressed within 0.2 s.

#### 4.3.2 Suppression effects of supplementary energy branches corresponding to different oscillation frequencies

The oscillation in Case 1, Case 2 and Case 3 are all sub/super-synchronous oscillation with frequency of 28–72 Hz, where the supplementary energy branches have relatively good suppression effect. To verify the adaptability of supplementary energy branches to different oscillation frequency bands, forced oscillation is used. Suppose 5–100 Hz harmonic current is injected to the grid which causes oscillation to occur in the system, and the suppression effect of supplementary energy branches is shown in Figure 8.

It can be seen from Figure 8(a,b) that, grid-side injected harmonic current causes forced oscillation to occur in the system at $t = 1$ s. When the forced oscillation is in 40–60 Hz frequency band, which does not belong to the range of sub/super-synchronous frequency, the output power of direct-drive wind turbine has no obvious variation after supplementary branches are added, i.e. supplementary energy branches basically have no suppression effect in this frequency band. According to Figure 8(c,h), when the forced oscillation is in 5–40 Hz or 60–95 Hz frequency bands, the oscillation amplitude of output power obviously drops after supplementary energy branches are added, i.e. the suppression effect of supplementary energy branches is relatively good in these frequency bands. However, due to the existence of external disturbance, the oscillation of wind turbine cannot converge. If the injected current is removed, the oscillation will converge rapidly. Besides, the bigger the difference between oscillation frequency and fundamental frequency is (i.e. the higher super-synchronous frequency is or the lower sub-synchronous frequency is), the larger the negative damping energy compensated by supplementary branches is, and the more obvious the oscillation suppression effect is.
FIGURE 7 Variation of active power after supplementary energy
(a) Supplementary energy branches are added in Case 1, (b) supplementary energy branches are added in Case 2, (c) supplementary energy branches are added in Case 3, (d) suppression effects of supplementary energy branches corresponding to different grid strengths

FIGURE 8 Suppression effects of supplementary energy branches corresponding to different oscillation frequencies
(a) 45/55 Hz, (b) 40/60 Hz, (c) 35/65 Hz, (d) 30/70 Hz, (e) 25/75 Hz, (f) 20/80 Hz, (g) 10/90 Hz, (h) 5/95 Hz
4.3.3 Impact of supplementary energy branches on fundamental frequency characteristic of direct-drive wind turbine

Furthermore, the impact of supplementary energy branches on the fundamental frequency characteristic of direct-drive wind turbine is analysed. Suppose supplementary energy branches are added at certain moment in normal operation state, the variation of fundamental-frequency voltage of wind turbine is shown in Figure 9. On this basis, LVRT simulation case is set to verify the compatibility of supplementary energy branches with fundamental frequency response of wind turbine. The variation curves of output current and voltage of wind turbine during LVRT are shown in Figure 10.

It can be seen from Figure 9(a,b) that, after supplementary energy branches are added, the output voltage of direct-drive wind turbine fluctuates, but the maximum fluctuation amplitude is only 0.02p.u, thus the constraints of fundamental-frequency voltage in (38) are still satisfied, i.e. the impact of supplementary branches on normal operation of direct-drive wind turbine is relatively small. It can be seen from Figure 10(a,b) that, when supplementary energy branches are added, the variation amplitude of current of wind turbine during LVRT is relatively small, thus system operation is not affected. According to Figure 9(c,d), when supplementary energy branches are added, the voltage of wind turbine scarcely changes, thus the LVRT characteristic of wind turbine is not affected. Therefore, the proposed supplementary energy branches are proved to be compatible with fundamental frequency dynamic response of wind turbine.

The above simulation results verify the correctness and effectiveness of the proposed method to suppress sub/super-synchronous oscillation of direct-drive wind turbine based on energy compensation.

5 CONCLUSION

A method to suppress sub/super-synchronous oscillation of direct-drive wind turbine based on energy compensation is proposed in this paper, the correctness and feasibility of which are verified by theoretical analysis and simulation tests. The main conclusions are as follows.

1. The positive damping energy and negative damping energy in system transient energy are key factors that characterize the stability level of system. In the transient energy model of direct-drive wind turbine, $W_{p2}$, $W_{1}$ and $W_{L1}$ are negative damping energy terms which reflect the amount of energy accumulated after the system is disturbed, thus they lead the oscillation and make against the stability of system.

2. Supplementary energy branches corresponding to the negative damping energy terms are constructed, and a scheme to optimize the compensation coefficients of multiple branches is established based on the ratio of compensation energy to increment of fundamental-frequency voltage. The optimized
supplementary energy branches do not affect the dynamic characteristics of wind turbine during LVRT and are compatible with fundamental-frequency response capability of wind turbine.

3. The proposed supplementary energy branches can effectively reduce the negative damping energy and improve the stability level of direct-drive wind turbine. They can suppress sub/super-synchronous oscillation in power grid with different strengths within 0.2 s and can suppress sub/super-synchronous oscillation in frequency bands of 5–40 Hz and 60–95 Hz.

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NOMENCLATURE

- \( U_G \): Voltage vector of direct-drive wind turbine
- \( I_G \): Injection current of direct-drive wind turbine
- \( I_{di}, I_{dq}, U_{di}, U_{dq} \): D-axis and q-axis components of current and voltage at the terminal of direct-drive wind turbine
- \( \Delta \theta_{pl} \): Dynamic angle of PLL
- \( k_{p2}, k_{i2} \): Proportion and integration coefficients of current inner loop
- \( i_{dci}^*, i_{qci}^* \): D-axis and q-axis reference values of current reactance of outlet line
- \( d \) and \( q \): D-axis and q-axis components of grid voltage in \( d-q \) coordinate system
- \( W'_p \): Transient energy led by current-loop proportion link
- \( W'_t \): Transient energy led by current-loop integration link
- \( W'_L \): Transient energy caused by the coupling between d-axis and q-axis
- \( i_{dci}, i_{qci} \): D-axis and q-axis measured currents at the terminal of grid-side converter
- \( U_L, U_T, \epsilon, \epsilon_t \): Amplitudes and initial phase angles of sub/super-synchronous frequency phase-A voltage
- \( U_{q1}, \phi_q \): Amplitude and initial phase angle of \( q \)-axis oscillation voltage
- \( V_{q2}, V_{q1}, V_{L1} \): Supplementary energy branches
- \( W_{1/2}, W_{1/2}, W_{1/3} \): Necessary compensation energy
- \( W'_1 \): Extra introduced energy
- \( k_{l1} \): Compensation coefficient of the \( l \)th supplementary energy branch
- \( W'_{1/2} \): Compensation energy of the \( l \)th supplementary energy branch
- \( \Delta u^*_{d(q)c(i)} \): Increment of \( d/q \)-axis fundamental-frequency voltage of the \( i \)th supplementary energy branch
- \( n \): Total number of supplementary energy branches
- \( \xi \): Damping ratio of supplementary branches \( V_{q2} \) and \( V_{q1} \)
- \( f_{PL} \): Control bandwidth of supplementary branches \( V_{q2} \) and \( V_{q1} \)
- \( f_{L} \): Control bandwidth of supplementary branch \( V_{L1} \)
- \( U_{r} \): Rated voltage at the terminal of direct-drive wind turbine

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REFERENCES

1. Du, W., et al.: Concept of modal repulsion for examining the sub-synchronous oscillations caused by wind farms in power systems. IEEE Trans. Power Syst. 34(1), 518–526 (2019)
2. Gu, K., Wu, F., Zhang, X.: Sub-synchronous interactions in power systems with wind turbines: a review. IET Renew. Power Gener. 13(1), 4–15 (2019)
3. Tao, S., et al.: Impedance network model of D-PMSG based wind power generation system considering wind speed variation for sub-synchronous oscillation analysis. IEEE Access 8, 114784–114794 (2020)
4. Liu, H., et al.: Subsynchronous interaction between direct-drive PMSG based wind farms and weak AC networks. IEEE Trans. Power Syst. 32(6), 4708–4720 (2017)
5. Jaikhang, W., Tunyaistrut, S., Permpoonsinsup, W.: Optimization PI controller of grid connected for wind turbine based on PMSG. In: 2017 International Electrical Engineering Congress. Pattaya, pp. 1–4 (2017)
6. Faried, S. O., et al.: Utilizing DFIG-based wind farms for damping sub-synchronous resonance in nearby turbine-generators. IEEE Trans. Power Syst. 28(1), 452–459 (2013)
7. Zhang, J., et al.: Subsynchronous control interaction analysis and trigger-based damping control for doubly fed induction generator-based wind turbines. Electr. Power Compon. Syst. 44(7), 713–725 (2016)
8. Tang, H., et al.: Impact of grid side converter of DFIG on sub-synchronous oscillation and its damping control. In: 2016 IEEE PES Asia-Pacific Power and Energy Engineering Conference (APPEEC). Xi’an, pp. 2127–2130 (2016)
9. Luo, J., et al.: Modal shift evaluation and optimization for resonance mechanism investigation and mitigation of power systems integrated with FCWG. IEEE Trans. Power Syst. 35(5), 4046–4055 (2020)
10. Chen, H., Guo, C., Chen, Q.: Sub-synchronous oscillation caused by HVDC and the damping characteristic analysis. Adv. Mater. Res. 971-973, 1353–1356 (2014)
APPENDIX A
The variation rates of extra energy introduced by supplementary energy branches $\Delta W'_{r1}$, $\Delta W'_{r2}$ and $\Delta W'_{r3}$ can be expressed as:

$$\Delta \dot{w}_{r1} = -2 \Delta \dot{\theta}_{r1} e^{\omega t} \cos(\omega t + \phi) - \omega \Delta \dot{\theta}_{r1} e^{\omega t} \cos(\omega t + \phi)$$  \hspace{1cm} (A.1)

$$\Delta \dot{w}_{r2} = -k_{2r2} e^{\omega t} \cos(\omega t + \phi) + 2 \Delta \dot{\theta}_{r2} e^{\omega t} \cos(\omega t + \phi) - \omega \Delta \dot{\theta}_{r2} e^{\omega t} \cos(\omega t + \phi)$$  \hspace{1cm} (A.2)

$$\Delta \dot{w}_{r3} = w_2 I_2$$  \hspace{1cm} (A.3)