Generation of second harmonic component of fault current in a doubly-fed induction generator and mitigation measures for transformer protection

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Abstract
The transient characteristics of short-circuit current (SCC) in doubly-fed induction generator (DFIG) are quite different from the widely researched conventional synchronous machines. However, the second harmonic characteristics of SCC that impact the reliability of the transformer protection have not been accurately analysed. This paper presents the generation mechanism of second harmonic SCC in DFIG by deducing the dynamic response of rotor-side converter, with particular attention to the influences of the voltage drop, harmonic component of stator voltage, frequency coupling, and deviation of the phase-locked loop. When grid fault occurs, the terminal voltage sag leads to fluctuations in the active power, then the response of converter to power fluctuation and the frequency coupling leads to the second harmonic current in the abc reference frame. And the second harmonic current injected into the grid leads to fluctuations in the voltage disturbance term and deviation of the phase-locked loop, which, in turn, affects the second harmonic current. Based on the analysis, the mitigation measures for the second harmonic current are proposed. Simulations are implemented to verify the theoretical analysis.

1 | INTRODUCTION

In recent years, wind power generation has been one of the most mature and promising renewable energy power generation technologies [1,2]. With the increase in wind power penetration in the power system, the operation flexibility and security stability of the power system have been greatly affected and impacted [3]. At present, among many types of wind turbines, doubly-fed induction generators (DFIGs) have been widely used in wind farms because of their relatively low cost and better performance [4–6]. The rotor winding of DFIG is supplied from back-to-back converters, known as the rotor-side converter (RSC) and grid-side converter (GSC), which makes the transient behaviour highly complex. Therefore, it is very important to master the transient characteristics of DFIGs for protection and control of the power system.

Under non-deep voltage drop, the excitation control is retained during a fault. In this case, the dynamic response of RSC has a large influence on the fault current characteristics of the DFIG. At present, several researchers have investigated the transient characteristics of a DFIG in three-phase short circuits. El Archi et al. [8] investigated the behaviour of the DFIG and found that the sudden change in the voltage led to changes in the stator flux, rotor current, and rotor voltage. However, there were no detailed expressions about the short-circuit rotor current. In [9], an expression to calculate the short-circuit rotor current using the motor voltage and control parameters of GSC was proposed; however, there was no detailed analysis on SCC. In [10–12], the SCC under excitation control was analysed in detail and proposed that the power fluctuation and voltage disturbance term were the main factors affecting SCC. In [10], the power-frequency SCC was only obtained from the power.
fluctuation in the static reference frame (SRF). In [11], the voltage disturbance term in the case of short-circuit fault was studied. El-Naggar and Erlich [12] further analysed the influence of controller on the SCC parameters, such as time constants, initial symmetrical SCC, and peak SCC. Based on the above papers, a more practical calculation model for SCC of DFIG in engineering was proposed in [13].

Existing studies focused on the power-frequency component of SCC. However, the high amplitude of SCC will also harm the transformer, which is the key equipment in the system. The second harmonic restrain element equipped in transformer protection is critical to ensure the correct protection action. Thus, it is also important to master the second harmonic characteristics. Ma et al. [14] presented that the fluctuations in the active and reactive power produced the second harmonic component of SCC when grid fault occurred. However, the outer loop power, which differs from that during normal operation when a fault occurs, was ignored. In addition, in the complex control system of DFIG, frequency coupling [15] and phase deviation caused by phase-locked loop (PLL) [16,17] may also affect the harmonic current; however, there was no specific analysis in [14] or other related studies. A comprehensive and detailed analysis of the harmonic component of SCC has been rarely reported.

The second harmonic component exceeding the limits may threaten the reliability of the second harmonic restraint criterion. Therefore, the suppression measures for harmonic components have also attracted extensive attention. Shapoval et al. [18] improved the topology of the DFIG system connected to a grid to control the output current to compensate the harmonic current, which was not suitable for the fault scenario. The suppression measures presented in [19] and [20] required additional proportional-integral (PI) and resonant (R) regulators, respectively. These additional regulators made the control structure more complex and changed the phase-frequency characteristics of the system significantly, resulting in stability risk of the power system.

Based on the literature review, the main contributions of the paper are as follows: (a) Analyse the generation mechanism of second harmonic SCC in DFIG, by considering the voltage drop, second harmonic of voltage, frequency coupling, and deviation of PLL. (b) Propose new mitigation measures to suppress the second harmonic component.

The paper is organised as follows: In Section 2, the frequency coupling as the precondition of harmonic current is analysed. In Section 3, the generation mechanism of the second harmonic SCC is proposed. In Section 4, the influence of the second harmonic current on the transformer protection is demonstrated using experimental data, and then the suppression measures are suggested. In Section 5, theoretical analyses are verified through simulation. Finally, Section 6 concludes the paper.

2 | FREQUENCY COUPLING IN THE CASE OF THE ASYMMETRY OF D- AND Q-AXES COMPONENTS

DFIG control process is carried out in two main parts composed of RSC and GSC, which are usually designed in dq rotation reference frame (RRF). Therefore, the reference frame transformation plays an important role in converter control. During the reference frame transformation, there will be a frequency coupling phenomenon.

Assume the d- and q-axes components of an electrical quantity are

\[
\begin{align*}
\begin{bmatrix}
    f_d \\
    f_q
\end{bmatrix} &= \begin{bmatrix}
    \cos(\omega_1 t) & -\sin(\omega_1 t) \\
    \sin(\omega_1 t) & \cos(\omega_1 t)
\end{bmatrix} \begin{bmatrix}
    f_d \\
    f_q
\end{bmatrix} \\
&= \frac{1}{2} \left[ F_d (\cos(\omega_1 t + \omega_d t + \varphi_d) + \cos(\omega_1 t - \omega_d t - \varphi_d)) \right. \\
&\left. + F_q (\cos(\omega_1 t + \omega_d t + \varphi_q) - \cos(\omega_1 t - \omega_d t - \varphi_q)) \right] \\
&\left. + F_q (\sin(\omega_1 t + \omega_d t + \varphi_q) - \sin(\omega_1 t - \omega_d t - \varphi_q)) \right].
\end{align*}
\]

Equation (2) can be expressed as a vector as

\[
\begin{align*}
f &= f_d + j f_q \\
&= \frac{1}{2} \left[ F_d e^{j(\omega_1 t + \omega_d t + \varphi_d)} + F_d e^{j(\omega_1 t - \omega_d t - \varphi_d)} \right. \\
&\left. + F_q e^{j(\omega_1 t + \omega_d t + \varphi_q)} - F_q e^{j(\omega_1 t - \omega_d t - \varphi_q)} \right].
\end{align*}
\]
3 | GENERATION MECHANISMS OF SECOND HARMONIC CURRENT OF DFIG SCC

This paper presents the generation mechanisms of the second harmonic component of DFIG SCC. Due to the electromagnetic coupling relationship between stator and rotor currents [21, 22], the second harmonic characteristics of the stator current can be obtained by deducing the rotor current. This paper focuses on the rotor current, and hence, stator current is not discussed in detail.

Considering the control exerted by the converter, the transient characteristics of the rotor current are mainly related to the transient response of RSC. RSC control is shown in Figure 1 [23]. In Figure 1, $K_{PP}$ and $K_{PI}$ are the proportional and integral coefficients of the PI regulator at the RSC outer loop power. $K_{IP}$ and $K_{II}$ are the proportional and integral coefficients of the PI regulator at the inner loop current. The equivalent gain of the pulse-width modulation converter $K_{PWM}$ is usually equal to 1, and $T_{sr}$ is the switching period, which is small enough to be ignored. $\sigma = 1 - (L_{m}^{2}/L_{r}L_{s})$ is the leakage coefficient of the generator.

Figure 1 shows that both the reference values of the rotor current ($i_{rd-ref}$ and $i_{rq-ref}$) and the voltage disturbance terms ($e_{rd}$ and $e_{rq}$) can influence the rotor current ($i_{rd}$ and $i_{rq}$) dynamics. Therefore, the second harmonic characteristics of the rotor current can be obtained by analysing the dynamic response of the rotor current to the reference values of the rotor current and voltage disturbance terms under two scenarios.

3.1 | Generation mechanisms of second harmonic current of DFIG SCC when the stator voltage drops

3.1.1 | Influence of the reference value of the rotor current

According to Figure 1, $i_{rd-ref}$ and $i_{rq-ref}$ during normal operation are mainly affected by the outer loop power. However, when grid fault occurs, the control strategy changes, as shown in the purple line in Figure 1. $i_{rd-ref}$ is still affected by the outer loop active power before reaching the limiting link, while $i_{rq-ref}$ is directly given according to the stator voltage after the fault. Therefore, the $d$- and $q$-axes are discussed separately below.

According to Figure 1, when the reference value of the stator active power ($P_{s-ref}$) is unchanged, $i_{rd-ref}$ is mainly determined by the instantaneous value of the stator active power ($P_{s}$). Adopting voltage-oriented control, the $d$-axis of the reference frame is aligned with the stator voltage. Thus, the stator voltage after the fault ($u_{s}$) in dq RRF is as follows:

$$u_{s} = u_{sd} + ju_{sq} = u_{sd} = |u_{s}| = U_{1}$$ (5)

where $u_{sq} = 0$; $U_{1}$ is the amplitude of the fundamental frequency component of the stator voltage after the fault occurs.

According to the magnetic flux linkage conservation law, a sudden drop in the stator voltage will induce the transient direct current (DC) component in stator current in $abc$ SRF ($i_{s-abc}$). Therefore, the stator current in dq RRF ($i_{s}$) can be given by

$$i_{s} = I_{1}e^{j\phi_{1}} + I_{0}e^{-j\omega_{1}t}e^{-t/\tau_{s}} = i_{sd} + ji_{sq}$$

$$= \left[I_{1} \cos \phi_{1} + I_{0} \cos (\omega_{1}t) e^{-t/\tau_{s}}\right] + j\left[I_{1} \sin \phi_{1} - I_{0} \sin (\omega_{1}t) e^{-t/\tau_{s}}\right]$$ (6)
where $i_1$ and $i_0$ are the amplitudes of the fundamental frequency component and the DC component of the stator current after fault, respectively; $\varphi_i$ is the initial phase angle between the fundamental frequency component of $i_1$ and d-axis. $\tau_i$ is the decay time constant of the transient DC component.

Combining (5) and (6), $P_s$ in $dq$ RRF is given as follows [24]:

$$ P_s(t) = \frac{3}{2} \left( a_{ad} i_{ad} + a_{sq} i_{sq} \right) $$

$$ = \frac{3}{2} \left( U_1 I_1 \cos \varphi_s + U_1 I_0 \cos (\omega_1 t) e^{-t/\tau_s} \right). \tag{7} $$

From (7), the decaying fundamental frequency component ($U_1 I_1 \cos (\omega_1 t) e^{-t/\tau_s}$) is generated in the stator active power when the stator voltage suddenly drops.

According to (7) and outer loop power in Figure 1, $i_{rd-ref}$ is given by

$$ i_{rd-ref}(t) = \left[ P_{s-ref}(s) - P_s(s) \right] \left( K_{pp} + \frac{K_{pq}}{s} \right) \tag{8} $$

$$ \text{where} \quad P_s(s) = \frac{3U_1I_1 \cos \varphi_s}{2s} $$

$$ + \frac{3U_1I_0}{4} \left( \frac{1}{s-j\omega_1+1/\tau_s} + \frac{1}{s+j\omega_1+1/\tau_s} \right). \tag{9} $$

From (8) and (9), the decaying fundamental frequency component of $i_{rd-ref}$ in (8) is attributed to the second term of $P_s$ in (9).

According to the inner loop current in Figure 1, the transfer function from $i_{rd-ref}$ to $i_{rd}$ can be obtained as follows:

$$ W_p = \frac{i_{rd}(s)}{i_{rd-ref}(s)} = \frac{K_{pp}+K_{q1}}{(s+\mu_1)(s+\mu_2)} \tag{10} $$

where detailed expressions of $\mu_1$ and $\mu_2$ are presented in Appendix A.

Combining (8) and (10), $i_{rd}$ in the complex-frequency domain is given by

$$ i_{rd}(s) = W_p i_{rd-ref}(s) $$

$$ = W_p \left( \frac{K_{pp}+K_{pq}}{s} \right) \left[ P_{s-ref}(s) - P_s(s) \right] $$

$$ = \frac{A_p}{s-j\omega_1+1/\tau_s} + \frac{B_p}{s+j\omega_1+1/\tau_s} + C_p \tag{11} $$

where $A_p$ and $B_p$ are the coefficients of the forward and reverse fundamental frequency components of $i_{rd}$, and $C_p$ represents the remaining components of $i_{rd}$. Detailed expressions of all of these are presented in Appendix A. Equation (11) suggests that $i_{rd}$ produces the fundamental frequency component.

Additionally, $i_{rq-ref}$ is as follows [25]:

$$ i_{rq-ref}(t) = \frac{U_1 - K_q (0.9 - U_1) I_s}{I_m} \tag{12} $$

where $K_q$ is the reactive current coefficient, usually $K_q \geq 1.5$.

Equation (12) suggests that $i_{rq-ref}$ is related to only the stator voltage amplitude so that there is no fundamental frequency component in it. As shown in Figure 1, the transfer function from $i_{rq-ref}$ to $i_q$ is the same as (10). Because $i_{rq-ref}$ does not contain the fundamental frequency component in (12), $i_q$ will not generate the fundamental frequency component.

Therefore, the time-domain expression of the fundamental frequency component of the rotor current is as follows:

$$ i_{r1-drop} = i_{rd1} + j i_{rq} = i_{rd1} + j 0 $$

$$ = A_p e^{j \omega_1 t} e^{-t/\tau_s} + B_p e^{-j \omega_1 t} e^{-t/\tau_s}. \tag{13} $$

where $i_{rd1}$ is the fundamental frequency component in (11).

The second harmonic component of rotor current in $abc$ SRF is as follows:

$$ i_{r2-drop} = A_p e^{j 2 \omega_1 t} e^{-t/\tau_s}. \tag{14} $$

In summary, the DC component generated by the stator voltage drop in $i_{a-b-c}$ is transformed to the fundamental frequency component in $i_s$ upon conversion from $abc$ SRF to $dq$ RRF, which will lead to the fundamental frequency component in $P_s$. Thus, $i_{rd-ref}$ generates the fundamental frequency component through the outer loop power and $i_{rd}$ generates the fundamental frequency component through the inner loop current. However, $i_{rq-ref}$ only contains the DC component; as a result, there is no fundamental frequency component in $i_{rq}$. Thus, the rotor current contains an asymmetric fundamental frequency component in $dq$ RRF. Based on the analysis in Section 2, the rotor current will generate the second harmonic component in $abc$ SRF. The complete generation mechanism of the second harmonic component of the rotor current when the stator voltage drops suddenly is revealed in Figure 2. In Figure 2, $f_0$ is the DC component, and $f_1$ is the fundamental frequency component, and $f_2$ is the second harmonic component.

### 3.1.2 Influence of the voltage disturbance term when stator voltage drops

The equation of the voltage disturbance term ($e_r$) is expressed as [26]

$$ e_r = \frac{I_m}{L_s} \frac{d}{dt} i_r. \tag{15} $$
If the stator resistance is ignored, the stator voltage equation is given by [27]

\[ u_s = j \omega_1 \psi_s + \frac{d\psi_s}{dt}. \]  

(16)

Combining (5) with (16), the stator flux in \( dq \) RRF is

\[ \psi_s = -\frac{u_s}{\omega_1} - j \left( \frac{u_0 - u_s}{\omega_1} \right) e^{-j\omega_1 t} \]  

(17)

where \( u_0 \) represents the stator voltage vector before the fault.

Combining (15) with (17), \( \epsilon_t \) can be expressed as follows:

\[ \epsilon_t = \frac{L_m}{T_s} (u_s - u_0) e^{-j\omega_1 t} = \epsilon_{rd} + j\epsilon_{rq} \]

\[ = \frac{L_m}{T_s} (u_s - u_0)[\cos(-\omega_1 t) + j \sin(-\omega_1 t)]. \]  

(18)

Equation (18) suggests that the fundamental frequency components of \( \epsilon_{rd} \) and \( \epsilon_{rq} \) generated by the sudden drop in stator voltage are symmetrical and reverse. According to the analysis in Section 2, there is no second harmonic component of \( \epsilon_t \) in \( abc \) SRF; therefore, the rotor current does not contain the second harmonic component generated by the voltage disturbance term.

On the basis of Section 3.1, when the stator voltage drops suddenly, the rotor current produces the second harmonic component, which depends only on the reference value of rotor current but not the voltage disturbance term.

The second harmonic current injects into the grid leading to the second harmonic component in the stator voltage. Therefore, the second harmonic current may be affected.

3.2 Generation mechanisms of second harmonic current of DFIG SCC when the stator voltage contains second harmonic component

The second harmonic component in the voltage has little effect when the capacity of the grid is large compared to the capacity of the wind farm. However, when it is a weak grid [28], the second harmonic component in the voltage is too obvious to be ignored, as shown in Figure 3, which will lead to an increment of the second harmonic component of the stator current. Thus, considering the second harmonic voltage, the stator voltage in \( dq \) RRF is given by

\[ u_s' = u_s + u_2 e^{j\omega_1 t} \]

(19)

where \( u_2 = U_2 e^{j\varphi_2} \), \( U_2 \), \( \varphi_2 \) are amplitude and initial phase angle of the second harmonic voltage, respectively. The influence of the second harmonic component of voltage on rotor current is analysed in detail below.

3.2.1 Influence of the reference value of the rotor current taking the phase-locked deviation into account

Combining (6) and (19), \( P_t \), taking second harmonic voltage into account can be calculated. The response of rotor current to it is similar to Section 3.1; hence, a detailed analysis is not given here.

Furthermore, the harmonic component of the voltage may affect the PLL, which plays an important role in reference frame transformation. Figure 4 shows a classical PLL structure. In Figure 4, \( K_{p,PLL} \) and \( K_{i,PLL} \) are the integral and proportional coefficients of the PI regulator of PLL, respectively, and \( \theta_{PLL} \) is the output phase angle. When stator voltage contains the second
harmonic component, the PI regulator cannot adjust PLL without static error, which hinders accurate tracking of the phase angle of the fundamental frequency voltage. In this case, PLL may produce a phase angle deviation ($\Delta \theta$), which will lead to the deviation component in the stator voltage and stator current, and thus may affect the active power.

At present, to mitigate the influence of harmonics on PLL, several improved PLLs are proposed. However, this paper analyzes the most serious case, which is the influence of the PLL deviation on the harmonic current when only the classical PLL is included in the system.

Assuming that $\theta_{PLL} = \theta_1 + \Delta \theta$, the deviation without considering the transient DC component is given by [26]

$$\Delta \theta(t) = 0.5j(D\varepsilon^{io_1 t} - D^* e^{-jio_1 t})$$  \hspace{1cm} (20)

where detailed expression of $D$ is given in Appendix A.

Combining (5) and (19), the stator voltage in abc SRF is given as follows:

$$\begin{align*}
\begin{cases}
\hspace{2cm} u'_{sa} = U_1 \cos(\omega_1 t + \theta_1) + U_2 \cos(2\omega_1 t + \varphi_2) \\
\hspace{2cm} u'_{sb} = U_1 \cos(\omega_1 t - 120^\circ) + U_2 \cos(2\omega_1 t + \varphi_2 - 120^\circ) \\
\hspace{2cm} u'_{sc} = U_1 \cos(\omega_1 t + 120^\circ) + U_2 \cos(2\omega_1 t + \varphi_2 + 120^\circ)
\end{cases}
\end{align*}$$

Combining (26) and (27), the rotor flux is

$$\begin{align*}
\begin{cases}
\hspace{2cm} i_{r1} = U_1 \mu_1 + U_2 \mu_2 e^{j\omega_1 t} + \left[ \frac{u_0 - u_d}{j\omega_1} - \frac{u_d}{j2\omega_1} \right] e^{j\omega_1 t} \\
\hspace{2cm} i_{r2} = \frac{I_{lm} (u_s - u_0)}{2} \left[ \frac{1}{s - j\omega_1} + \frac{1}{s + j\omega_1} \right] \\
\hspace{2cm} i_{r3} = \frac{I_{lm} (u_s - u_0)}{2} \left[ \frac{1}{s - j\omega_1} - \frac{1}{s + j\omega_1} \right]
\end{cases}
\end{align*}$$

Comparing (18) and (26), the fundamental frequency components of $\epsilon_{rd}$ and $\epsilon_{rq}$ are asymmetric because of the second harmonic voltage ($u_d$).

The transfer function from $\epsilon_s$ to the rotor current can be obtained from Figure 1

$$W_{er}(s) = \frac{i_r(s)}{\epsilon_s(s)} = \frac{s}{(s + \mu_3)(s + \mu_4)}$$  \hspace{1cm} (27)

and detailed expressions of $\mu_3$ and $\mu_4$ are presented in Appendix A.

Combining (26) and (27), $i_{rd-er}$ and $i_{rq-er}$ can be obtained from $i_{rd-er}(s) = W_{er}^* \epsilon_{rd}$ and $i_{rq-er}(s) = W_{er}^* \epsilon_{rq}$.

3.2.2 Influence of the voltage disturbance term when stator voltage contains second harmonic component

Section 3.1 demonstrates that, when the stator voltage suddenly drops, $\epsilon_d$ does not affect the second harmonic current. But when the voltage contains the second harmonic component, the rotor current may respond to $\epsilon_d$ differently.

Combining (16) with (19), the stator flux is

$$\psi_s = U_1 \frac{u_s}{j\omega_1} + U_2 \frac{u_d}{j2\omega_1} e^{j\omega_1 t} + \left[ \frac{u_0 - u_d}{j\omega_1} - \frac{u_d}{j2\omega_1} \right] e^{j\omega_1 t}$$

Combining (15) with (25), $\epsilon_{rd}$ and $\epsilon_{rq}$ can be expressed as follows:

$$\begin{align*}
\epsilon_{rd}(s) &= \frac{I_{lm}}{\mu_1} \left( \frac{u_s - u_0}{2} \left( \frac{1}{s - j\omega_1} + \frac{1}{s + j\omega_1} \right) \\
\epsilon_{rq}(s) &= \frac{I_{lm}}{\mu_2} \left( \frac{u_s - u_0}{2} \left( \frac{1}{s - j\omega_1} - \frac{1}{s + j\omega_1} \right) \right)
\end{align*}$$

According to (24), when $\Delta \theta$ is taken into account, the fundamental frequency components of stator voltage ($U_2 e^{j\omega_2 t}$) in dq RRF comes from the second harmonic component in abc SRF. However, if $\Delta \theta$ is taken into account, the fundamental frequency components of stator voltage ($0.5DU_1 e^{j\omega_1 t} - 0.5DU_1 e^{-j\omega_1 t} + U_2 e^{j\omega_2 t} e^{j\omega_1 t}$) in dq RRF come from the fundamental frequency component and the second harmonic component in abc SRF.
Similarly, \( i_q-er \) is as follows:

\[
i_{q-er}(t) = \frac{A_{eq}}{s - j\omega_1} + \frac{B_{eq}}{s + j\omega_1} + C_{eq}
\]

where \( A_{eq} \) and \( B_{eq} \) are the coefficients of the forward and reverse fundamental frequency components of \( i_{q-er} \), respectively, and \( C_{eq} \) represents the remaining components of \( i_{q-er} \). Detailed expressions of all of these are presented in Appendix A.

Therefore, the time-domain expression of the fundamental frequency component of the rotor current is as follows:

\[
i_{r1-er} = i_{d-er1} + ji_{q-er1}
\]

\[
= (A_{er} + jA_{erq}) e^{\omega_1 t} + (B_{er} + jB_{erq}) e^{-j\omega_1 t}
\]

where \( i_{d-er1} \) and \( i_{q-er1} \) is the fundamental frequency component in (28) and (29), respectively.

The second harmonic component of rotor current in abc SRF is as follows:

\[
i_{r2-er} = (A_{er} + jA_{erq}) e^{2\omega_1 t}.
\]

According to the above analysis, \( \epsilon_d \) and \( \epsilon_q \) contain the fundamental frequency components generated by a sudden drop of stator voltage. But only \( \epsilon_d \) contains the fundamental frequency component generated by \( \omega_2 \), which will lead to the asymmetry of fundamental frequency components of \( \epsilon_q \) and \( \epsilon_r \). Thus, \( i_{d-er1} \) and \( i_{q-er1} \) contain asymmetric fundamental frequency components. Upon conversion to abc SRF, the rotor current will produce the second harmonic component. The process is revealed in Figure 5. In Figure 5, \( f_1 \) is the fundamental frequency component, and \( f_2 \) is the second harmonic component.

The complete expression of the second harmonic component of the rotor current is formed by the superposition of the expressions of the second harmonic component in the rotor current calculated in Sections 3.1.1, 3.2.1, and 3.2.2. Because the expression of the second harmonic component is complex, this paper does not provide the complete equation.

![FIGURE 5 Generation mechanism of the second harmonic of rotor current when the voltage contains second harmonic](image)

### TABLE 1 Second harmonic ratio of SCC

| Operating conditions | A | B | C |
|----------------------|---|---|---|
| super-synchronous    | 33% | 25% | 44% |
| sub-synchronous      | 49% | 34% | 54% |

#### 4 INFLUENCE OF SECOND HARMONIC COMPONENT OF DFIG ON TRANSFORMER PROTECTION AND MITIGATION MEASURES

##### 4.1 DFIG experimental data analysis and its influence on transformer protection

Low voltage ride through data was collected from an actual wind turbine to analyse the second harmonic ratio in the SCC. The short-circuit experiment was conducted under two circumstances: (1) in a super-synchronous operating state, where the slip rate of the wind turbine before the short circuit was \(-0.2\) per-unit value (pu); and (2) in a sub-synchronous operating state, where the slip rate of the wind turbine before the short circuit was \(0.2\) pu. In both cases, the three-phase short-circuit fault occurred at the terminal of DFIG, and the voltage dropped to 0.23 pu. Crowbar protection did not initiate in either case, indicating continuous operation of the converter.

A fast Fourier transform (FFT) algorithm was used to extract the second harmonic ratio of the DFIG SCC, as shown in Table 1. The FFT analysis results show that the second harmonic ratio of the SCC reaches up to 54%. If an internal fault occurs in the transformer, the second harmonic component of DFIG will threaten the reliability of the second harmonic restraint criterion, as a result, the differential protection may be locked.

##### 4.2 Mitigation measures for second harmonic component

According to the analysis in Section 3, the fundamental frequency fluctuations in both active power and voltage disturbance term can directly affect the second harmonic component of DFIG SCC. Therefore, this paper proposes the following two mitigation measures that can be implemented in RSC.

First, as shown in Figure 6, the fundamental frequency component of the active power is filtered out using a second-order notch filter having the transfer function

\[
G(s) = \frac{G_0 (\omega_0^2 + \omega_0^2)}{\omega_0^2 + 2\epsilon\omega_0^2 + \omega_0^2}
\]

where \( G_0 = 1 \) is the gain coefficient; \( \epsilon \) is the damping coefficient and is set at \( \epsilon = 0.707 \) considering the filtering effect and stability of the control system; \( \omega_0 = 100\pi \) rad/s is the cut-off...
simulation verification of second harmonic and \( \Delta e \) in Figure 7. The magnitude response of the notch filter is shown in Figure 7.

According to Figure 7, due to the extremely low amplitude at 50 Hz, the notch filter can effectively filter the fundamental frequency component.

Second, the voltage disturbance term can be offset by adopting the voltage compensation control.

The stator and rotor voltage equations can be obtained as follows [29]:

\[
    u_s = R_s i_s + j\omega_1 (L_m i_r + L_{sw} i_d) + \frac{di_s}{dt}
\]

\[
    u_r = \left( R_r i_r + \sigma L_r \frac{di_r}{dt} \right) + j\omega_{slip} (L_m i_s + L_{sw} i_d) + \frac{I_{sw}}{T_{sw}} \frac{di_r}{dt}.
\]

The RSC control is designed according to (34) in Figure 1. The PI controller is designed according to the first term \((R_r i_r + \sigma L_r \frac{di_r}{dt})\), and the cross-coupling term is introduced according to the second term \((j\omega_{slip} (L_m i_s + L_{sw} i_d))\). The third term presents \(\epsilon_{rd}\) and \(\epsilon_{rq}\) in the physical system in Figure 1. Since the third item is 0 in normal operation, the third item is not compensated during general control. But when a fault occurs, \(\epsilon_{rd}\) and \(\epsilon_{rq}\) in the physical system are no longer equal to 0. Therefore, this study proposes to introduce voltage compensation \((\Delta \epsilon_{rd}\) and \(\Delta \epsilon_{rq}\)) into the RSC control to offset the influence of voltage disturbance term, as shown in Figure 6.

According to (33), \(\Delta \epsilon_d\) can be obtained from the following equation:

\[
    \Delta \epsilon_d = \frac{I_{sw}}{T_{sw}} \frac{di_d}{dt} = \frac{I_{sw}}{T_{sw}} \left[ u_r - R_r i_r - j\omega_1 (L_m i_s + L_{sw} i_d) \right]
\]

where \(u_s\), \(i_s\), and \(i_r\) can be measured.

5 | Simulation

The simulation model is built in Matlab/Simulink, as shown in Figure 8. The wind farm is integrated by a 25 kV/120 kV step-up transformer \(T_1\) and 30-km transmission line \(L_{trans}\). The wind farm is composed of 6 DFIGs (1.5 MW). The parameters of DFIG are given in Appendix B. The system equivalent impedance \(X_1\) is 1.8 + j10 \( \Omega \). In Figure 8, \(I_1\) and \(I_2\) are the primary currents at the high and low sides of the transformer \(T_1\), respectively; \(I'_1\) and \(I'_2\) are the secondary current of current transformer. \(I_g\) is the differential current.

5.1 | Verification of second harmonic characteristic of DFIG SCC

At \(t = 0.4\) s, a three-phase internal fault occurs in transformer \(T_1\), and stator voltage drops to 0.2 pu. The terminal voltage and stator current and other key variables of DFIG and differential current are shown in Figure 9. According to Figure 9(a), the terminal voltage has obvious harmonic distortion. According to Figure 9(b), when a fault occurs, the amplitude of the stator current suddenly increases with an obvious DC component, and the second harmonic ratio of stator current is up to 30.07%. In Figure 9(c) and (d), after the fault occurs, the active power and voltage disturbance terms produce decaying fundamental frequency fluctuations. According to Figure 9(c), the differential current produces obvious harmonic distortions, threatening the reliability of transformer protection. The results of the simulation shown in Figure 9 are consistent with the theoretical analysis.

The simulations are performed again under different voltage drop and operating conditions. The FFT algorithm is applied to extract the second harmonic ratio of the transformer differential current. Table 2 shows the second harmonic ratio under different conditions. The second harmonic restraint ratio is set at 15% [31], and the ratios that exceed this limit are given in red. According to Table 2, before the mitigation measures are adopted, the second harmonic component is less when the grid voltage drops to 0.8 pu. When the voltage drops to 0.6 pu, the second harmonic ratio of phases A and B exceeds 15% and reaches as high as 19.97%. As the voltage drops to 0.4 pu, the second harmonic ratio generally exceeds 20% and reaches as high as 34.61%. When the voltage further drops to 0.2 pu, the three-phase second harmonic ratio is approximately 30%, reaching as high as 36.59%. Thus, the simulation results demonstrate that the second harmonic ratio increases gradually as the
FIGURE 9  Key variable waveforms after a three-phase short circuit (a) terminal voltage, (b) stator current, (c) stator active power, (d) voltage disturbance terms, (e) differential current

As shown in Table 2, when the voltage drops to 0.8 or 0.6 pu, all measures can suppress the second harmonic component. When the voltage drops to 0.4 or 0.2 pu, only measure 3 can suppress the second harmonic ratio to 15% or less. Taking the data marked by the red boxes as an example, the second harmonic can be reduced by 27.64%. The simulation results show that all the mitigation measures can suppress the second harmonic component effectively. In particular, there is no significant difference in the inhibition effect between measures 1 and 2, and measure 3 offers better performance.

The waveform of stator voltage and other key variables for the red box part in Table 2 is shown in Figures 10, and 11, respectively. Comparing Figure 9(a) with Figure 10, the harmonic distortion in Figure 9(a) is the largest. Figures 10(a) and (b) have similar harmonic distortion, while the harmonic distortion in Figure 10(c) is the smallest. It is found that the suggested mitigation measures can successfully suppress the second harmonic component, with measure 3 providing the best result.

5.2 Verification of mitigation measures

Using similar fault conditions as described in Section 5.1, the mitigation measures are applied independently and together, to assess their effect.

The second harmonic ratio of the transformer differential current with mitigation measures is extracted by FFT algorithm, as shown in Table 2 where measure 1 is the second-order notch filter, measure 2 is the voltage compensation control, and measure 3 is the combination of measures 1 and 2.

According to Table 2, when the voltage drops to 0.8 or 0.6 pu, all measures can suppress the second harmonic component. When the voltage drops to 0.4 or 0.2 pu, only measure 3 can suppress the second harmonic ratio to 15% or less. Taking the data marked by the red boxes as an example, the second harmonic can be reduced by 27.64%. The simulation results show that all the mitigation measures can suppress the second harmonic component effectively. In particular, there is no significant difference in the inhibition effect between measures 1 and 2, and measure 3 offers better performance.

The waveform of stator voltage and other key variables for the red box part in Table 2 is shown in Figures 10, and 11, respectively. Comparing Figure 9(a) with Figure 10, the harmonic distortion in Figure 9(a) is the largest. Figures 10(a) and (b) have similar harmonic distortion, while the harmonic distortion in Figure 10(c) is the smallest. It is found that the suggested mitigation measures can successfully suppress the second harmonic component, with measure 3 providing the best result.

According to Figure 11, after applying the mitigation measures, the fundamental frequency fluctuations in active power
| Terminal voltage | Slip rate | A (%) | B (%) | C (%) | A (%) | B (%) | C (%) | A (%) | B (%) | C (%) |
|------------------|-----------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
|                  | -0.2      |       |       |       |       |       |       |       |       |       |
| 0.8 p.u.         | No measures | 7.87  | 9.15  | 4.02  | 7.76  | 8.26  | 11.38 | 8.72  | 7.75  | 12.42 |
|                  | Measure 1 | 4.68  | 5.16  | 7.66  | 4.40  | 6.19  | 9.34  | 8.30  | 7.53  | 10.42 |
|                  | Measure 2 | 7.37  | 4.98  | 4.03  | 7.35  | 7.41  | 6.17  | 7.78  | 7.74  | 3.47  |
|                  | Measure 3 | 2.22  | 4.64  | 3.09  | 3.07  | 6.36  | 4.82  | 4.42  | 3.10  | 1.80  |
| 0.6 p.u.         | No measures | 19.97 | 16.20 | 13.15 | 19.81 | 15.83 | 10.39 | 18.58 | 16.48 | 13.47 |
|                  | Measure 1 | 9.86  | 11.01 | 10.21 | 14.17 | 9.93  | 8.94  | 11.97 | 12.54 |       |
|                  | Measure 2 | 13.86 | 10.34 | 9.08  | 14.35 | 10.40 | 7.41  | 10.29 | 9.72  | 12.17 |
|                  | Measure 3 | 5.18  | 4.76  | 7.84  | 6.69  | 5.41  | 1.50  | 4.67  | 7.24  | 4.48  |
| 0.4 p.u.         | No measures | 22.97 | 24.75 | 10.62 | 23.19 | 25.18 | 10.99 | 22.24 | 23.45 | 34.61 |
|                  | Measure 1 | 13.13 | 10.89 | 5.64  | 17.20 | 10.98 | 10.67 | 13.75 | 14.64 | 11.89 |
|                  | Measure 2 | 13.68 | 9.74  | 7.55  | 18.38 | 18.60 | 10.76 | 15.17 | 16.13 | 11.29 |
|                  | Measure 3 | 4.73  | 8.91  | 4.53  | 12.59 | 8.56  | 5.29  | 8.05  | 5.24  | 7.16  |
| 0.2 p.u.         | No measures | 22.91 | 29.66 | 35.35 | 32.16 | 36.59 | 27.36 | 18.91 | 29.80 | 33.30 |
|                  | Measure 1 | 15.32 | 16.08 | 20.60 | 9.41  | 18.52 | 14.02 | 13.13 | 19.53 | 16.98 |
|                  | Measure 2 | 16.78 | 10.40 | 15.45 | 13.38 | 18.69 | 17.13 | 15.90 | 18.58 | 23.71 |
|                  | Measure 3 | 10.74 | 6.79  | 12.05 | 5.39  | 8.95  | 12.29 | 8.29  | 14.80 | 10.42 |

FIGURE 11 Key variable waveforms with different mitigation measures (a) active power, (b) D-axis voltage disturbance, (c) Q-axis voltage disturbance

and voltage disturbance term are reduced. The effect of applying the notch filter and adopting the voltage compensation is significant, and measure 3, which is the combination of measures 1 and 2, is better than measures 1 and 2, which is consistent with the theoretical analysis.

Nomenclature

- \( \psi \) Flux linkage vector
- \( dq \) Synchronous \( dq \)-axis
- \( e \) Voltage disturbance term vector
- \( e \) Voltage disturbance term
- \( L_m, L_s, L_r \) Magnetizing, stator and rotor inductance
- \( P, Q \) Active, reactive power
- \( \text{ref} \) Reference value
- \( R_s \) Stator resistance
- \( s, r \) Stator- and rotor-side quantities

Subscript

- \( u, i \) Voltage and current vectors
- \( u_s, i_s \) Voltage and current
- \( \alpha \beta \) Stationary \( \alpha \beta \)-axis
- \( \omega, \omega_{\text{slip}} \) Fundamental and slip frequency

6 | CONCLUSION

The second harmonic characteristics play an important role in the performance of transformer differential protection. However, research on the second harmonic current contributed by DFIG is insufficient at present. This paper analyses the second harmonic transient characteristics of DFIG comprehensively, considering the voltage drop, the harmonic component of stator voltage, frequency coupling, and phase-locked deviation. Based on this, the control measures for suppressing the
second harmonic currents of DFIG are proposed. The main conclusions of this paper are as follows.

(1) The precondition for the second harmonic component generation in the SCC of DFIG is the asymmetry of the fundamental frequency component in the d- and q-axes.

(2) The second harmonic component of DFIG SCC is mainly generated by two factors. One is the sudden drop in stator voltage, which makes the active power to generate the fundamental frequency component. The other is the second harmonic component of stator voltage, which leads to the asymmetric fundamental frequency component in the voltage disturbance term. The rotor current responds to the active power and voltage disturbance term, to generate the second harmonic component in abc SRF.

(3) The second harmonic component of DFIG SCC can be suppressed by applying a notch filter to filter out the fundamental frequency component of the stator active power and adopting voltage compensation measures to offset the voltage disturbance term.

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APPENDIX A

1. Detailed expressions of \( \mu_1 \) and \( \mu_2 \) in (10)
\[
\mu_{1,2} = \frac{-(R_r + K_{Ip}) \pm \sqrt{(R_r + K_{Ip})^2 - 4\sigma L_r K_{II}}}{2\sigma L_r}, \quad (A1)
\]

2. Detailed expressions of coefficients in (11)
\[
A_p = -\frac{3U_1 l_0}{4} J \left[ \frac{K_{Ip} (j\omega_1 - 1/\tau_r) + K_{II} [K_{Ip} (j\omega_1 - 1/\tau_r) + K_{II}]}{(j\omega_1 - 1/\tau_r + \mu_1)(j\omega_1 - 1/\tau_r + \mu_2)(j\omega_1 - 1/\tau_r)} \right]
\]
\[
B_p = -\frac{3U_1 l_0}{2} J \left[ \frac{K_{Ip} (-j\omega_1 - 1/\tau_r) + K_{II} [K_{Ip} (-j\omega_1 - 1/\tau_r) + K_{II}]}{(-j\omega_1 - 1/\tau_r + \mu_1)(-j\omega_1 - 1/\tau_r + \mu_2)(-j\omega_1 - 1/\tau_r)} \right]
\]
\[
C_p = \frac{3U_1 l_0}{4} J \left[ \frac{-K_{II} K_{IP}}{\mu_1 \mu_2 (j\omega_1 + 1/\tau_r) s} + \frac{(-K_{IP} \mu_1 + K_{II}) (-K_{IP} \mu_1 + K_{II})}{\mu_1 (\mu_1 - \mu_2) (j\omega_1 + 1/\tau_r - \mu_1) (s + \mu_1)} + \frac{(-K_{IP} \mu_2 + K_{II}) (-K_{IP} \mu_2 + K_{II})}{\mu_2 (\mu_1 - \mu_2) (1/\tau_r - \mu_1 - j\omega_1) (s + \mu_1)} \right]
\]
\[
\times \frac{3U_1 l_0}{4} J \left[ \frac{K_{II} K_{IP}}{\mu_1 \mu_2 (-j\omega_1 + 1/\tau_r) s} + \frac{(-K_{IP} \mu_1 + K_{II}) (-K_{IP} \mu_1 + K_{II})}{\mu_1 (\mu_1 - \mu_2) (1/\tau_r - \mu_1 - j\omega_1) (s + \mu_1)} + \frac{(-K_{IP} \mu_2 + K_{II}) (-K_{IP} \mu_2 + K_{II})}{\mu_2 (\mu_1 - \mu_2) (1/\tau_r - \mu_1 - j\omega_1) (s + \mu_1)} \right]. \quad (A2)
\]

3. Detailed expressions of coefficients in (20)
\[
D = -\frac{K_{P2LL} - j\omega_1 K_{P2PLL}}{(\lambda_1 - j\omega_1)(\lambda_2 - j\omega_1)} u_2, \quad (A5)
\]

4. Detailed expressions of \( \mu_3 \) and \( \mu_4 \) in (27)
\[
\mu_{3,4} = \frac{-(R_r + R_s K_{IP} + \sigma L_r K_{II}) \pm \sqrt{(R_r + R_s K_{IP} + \sigma L_r K_{II})^2 - 4\sigma L_r (1 + K_{IP}) R_s K_{II}}}{2\sigma L_r (1 + K_{IP})} \quad (A6)
\]

5. Detailed expressions of coefficients in (28)
\[
A_{cr} = \frac{I_m (u_3 - u_2)}{I_s} \left( \frac{\kappa_1}{j\omega_1 + \mu_3} - \frac{\kappa_2}{j\omega_1 + \mu_4} \right),
\]
\[
B_{cr} = \frac{I_m (u_3 - u_2)}{I_s} \left( \frac{\kappa_2}{j\omega_1 + \mu_3} - \frac{\kappa_1}{j\omega_1 + \mu_4} \right)
\]
\[
C_{cr} = \frac{I_m (u_3 - u_2)}{I_s} \left[ \left( -\frac{\kappa_1}{(j\omega_1 + \mu_3) (s + \mu_3)} + \frac{\kappa_2}{(j\omega_1 + \mu_4) (s + \mu_4)} \right) \right.
\]
\[
\left. + \frac{\kappa_1}{(j\omega_1 - \mu_3) (s + \mu_3)} - \frac{\kappa_2}{(j\omega_1 - \mu_4) (s + \mu_4)} \right] \quad (A7)
\]

6. Detailed expressions of coefficients in (29)
\[
A_{cr} = \frac{I_m (u_6 - u_6)}{I_s} \left( \frac{\kappa_1}{j\omega_1 + \mu_3} - \frac{\kappa_2}{j\omega_1 + \mu_4} \right),
\]
\[
B_{cr} = \frac{I_m (u_6 - u_6)}{I_s} \left( \frac{\kappa_2}{j\omega_1 + \mu_3} - \frac{\kappa_1}{j\omega_1 + \mu_4} \right)
\]
\[
C_{cr} = \frac{I_m (u_6 - u_6)}{I_s} \left[ \left( -\frac{\kappa_1}{(j\omega_1 + \mu_3) (s + \mu_3)} + \frac{\kappa_2}{(j\omega_1 + \mu_4) (s + \mu_4)} \right) \right.
\]
\[
\left. + \frac{\kappa_1}{(j\omega_1 - \mu_3) (s + \mu_3)} - \frac{\kappa_2}{(j\omega_1 - \mu_4) (s + \mu_4)} \right] \quad (A10)
\]

\[
\kappa_1 = \frac{\mu_3}{\mu_3 - \mu_4}, \quad \kappa_2 = \frac{\mu_4}{\mu_3 - \mu_4}. \quad (A9)
\]

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## APPENDIX B

### TABLE B  Parameters of 1.5 MW DFIG

| Parameters          | Quantity     | Parameters                  | Quantity   |
|---------------------|--------------|-----------------------------|------------|
| Rated power         | 1.5 MW       | Stator leakage inductance   | 0.18 pu    |
| Stator voltage      | 575 V        | Rotor leakage inductance    | 0.16 pu    |
| Rotor voltage       | 1975 V       | Magnetizing inductance      | 2.9 pu     |
| Stator resistance   | 0.023 pu     | DC-link voltage             | 1150 V     |