Design of Control Method for Improving Current Quality of Wind Power Grid-Connected Inverter

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Abstract. The problem of suppression of nonlinear random impulse disturbance in grid-connected wind power generation is studied in this paper. The mathematical model of grid side converter of wind power system is obtained by using Kirchhoff law. A feedback synchronization controller is designed to suppress the disturbance of current. With the help of Lyapunov stability theory, the effectiveness of the synchronization controller is verified. Further effectively restrain the nonlinear random disturbance caused by the current connected to the grid, so that the current generated by the wind turbine is synchronized with the current generated by the power grid. Finally, the simulation verification is carried out. The simulation results show that the effectiveness of the proposed control method.

1. Introduction

As the core mechanism of the energy conversion of the entire wind power system, the wind power converter is responsible for converting time-varying wind energy into constant frequency electric energy. The quality of its control performance will affect the safety and stable operation of the entire wind power system. Wind turbines at the end of the power grid are generally connected to the main power grid through long-distance transmission lines, and the grid connection point is extremely susceptible to impact and fluctuating load interference. Nonlinear impulse disturbances can cause negative effects such as three-phase current distortion, bus voltage and grid-connected power fluctuations of the wind power grid-connected converter, which will reduce the quality of grid-connected power generation and affect the safe operation of the wind power system [1].

In the current control of grid-connected inverters, PI control is widely used because of its good dynamic performance and simple digital implementation [2], but it cannot achieve instability error tracking of AC signals, and the low-order harmonics of the system cannot be effectively suppressed [3]. In reference [4] adopts PR (proportional resonance) control with infinite gain at the fundamental angular frequency, which can theoretically track the fundamental frequency input signal without error, while suppressing the disturbance of the grid voltage at the fundamental frequency. PR control is easy to realize the compensation of low-order harmonics, but to compensate for the harmonics of multiple
frequencies, and a corresponding number of PR controllers are required, which makes the system structure complicated and is not conducive to system stability [5]. In addition, the dynamic response of the PR controller is slow, and the transition time at the beginning is long, which is not conducive to the rapid stability of the system [6]. In reference [7], RC (repeat control) control method based on internal model principle controls the grid-connected current and can obtain a good current waveform. At the same time, RC control has control coupling with PI in its mechanism [8], and if this is not improved, the grid-connected current is prone to distortion.

In this paper, the problem of synchronization control with nonlinear impulse disturbance in grid connection of high-power wind power generation is studied, and an appropriate feedback synchronization controller is designed. With the help of Lyapunov stability theory, the effectiveness of the synchronization controller is verified. The corresponding algorithm is given for the problem studied. Finally, the simulation design is carried out to verify the effectiveness of the theoretical results.

2. Wind power inverter model

The topology of wind power grid-connected inverter is shown in figure 1. In figure 1, \( u_{dc} \) is DC side capacitance voltage. \( i_{bus} \) is DC side current and \( i_{dc} \) is capacitance current. \( R \) is resistance shunt reactor of grid-side converter, and \( L \) is the grid-side inductance. \( C \) is DC side capacitance. \( e_a, e_b, e_c \) are A-phase voltage, B-phase voltage, C-phase voltage of power grid, respectively. Similarly \( i_a, i_b, i_c \) are three phase currents of power grid.

\[
\begin{align*}
S_{ap} & \quad S_{bp} \quad S_{cp} \quad S_{an} \quad S_{bn} \quad S_{cn} \\
\text{Inverter} & \quad \text{Power Grid} \\
i_{bus} & \quad i_d \quad \text{s} \quad \text{m} \quad \text{n} \quad \text{p} \\
L & \quad R & \quad C & \quad u_{dc} & \quad \text{O}
\end{align*}
\]

Figure 1. Topology of grid-connected inverter

\( S_{ap}, S_{bp}, S_{cp}, S_{an}, S_{bn} \) and \( S_{cn} \) are IGBT devices. \( S_m \) (\( m = a, b, c \)) is switching function, \( S_m \) can be represented as follows:

\[
s_m = \begin{cases} 
1 & \text{for turnon} \\
0 & \text{for turnoff}
\end{cases}
\] (1)

Based on Kirchhoff's law, the grid-side converter mathematical model is obtained [9].

\[
\begin{align*}
\frac{di_a}{dt} &= -\frac{R}{L} i_a + e_a - \left( s_a - \frac{s_a + s_b + s_c}{3} \right) u_{dc} \\
\frac{di_b}{dt} &= -\frac{R}{L} i_b + e_b - \left( s_b - \frac{s_a + s_b + s_c}{3} \right) u_{dc} \\
\frac{di_c}{dt} &= -\frac{R}{L} i_c + e_c - \left( s_c - \frac{s_a + s_b + s_c}{3} \right) u_{dc} \\
\frac{di_{bus}}{dt} &= \frac{s_a}{C} i_a + \frac{s_b}{C} i_b + \frac{s_c}{C} i_c - \frac{1}{C} i_{bus}
\end{align*}
\] (2)

The model in equation (2) includes the switching function \( s_m \) (\( m = a, b, c \)). The switching device has high frequency components during the turn-on or turn-off process, which is not conducive to the design of the controller. The frequency of the switching device is much higher. It is the fundamental frequency of the power grid. The mathematical model is simplified by ignoring the high frequency components of the switching device during the turn-on or turn-off process. In the simplified mathematical model, only low-frequency components are considered, and the duty cycle parameter is...
introduced into the low-frequency mathematical model [10]. The simplified mathematical model, namely the low-frequency converter model, is suitable for control system analysis. The simplified mathematical model can be used for control method design.

The model in equation (2) is simplified, and the simplified mathematical model is transformed from three-phase static coordinate system to two-phase static coordinate system [11]. The simplified mathematical model of converter under two-phase stationary coordinate system is shown in equation (3).

\[
\begin{align*}
\frac{di_a}{dt} &= -\frac{R}{L}i_a - \frac{D_a}{L}u_{dc} + \frac{1}{L}u_a \\
\frac{di_\beta}{dt} &= -\frac{R}{L}i_\beta - \frac{D_\beta}{L}u_{dc} + \frac{1}{L}u_\beta \\
\frac{du_{dc}}{dt} &= \frac{3}{2C}D_\alpha i_\alpha - \frac{3}{2C}D_\beta i_\beta - \frac{1}{C}i_{bus}
\end{align*}
\]

In which \(D_\alpha\) and \(D_\beta\) is duty cycle under \(a\beta\) coordinate system, respectively. \(u_a, u_\beta\) is the voltage under two-phase static coordinate system, respectively. \(i_a, i_\beta\) is the current of under \(a\beta\) coordinate system, respectively.

Due to the influence of weather changes, the wind speed shows strong nonlinearity, randomness and uncertainty, which makes the nonlinear dynamic characteristics of wind power system current more obvious than that of conventional power system. In order to simulate the nonlinear disturbance of grid-side current caused by external interference, the characteristics of Chua's diode is introduced in this paper [12]. Chua's diode is incorporated into the power grid, as shown in figure 2.

![Figure 2. Circuit model of wind power grid-connected inverter with nonlinear disturbance.](image)

Figure 2 shows the converter model which is incorporated into chua's diode on power grid side, which can simulate nonlinear disturbance. From Figure 2, \(e_a = f(i_a), e_b = f(i_b), e_c = f(i_c)\) is replaced by \(e_a, e_b, e_c\). According to equation (3), we can get the mathematical model shown in equation (4).

\[
\begin{align*}
\frac{di_a}{dt} &= -\frac{R}{L}i_a - \frac{D_a}{L}u_{dc} + \frac{1}{L}f(i_a) \\
\frac{di_\beta}{dt} &= -\frac{R}{L}i_\beta - \frac{D_\beta}{L}u_{dc} + \frac{1}{L}f(i_\beta) \\
\frac{du_{dc}}{dt} &= \frac{3}{2C}D_\alpha i_\alpha - \frac{3}{2C}D_\beta i_\beta - \frac{1}{C}i_{bus}
\end{align*}
\]

\[
\begin{align*}
\left\{ f(i_a) = u_a &= G_a i_\alpha + 0.5(G_a - G_b) [y_a + I - \|y_a - I\|] \\
\left\{ f(i_\beta) = u_\beta &= G_b i_\beta + 0.5(G_a - G_b) [y_\beta + I - \|y_\beta - I\|] \\
\end{align*}
\]

In which \(I, G_a, G_b\) is Chua's diode parameters. For easy derivation, let \(x_1 = i_a, y_1 = i_\beta, z_1 = u_{dc}\). Let:
\[
\begin{align*}
\{ h(x_1) &= \frac{1}{L} f(x_1) = G_a x_1 + 0.5(G_a - G_b) \left[ \frac{y_1 + y_1}{L} \right] \\
h(y_1) &= \frac{1}{L} f(y_1) = G_b y_1 + 0.5(G_a - G_b) \left[ \frac{y_1 + y_1}{L} \right]
\end{align*}
\] (6)

Let: \( m_0 = G_b / L \), \( m_1 = G_a / L \). And we divide \( h(x_1) \) into three segments, as follows:

\[
h(x_1) = \begin{cases} 
m_0 x_1 + (m_1 - m_0) I & x_1 > I \\
m_1 x_1 & |x_1| \leq I \\
m_0 x_1 - (m_1 - m_0) I & x_1 < -I
\end{cases}
\] (7)

Figure 3 is the curve of \( h(x_1) \). From Figure 3, it can see that the curve of \( h(x_1) \) is different in different regions of \( x_1 \).

3. Analysis of Nonlinear Perturbation and Impulse Disturbance

If for any \( x_0 \in R \), a domain \( U = U(x_0) \subset R \) of \( x_0 \) is existence. And a constant \( I > 0 \) is existence. For any \( x_1, x_2 \) has \( |h(x_2) - h(x_1)| \leq I |x_2 - x_1| \). On \( x \in R \), \( h(x) \) meets local Lipschitz condition.

Let:

\[
A = \begin{bmatrix} R/L & 0 & D_a/L \\ -R/L & D_b/L \\
3D_a/2C & 3D_b/2C & i_{bus}/C \end{bmatrix}
\] (8)

In which \( R, L, C \) is a known constant respectively. \( D_a, D_b \) is also a constant, and \( i_{bus} \) is also a constant.

Transform and organize equation (4), and the mathematical model of the grid-side converter is shown in equation (9).

\[
\begin{align*}
\dot{x}_1 &= -\frac{R}{L} x_1 - \frac{D_a}{L} z_1 + \frac{1}{L} u_a \\
\dot{y}_1 &= -\frac{R}{L} y_1 - \frac{D_b}{L} z_1 + \frac{1}{L} u_b \\
\dot{z}_1 &= \frac{3D_a}{2C} x_1 + \frac{3D_b}{2C} y_1 - \frac{i_{bus}}{C}
\end{align*}
\] (9)

Obviously, equation (9) is a mathematical model that system is not disturbed. In order to ensure the synchronization between the drive system and the response system, we construct a response system model with nonlinear disturbance as follows:
\[
\begin{bmatrix}
\dot{x}_2 = -\frac{R}{L} x_2 - \frac{D_0}{L} z_2 + h(x_2) + u_{c1} + u_{s1} \\
\dot{y}_2 = -\frac{R}{L} y_2 - \frac{D_0}{L} z_2 + h(y_2) + u_{c2} + u_{s2} \\
\dot{z}_2 = \frac{3D_u}{2C} x_2 + \frac{3D_b}{2C} y_2 - \frac{i_{bus}}{C} + u_{c3} + u_{s3}
\end{bmatrix}
\]  \quad (10)

In which \( u_c = [u_{c1} \ u_{c2} \ u_{c3}] \) is a synchronic controller.

Equation (9) and equation (10) show different circuit structures. \( u_s = [u_{s1} \ u_{s2} \ u_{s3}] \) is compensator. By adding a compensator, the circuit structure represented by the equation (9) and equation (10) can be made the same.

During the conversion process of wind power grid-connected converter, multiple groups of switch devices are always on and off, which is causing spike current. In order to suppress the spike current, we designed the controller. Equation (9) can be transformed into the following form.

\[
\begin{bmatrix}
\dot{x} = Ax + S \\
\Delta x(t) = x(t)
\end{bmatrix}
\]  \quad (11)

In which \( x = [x_1(t) \ y_1(t) \ z_1(t)]^T \), \( S = \begin{bmatrix} \frac{u_{a}}{L} & \frac{u_{b}}{L} & 0 \end{bmatrix}^T \).

Equation (11) is a mathematical model that is not disturbed, and it is taken as a driving system. We constructed a response system model as follows.

\[
\begin{align*}
\dot{y}(t) &= Ay(t) + \phi(y(t)) + u_c + u_s \quad t \neq t_k \\
\Delta y(t) &= B_k y(t) \quad t = t_k \quad (k \in \mathbb{N}^+) \\
y(t_0) &= y_0
\end{align*}
\]  \quad (12)

In which \( y(x), \Delta y(t_k), \phi(y(t)) \) are:

\[
\begin{bmatrix}
y(t) = [x_2(t) \ y_2(t) \ z_2(t)] \\
\Delta y(t_k) = y(t_k^+) - y(t_k^-) \\
\phi(y(t)) = [h(x_2(t)) \ h(y_2(t)) \ 0]^T
\end{bmatrix}
\]  \quad (13)

In which \( y(t_k^+) = \lim_{t \to t_k^+} y(t), \ y(t_k^-) = \lim_{t \to t_k^-} y(t) \). Because the left point is continuous when the IGBT device is closed, there are \( y(t_k^-) = \lim_{t \to t_k^-} y(t) = y(t_k) \) . \( \{t_k\} \) satisfies \( 0 < t_1 < t_2 < \cdots < t_k < \cdots, t_k \to \infty \), \( u_s = [u_{s1} \ u_{s2} \ u_{s3}]^T \) is a structural compensator, and \( u_c = [u_{c1} \ u_{c2} \ u_{c3}]^T \) is a feedback controller. \( B_k \in \mathbb{R}^{3 \times 3} \) is a diagonal matrix which is representing impulse controller and all diagonal elements are less than 1.

Let \( \Omega \subset \mathbb{R}^n \), \( \Omega \) be an n-dimensional open subset of \( \mathbb{R}^n \) space with origin, the function \( V(t, x) \) is defined in \( S \times \Omega \to \mathbb{R} \), and the time \( t \) belongs to an open interval \( S = (t_1, t_2) \). The function \( V(t, x) \) is continuous and has a first-order continuous partial derivative, which is a single-valued function, and satisfy \( V(t, 0) = 0 (\forall t \in S) \). so the function \( V(t, x) \) is a Lyapunov function.

Equation (11) is the driving system, and equation (12) is the response system, which satisfies \( \lim_{t \to x_0} \| \phi(t) \| = \lim_{t \to x_0} \| y(t, y_0) - x(t, x_0) \| = 0 \) for any initial state \( x_0 \) and \( y_0 \). so the driving system and the response system are said to be synchronous.
4. Feedback controller design

4.1. Design of feedback controller for suppressing nonlinear perturbation

We define the error variable, as follows.

\[
\begin{align*}
    e_1 &= x_2 - x_1 \\
    e_2 &= y_2 - y_1 \\
    e_3 &= z_2 - z_1
\end{align*}
\]  
(14)

Use (10) and (9) to make a difference, and take:

\[
\begin{align*}
    u_{s1} &= \frac{u_a}{L} - h(x_1) \\
    u_{s2} &= \frac{u_b}{L} - h(y_1) \\
    u_{s3} &= 0
\end{align*}
\]  
(15)

We can get the error system model, as follows.

\[
\begin{align*}
    \dot{e}_1 &= -\frac{R}{L}e_1 - \frac{D_a}{L}e_3 + h(x_2) - h(x_1) + u_{s1} \\
    \dot{e}_2 &= -\frac{R}{L}e_2 - \frac{D_b}{L}e_3 + h(y_2) - h(y_1) + u_{s2} \\
    \dot{e}_3 &= \frac{3D_a}{2C} e_1 + \frac{3D_b}{2C} e_2 - \frac{i_{bus}}{C} e_2 + u_{s3}
\end{align*}
\]  
(16)

Taking Lyapunov function \( V = (e_1^2 + e_2^2 + e_3^2)/2 \), and nonlinear function \( h(x_1) \) meets local Lipschitz condition \([15-16]\), as follows.

\[
\dot{V} = e_1 \dot{e}_1 + e_2 \dot{e}_2 + e_3 \dot{e}_3
\]

\[
\begin{align*}
    &= e_1(-\frac{R}{L}e_1 - \frac{D_a}{L}e_3 + h(x_2) - h(x_1) + u_{s1}) + e_2(-\frac{R}{L}e_2 - \frac{D_b}{L}e_3 + h(y_2) - h(y_1) + u_{s2}) + e_3(\frac{3D_a}{2C} e_1 + \frac{3D_b}{2C} e_2 - \frac{1}{R(C)} e_2 + u_{s3}) \\
    &\leq -ae_1^2 + \frac{d-b}{2}(e_1^2 + e_3^2) + l_1 e_1^2 - k_1 e_3^2 - ae_2^2 + \frac{e-c}{2} (e_2^2 + e_3^2) + l_2 e_2^2 - k_2 e_3^2 - fe_3^2 - k_3 e_3^2 \\
    &\leq (a+k_1 + \frac{1}{2}b - \frac{1}{2}d - l_1)e_1^2 + (a+k_2 + \frac{1}{2}c - \frac{1}{2}e - l_2)e_2^2 + (k_3 + f + \frac{1}{2}b + \frac{1}{2}c - \frac{1}{2}d - \frac{1}{2}e)e_3^2 \\
    &\leq -\lambda V = -\frac{\lambda}{2}(e_1^2 + e_2^2 + e_3^2)
\end{align*}
\]  
(17)

In which \( \lambda \) as follows:

\[
\lambda = \min \left\{ \frac{2a + 2k_1 + b - 2l_1 - d}{2a + 2k_2 + c - 2l_2 - e}, \frac{2k_3 + 2f + b + c - d - e}{2k_3 + 2f + b + c - d - e} \right\} > 0
\]  
(18)

According to equation (17), we can get \( \dot{V}/V \leq -\lambda \). Integrating two sides of the inequality from \( 0 \rightarrow t \), and we can get \( V(t) \leq e^{-\lambda t} \). Because \( V(t) \geq 0, V(t) \rightarrow 0 \) is known when \( t \rightarrow \infty \), so \( e_1 \rightarrow 0, e_2 \rightarrow 0, e_3 \rightarrow 0 \). Equation (9) and equation (10) are synchronized.

According to the Lagrange mean value theorem: \( f(x_2) - f(x_1) = f'(\xi)|x_2 - x_1| \), takes \( l_1, l_2 = \max \{ h'(\xi) \} \). The value of \( a, b, c, d, e \) and \( f \) are as follows.
The difference between (11) and (12) is:

\[
\begin{align*}
\dot{e}(t) &= Ae(t) + \varphi(y(t)) - \varphi(x(t)) + u_i \\
\Delta e(t) &= B_k(y(t) - x(t)) \leq B_k(y(t) - x(t)) = B_k e(t) \\
&= t = t_k, k \in \mathbb{N}^+
\end{align*}
\]

According to impulsive differential equation theory, Choosing Lyapunov function \( V = e(t)^T e(t)/2 \), then there is:

\[
\dot{V} = \frac{1}{2}(Ae(t) + \varphi(y(t)) - \varphi(x(t)) + u_i)^T e(t) + \frac{1}{2}e(t)^T (Ae(t) + \varphi(y(t)) - \varphi(x(t)) + u_i)
\]

\[
= e(t)^T \left( \frac{A}{2} e(t) + (h(x_2) - h(x_1))e_1(t) + (h(y_2) - h(y_1))e_2(t) - k_1 e_1^2(t) - k_2 e_2^2(t) - k_3 e_3^2(t) \right)
\]

\[
\leq 2\lambda V(t) + (l_1 - k_1) e_1^2(t) + (l_2 - k_2) e_2^2(t) - k_3 e_3^2(t)
\]

\[
\leq 2(\lambda + M) V(t)
\]

In which \( M = \max \left\{ l_1, l_2, l_2 \right\} \), \( \min (k_i) = \rho - H \), and \( 0 < \rho < M \) is a constant. \( l_1, l_2 = \max \left\{ h(\xi) \right\} \), then there is:

\[
V(t) \leq V(t_{k-1}) \exp[2(\lambda + M)(t - t_{k-1})]
\]

Wherein \( t \in [t_{k-1}, t_k) \), \( k = 1, 2, 3, \ldots \).

On the other hand [17-19]:

\[
A = \begin{bmatrix}
- \frac{R}{L} & 0 & - \frac{D_a}{L} \\
0 & - \frac{R}{L} & - \frac{D_b}{L} \\
\frac{3D_a}{2C} & \frac{3D_b}{2C} & \frac{1}{C}
\end{bmatrix}
\]
\[ \Delta e(t_k) = e(t_k^*) - e(t_k^-) \]
\[ \Rightarrow \Delta e(t_k^-) + e(t_k^-) = e(t_k^*) \]
\[ \Rightarrow e(t_k^-) \leq (B_k + E)e(t_k^-) \]  \hspace{1cm} (24)

When \( t = t_k^* \), there is:
\[ V(t_k^*) = \frac{1}{2} e^T (t_k^*) e(t_k^-) \leq \frac{1}{2} [(B_k + E)e(t_k^-)]^T [(B_k + E)e(t_k^-)] \]
\[ \leq \frac{1}{2} \lambda_{\text{max}} [(B_k + E)^T (B_k + E)] e^T (t_k^-) e(t_k^-) \]
\[ = \beta_k V(t_k^-) \]  \hspace{1cm} (25)

For inequality (23), when \( k=1 \), for any \( t \in (t_0, t_1) \), there is:
\[ V(t) \leq V(t_{k-1}^*) \exp[2(\lambda + M)(t - t_{k-1})] \Rightarrow V(t_1) \leq V(t_0^*) \exp[2(\lambda + M)(t_1 - t_0)] \]  \hspace{1cm} (26)

According to (25), there is:
\[ V(t_1^-) \leq \beta_1 V(t_1) \leq \beta_1 V(t_0^*) \exp[2(\lambda + M)(t_1 - t_0)] \]  \hspace{1cm} (27)

Similarly, for \( t \in (t_1, t_2) \), there is \( V(t) \leq V(t_0^*) \beta_1 \exp[2(\lambda + M)(t_1 - t_0)] \). Repeat the same process, when \( t \in (t_k, t_{k+1}) \), there is:
\[ V(t) \leq V(t_{k+1}^*) \beta_1 \beta_2 \cdots \beta_k \exp[2(\lambda + M)(t - t_0)] \]  \hspace{1cm} (28)

Because \( \beta_k \exp[2(\lambda + M)(t_k - t_{k-1})] \leq 1/\xi, (k = 1, 2, \cdots) \), further simplifies inequality (28):
\[ V(t) \leq V(t_0^*)[\beta_1 \exp[2(\lambda + M)(t_1 - t_0)]] \times \cdots \times [\beta_k \exp[2(\lambda + M)(t_k - t_{k-1})]] \]
\[ \leq V(t_0^*) \frac{1}{\xi^k} \exp[2(\lambda + M)(t - t_0)] \]  \hspace{1cm} (29)

5. Simulation verification

In order to verify the effectiveness of control strategy, Matlab/Simulink is used to simulate the α-axis sinusoidal current. A model with nonlinear current perturbation can be suppressed on Simulink. Figure 4 show diagram of the proposed control method.

![Figure 4. Block diagram of grid-side current disturbance control](image)
5.1. Nonlinear perturbation simulation verification
As can be seen from Figure 4, the controller model is divided into two parts:
(a) $\alpha/\beta$ axis perturbation current model.
(b) $\alpha/\beta$ axis perturbation current control.
Because most nonlinear systems can be transformed into linear part and nonlinear part, $\alpha$ axis and $\beta$ axis current equations are transformed into linear part and nonlinear part. The linear part takes $u_{dc}$ and $i_{\alpha}/i_{\beta}$ as input. The transfer function of linear part is obtained by Laplace transform. Based on description function method [20-24] in nonlinear control system, the transfer function of nonlinear part is obtained. Based on the transfer function of nonlinear part, a nonlinear perturbation model of Chua’s diode is designed on Simulink, that is, the nonlinear perturbation model in figure 5. The detailed model of nonlinear perturbation module is shown in figure 6.

![Figure 5. Controller block diagram of nonlinear perturbation.](image)

![Figure 6. Detailed Model of nonlinear perturbation Module.](image)

Figure 7 shows the nonlinear perturbation AC waveform obtained by sinusoidal wave passing through nonlinear perturbation module. The AC waveform in figure 7 is in accordance with perturbation characteristics of Chai’s diode to sinusoidal AC current. Obviously, such AC current does not meet the requirements of grid-connected current.

![Figure 7. Nonlinear disturbance current.](image)
perturbation of the controller $u_{c1}$, $u_{c2}$, $u_{c3}$ can be calculated, taking $L=10^{-1}\text{H}$, $R=0.52\Omega$, $D_a=0.2$, $C=1.485\times10^{-4}\text{F}$, $G_a=-0.4$, $\alpha$ axis AC controller parameters range is $k_1>999.5$. When $-k_1=-1000$, the resulting value is substituted into the model of Figure 5 to obtain the waveform of Figure 8. It can be seen from Figure 8 that the amplitude and phase angle of the two waveform are exactly the same, so the controller designed can effectively suppress the nonlinear disturbances current, and the current that is integrated into the grid is healthy. From Figure 9, we can see that the error tends to zero under the proposed controller, thus effectively suppressing the nonlinear disturbance current.

5.2. Nonlinear impulse perturbation simulation verification

According to the chapter of feedback controller design to suppress spike current, the control simulation model of nonlinear impulse perturbation is built on Simulink. Figure 10 shows the block diagram of AC current model under nonlinear impulse disturbance. The current waveform with nonlinear impulse disturbance is shown in Figure 11. The instantaneous sudden change caused by the continuous breaking of switching devices on the grid-connected current.

![Figure 8. Comparison of $\alpha$ axis standard sinusoidal current and regulated nonlinear perturbation AC current.](image)

![Figure 9. $\alpha$ axis error curve.](image)

![Figure 10. AC current model diagram with nonlinear impulse disturbance.](image)

![Figure 11. Nonlinear impulse disturbance current.](image)
Figure 12 is a designed controller model for suppressing spike current. Let $\xi=1.12$, the initial values of the drive system and the response system are $x(0) = (0.83, 0.68, 0.57)$ and $z(0) = (0.71, 0.53, 0.41)$. Select $M=362.61$, the eigenvalue of matrix $(A + A^T)/2$ is $-1.437$, $-0.0001$, $0.0919$, because $\lambda = \lambda_x(((A + A^T)/2) = 0.0919$, the impulse control gain matrix $B_k$ is a constant matrix $B = \text{diag} \{ b_1, b_2, b_3 \}$. Taking $\alpha$ axis current as an example, when $\rho=306.42$, $-k=310.5$ and $b=0.032$ can be obtained. The parameters are substituted into the two control modules in the control block diagram model of figure 12, and the waveform of figure 13 is obtained after running model on Simulink.

$$\text{Figure 12. Controller block diagram of nonlinear impulse perturbation.}$$

It can be seen from Figure 13 that the amplitude and phase angle of the two waveforms are the same, so the designed feedback controller can effectively suppress nonlinear impulse disturbance current and synchronize the disturbance current and the normal current. From Figure 14, it can be seen that under the action of the feedback controller, the error asymptotically converges to 0, that is, the nonlinear impulse disturbance current approaches the normal current. Similarly, $\beta$ axis sinusoidal current can be controlled.

6. Conclusions

In this paper, the problem of nonlinear impulse disturbance in the grid connection of high-power wind power generation is analyzed and discussed. A nonlinear impulse disturbance model based on the differential equation of the main circuit of the grid-side converter is established. In order to effectively restrain the nonlinear impulse disturbance in the current, an error system is constructed and a controller is designed to suppress the grid-connected current disturbance. The accurate algorithm of
the controller is given with the help of Lyapunov stability theory. The effectiveness of the algorithm is proved by simulation design on Simulink in Matlab.

References
[1] Serban E, Ordonez M and Pondiche C 2015 Dc-bus voltage range extension in 1500 V photovoltaic inverters IEEE J. Emerg. Sel. Top. Power Electron. 3 901-17
[2] Serban E, Paz F and Ordonez M 2017 Improved pv inverter operating range using a mini-boost IEEE Trans. Power Electron 32 8470-85
[3] Duc-Tri D and Minh-Khai N 2018 Three-level quasi-switched boost T-type inverter: analysis PWM control and verification IEEE Trans. Ind. Electron 65 8320-29
[4] Liu Y 2014 Effects of converter pulse voltage on insulation life of doubly-fed wind generators Power Equipment 28 186-8
[5] Sainz L and Mesas J 2010 Deterministic and stochastic study of wind farm harmonic currents IEEE Trans. Energy Convers. 25 1071-80
[6] Yao J, Xia X F, Chen X Y and Liao Y 2012 Harmonic currents suppression for full size power grid-connection converter used for wind power generation Proceeding of the CSEE 32 17-25
[7] Yang H J, Li P, Xia Y Q and Yan C 2019 Double-loop stability for high frequency networked control systems subject to actuator saturation IEEE T. Cybern. 49 1454-62
[8] Chang X H and Wang Y M 2018 Peak-to-peak filtering for networked nonlinear dc motor systems with quantization IEEE Trans. Ind. Inform. 14 5378-88
[9] Zhang C Y 2007 Stability analysis and design of impulsive control systems with time delay IEEE Trans. Autom. Control 52 1448-54
[10] Dong L Z D and Yasuhiro T 2013 Impulsive control of multiple lotka–volterra systems Nonlinear Anal.-Real World Appl. 14 1144-54
[11] Li S K, Zhang J X and Tang W S 2012 Robust H ∞ control for impulsive switched complex delayed networks Mathematical and Computer Modelling 56 257-67
[12] Yuan C Z 2017 Robust H∞consensus for multi-agent systems with time-varying input delay using dynamic IQCs American Control Conference (ACC) 2017 930-35
[13] Yang M, Wang Y W, Xiao J W and Huang Y H 2012 Robust synchronization of singular complex switched networks with parametric uncertainties and unknown coupling topologies via impulsive control Commun. Nonlinear Sci. Numer. Simul. 17 4404-16
[14] Geng H, Liu C and Yang G 2013 LVRT capability of DFIG based WECS under asymmetrical grid fault condition IEEE Trans. Ind. Electron. 60 2495-509
[15] Rakkiyappan R, Velmurugan G and Cao J D 2014 Finite-time stability analysis of fractional-order complex-valued memristor-based neural networks with time delays Nonlinear Dyn. 78 2823-36
[16] Shi Z F, Peter I and Tu S Z 2007 Global flows for stochastic differential equations without global Lipschitz conditions Mathematics and statistics online 35 180-205
[17] Sun Y and Cao J 2007 Adaptive synchronization between two different noise-perturbed chaotic systems with fully unknown parameters Physical A 376 253-65
[18] Rakkiyappan R, Chandrasekar A and Pchiammal G 2014 Non-fragile robust synchronization for Markovian jumping chaotic neural networks of neutral-type with randomly occurring uncertainties and mode-dependent time-varying delays ISA Transactions 53 1760-70
[19] Wang H M, Duan S K, Li C D, Wang L D and Huang T W 2015 Stability of impulsive delayed linear differential systems with delayed impulses Journal of the Franklin Institute 352 3044-68
[20] Velmurugan G, Rakkiyappan R and Cao J D 2015 Further analysis of global μ-stability of complex-valued neural networks with unbounded time-varying delays Neural Networks 67 14-27
[21] Wen S P, Zeng Z G, Huang T W and Li C J 2015 Passivity and passification of stochastic impulsive memristor-based piecewise linear system with mixed delays Int. J. Robust

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Nonlinear Control 25 610-24

[22] Yang X S and Cao J D C 2014 Hybrid adaptive and impulsive synchronization of uncertain complex networks with delays and general uncertain perturbations Appl. Math. Comput. 277 480-93

[23] Briat C 2015 Stability analysis and control of LPV systems with piecewise constant parameters Syst. Control Lett 82 10-17

[24] Zhang Z Y and Wang P G 2019 Research and implementation of natural sampling SPWM digital method for three-level inverter of photovoltaic power generation system based on FPGA IEEE ACCESS 7 114449-58