Negative Sequence Current and Reactive Power Comprehensive Compensation for Freight Railway Considering the Impact of DFIGs

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Abstract—To solve the power quality problems caused by freight railways in weak grids with high penetration of wind generation, this paper proposes a comprehensive control method for negative sequence current (NSC) suppression and reactive power compensation. Firstly, a co-phase traction power supply system (CTPSS) is introduced, and its compensation principle is analyzed. Secondly, to bring a doubly fed induction generator (DFIG) into full play in suppressing voltage unbalance (VU) in the grid, a VU compensation model of stator is developed. Moreover, a comprehensive compensation method is presented to achieve the dynamic compensation of VU and reactive power. Finally, the effectiveness of the proposed approach is demonstrated using a simulation, which can fully solve the power quality issues and effectively reduce the capacity of the CTPSS.

Index Terms—Co-phase traction power supply system, doubly fed induction generator, freight railway, reactive power, voltage unbalance.

I. INTRODUCTION

WITH the development of freight railway transport, the electrical sectioning issues and power quality issues represented by negative sequence current (NSC) and reactive power have restricted the safety and high-quality operation for freight railway [1]. The typical voltage unbalance factor (VUF) curve and power factor (PF) distribution is shown in Fig. 1. It can be seen that VUF has unsatisfied the power quality standard since the power grid connected with railway is weak. Meanwhile, the SS Class and HXD Class are widely used in freight railways, and the low PF (namely reactive power) is a strong challenge. Simultaneously, numerous wind turbines based on a doubly fed induction generator (DFIG) have been built along the railway for the demand of low-carbon and energy-saving [2], which causes traction substation and wind turbines to be connected to a point of common coupling (PCC). On the one hand, the power quality issues of PCC would seriously interfere with the stable operation of wind turbines. On the other hand, the

Fig. 1. Measured data of the Nanning-Kunming heavy-haul railway for 1 day. (a) Measured VUF curve. (b) Scatter diagram between PF and active power.

DFIG system has an attenuation effect on the voltage unbalance (VU) of PCC [3]–[4]. Therefore, there is an urgent demand to solve the power quality problem of freight railways considering the impact of DFIG systems.

There are a lot of technical schemes have been proposed to improve the power quality. Two approaches had been carried out in many references, i.e., install compensation device and change of power supply structure. For the first approach, compensating devices, including static var compensator (SVC), active power filter (APF) and railway power conditioner (RPC), can be added on high voltage side of the traction transformer or the traction side [5]–[7]. These devices have been widely used for NSC suppression and reactive power compensation, but the electrical sectioning issues remained. For the second approach, an advanced co-phase traction power supply system (CTPSS) scheme has been proposed and developed in [8]–[10], which can eliminate power quality problems and neutral section completely. Several compensation strategies for CTPSS have been reported in some literature [11]–[13]. However, these strategies were too stiff to be applied in the remote areas where traction power supply system (TPSS) connected with DFIGs, as the influence of DFIGs on PCC has been ignored.

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There is a focused interest in researching the impact of DFIG on power quality of PCC, especially for the impact on VU. In [14], the attenuation effect of the DFIG on VU propagation has been discussed according to the power flow analysis. Nevertheless, it not involved the mechanism analysis. [15] has established a clear mathematical relationship between the VU and DFIG, which portrayed the power performance of DFIG under the unbalance condition. Meanwhile, the active compensation capability of DFIG has been mostly used in a weak grid [16]–[17], which improved the VU of PCC by properly controlling the NSC injection.

Therefore, this paper presents a comprehensive control method for CTPSS considering the impact of DFIGs. The main contributions of this paper can be summarized as follows:

- 1) To address the power quality issues of freight railways, the structure of CTPSS is introduced. On this basis, a mathematical model of NSC and PF is established to analyze the compensation principle of CTPSS.
- 2) To bring DFIG into full play in suppressing VU in the grid, a VU compensation model of stator is built. Then, a mathematical function of NSC between PCC, CTPSS and DFIGs is derived.
- 3) To effectively reduce the capacity of the CTPSS, a comprehensive compensation method is presented to achieve the dynamic compensation of VU and reactive power, which considers the VU compensation ability of DFIG.

The rest of this paper is organized as follows: Section II analyzes the compensation principle of the CTPSS. Section III builds the VU compensation model of DFIG. In Section IV, the comprehensive control method is given. Simulation results are drawn in Sections V. Section VI concludes the paper.

II. COMPENSATION PERFORMANCE ANALYSIS OF CTPSS

The structure of CTPSS is made up of a single-phase traction transformer (TT) and a power flow controller (PFC) as shown in Fig. 2. The main circuit of PFC is a back-to-back converter. On the grid side, PFC adopts a YNd11 connection transformer and the port of PFC called α phase. On the traction side, PFC adopts a single-phase transformer and the port of PFC called β phase current. The compensation performance of CTPSS is realized by the control of two ports of PFC. This section will discuss the compensation principle of the CTPSS in detail.

A. NSC Compensation Method

The relationship between three-phase current of the power grid and primary phase current of TT and YNd11 connection transformer can be derived as [12]:

$$\begin{bmatrix} \dot{I}_A \\ \dot{I}_B \\ \dot{I}_C \end{bmatrix} = \begin{bmatrix} \frac{1}{N_1} & -\frac{1}{3N_2} \\ 0 & \frac{2}{3N_2} \\ -\frac{1}{N_1} & -\frac{1}{3N_2} \end{bmatrix} \begin{bmatrix} \dot{I}_{TT2} \\ \dot{I}_\alpha \end{bmatrix} \quad (1)$$

where $\dot{I}_A, \dot{I}_B$ and $\dot{I}_C$ are the three-phase current of the power grid.

Fig. 2. Structure of the grid.

$\dot{I}_{TT2}$ is the current in the load side of the TT. $\dot{I}_\alpha$ is the current of α phase. N_1 is the ratio of the TT, N_2 is the ratio of the YNd11 connection transformer.

According to the symmetric component method, the positive sequence and the negative sequence components of the grid can be expressed as:

$$\begin{bmatrix} \dot{I}^+ \\ \dot{I}^- \end{bmatrix} = \begin{bmatrix} \frac{1-a^2}{3N_1} & \frac{a}{3N_2} \\ \frac{1-a}{3N_1} & \frac{a^2}{3N_2} \end{bmatrix} \begin{bmatrix} \dot{I}_{TT2} \\ \dot{I}_\alpha \end{bmatrix} \quad (2)$$

where $a = e^{j120^\circ}$. Superscripts $+$, $-$ represent the positive sequence and negative sequence components.

$\dot{U}_A, \dot{U}_B, \dot{U}_C$ is the three-phase voltage of power grid. $\dot{U}_T$ is the voltage in the traction side of the TT. $\dot{U}_\alpha, \dot{U}_\beta$ is the voltage of α phase and β phase, respectively. Take $\dot{U}_A$ as a reference:

$$\dot{I}_{TT2} = I_{TT2} e^{-j(30^\circ + \varphi_T)} \quad (3)$$

$$\dot{I}_\alpha = I_\alpha e^{-j(120^\circ + \varphi_\alpha)} \quad (4)$$

where φ_T is the lagging phase angle of $\dot{I}_{TT2}$ against $\dot{U}_T$, φ_α is the lagging phase angle of $\dot{I}_\alpha$ against $\dot{U}_\alpha$.

Thus, the negative sequence characteristic of CTPSS can be expressed by the complex current unbalance factor (CCUF):

$$CCUF_{CTPSS} = \frac{\dot{I}^-}{\dot{I}^+} = \frac{\frac{1}{\sqrt{3}k} I_{TT2} e^{-j(60^\circ + \varphi_T)} + I_\alpha e^{-j(120^\circ + \varphi_\alpha)}}{\frac{2}{k} I_{TT2} e^{-j\varphi_T} + I_\alpha e^{-j\varphi_\alpha}} \quad (5)$$

where $k = U_\alpha/U_T$.

It can be seen that the current balance is related to the traction side of the TT and the α phase converter of the PFC, which can be neutralized by controlling the phase angle and amplitude of $\dot{I}_\alpha$. Therefore, the CTPSS can achieve the full compensation of NSC and eliminate the neutral section at the exit of the substation.

B. Reactive Power Compensation Method

The active power of the locomotive is supplied by the TT and α phase converter of the PFC, which is absorbed from the grid. The reactive power of the locomotive is transmitted to the grid through the TT and β phase converter of the PFC. Thus, the power flow of the CTPSS can be deduced:

$$\begin{cases} U_T I_{TT2p} + U_\alpha I_{\alpha p} = U_T I_{Lp} \\ U_T I_{TT2q} + U_\beta I_{\beta q} = U_T I_{Lq} \\ U_\alpha I_{\alpha p} = U_\beta I_{\beta p} \end{cases} \quad (6)$$

where I_β is the current of β phase and I_L is current of the locomotive. Subscripts p, q represent the horizontal and vertical components, which take voltage of the same port as a reference.

Furthermore, the PF after compensation in the grid side can be derived as:

$$PF = \frac{U_T I_{Lp}}{\sqrt{(U_T I_{Lp})^2 + (U_T I_{TT2q} + U_\beta I_{\beta q})^2}} \quad (7)$$

It can be seen that the reactive power compensation is performed by the β phase converter of the PFC and can achieve the dynamic compensation of the PF.

III. VU COMPENSATION PERFORMANCE OF A DFIG

A typical DFIG system is shown in Fig. 2. The stator winding of the DFIG is directly connected to the grid; the rotor winding is connected to the grid via a back-to-back converter, which is called grid side converter (GSC) and rotor side converter (RSC), respectively. As a result, the rotor circuit can transmit power through the converters to the grid. Noting that the DFIG-based wind farm still needs a static synchronous compensator (STATCOM) to provide dynamic reactive power for supporting the voltage at the PCC [18], so this paper does not consider the reactive power compensation of the DFIG system.

Under the positive synchronous ($dq+$) reference frame rotating at an angular speed of ω_s , the voltage and flux linkage of stator and rotor can be written as in [15]:

$$\dot{U}_{sdq} = R_s \dot{I}_{sdq} + \frac{d\psi_{sdq}}{dt} + j\omega_s \psi_{sdq} \quad (8)$$

$$\dot{U}_{rdq} = R_r \dot{I}_{rdq} + \frac{d\psi_{rdq}}{dt} + j(\omega_s - \omega_r) \psi_{rdq} \quad (9)$$

$$\dot{\psi}_{sdq} = L_s \dot{I}_{sdq} + L_m \dot{I}_{rdq} \quad (10)$$

$$\dot{\psi}_{rdq} = L_m \dot{I}_{sdq} + L_r \dot{I}_{rdq} \quad (11)$$

where R_s and R_r are the resistance of stator and rotor. I is the current and ω_r is the angular speed of rotor. L_s and L_r are the self-inductances of stator and rotor windings, L_m is the mutual inductance. Subscripts sdq, rdq represent components of d, q axes of stator and rotor.

By ignoring the stator and rotor resistances and considering that the stator voltage is constant in steady states, the active power and reactive power of the stator can be expressed by:

$$P_s = 1.5 U_s i_{sd} \quad (12)$$

$$Q_s = -1.5 U_s i_{sq} \quad (13)$$

The stator current can be decomposed into positive and negative sequence components, as shown below:

$$\dot{I}_{sdq} = \dot{I}_{sdq+} + \dot{I}_{sdq-} e^{-j2\omega_s t} \quad (14)$$

where subscripts $+, -$ represent the positive and negative synchronous reference frames.

In the steady state, $\dot{I}_{sdq+}$ and $\dot{I}_{sdq-}$ are dc values. The positive sequence component $\dot{I}_{sdq+}$ depends on the stator active power determined by the maximum wind power tracking. The negative sequence component $\dot{I}_{sdq-}$ can be controlled by the RSC according to (8)–(11). The reference value $\dot{I}_{sdqref-}$ is obtained by the control centre.

$$\begin{bmatrix} \dot{I}_{Aref} \\ \dot{I}_{Bref} \\ \dot{I}_{Cref} \end{bmatrix} = \begin{bmatrix} \sin(-\omega_s t) & \cos(-\omega_s t) \\ \sin(-\omega_s t - \frac{2}{3}\pi) & \cos(-\omega_s t - \frac{2}{3}\pi) \\ \sin(-\omega_s t + \frac{2}{3}\pi) & \cos(-\omega_s t + \frac{2}{3}\pi) \end{bmatrix} \begin{bmatrix} \dot{I}_{sqref-} \\ \dot{I}_{sdref-} \end{bmatrix} \quad (15)$$

By using the method of symmetrical components, the negative sequence component can be expressed as:

$$\dot{I}_{Wref-} = \frac{1}{3} (\dot{I}_{Aref} + a^2 \dot{I}_{Bref} + a \dot{I}_{Cref}) \quad (16)$$

Thus, the NSC of DFIG can be written as:

$$\dot{I}_{Wref-} = \frac{1}{2} (\dot{I}_{sqref-} - j \dot{I}_{sdref-}) e^{-j\omega_s t} \quad (17)$$

$$|\dot{I}_{Wref-}|^2 \leq \frac{1}{4} \max \left[(|\dot{I}_{sd-} - \dot{I}_{sd+}|^2 + |\dot{I}_{sq-} - \dot{I}_{sq+}|^2) \right] \quad (18)$$

$\dot{I}_{Wref-}$ is injected into the grid, which reflects the unbalance compensation ability of the DFIG. From (18), the $|\dot{I}_{Wref-}|$ is restricted to the $\dot{I}_{sdq+}$ which illustrates that the unbalance compensation ability of the DFIG is related to the wind power.

IV. COMPREHENSIVE COMPENSATION METHOD FOR CTPSS CONNECTED WITH DFIGs

A. Compensation Principle

1) VU Compensation

The positive sequence and negative sequence equivalent

Fig. 3. Equivalent circuit. (a) Positive sequence and (b) negative sequence.

circuit of the system is established, as shown in Fig. 3. The DFIGs is represented by two DFIG systems, and the DFIG can be equivalent to an NSC controller according to the above analysis.

The positive sequence voltage and negative sequence voltage at PCC can be expressed as:

$$\dot{U}_{PCC}^- = \dot{I}_S^- Z_S^- \quad (19)$$

$$\dot{U}_{PCC}^+ = Z_T^+ \dot{I}_{TPSS}^+ + \dot{U}_{TPSS}^+ \quad (20)$$

where Z_S , Z_T , Z_W is the impedance of the transmission line, Z_{TPSS} is the impedance of the traction substation. Z_D is the impedance of DFIG.

Thus, complex voltage unbalance factor (CVUF) at PCC bus can be written as:

$$CVUF_{PCC} = \frac{\dot{U}_{PCC}^-}{\dot{U}_{PCC}^+} = \frac{\dot{I}_S^- Z_S^-}{Z_T^+ \dot{I}_{TPSS}^+ + \dot{U}_{TPSS}^+} \quad (21)$$

Furthermore, $\dot{I}_S^-$ and $\dot{U}_{TPSS}^+$ can be expressed as:

$$\dot{I}_S^- = \dot{I}_{TPSS}^- - \dot{I}_{WF}^- \quad (22)$$

$$\dot{U}_{TPSS}^+ = \dot{I}_{TPSS}^+ Z_{TPSS}^+ \quad (23)$$

According to (19)–(23), $CVUF_{PCC}$ can be rewritten as:

$$CVUF_{PCC} = k_1 (CCUF_{TPSS} - k_2 CCUF_{WF}) \quad (24)$$

where

$$k_1 = \frac{Z_S^-}{Z_{TPSS}^+ + Z_T^+}, k_2 = \frac{\dot{I}_{WF}^+}{\dot{I}_{TPSS}^+} \quad (25)$$

From (24), it is clear that VU of PCC is contributed by downstream load, i.e., CTPSS and DFIGs. The CTPSS is

the source of VU, and caused VU propagation in the grid. Assuming that DFIGs have no output NSC, in other words, the DFIGs is equivalent to impedance in negative sequence circuit, CVUF at PCC bus can be written as:

$$CVUF_{PCC} = k_1 CCUF_{TPSS} \times \frac{1}{1 + \frac{Z_S^-}{Z_W^- + Z_{D1}^- + Z_{D2}^-}} \quad (26)$$

So the attenuation effect of the DFIGs on VU propagation is mainly expressed in the unbalance power consumption of negative sequence impedance.

Compared (24) with (27), the compensation effort of the DFIGs is considered, which reduces $CVUF_{PCC}$ further.

Combining the negative sequence characteristic of CTPSS, the total compensation current reference of PCC can be given as:

$$\dot{I}_{ref}^- = \frac{\dot{I}_{TPSS}^+}{k_1} VUF_{PCCref} - \dot{I}_L^- \quad (27)$$

where $\dot{I}_L^-$ is caused by locomotive.

2) Reactive Power Compensation

To fairly regulate power users and reduce the losses of the power companies, the government has strictly formulated the national standard of PF. For railway users, the PF must be higher than 0.9. Otherwise the railway transport companies will face heavy fines. Thus, the reactive power compensation equipment is indispensable to freight railway.

B. Comprehensive Compensation Method

In this paper, the PFC of CTPSS and DFIGs work together to govern the power quality issues, but the latter only participates in the NSC compensation. The compensating control of PFC and DFIGs is shown in Fig. 4.

The compensation currents calculation of the PFC have been researched in [15]:

$$\begin{cases} I_{ap}^{ref} = \frac{\sqrt{3} N_2}{N_1} (I_{Lp} - m) \\ I_{aq}^{ref} = -\frac{\sqrt{3} N_2}{N_1} \left[\sqrt{\left(\frac{I_{Lp}}{PF} \right)^2 - (I_{Lp})^2} + m \right] \\ I_{\beta p}^{ref} = N_3 (I_{Lp} - m) \\ I_{\beta q}^{ref} = N_3 (I_{Lq} - m) \end{cases} \quad (28)$$

where m is the comprehensive compensation target, including VU and PF.

The compensating power of DFIG should be given as [4]:

$$\begin{bmatrix} P_{scom} \\ Q_{scom} \end{bmatrix} = -\frac{3}{2} \begin{bmatrix} u_{sd}^- & u_{sq}^- & u_{sd}^+ & u_{sq}^+ \\ u_{sq}^- & -u_{sd}^- & u_{sd}^+ & -u_{sq}^+ \end{bmatrix} \begin{bmatrix} i_{sd}^+ \\ i_{sq}^+ \\ i_{sdref}^- \\ i_{sqref}^- \end{bmatrix} \quad (29)$$

Quantity	Values
Grid voltage	220 kV
Short-circuit capacity	2000 MVA
Line length of PCC to grid	50 km
Line length of CTPSS to PCC	10 km
Line length of DFIGs to PCC	25 km
Number of DFIG	15
Apparent power of locomotive	20 MVA

	VUF target	PF target	Time interval/s
Case 1	/	/	0–2
Case 2	2%	0.95	2–3
Case 3	0	0.95	3–4

The compensation results are shown in Fig. 5. In order to evaluate the performance and advantages of the proposed compensation method, the proposed method is compared with the compensation method in [15]. As shown in Fig. 5, it is clear that the VUF_{PCC} is 2.5% at first, which unsatisfied the national

TABLE V
COMPENSATION METHOD COMPARISONS BETWEEN THIS PAPER AND PROPOSED IN [15]

	Case 2 in [15]	Case 2 in this paper
α, β phase voltage	27.5 kV	27.5 kV
α phase current	124 A	100 A
β phase current	67 A	40 A
Compensation power	5.25 MVA	3.85 MVA

Fig. 6. VU compensation current reference. (a) PFC and (b) DFIG.

Fig. 7. Compensation current reference and actual output of two phases in PFC. (a) α phase and (b) β phase.

standard of VU. In case 2, the VUF is controlled to 2% and PF equals 0.95, which proves the effectiveness of the proposed method. The capacity comparisons of the PFC are shown in

Fig. 8. Compensation performance of DFIGs.

Fig. 9. The influence of wind speed. (a) maximum power coefficient tracking and (b) impact of wind speed to VU compensation.

Table V. It can be seen that the capacity is decreased by 26.7% to 3.85 MVA. This is because the VU compensation ability of DFIG is considered in this paper, which can share the effort of PFC so as to effectively reduce the capacity of PFC. In case 3, it can be seen that the proposed method follows the change of target well, but the method in [15] cannot due to the capacity limitation of PFC.

Fig. 6 shows the VU target sharing between PFC and DFIG, which embodies they are responsible for the compensation of VU together. Fig. 7 shows the current waveform of PFC, and the values are normalized. It can be seen that the output current of two phases can accurately track references and adapt to the rapid change of the compensation target.

Fig. 8 shows the electrical parameters of DFIGs, including output NSC $|\vec{I}_{WF}|$ and DC-link voltage of RSC. It can be seen that DC-link voltage has the pulsation, because DFIGs outputs NSC in the stator, which will inevitably cause electromagnetic torque pulsation. Fig. 9 shows the influence of wind speed. As stated in Section IV, the average active power of DFIG generally uses the maximum power coefficient tracking method, and its power curve is shown in Fig. 9(a). The wind speed would affect P_{s0} so as to affect the stator current as demonstrated in Fig. 9(b), which qualitatively reflects the relationship between compensation performance and wind energy.

VI. CONCLUSION

This paper proposed a comprehensive control method of CTPSS connected with DFIGs, which suppressed the NSC and compensated the reactive power. A VU compensation model of stator is built. Secondly, based on the classical circuit theory, a mathematical function of NSC between PCC, CTPSS and DFIGs is derived. Furthermore, a comprehensive compensation method is presented to achieve the dynamic compensation of VU and reactive power. Finally, the simulation results have proved the effectiveness and good control performance of the proposed strategy.

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