

Fault Ride through Strategy for Virtual Synchronous Control based Doubly-Fed Induction Generators

Xuekun Cheng^{1,2}, Hui Liu^{1,2}, Peng Song^{1,2} and Hao Jiang^{1,2}

¹ State Grid Jibei Electric Power Co. Ltd. Research Institute, Beijing, China

² Grid-connected Operation Technology for Wind-Solar-Storage Hybrid System State Grid Corporation Key Laboratory, Beijing, China.

E-mail: chengxk027@126.com

Abstract. Virtual Synchronous Control (VSynC) strategy for Doubly-Fed Induction Generator (DFIG) has attracted much attention because of its advantages in providing dynamic supports of frequency and voltage. In this way, most researches of VSynC strategy concentrate on analysis of its electromechanical behaviours, but pay little attention to its electromagnetic transient responses and fault characteristics, which may hinder its promotion in engineering application. This paper pays special attention to the electromagnetic transient behaviours of VSynC-based DFIG and proposes a voltage compensation VSynC strategy to implement fault ride through during symmetrical grid faults. The proposed strategy improves the transient response of existing VSynC strategy, capable of limiting the overcurrent in DFIG rotor circuits and suppressing the oscillations of electromagnetic torque. Simulation results validate the effectiveness of the proposed strategy.

1. Introduction

The scale of wind power integrated to the grid has been tremendously increasing, in this situation, Virtual Synchronous Control (VSynC) strategy [1]-[3] outweighs Vector Control (VC) strategy for providing expected inertial supports and enhancing the stability of system operation. However, existing VSynC strategy for Doubly-Fed Induction Generator (DFIG) concentrates mainly on its steady-state performances and electromechanical dynamic behaviours, paying little attention to electromagnetic transient process and fault characteristics [4], which are of equal importance due to the following two reasons. Firstly, DFIG is directly connected to the grid, making it vulnerable to grid faults [5]. Secondly plenty of researches have been carried out on the behaviours of VC-based DFIG during grid faults [6]-[9], indicating that grid faults will bring about severe fault currents and great possibility of damaging the converters. Therefore, it's quite necessary to study the fault characteristics of VSynC-based DFIG, verify the applicability of existing VSynC strategy during grid faults and improve its fault ride through capability.

Previous researches have studied the VSynC strategy for DFIG under asymmetrical grid faults [13]. Enlightening and innovative as paper [13] is, there is much to improve in aspects of depth of analysis. Considering that symmetrical grid faults are more frequent and more serious in practical operation, this paper pays special attention to VSynC strategy for DFIG during symmetrical grid faults, and the study goes further and deeper on the basis of researches in paper [13]. The paper is organized as follows. Section II analyses the principle of existing VSynC strategy and reveals the mechanism of DFIG synchronization. Then the fault characteristics of VSynC-based DFIG are carefully studied in Section III, which is followed by the discussion of the proposed voltage compensation VSynC strategy



in Section IV. Simulation results on a 1.5MW DFIG system are provided in Section V to validate the effectiveness of the proposed strategy. And finally, conclusions are drawn in Section VI.

2. Fault characteristics of VSynC-based DFIG during symmetrical grid faults

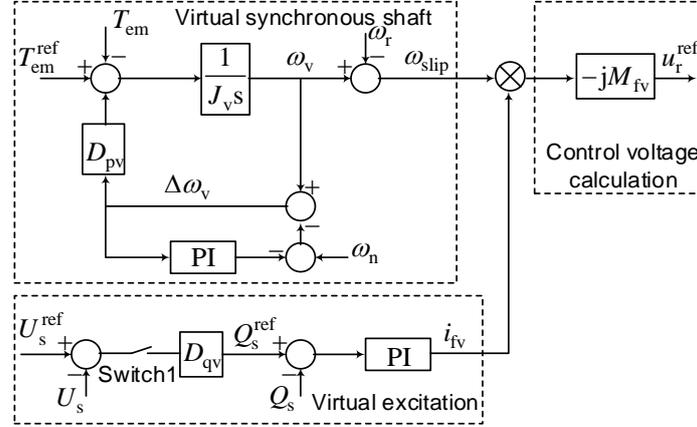


Figure 1. Existing VSynC strategy for DFIG.

Fig.1 shows a typical VSynC strategy for DFIG [10], where J_v and D_{pv} are virtual inertia and virtual damping coefficient, D_{qv} represents virtual droop coefficient. T_{em} and T_{emref} are electromagnetic torque and its reference value, ω_v is electrical angular velocity of virtual shaft, $\Delta\omega_v$ is the deviation of ω_v from grid frequency ω_s , i_{fv} is virtual excitation current, and M_{fv} is the mutual inductance between stator and virtual excitation windings.

Paper [13] has defined virtual stator electromagnetic force (EMF) e_{0v} by referring to the excitation characteristics of synchronous generator,

$$e_{0v} = \omega_v M_{fv} i_{fv} e^{-j\frac{\pi}{2}} - M_{fv} \frac{di_{fv}}{dt} e^{-j\frac{\pi}{2}} \quad (1)$$

And at the same time, DFIG stator EMF has also been defined as,

$$e_m = jL_m \omega_v \Psi_r / L_r \quad (2)$$

where Ψ_r is rotor flux, L_r is inductance of rotor windings, and L_m is mutual inductance between stator and rotor windings.

It has been illustrated that DFIG stator EMF can be controlled by adjusting the reference value of DFIG rotor voltage, once the equation (3) is satisfied, DFIG will successfully imitate the electromechanical and electromagnetic characteristics of synchronous generator.

$$e_m = e_{0v} \quad (3)$$

During symmetrical grid faults, the drop of DFIG stator voltage will exert impact on stator flux Ψ_s , and furthermore influence rotor electromotive force e_r , rotor current i_r and electromagnetic torque. The analysis of fault characteristics of VSynC based DFIG is conducted by analysing the fault characteristics of physical quantities above.

Assume that the amplitude of DFIG stator voltage before grid faults is V_s , and at the time $t=0$, the amplitude drops to λV_s because of grid faults, then the stator flux can be expressed as

$$\Psi_s = \frac{\lambda V_s}{\omega_s} e^{j\omega_s t} + \frac{(1-\lambda)V_s}{\omega_s} e^{-t/\tau_s} \quad (4)$$

where $\tau_s = L_s/R_s$ is the time constant of stator windings.

In equation (4), the first item is the steady state component of stator flux ψ_{sw} , corresponding to stator voltage during grid faults; the second item is the transient state component of stator flux ψ_{st} , functioning to maintain the continuity of stator flux at the instant of voltage drop.

The rotor voltage equation of DFIG can be expressed as [12]

$$\mathbf{u}_r = \frac{L_m}{L_s} \left(\frac{d}{dt} - j\omega_r \right) \boldsymbol{\psi}_s + (R_r + L_{r\sigma} \frac{d}{dt} - j\omega_r L_{r\sigma}) \mathbf{i}_r \quad (5)$$

where R_r and $L_{r\sigma}$ represent rotor resistance and leak inductance respectively.

DFIG rotor electromotive force can be obtained as:

$$\mathbf{e}_r = \frac{L_m}{L_s} \left(\frac{d}{dt} - j\omega_r \right) \boldsymbol{\psi}_s \quad (6)$$

During the transient process of symmetrical grid faults, the steady state component and the transient state component of stator flux will correspondingly induce rotor electromotive force \mathbf{e}_{rw} and \mathbf{e}_{rt} , which can be derived from equation (6) as

$$\mathbf{e}_{rw} = j\omega_{slip} \frac{L_m}{L_s} \boldsymbol{\psi}_{sw} \quad (7)$$

$$\mathbf{e}_{rt} = -j\omega_r \frac{L_m}{L_s} \boldsymbol{\psi}_{st} \quad (8)$$

The amplitude of rotor electromotive force is the superposition of its components, and its maximum value should be

$$|\mathbf{e}_r|_{\max} = |\mathbf{e}_{rw}| + |\mathbf{e}_{rt}| \quad (9)$$

Fig. 2 demonstrates the variation of $|\mathbf{e}_r|_{\max}$ with slip and the depth of voltage dip. It can be seen that with the increase of the absolute value of slip and the depth of voltage dip, grid faults exert greater impact on DFIG.

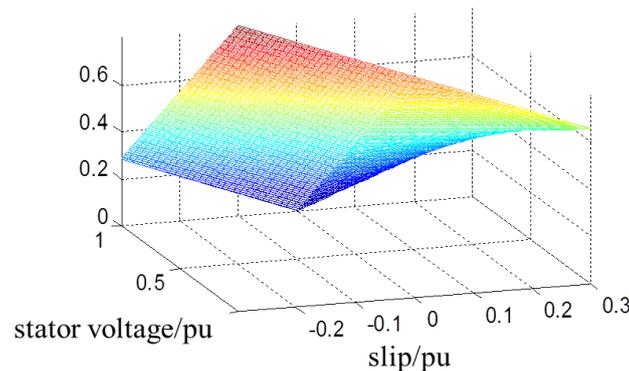


Figure 2. Variation of $|\mathbf{e}_r|_{\max}$ with slip and stator voltage.

Currents in DFIG rotor windings satisfy

$$-\mathbf{e}_{rw} + \mathbf{u}_{rw} = \mathbf{i}_{rw} (R_r + j\omega_{slip} L_{r\sigma}) \quad (10)$$

$$-\mathbf{e}_{rt} + \mathbf{u}_{rt} = \mathbf{i}_{rt} (R_r - j\omega_r L_{r\sigma}) \quad (11)$$

where the subscript w and t represent the steady state and transient state components of parameters. It has been figured out that existing VSynC strategy responds to grid faults in inertia time constant^[13]. Therefore, during symmetrical grid faults, existing strategy cannot generate corresponding

components of rotor voltage to counteract the fault components of rotor electromotive force, namely, $u_{rt} = 0$. This will induce overcurrent in rotor windings as well as oscillations of electromagnetic torque, making it difficult for DFIG to realize fault ride through.

3. Voltage compensation VSynC strategy for DFIG

It can be seen that it's necessary for VSynC strategy to take the fault characteristics of DFIG into consideration, in order to realize fault ride through during symmetrical grid faults. Analysis in part II indicates that the major supplementary should be the fault characteristics of virtual excitation current and virtual stator electromagnetic force, which will be studied in this part, and then an improved VSynC strategy for DFIG will be proposed.

During symmetrical grid faults, transient state component of DFIG stator flux will induce transient state component of flux in virtual excitation windings, i.e.

$$\psi_{fv} = \frac{M_{fv}\psi_{st}}{L_v} \quad (12)$$

Therefore, the transient state component of virtual stator electromotive force can be obtained as^[13],

$$e_{0vt} = -j\omega_v \frac{M_{fv}^2}{L_v L_{fv}} \psi_{st} \quad (13)$$

Based on analysis above, a voltage compensation VSynC strategy for DFIG is proposed as shown in Fig 3. Improvement is made by designing the voltage compensation part, which functions to accelerate the response to symmetrical grid faults and weaken the influence of the fault components of rotor electromotive force. In order to compensate the rotor voltage, the proposed strategy should satisfy,

$$u_{rt} = e_{0vt} = e_{rt} \quad (14)$$

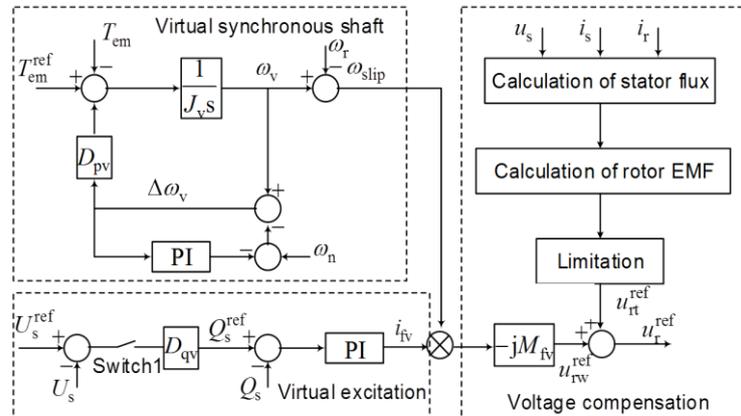


Figure 3. Voltage compensation VSynC strategy for DFIG.

The limitation of output voltage of rotor-side converter should be considered, referring to paper [13], the limitation of compensation voltage can be determined as

$$|u_{rc}|_{lim} = \frac{U_{dc_max}}{\sqrt{2} \cdot \sqrt{3} U_{rN}} - |e_{rw}| \quad (15)$$

where U_{rN} is the nominal phase voltage of DFIG rotor, and U_{dc_max} is the setting voltage of dc bus protection.

Once DFIG stator voltage drops deeply, the amplitude of e_{rt} may surpass $|u_{rc}|_{lim}$, thus the transient state component will be partially compensated. Figure 4 illustrates the range where the proposed strategy can implement full compensation.

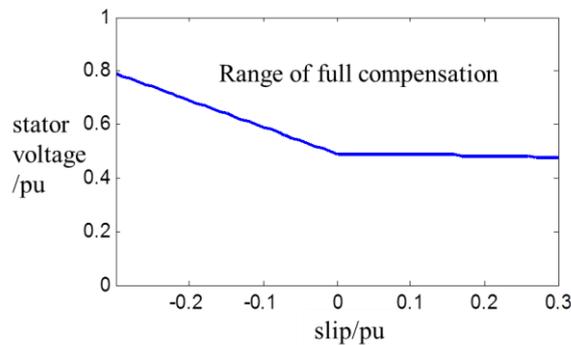


Figure 4. Range of full compensation with proposed strategy.

4. Simulation verification

In this part, simulation has been conducted in 1.5MW DFIG system to evaluate the control effect of proposed strategy. Parameters are given in Table I. Assume that under normal operation, DFIG stator voltage is nominal, the rotor speed $\omega_r=0.9$ pu, output active power $P_s=1.0$ pu, and output reactive power $Q_s=0$ pu.

Table 1. Parameters of DFIG system.

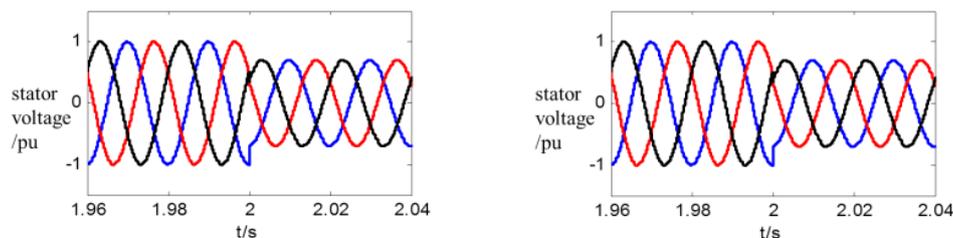
parameters	value	parameters	value
Rated power (MW)	1.5	L_m (pu)	2.9
Stator voltage (V)	690	R_r (pu)	0.016
Pole pairs	1	$L_{r\sigma}$ (pu)	0.16
R_s (pu)	0.023	Dc bus voltage (V)	1150
$L_{s\sigma}$ (pu)	0.18	Stator/rotor turns ratio	1/2.86

4.1. Mild symmetrical grid faults

At the first instance, mild symmetrical grid faults are simulated. At 2s, DFIG stator voltage drops to 0.7pu, corresponding to point (0.1, 0.7) in Fig 4, indicating that the transient state component of rotor electromotive force can be fully compensated. Fig. 5 compares the simulated results with existing VSynC strategy and voltage compensation VSynC strategy.

Fig. 5(a) clearly illustrates that with existing VSynC strategy, severe overshoot of fault currents and oscillations of electromagnetic torque are inevitable, which may cause severe damage to power electronic devices and wind turbine shafts. The sudden overshoot of rotor current reaches 2.0pu, and the amplitude of oscillations of electromagnetic torque is up to 1.5pu. Obviously, it's difficult for existing VSynC-based DFIG to implement symmetrical fault ride through.

Once DFIG rotor control voltage is fully compensated, the amplitude of DFIG currents hardly show any fluctuation before and after symmetrical grid faults. Moreover, the oscillations of electromagnetic torque are obviously limited, the amplitude of oscillations drops from 1.5pu to 0.55pu, decreasing by 63.3%, thus relieving the mechanical stress of DFIG shaft.



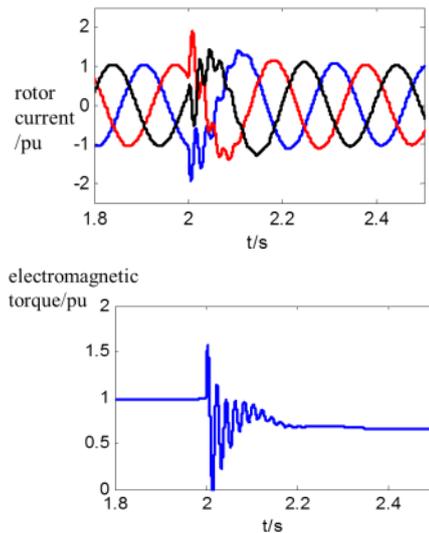


Figure 5(a). Simulation results of existing VSynC strategy under mild symmetrical grid faults.

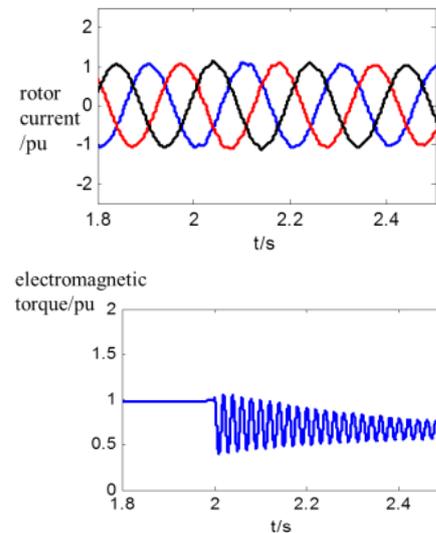


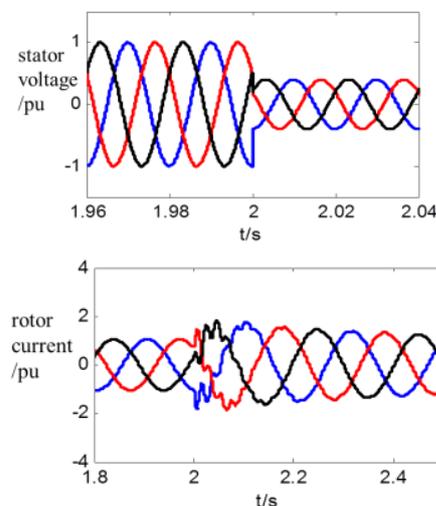
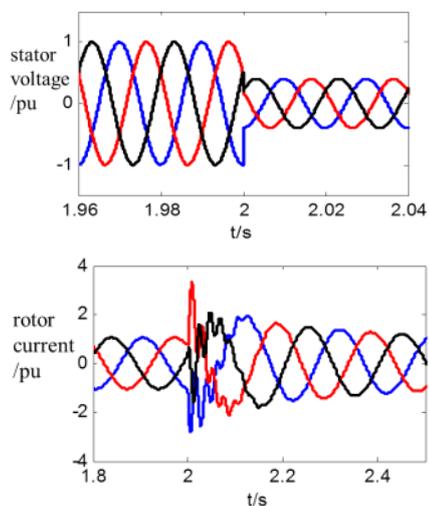
Figure 5(b). Simulation results of proposed VSynC strategy under mild symmetrical grid faults.

4.2. Severe symmetrical grid faults

This time, the proposed strategy is verified under severe symmetrical grid faults. At 2s, DFIG stator voltage drops to 0.4pu, corresponding to point (0.1, 0.4) in Fig 4, indicating that the transient state component of rotor electromotive force can only be partially compensated. Fig. 6 compares the simulated results with existing VSynC strategy and voltage compensation VSynC strategy.

It's obvious that the increase of severity of symmetrical grid faults will contribute to more violent electromagnetic transient characteristics, namely higher current overshoot and larger oscillations of electromagnetic torque. However rotor control voltage can only be partially compensated, overcurrents still exist but are significantly reduced. The amplitude of DFIG rotor current is decreased by 43% from 3.5pu to 2.0pu, and the overshoot of electromagnetic torque is suppressed from 3.0pu to 1.4pu.

The simulation results in Fig. 5 and Fig. 6 confirm the effectiveness of voltage compensation VSynC strategy, which is able to limit DFIG fault currents and suppress the oscillations of electromagnetic torque by making full use of the voltage output ability of rotor-side converter, therefore effectively enhancing DFIG symmetrical fault ride through capability.



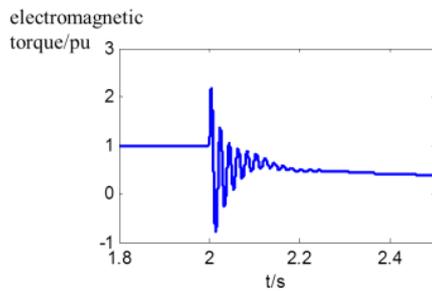


Figure 6(a). Simulation results of existing VSynC strategy under mild symmetrical grid faults.

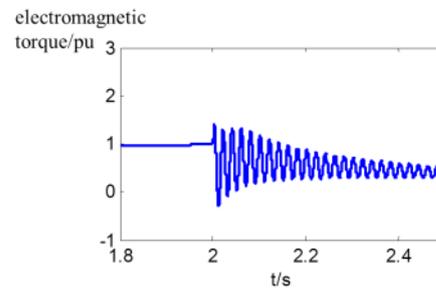


Figure 6(b). Simulation results of existing VSynC strategy under mild symmetrical grid faults.

5. Conclusions

This paper has carefully studied the symmetrical fault characteristics of DFIG based on existing VSynC mechanism, pointing out the incapability of existing strategy on implementing fault ride through during symmetrical grid faults. After investigating the defect of existing VSynC strategy and determining the main challenges in symmetrical fault ride through, a voltage compensation VSynC strategy is then proposed. The main principle is to compensate the transient state components of DFIG rotor voltage, and in this way, the overcurrent of DFIG can be completely diminished under mild symmetrical grid faults and significantly suppressed under severe symmetrical grid faults. Moreover, electromagnetic torque oscillations are effectively limited. Above all, the proposed strategy successfully enhances the fault ride through ability of VSynC-based DFIG.

6. References

- [1] Wang S, Hu J and Yuan X 2015 *IEEE J. Emerg Selec Top Pow Electr* **3** 932-44.
- [2] Zhong Q and Weiss G 2011 *IEEE Trans. Indus Electr* **58** 1259-67.
- [3] Wang K, Wang Z and Chai J 2015 *Autom Electric Pow Sys* **39** 152-8.
- [4] Lei S, Hu J and Yuan X 2017 *Proceedings of the CSEE* **37** 403-11.
- [5] Yang S and Chen Y 2015 *Autom Electric Pow Sys* **39** 12-8.
- [6] Zhang X, Xu D and Pan W 2010 *Autom Electric Pow Sys* **38** 13-9.
- [7] Yang S, Chen L and Sun D 2014 *Autom Electric Pow Sys* **38** 13-9.
- [8] Hu J, Sun D and He Y 2006 *Autom Electric Pow Sys* **30** 21-6.
- [9] Xiang D, Ran L, Tavner P J and Yang S 2006 *IEEE Trans Ener Convers* **21** 652-65.
- [10] Zhao Y, Chai J and Sun X 2015 *Proceedings of Applied Power Electronics Conference and Exposition, Charlotte (USA)* p 2980-3.
- [11] Hu S, Lin X, Kang Y and Zou X 2011 *IEEE Trans Pow Electr* **26** 3653-65.
- [12] Xu L 2008 *IEEE Trans Ener Convers* **23** 1073-81.
- [13] Cheng X, Sun X, Chai J and Zhao Y 2017 *Proceedings of Electrical Machines and Systems, Sydney (Australia)* p 2980-3.