

RESPONSE OF ROTOR OVER-VOLTAGE IN DFIG BASED WIND GENERATOR UNDER RECURRING VOLTAGE SAGS

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ABSTRACT

The automatic reclosing device may cause recurring voltage sags at grid connection point (GCP) of wind farm. In order to improve the low voltage ride through (LVRT) capability of DFIG based wind generator under recurring grid faults, this paper investigates the response of rotor over-voltage in DFIG based wind Generator. The study considered impacts of voltage magnitude, phase-angle jump (PAJ) and point-on-wave (POW) of single voltage sag event. And the effects of sag duration and the time interval between two adjacent sag on the DFIG flux and voltage are emphatically studied. The superposition and attenuation mechanism of stator flux and rotor over voltage of DFIG is analysed with related simulation.

Key words: DFIG, voltage sag, phase angle jump, point on wave, stator flux, rotor overvoltage

INTRODUCTION

Voltage sag event is unavoidable in modern power grid. The integrated DFIG based wind generator is extremely vulnerable to sag event. At present, amount of researches focus on the electromagnetic response and LVRT capability of DFIG under single voltage sag [1-2, 5-8]. A voltage sag may lead to the rotor over-voltage and over-current through the stator flux linkage natural component [1-2]. Further study focus on impact of multiple features of voltage sag on the transient process of DFIG is underway [6-9]. Except for amplitude and duration, PAJ may aggravate the stator flux oscillation and affect the rotor over-current and coordinate orientation of vector control [6-9]. Under asymmetrical voltage sags, POW will affect transient response of DFIG like peak rotor voltage [8-9].

Fault is a main reason of sags. After the fault is removed by the circuit breaker, the GCP voltage will recover. However, due to the existence of automatic reclosing device, after the setting time, the circuit breaker is closed again. At this time, if the fault still exists, the fault will occur again and cause another voltage sag [10]. The current research mainly focuses on single voltage sag and transient response of DFIG under recurring voltage sags need to be deeply researched. Under this case, the electromagnetic oscillation caused by the previous voltage sag may not have disappeared, which will bring more complicated electromagnetic process and more serious impact to DFIG after the later voltage sag [10]. Some countries have written the recurring voltage sags into the integrated standard of wind farm, which requires wind generator to meet the requirements of LVRT curve, reactive power support and active power recovery under recurring sags. The grid code in Denmark has required that

the wind generator should ride through two independent faults within 0.5–3 s, and less than six independent faults in 5 min, as shown in Fig. 1[5]. Thus, it is necessary to investigate the Complex dynamic responses of DFIG under recurring sags.

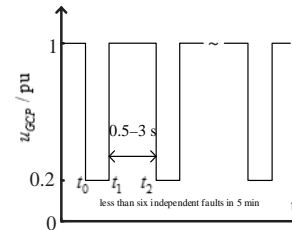


Fig. 1 The grid code in Denmark about recurring voltage sags

In this paper, impacts of multi-characteristics of sag event especially sag duration and the time interval between two adjacent sag on the rotor over-voltage of DFIG are investigated. Firstly the superposition and attenuation mechanism of stator flux is analysed. Then, Simulation verification of rotor voltage under different sag duration and the time interval is carried out. The most and the least serious cases under different fault types are discussed respectively.

DYNAMIC RESPONSE OF STATOR FLUX

The space vector models of DFIG in α - β static reference frame are:

$$\mathbf{u}_s = R_s \mathbf{i}_s + \frac{d\boldsymbol{\psi}_s}{dt} \quad (1)$$

$$\mathbf{u}_r = R_r \mathbf{i}_r + \frac{d\boldsymbol{\psi}_r}{dt} - j\omega_r \boldsymbol{\psi}_r \quad (2)$$

$$\boldsymbol{\psi}_s = L_s \mathbf{i}_s + L_m \mathbf{i}_r \quad (3)$$

$$\boldsymbol{\psi}_r = L_r \mathbf{i}_r + L_m \mathbf{i}_s \quad (4)$$

In (1-4), equaled to stator side, \mathbf{u}_s and \mathbf{u}_r are voltage vectors of stator and rotor; \mathbf{i}_r is rotor current vector; $\boldsymbol{\psi}_s$ and $\boldsymbol{\psi}_r$ are stator and rotor flux vector; R_s and R_r are stator and rotor resistances; L_s , L_r and L_m are stator and rotor self-inductances and mutual inductance; ω_r is rotor angular frequency and t is time.

The model of rotor voltage of DFIG is [1, 2],

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

Ignoring the rotor current, the rotor voltage is nearly equaled to the rotor open-circuit voltage [2].

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

When the rotor is open-circuit, substitute (3) into (1), the first-order response equation of DFIG stator flux is:

$$\frac{d\psi_s}{dt} = \mathbf{u}_s - \frac{R_s \psi_s}{L_s} \quad (7)$$

The analysis of recurring voltage sags shown in Fig. 1 is simplified as two adjacent voltage sag. Suppose the two voltage sag are happened at t_0 and t_1 respectively, think of before sag, the first sag, voltage recovery, the second sag as four voltage events, the positive and negative grid voltage are:

$$\begin{cases} \mathbf{u}_{s1}^+ = U_1^+ e^{j\omega_s t} = j\omega_s \psi_{s1f}^+ & t < t_0 \\ \mathbf{u}_{s1}^- = U_1^- e^{-j\omega_s t} = -j\omega_s \psi_{s1f}^- = 0 & t < t_0 \end{cases} \quad (8)$$

$$\begin{cases} \mathbf{u}_{s2}^+ = U_2^+ e^{j(\omega_s t + \theta_1^+)} = j\omega_s \psi_{s2f}^+ & t_0 < t \leq t_1 \\ \mathbf{u}_{s2}^- = U_2^- e^{-j(\omega_s t + \theta_1^-)} = -j\omega_s \psi_{s2f}^- & t_0 < t \leq t_1 \end{cases} \quad (9)$$

$$\begin{cases} \mathbf{u}_{s3}^+ = U_1^+ e^{j\omega_s t} = j\omega_s \psi_{s3f}^+ & t_1 < t \leq t_2 \\ \mathbf{u}_{s3}^- = U_1^- e^{-j\omega_s t} = -j\omega_s \psi_{s3f}^- = 0 & t_1 < t \leq t_2 \end{cases} \quad (10)$$

$$\begin{cases} \mathbf{u}_{s4}^+ = U_3^+ e^{j(\omega_s t + \theta_2^+)} = j\omega_s \psi_{s4f}^+ & t \geq t_2 \\ \mathbf{u}_{s4}^- = U_3^- e^{-j(\omega_s t + \theta_2^-)} = -j\omega_s \psi_{s4f}^- & t \geq t_2 \end{cases} \quad (11)$$

where the POW of two adjacent voltage sag $\varphi_1 = \omega_s t_0$, $\varphi_2 = \omega_s t_1$. θ^+ and θ^- are phase of the positive and negative sequence stator voltage if ignore the POW, which as well as voltage magnitude can be calculated by another important characteristic of voltage sag-PAJ using the method described in literature [8, 9]. Literature [3] gives the definition and calculation method of PAJ.

Solve (7) according to the expression for the voltage, the full response of stator flux linkage can be divided into two parts: the forced flux which is a rotational term determined by the grid voltage, and the natural flux which decays progressively with a constant angle [1, 2].

The stator flux linkage expression before and after the first sag are:

$$\psi_{s1} = \psi_{s1f}^+ = \frac{\mathbf{u}_{s1}^+}{j\omega_s} \quad (12)$$

$$\begin{aligned} \psi_{s2} = \psi_{s2f}^+ + \psi_{s2f}^- + \psi_{s2n} = \frac{\mathbf{u}_{s2}^+}{j\omega_s} + \frac{\mathbf{u}_{s2}^-}{-j\omega_s} \\ + \left[\psi_{s1}(t_0) - \psi_{s2f}^+(t_0) - \psi_{s2f}^-(t_0) \right] e^{-(t-t_0)/\tau_s} \end{aligned} \quad (13)$$

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

The stator flux linkage expression after the recovery of the first sag are:

$$\begin{aligned} \psi_{s3} = \psi_{s3f}^+ + \psi_{s3f}^- + \psi_{s3n} = \frac{\mathbf{u}_{s3}^+}{j\omega_s} + \frac{\mathbf{u}_{s3}^-}{-j\omega_s} \\ + \left[\psi_{s1}(t_0) - \psi_{s2f}^+(t_0) - \psi_{s2f}^-(t_0) \right] e^{-(t-t_0)/\tau_s} + \\ \left[\psi_{s2f}^+(t_1) - \psi_{s2f}^-(t_1) - \psi_{s3f}^+(t_1) - \psi_{s3f}^-(t_1) \right] e^{-(t-t_1)/\tau_s} \end{aligned} \quad (14)$$

The stator flux linkage expression after the later sag are:

$$\begin{aligned} \psi_{s3} = \psi_{s3f}^+ + \psi_{s3f}^- + \psi_{s3n} = \frac{\mathbf{u}_{s3}^+}{j\omega_s} + \frac{\mathbf{u}_{s3}^-}{-j\omega_s} \\ + \left[\psi_{s1}(t_0) - \psi_{s2f}^+(t_0) - \psi_{s2f}^-(t_0) \right] e^{-(t-t_0)/\tau_s} + \\ \left[\psi_{s2f}^+(t_1) - \psi_{s2f}^-(t_1) - \psi_{s3f}^+(t_1) - \psi_{s3f}^-(t_1) \right] e^{-(t-t_1)/\tau_s} \\ + \left[\psi_{s3f}^+(t_2) - \psi_{s3f}^-(t_2) - \psi_{s4f}^+(t_2) - \psi_{s4f}^-(t_2) \right] e^{-(t-t_2)/\tau_s} \end{aligned} \quad (15)$$

From (12-15), if the time interval of each voltage event is insufficient, the stator natural flux caused by the previous voltage change can't decay to 0, it will further affect the response of DFIG under the later voltage event.

Substitute the stator flux linkage expression into (6), the rotor voltage expressions of each stage can be obtained.

ROTOR OVER VOLTAGE UNDER RECURRING SYMMETRICAL VOLTAGE SAGS

In order to simplify the analysis, it is assumed that the amplitude and phase jump of two adjacent voltage sag are the same, and the influence of time interval is mainly analysed.

For symmetrical sags, there are no negative sequence components in voltage and flux. The simplest case is the internal time of four voltage events is long enough and the stator natural flux decay to 0. At this time, the rotor voltage amplitude of voltage recovery and second sag is basically the same as that of the first sag, as shown in Fig. 2. The blue, black, and green colors in the simulation represent the first voltage sag, the voltage recovery, and the second voltage sag, respectively.

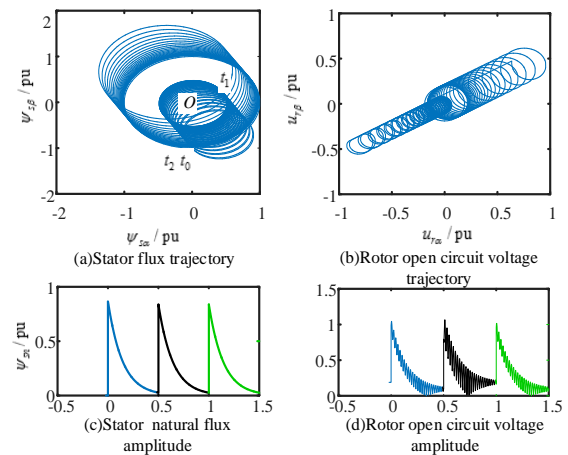


Fig. 2 $t_0=0$ s, sag occurs, $t_1=0.5$ s, sag recovers, $t_2=1$ s, the second sag occurs. (0.5pu $\Delta\varphi = -60^\circ$ symmetrical sag)

Suppose the time interval of each voltage event is insufficient, if the duration is an odd multiple of half a cycle, stator natural flux is superimposed in the same direction, resulting in greater rotor overvoltage. Fig. 3

shows the worst case. Although the magnitude of the two voltage sags is the same, the later sag produces almost twice the rotor over-voltage, because stator natural flux is superimposed twice.

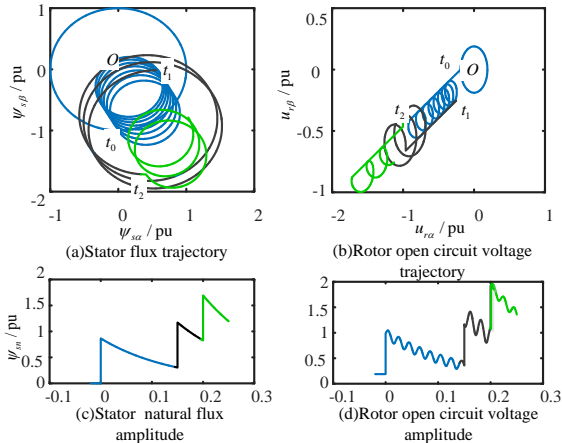


Fig. 3 $t_0=0$, sag occurs, $t_1=150$ ms, sag recovers, $t_2=0.2$ s, the second sag occurs. (0.5pu $\Delta\varphi=-60^\circ$ symmetrical sag)

If the duration is an even multiple, stator natural flux will be counterbalanced, resulting in smaller rotor overvoltage. As can be seen in Fig. 4, due to the reverse cancellation, the attenuation of the stator natural flux is promoted, which even causes the over-voltage under the second sag smaller.

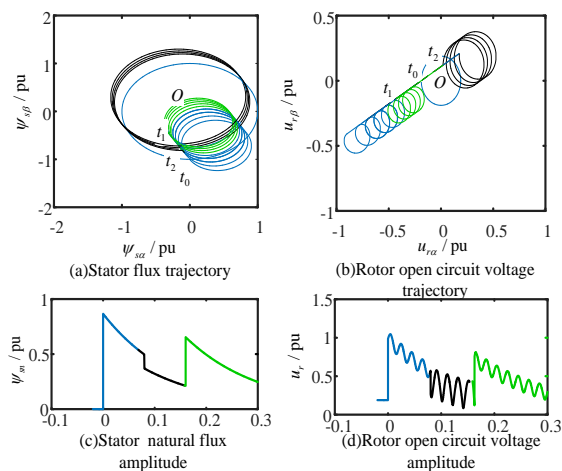


Fig. 4 $t_0=0$, sag occurs, $t_1=80$ ms, sag recovers, $t_2=0.16$ s, the second sag occurs. (0.5pu $\Delta\varphi=-60^\circ$ symmetrical sag)

ROTOR OVER VOLTAGE UNDER RECURRING ASYMMETRICAL VOLTAGE SAGS

For asymmetrical sags, the same assumption is made for symmetric sag analysis. In addition to the time interval, the POW of sags will also affect the rotor overvoltage. Due to the influence of PAJ, the POW generating the maximum and minimum rotor over-voltages is no longer 0° and 90° , literature [9] introduces relevant calculation methods. Similarly, when the time interval is long enough, the overvoltage caused by each voltage change will be basically the same.

In an ideal case, if the time interval is an integer multiple

of a half cycle wave, and the POW of sags are the one that causes the minimum rotor over-voltage, stator natural flux will be closed to zero, which is the better case. Take type B and type C voltage sag as an example, in the case shown in Fig. 5, the rotor voltage is almost only composed of positive and negative sequence components.

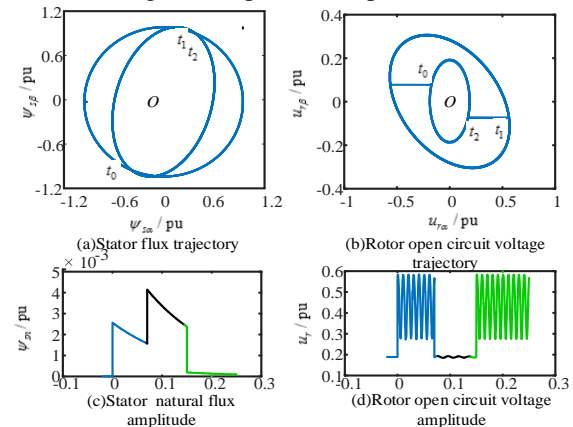


Fig. 5 $t_0=0$, sag occurs, $t_1=70$ ms, sag recovers, $t_2=0.15$ s, the second sag occurs. (0.5pu $\Delta\varphi=-30^\circ$ $\varphi_1=\varphi_2=-24^\circ$ Type B sag)

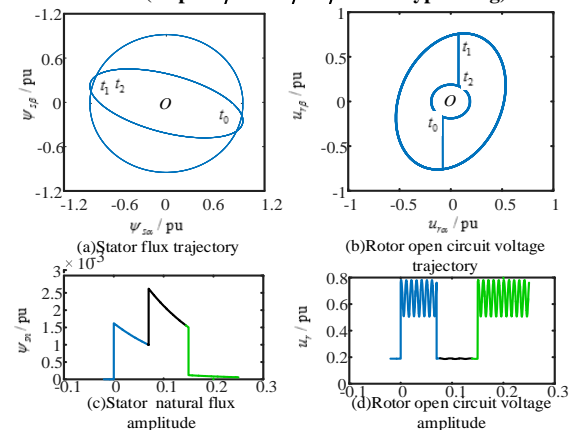


Fig. 6 $t_0=0$, sag occurs, $t_1=70$ ms, sag recovers, $t_2=0.15$ s, the second sag occurs. (0.5pu $\Delta\varphi=-30^\circ$ $\varphi_1=\varphi_2=66^\circ$ Type C sag)

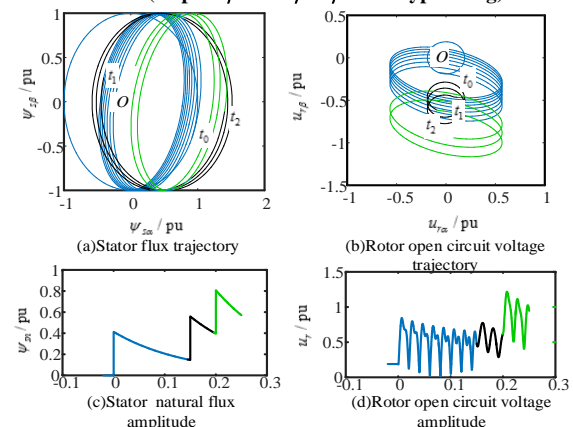


Fig. 7 $t_0=0$, sag occurs, $t_1=150$ ms, sag recovers, $t_2=0.2$ s, the second sag occurs. (0.5pu $\Delta\varphi=-30^\circ$ $\varphi_1=\varphi_2=66^\circ$ Type B sag)

If the POW of sags are the one that causes the maximum rotor over-voltage, stator natural flux will be greater. In this case, it is similar to a symmetrical sag. When the duration is an odd multiple of half a cycle, stator natural

flux is superimposed and resulting in greater rotor overvoltage, as shown in Fig. 7. The most extreme case occurs when the previous voltage sag is recovered after half a cycle and the next sag occurs after half a cycle. Comparing Fig. 8 with Fig.6, the rotor overvoltage can even be up to three times.

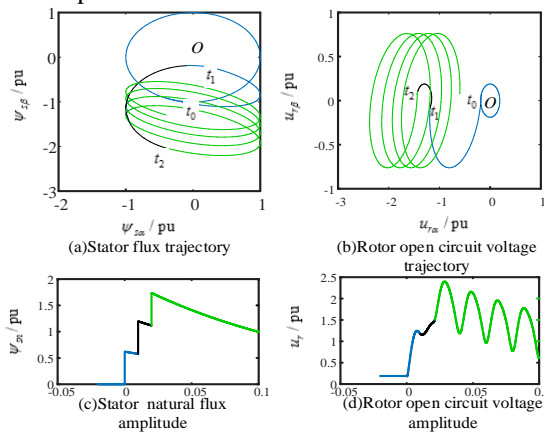


Fig. 8 $t_0=0$,sag occurs, $t_1=10$ ms,sag recovers, $t_2=20$ ms,the second sag occurs.(0.5pu $\Delta\phi=-30^\circ \phi=\phi_2=-24^\circ$ Type C sag)

If the duration is an even multiple, stator natural flux will result in smaller rotor over-voltage, as shown in Fig. 9, 10.

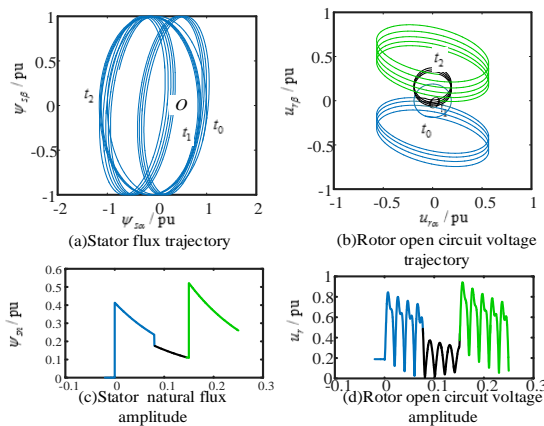


Fig. 10 $t_0=0$,sag occurs, $t_1=80$ ms,sag recovers, $t_2=0.15$ s,the second sag occurs.(0.5pu $\Delta\phi=-30^\circ \phi=\phi_2=66^\circ$ Type B sag)

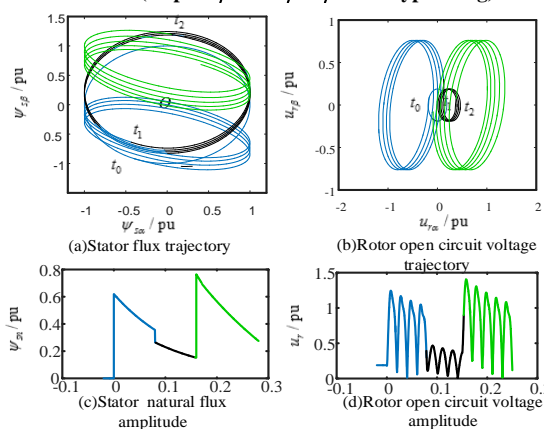


Fig. 10 $t_0=0$,sag occurs, $t_1=80$ ms,sag recovers, $t_2=0.15$ s,the second sag occurs.(0.5pu $\Delta\phi=-30^\circ \phi=\phi_2=-24^\circ$ Type C sag)

CONCLUSION

Under recurring voltage sags, sag duration and the time interval between two adjacent sag greatly affect the rotor over-voltage of DFIG. When the duration is an even multiple of half a cycle, the transient response of the next voltage change event will be alleviate. In contrast, when it's an odd multiple, stator natural flux will result in greater rotor over-voltage. DFIG which in line with the LVRT standard may disconnect with the grid during the second sag because of more severe transient electromagnetic oscillations. Therefore, it is necessary to add recurring voltage sag cases to existing standards and tests, and the time intervals and POW conditions causing more severe oscillations should be analyzed during LVRT test.

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