IMPACT OF PAJ WITH VARYING POW IN VOLTAGE SAG ON ROTOR OVER-VOLTAGE IN DFIG BASED WIND GENERATOR

Jie REN
Sichuan University – China
renjieholmesjay@163.com

Xian-Yong XIAO
Sichuan University – China
xiaoxianyong@163.com

Yuan-Fan LIU
Sichuan University – China
liuyuanfan526@163.com

Zi-Xuan ZHENG
Sichuan University – China
scuzzx@163.com

Wen-Bo CHEN
Nanjing Golden cooperate Information & Automation Technology CO. Ltd. – China
Chenwenbo@gc-bank.com

ABSTRACT

By the help of the vector analysis, this paper studied the impact of voltage sag with different characteristics on the rotor over-voltage of DFIG using the stator flux analysis. The influence principle of phase angle jump (PAJ) with varying point on wave (POW) on DFIG is presented. Vector analysis method is used to relate voltage sag features, stator flux and rotor voltage for symmetrical and unsymmetrical voltage sags. Considering the practical constraints of PAJ, the general variation rules of DFIG rotor over-voltage caused by PAJ with varying POW in voltages sag are validated by simulation.

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

I. INTRODUCTION

With advantages of a small converter capacity, flexible power control and wide operating speed range, DFIG is widely used in wind power generations. Since the stator directly coupled to the grid, the integrated DFIG is extremely vulnerable to unavoidably voltage sag [1]. As the wind power penetration rises, DFIG is required to have low voltage ride-through (LVRT) capability during sag event to maintain power system stability.

Nowadays extensive research on behaviors and control strategies of DFIG based LVRT capability are carried out [1-12]. A voltage dip may cause the stator flux linkage oscillation which will induce a notably increasing rotor electromagnetic force (EMF) [2-4]. If the over-voltage isn't compensated, it will originate over-current in the rotor [2]. The rotor converter may saturate and even lose control of the machine under severe over-currents [5-6].

Studies mentioned above only consider the magnitude and duration characteristics of low voltage events. In fact, multiple features of voltage sag seriously affect the transient process of DFIG and shouldn't be ignore. When X/R ratios of the system and fault impedance of integrated wind farm are different, PAJ occurs in voltage sags as the third important feature defined by IEEE Std1564-2014 [7-8]. Existing study shows that PAJ may aggravate the stator flux oscillation, affect the rotor over-voltage, over-current and coordinate orientation of vector control [9-12]. During asymmetrical voltage sags, different POW will affect the rotor over-voltage through stator natural flux [3, 4, 6]. However, Current researches mainly focus on simulation analysis and expression calculation, concise explanation to the principle of PAJ acting on DFIG parameters is less. It is necessary to investigate the impacts of voltage magnitude, sag duration, PAJ and POW of single sag event on LVRT capability of DFIG comprehensively.

In this paper, multi-characteristics of sag event and their impacts on the rotor over-voltage of DFIG are investigated. Firstly, through the stator flux linkage and rotor voltage vector analysis, how PAJ affects DFIG in essence is intuitively analyzed. Based on the study of symmetrical sag, the transient characteristics of DFIG under single-phase sags with PAJ and POW are presented. Mathematical expressions of the stator flux and rotor over-voltage are also given. Considering the practical constraints of PAJ, variation law of DFIG rotor over-voltage under different features of sag events is discussed, as well as voltage sag parameters with respect to the case where the rotor voltage is most severely affected by PAJ.

II. INFLUENCE PRINCIPLE OF PAJ ON DFIG ROTOR OVER-VOLTAGE

Based on the space vector models of DFIG in α-β static reference frame, the rotor voltage of DFIG is [2, 3]:

$$\boldsymbol{u}_{\mathrm{r}}=\frac{L_{\mathrm{m}}}{L_{\mathrm{s}}}\left(\frac{\mathrm{d}}{\mathrm{d}t}-\mathrm{j}\omega_{\mathrm{r}}\right)\boldsymbol{\psi}_{\mathrm{s}}+\left[R_{\mathrm{r}}+\sigma L_{\mathrm{r}}\left(\frac{\mathrm{d}}{\mathrm{d}t}-\mathrm{j}\omega_{\mathrm{r}}\right)\right]\boldsymbol{i}_{\mathrm{r}} \quad (1)$$

Ignoring the rotor current, the rotor voltage is nearly equaled to the rotor open-circuit voltage [3].

$$\boldsymbol{u}_{\mathrm{ro}}=\frac{L_{\mathrm{m}}}{L_{\mathrm{s}}}\left(\frac{\mathrm{d}\boldsymbol{\psi}_{\mathrm{s}}}{\mathrm{d}t}-\mathrm{j}\omega_{\mathrm{r}}\boldsymbol{\psi}_{\mathrm{s}}\right) \quad (2)$$

When the rotor is open-circuit, the first-order response equation of DFIG stator flux is:

$$\frac{\mathrm{d}\boldsymbol{\psi}_{\mathrm{s}}}{\mathrm{d}t}=\boldsymbol{u}_{\mathrm{s}}-\frac{R_{\mathrm{s}}\boldsymbol{\psi}_{\mathrm{s}}}{L_{\mathrm{s}}} \quad (3)$$

In (1) (2) (3), equaled to stator side, $\boldsymbol{u}_{\mathrm{s}}$ and $\boldsymbol{u}_{\mathrm{r}}$ are voltage vectors of stator and rotor; $\boldsymbol{i}_{\mathrm{r}}$ is rotor current vector; $\boldsymbol{\psi}_{\mathrm{s}}$ is stator 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 solution of equation (3) can be divided into two parts: the homogeneous and the nonhomogeneous solution. The latter is the forced flux which is a rotational term determined by the grid voltage; the former is the natural flux which decays progressively with a constant angle [3].

A. Vector analysis of symmetrical voltage sags

When a three-phase voltage sag occurs, excluding the impact of PAJ ($\Delta\varphi = 0^{\circ}$), the grid voltage is rotated at the grid frequency ω_s and drops from $\boldsymbol{u}_1$ to $\boldsymbol{u}_2'$. The forced flux $\boldsymbol{\psi}_{sf}'$ and the natural flux $\boldsymbol{\psi}_{sn}'$ are in line with the pre-fault stator flux linkage $\boldsymbol{\psi}_1$. Accordingly, the forced voltage $\boldsymbol{u}_{rf}'$ and the natural voltage $\boldsymbol{u}_{rn}'$ are also in line with the pre-fault rotor voltage $\boldsymbol{u}_{ro}$ [2].

Considering the impact of PAJ ($\Delta\varphi \neq 0^{\circ}$), PAJ directly reflects that the stator voltage and forced flux linkage after fault ($\boldsymbol{u}_2$ and $\boldsymbol{\psi}_{sf}$) are no longer consistent with the pre-fault direction, but have a $\Delta\varphi$ deviation. So after vector synthesis, the stator natural flux $\boldsymbol{\psi}_{sn}$ amplitude increases and its phase changes. Similarly $\boldsymbol{u}_{rf}'$ turns to $\boldsymbol{u}_{rf}$ after angle jump $\Delta\varphi$, and the amplitude of the rotor natural voltage $\boldsymbol{u}_{rn}$ increases observably. Only $\boldsymbol{u}_{rf}$ turns θ_m and in phase with $\boldsymbol{u}_{rn}$, the rotor voltage can reach its peak value. Detailed vector illustration is shown in Fig. 1.

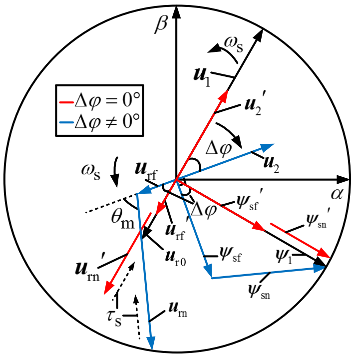


Fig. 1 Vector diagram of stator flux and rotor voltage with PAJ under three-phase voltage sag (s<0)

It is intuitive to see that PAJ eventually leads to an aggravated oscillation of stator flux linkage. The amplitude of rotor voltage increases significantly, and its peak value no longer occurs at the fault moment but after a time delay related to θ_m.

B. Vector analysis of single-phase voltage sags

During asymmetrical voltage sags, a negative sequence voltage that rotates at a frequency $-\omega_s$ will generates a large inducted voltage in the rotor which frequency is approximately twice the grid frequency [3, 11]. The stator natural flux changes with varying POW [3]. Based on the investigations of symmetrical voltage sag event, PAJ also increases the natural component by affecting the phase angle of the voltage and flux linkage vectors under asymmetrical sags. However, PAJ only occurs at the fault-phase and the effect of PAJ on the stator voltage positive and negative sequence components are different[11]. Affected by PAJ, the maximum and minimum values of the rotor voltage are no longer present at a time when the POW is 0° or 90°.

As the most common fault type in power system, this paper mainly focuses on the one-phase-ground fault caused low voltage event. If at the fault time t_0, the fault-phase grid voltage drops from U_0 to pU_0 where p is the depth of voltage sags, phase jumps from φ_0 to φ_1. Thus the PAJ value $\Delta\varphi = \varphi_1 - \varphi_0$, the POW $\varphi_0 = \omega_s t_0$. Assumed the fault occurs at phase A, the three-phase grid voltage after fault can be expressed as:

$$\begin{cases} \boldsymbol{u}_a = pU_0 e^{j(\omega_s t+\varphi_0+\Delta\varphi)} = pU_0 e^{j(\omega_s t+\varphi_1)} \\ \boldsymbol{u}_b = U_0 e^{j(\omega_s t+\varphi_0)} \cdot a^2 \\ \boldsymbol{u}_c = U_0 e^{j(\omega_s t+\varphi_0)} \cdot a \end{cases} \tag{4}$$

where a is a unitary vector at an angle of 120°.

Through symmetrical component method, the positive and negative grid voltage before and after fault are:

$$\begin{cases} \boldsymbol{u}_{s1}^{+} = U_1^{+} e^{j(\omega_s t+\varphi_0)} = j\omega_s \boldsymbol{\psi}_{s1}^{+} & t < t_0 \\ \boldsymbol{u}_{s1}^{-} = U_1^{-} e^{-j(\omega_s t+\varphi_0)} = -j\omega_s \boldsymbol{\psi}_{s1}^{-} = 0 & t < t_0 \end{cases} \tag{5}$$

$$\begin{cases} \boldsymbol{u}_{s2}^{+} = U_2^{+} e^{j(\omega_s t+\varphi_0+\theta^{+})} = j\omega_s \boldsymbol{\psi}_{s2}^{+} & t \geq t_0 \\ \boldsymbol{u}_{s2}^{-} = U_2^{-} e^{-j(\omega_s t+\varphi_0+\theta^{-})} = -j\omega_s \boldsymbol{\psi}_{s2}^{-} & t \geq t_0 \end{cases} \tag{6}$$

where $\boldsymbol{u}_{s1}^{+}$, $\boldsymbol{u}_{s1}^{-}$, $\boldsymbol{\psi}_{s1}^{+}$, $\boldsymbol{\psi}_{s1}^{-}$ are the positive and negative sequence component of stator voltage and flux before the fault; $\boldsymbol{u}_{s2}^{+}$, $\boldsymbol{u}_{s2}^{-}$, $\boldsymbol{\psi}_{s2}^{+}$, $\boldsymbol{\psi}_{s2}^{-}$ are those variables after the fault; U_1^{+}, U_1^{-}, U_2^{+}, U_2^{-} are the amplitude of $\boldsymbol{u}_{s1}^{+}$, $\boldsymbol{u}_{s1}^{-}$, $\boldsymbol{u}_{s2}^{+}$, $\boldsymbol{u}_{s2}^{-}$ respectively; θ^{+} and θ^{-} are phase of the positive and negative sequence stator voltage if ignore the POW.

Based on (4), the parameters in (5) (6) are:

$$\begin{cases} U_2^{+} = \frac{1}{3} U_0 \sqrt{[p\cos\Delta\varphi + 2]^2 + [p\sin\Delta\varphi]^2} \\ \theta^{+} = \arcsin\Big[p\sin\Delta\varphi / \\ \qquad \sqrt{[p\cos\Delta\varphi + 2]^2 + [p\sin\Delta\varphi]^2} \Big] \end{cases}$$

$$\begin{cases} U_2^{-} = \frac{1}{3} U_0 \sqrt{[p\cos\Delta\varphi - 1]^2 + [p\sin\Delta\varphi]^2} \\ \theta^{-} = \arcsin\Big[p\sin\Delta\varphi / \\ \qquad \sqrt{[p\cos\Delta\varphi - 1]^2 + [p\sin\Delta\varphi]^2} \Big] \end{cases} \tag{7}$$

From (5) (6) (7), it is obvious that PAJ can change the magnitude and initial phase angle of the positive and negative sequence component of stator voltage and flux.

Solve the differential equation (3), the stator flux linkage expression at the fault moment is:

$$\begin{aligned} \boldsymbol{\psi}_s(t) &= \boldsymbol{\psi}_{s2}^{+} + \boldsymbol{\psi}_{s2}^{-} + \boldsymbol{\psi}_{sn}^{+}(t_0) + \boldsymbol{\psi}_{sn}^{-}(t_0) \\ &= \frac{U_2^{+}}{j\omega_s} e^{j(\omega_s t+\varphi_0+\theta^{+})} + \frac{U_2^{-}}{-j\omega_s} e^{-j(\omega_s t+\varphi_0+\theta^{-})} + \\ &\quad \frac{U_1^{+} - U_2^{+} e^{j\theta^{+}}}{j\omega_s} e^{j(\omega_s t_0+\varphi_0)} e^{-(t-t_0)/\tau_s} - \\ &\quad \frac{U_2^{-} e^{-j\theta^{-}}}{-j\omega_s} e^{-j(\omega_s t_0+\varphi_0)} e^{-(t-t_0)/\tau_s} \end{aligned} \tag{8}$$

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

From (8), much more complex than the symmetrical sag, stator natural flux $\boldsymbol{\psi}_{sn}(t_0)$ is also composed of positive and

negative sequence components $\psi_{sn}^{+}(t_0)$ and $\psi_{sn}^{-}(t_0)$. When these two fluxes are opposed and offset each other, the rotor over-voltage reaches its minimum. When they are in line and overlay, the over-voltage will be the largest.
Substitute (7) into (8), the stator natural flux at time t_0 is:

$$\psi_{sn}(t_0)=\frac{2}{3}U_0\left[\sin\varphi_1-p\sin\left(\varphi_1+\Delta\varphi\right)\right] \quad (9)$$

The stator natural flux is affected by both PAJ and POW. Substitute (8) into (2), due to the large stator flux time constant, ignoring the 1 / τ_s term, the rotor open-circuit voltage equation is:

$$\boldsymbol{u}_{ro}=\boldsymbol{u}_{r2}^{+}+\boldsymbol{u}_{r2}^{-}+\boldsymbol{u}_{rn}^{+}(t_0)+\boldsymbol{u}_{rn}^{-}(t_0)=\frac{L_m}{L_s}$$
$$\Big[sU_2^{+}e^{j(\omega_s t+\varphi_0+\theta^{+})}+(2-s)U_2^{-}e^{-j(\omega_s t+\varphi_0+\theta^{-})}$$
$$+(s-1)(U_1^{+}-U_2^{+}e^{j\theta^{+}})e^{j(\omega_s t_0+\varphi_0)}e^{-(t-t_0)/\tau_s}$$
$$+(s-1)U_2^{-}e^{-j\theta^{-}}e^{-j(\omega_s t_0+\varphi_0)}e^{-(t-t_0)/\tau_s}\Big] \quad (10)$$

where $\boldsymbol{u}_{s2}^{+}$ and $\boldsymbol{u}_{s2}^{-}$ are the positive and negative rotor forced voltage; $\boldsymbol{u}_{rn}^{+}(t_0)$ and $\boldsymbol{u}_{rn}^{-}(t_0)$ are the positive and negative rotor natural voltage.
Based on the vector analysis method on symmetrical voltage sag, a detailed vector illustration about PAJ influences is shown in Fig. 2.

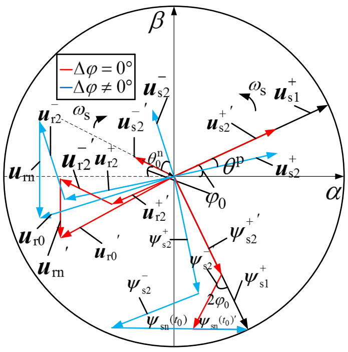


Fig. 2 Vector diagram of stator flux and rotor voltage with PAJ under single-phase voltage sag (s<0)

When a single-phase fault occurs, excluding the impact of PAJ ($\Delta\varphi = 0^{\circ}$), from the beginning time $\theta^{+} = 0°$ and $\theta^{-} = -180°$[11], the positive and negative grid voltage ($\boldsymbol{u}_{s2}^{+\prime}$ and $\boldsymbol{u}_{s2}^{-\prime}$) rotate φ_0 oppositely. When $\varphi_0 = 0°$, the natural flux $\psi_{sn}(t_0)'$ is zero because at this moment the positive and negative fluxes ($\psi_{s2}^{+\prime}$ and $\psi_{s2}^{-\prime}$) are aligned which lead to a minimum rotor over-voltage. To the opposite, when $\varphi_0 = 90°$, the natural flux initial value is the largest since the positive and negative fluxes are opposed [3].
Considering the impact of PAJ ($\Delta\varphi \neq 0^{\circ}$), the phase angle of the positive and negative grid voltage jump θ^{+} and θ_0^{-} to $\boldsymbol{u}_{s2}^{+}$ and $\boldsymbol{u}_{s2}^{-}$ severally. The stator forced flux phase changes the same to ψ_{s2}^{+} and ψ_{s2}^{-}, which generate the sequences natural components ($\psi_{sn}^{+}(t_0)$ and $\psi_{sn}^{-}(t_0)$) to suppress the flux linkage mutation. The magnitude of the synthesized stator natural flux $\psi_{sn}(t_0)$ is thus greatly increased and changes with POW. Obviously PAJ can not only change the amplitude and phase angle of positive and negative stator flux but also amplitude of natural flux. As PAJ increases, the negative and natural fluxes rise, but the positive flux decreases. The phase of natural flux is not change. Variation of rotor voltage vectors with $\Delta\varphi$ is similar to stator flux, the phase of natural voltage is not change either, but the amplitude of rotor voltage increases from $\boldsymbol{u}_{r0}'$ to $\boldsymbol{u}_{r0}$.

III. VARIATION LAW OF DFIG ROTOR OVER-VOLTAGE

According to the definition and variation in reference [7-8], PAJ is limited under different fault voltages. Variation of DFIG rotor over-voltage under voltage sag events, which each feature is under mutual influence and constraints is necessary to be focused on.

A. Variations on symmetrical voltage sags

The relationship between the PAJ and amplitude of the fault voltage at different impedance angles is shown in Fig. 3. In practice, the PAJ does not always reach its maximum at different amplitudes. In view of PAJ and magnitude features, using MATLAB simulation, the relationship between the addition of the peak value of rotor over-voltage ΔU_{r_max} and the fault voltage amplitude U_2 under different PAJ is shown in Fig. 4. Where Fig. 4 (A) shows the case that PAJ always reach its max value defined by the impedance angle; Fig. 4 (B) shows the case that PAJ is limited defined by Fig. 3.

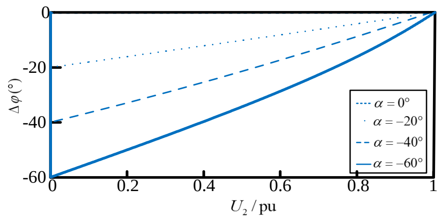
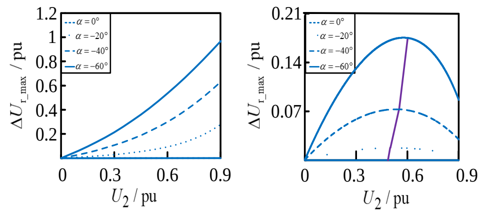


Fig. 3 Relation between PAJ and post-fault voltage magnitude



(A) (B)

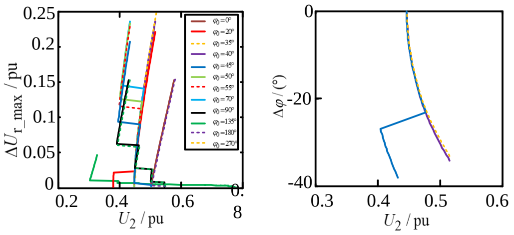
Fig. 4 Variation of the addition of peak rotor voltage under three-phase voltage sags($s = -0.2$)

Comparing the two figures in Fig. 4, their trend is similar when U_2 is little. However, when U_2 is large, the two change opposite. With varying PAJ, the larger the voltage, the greater the increase. The sag magnitude which results in the largest increase in DFIG rotor voltage is 0.9 p. u. With limited PAJ, the curve is approximately parabolic.
Plotting curves which fitted to the points with the largest over-voltage in different PAJs, the range of the sag voltage amplitude which results in the maximum rotor voltage increases is 0.5~0.6 p. u shown in Fig. 4 (B).

B. Variations on single-phase voltage sags

Similar as the analysis about symmetrical voltage sags, PAJ and drop voltage in the fault-phase has the same relation in Fig. 3. With the POW given, considering the practical constraints in Fig. 3, the relationship between ΔU_{r_max} and U_2 under single-phase voltage sags is much similar with that shown in Fig. 4 (B). However, POW will affect the variation of the addition of peak rotor voltage and the most sensitive voltage sag ranges, so the most serious POW restrictions should be considered.

With varying given POW, using MATLAB simulation, curves which fitted to the points with the largest over-voltage in different PAJs under each POW are shown in Fig.5 (A). It can be seen that with different POW, the maximum amplitude and trends of rotor over-voltage caused by PAJ are significantly different. Three of these POWs are selected which lead to the most serious over-voltage. The relations between the PAJ value and the amplitude of the fault voltage under those three given POW are shown in Fig.5 (B).



(A) (B)

Fig. 5 Variation of the addition of peak rotor voltage under single-phase voltage sags with different POW($s = -0.2$)

The conclusion is that considering the PAJ, varying POW and magnitude characteristics of single-phase sag events comprehensively, the voltage sag event ranges which leads to the most serious DFIG based rotor over-voltage under PAJ are the case when the magnitude varies from 0° to -35°; the PAJ value varies from 0.4 p. u. to 0.5 p. u.; the POW varies from 35° to 45°. The most sensitive voltage sag test points for the PAJ can be referred to the engineering applications.

IV. CONCLUSION

There are multiple characteristics of grid voltage sag event include magnitude, deration, PAJ and varying POW. They all have a significant effect on DFIG based voltage and flux linkage transient characteristics. With analysis of the single-phase voltage sag event, the conclusions based on this paper are as following:

The first, PAJ visually reflects that the sequences stator voltage and forced flux linkage after fault are no longer consistent with the pre-fault direction, but have an angle deviation, the magnitude of them are also changed. Those influences lead to an aggravated oscillation of stator flux linkage and increasing rotor over-voltage which peak value occurs after a time decay.

The second, the POW features mainly affect the natural component of stator flux. The maximum and minimum values of the natural flux are no longer present at a time when the POW is 0° or 90° but a POW defined with PAJ. The rotor voltage will also have a corresponding impact.

Finally, considering PAJ, POW and magnitude features of sag events comprehensively, the most sensitive sag voltage is around 0.5 p. u which can be referred to the engineering applications.

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