Double fed asynchronous generator connected to an unbalanced electric grid

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Abstract: In this paper, one proposes to study the adaptability of doubly fed asynchronous generator (DFAG) with an unbalanced electrical supply network. One understands by imbalance an inequality of the modules of the voltages system of the network, an imbalance of the phases or frequency of the electrical supply network. The studied system consists of a doubly fed asynchronous generator connected to a network unbalanced via a chain of controlled converters, consisted of a rectifier and an converter all two ordered in Pulse Width Modulation PWM. We carried out an insulation of the DFAG as well as converter side machine (CM) by action on the field of variation of the tension of the continuous bus. Consequently, the fluctuations of the latter, in the event of imbalance, remain in a tolerable margin by the requirements of the DFAG.

Key words: Unbalance**,** symmetrical components doubly fed asynchronous generator (DFAG), transform of Park, transform of Fortescue, systems direct, opposite and homopolar, reference mark of Concordia, fuzzy controller, fuzzy rules, converter side machine CM, converter side network CR, continuous bus, Pulse Width Modulation PWM, chain of conversion, estimate.

I- Model of the doubly fed asynchronous generator

The doubly fed asynchronous generator (DFAG) is connected to an unbalanced network via a cascade of converters (CM) and (CR) connected by a continuous bus [5].

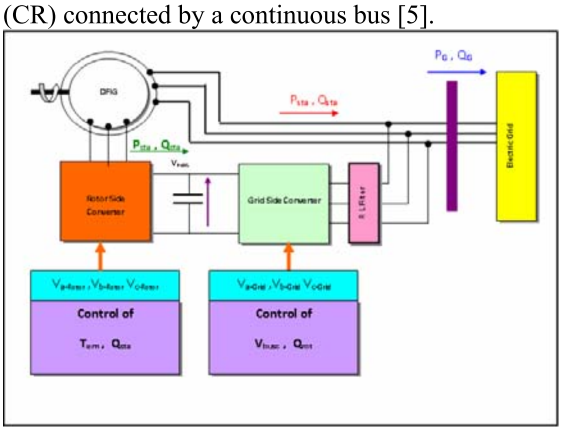

Fig.1.1: Synoptic diagram of the studied system.

The equations of stator and rotor flux are:

$$\frac{d\left[\phi_{sdq0}\right]}{dt}=\left[v_{sdq0}\right]-\left[R_s\right]\left[i_{sdq0}\right]-\left[I\right]\left[\phi_{sdq0}\right]\frac{d\theta_s}{dt}$$

$$\frac{d\left[\phi_{rdq0}\right]}{dt}=\left[v_{rdq0}\right]-\left[R_r\right]\left[i_{rdq0}\right]-\left[I\right]\left[\phi_{rdq0}\right]\frac{d\theta_r}{dt} \quad (1.1)$$

The electromagnetic couple is expressed according to the stator sizes:

$$C_{em} = p(\Phi_{ds} i_{qs} - \Phi_{qs} i_{ds}) \quad (1.2)$$

Stator and rotor fluxes are governed by the following equations:

$$\frac{d\Phi_{ds}}{dt} = v_{ds} - R_s i_{ds} + \omega_s \Phi_{qs} \quad (1.3)$$

$$\frac{d\Phi_{qs}}{dt} = v_{qs} - R_s i_{qs} - \omega_s \Phi_{ds} \quad (1.4)$$

$$\frac{d\Phi_{dr}}{dt} = v_{dr} - R_r i_{dr} + \omega_r \Phi_{qr} \quad (1.5)$$

$$\frac{d\Phi_{qr}}{dt} = v_{qr} - R_r i_{qr} - \omega_r \Phi_{dr} \quad (1.6)$$

If the statorique q axis flux is zero ($\Phi_{qs} = 0$) we obtain:

$$i_{qs} = -\frac{M}{L_s} i_{qr} \qquad (1.7)$$

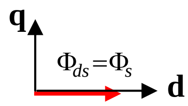

Fig.1.2: Vectorial diagram, orientation of stator flow.

The stator direct current is given by :

$$i_{ds} = \frac{\Phi_{ds} - Mi_{dr}}{L_s} \qquad (1.8)$$

Thus the (d,q) axis components of the rotor flux will be :

$$\Phi_{dr} = (L_r - \frac{M^2}{L_s})i_{dr} + \frac{M}{L_s}\Phi_{ds} = L_r\sigma i_{dr} + \frac{M}{L_s}\Phi_{ds} \qquad (1.9)$$

$$\Phi_{qr} = L_r i_{qr} - \frac{M^2}{L_s} i_{qr} = L_r \sigma i_{qr} \qquad (1.10)$$

σ : Scatter coefficient between the (d, q) winding :

$$\sigma = 1 - \frac{M^2}{L_r L_s}$$

Thus, the expressions of the stator and rotor voltages will be:

$$v_{ds} = \frac{R_s}{L_s}\Phi_{ds} - \frac{R_s}{L_s} Mi_{dr} + \frac{d\Phi_{ds}}{dt} \qquad (1.11)$$

$$v_{qs} = -\frac{R_s}{L_s} Mi_{qr} + \omega_s \Phi_{ds} \qquad (1.12)$$

$$v_{dr} = R_r i_{dr} + L_r\sigma \frac{di_{dr}}{dt} + \frac{M}{L_s}\frac{d\Phi_{ds}}{dt} - L_r\omega_r\sigma i_{qr} \qquad (1.13)$$

$$v_{qr} = R_r i_{qr} + L_r\sigma \frac{di_{qr}}{dt} + \omega_r \frac{M}{L_s}\Phi_{ds} + L_r\omega_r\sigma i_{dr} \qquad (1.14)$$

The variations of the rotor currents are given by:

$$\frac{di_{dr}}{dt} = \frac{1}{L_r\sigma}(v_{dr} - R_r i_{dr} - E_d) \qquad (1.15)$$

$$\frac{di_{qr}}{dt} = \frac{1}{L_r\sigma}(v_{qr} - R_r i_{qr} - E_q - E_\Phi) \qquad (1.16)$$

One notes by:

$$E_d = -\omega_r L_r \sigma i_{qr} + \frac{M}{L_s}\frac{d\Phi_{ds}}{dt}) \qquad (1.17)$$

$$E_\Phi = \omega_r \frac{M}{L_s}\Phi_{ds} \qquad (1.18)$$

$$E_q = \omega_r L_r \sigma i_{dr} \qquad (1.19)$$

The torque expression is :

$$C_{em} = -p\frac{M}{L_s}\Phi_{ds} i_{qr} \qquad (1.20)$$

The estimate of the stator flux of d axis is given by:

$$\Phi_{ds-est} = \frac{1}{1+T_s s}(T_s v_{ds} + Mi_{dr}) \qquad (1.21)$$

With:

$$\Phi_{ds} = L_s i_{ds} + Mi_{dr} \; ; \qquad (1.22)$$

$$T_s = \frac{L_s}{R_s}$$

We will establish an algorithm allowing controlling the DFAG by minimization of the losses by Joule effect. We write then:

$$P_j = \frac{3}{2}\left[R_s(i_{ds}^2 + i_{qs}^2) + R_r(i_{dr}^2 + i_{qr}^2)\right] \qquad (1.23)$$

Cette relation peut s'écrire sous la forme :

$$P_j = F_1(i_{ds}, \phi_{ds}) + F_2(i_{qs}, \phi_{ds}) \qquad (1.24)$$

Avec :

$$F_1(i_{ds}, \phi_{ds}) = \left[(R_s + \frac{L_s^2}{M^2}R_r)i_{ds}^2 - 2\frac{L_s R_r}{M^2} i_{ds}\Phi_{ds}\right]$$

$$F_2(i_{qs}, \phi_{ds}) = \left[(R_s + \frac{L_s^2}{M^2}R_r)i_{qs}^2 + \frac{R_r}{M^2}\Phi_{ds}\right]$$

Le minimum de cette puissance est donné par la valeur du courant i_{ds} :

$$i_{ds} = \frac{L_s R_r}{R_s M^2 + R_r L_s^2}\Phi_{ds} \qquad (1.25)$$

Et ainsi, on peut calculer la valeur de référence à imposer pour la composante directe du courant roto :

$$i_{dr-réf} = \frac{MR_s}{R_s M^2 + R_r L_s^2}\Phi_{réf} \qquad (1.26)$$

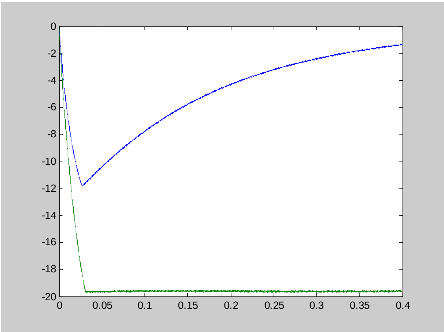

Fig.1.3: evolution of the rotor currents.

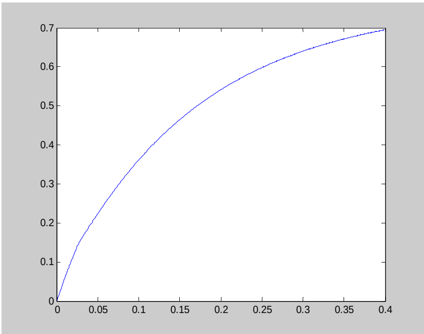

Fig 1.4: evolution of the statoric flux.

II- Fuzzy controller

In order to control the rotor currents of the generator on the one hand and to maintain the fluctuations of the tension drunk continuous in an acceptable margin on the other hand, we used in our study two fuzzy regulators [10].

One calculates the errors of the currents of axes (d, q), ($i_{dr-ref} - i_{dr}$) and ($i_{qr-ref} - i_{qr}$) and variations of the errors ($i_{dr0} - i_{dr}$) and ($i_{qr0} - i_{qr}$). Consequently, one will evaluate by the fuzzy regulator [9] the currents of control i_{dc} and i_{qc}, figure 2.1, in order to reach the values of reference $i_{dr-réf}$ et $i_{qr-réf}$. Even procedure's under taken for the q axis currents.

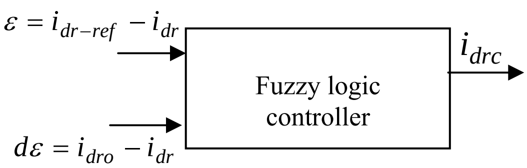

Fig. 2.1: General diagram of the fuzzy controller.

ε : Error, $d\varepsilon$: Variation of the error.

We represented on figure the 2.2 functions of membership as well as the degrees of membership of the input and output variables of the fuzzy controller. We indicate by:
NL: Negative large, Nm: Negative Means, NS: Negative Small, Z: Zero, PL: Positive large, PM: Positive Means, PS: Positive Small

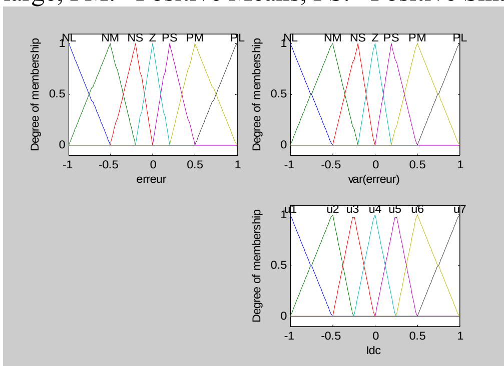

Fig. 2.2: Membership functions of the fuzzy variables.

Each variable treated by the fuzzy controller, the error ε, the variation of the error $d\varepsilon$ and the control vector i_{dc}, has seven functions of membership. It is followed from there then, forty-nine fuzzy rules to test, figure 2.3.

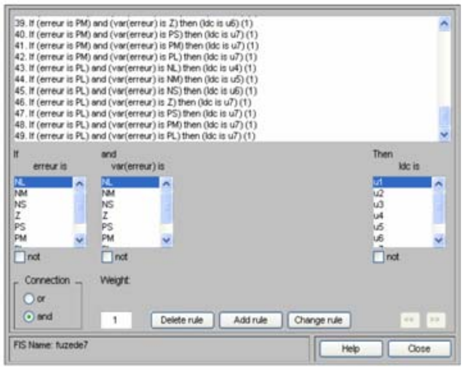

Fig. 2.3: Observed fuzzy rules.

Figure 2.4 highlights the correct action of the fuzzy controller on the continuous bus voltage like on the rotor currents reconstituted in the stator reference frame.

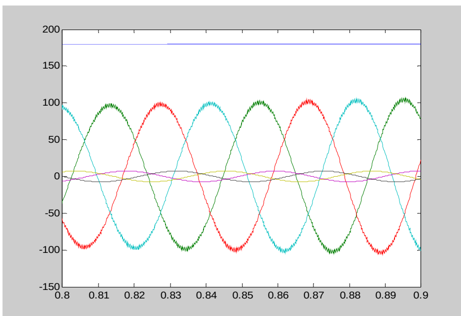

Fig. 2.4: Temporal evolution of the rotor currents and continuous bus voltage V_{Busc}

1II- filtering Module of the continuous bus voltage

The voltage V_e delivered by the converter CM must be filtered before being treated by the fuzzy controller. Indeed, imbalance affecting the network should not in no case to be perceived by the continuous bus. Figure 3.1 illustrates the module of adopted filtering.

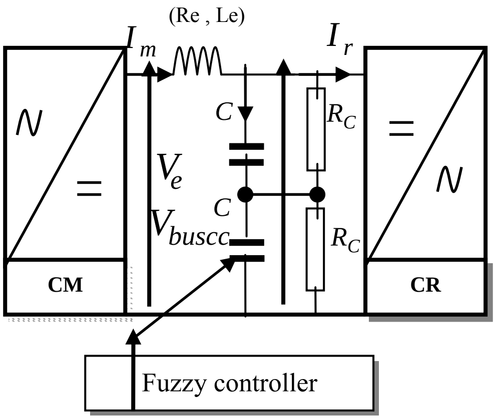

Fig.3.1: Filtering modul of the continuous bus voltage.

The module of filtering is governed by the model of state (3.1).

$$\frac{dI_m}{dt} = \frac{V_e - V_c - R_e I_m}{L_e} = F(I_m, V_c, t)$$

$$\frac{dV_c}{dt} = \frac{2}{C}(I_m - I_r) = G(I_m, V_c, t)$$

(3.1)

The system of equations (3.1) is written in the form of the equation of state (3.2).

$$\frac{dX}{dt} = AX + BU$$

(3.2)

With:

$$X = \begin{bmatrix} I_m \\ V_c \end{bmatrix} \; ; \; U = \begin{bmatrix} I_r \\ V_e \end{bmatrix}$$

$$A = \begin{bmatrix} \frac{-R_e}{L_e} & \frac{-1}{L_e} \\ \frac{2}{C} & 0 \end{bmatrix} \; ; \; B = \begin{bmatrix} 0 & \frac{1}{L_e} \\ -\frac{2}{C} & 0 \end{bmatrix}$$

The current I_r is calculated according to the currents output on the network, the voltage V_e is provided by the converter CM. We apply the method of Runge Kutta of order 4 to calculate I_m and V_c .

$$I_m(k+\delta t) = I_m(k) + \frac{1}{6}\delta t(H_1 + 2H_2 + 2H_3 + H_4) \quad (3.3)$$

$$V_c(k+\delta t) = V_c(k) + \frac{1}{6}\delta t(L_1 + 2L_2 + 2L_3 + L_4) \quad (3.4)$$

With :

$$H_i = F(I_{mi}, V_{ci}, t_i) \; ; \; L_i = G(I_{mi}, V_{ci}, t_i)$$

IV- Model of the converter (CR) with unbalanced system

We took account of imbalance at the time of the modelling of the converter CR and this by the decomposition of the unbalanced voltage system in its Fortescue components. Components of the direct vectors voltages and opposite provided by the converter CR, in the reference frame (α, β), [8] [10] are formulated in table 4.1 per application of the relations 4.1 and 4.2.

$$V_{\alpha d} = \sqrt{\frac{3}{2}} V_d \; ; \; V_{\beta d} = -j\sqrt{\frac{3}{2}} V_d \quad (4.1)$$

$$V_{\alpha i} = \sqrt{\frac{3}{2}} V_d \; ; \; V_{\beta i} = j\sqrt{\frac{3}{2}} V_d \quad (4.2)$$

			Direct system		Inverse System	
K_1	K_2	K_3	$V_{\alpha d}$	$V_{\beta d}$	$V_{\alpha i}$	$V_{\beta i}$
1	1	1	0	0	0	0
1	0	0	$\sqrt{\frac{2}{3}}\frac{U}{2}$	$-j\sqrt{\frac{2}{3}}\frac{U}{2}$	$\sqrt{\frac{2}{3}}\frac{U}{2}$	$j\sqrt{\frac{2}{3}}\frac{U}{2}$
1	1	0	$-a^2\sqrt{\frac{2}{3}}$	$ja^2\sqrt{\frac{2}{3}}\frac{U}{2}$	$-a\sqrt{\frac{2}{3}}\frac{U}{2}$	$-ja\sqrt{\frac{2}{3}}\frac{U}{2}$
1	0	1	$-a\sqrt{\frac{2}{3}}\frac{U}{2}$	$aj\sqrt{\frac{2}{3}}\frac{U}{2}$	$-a^2\sqrt{\frac{2}{3}}$	$-ja^2\sqrt{\frac{2}{3}}\frac{U}{2}$
0	1	1	$-\sqrt{\frac{2}{3}}\frac{U}{2}$	$j\sqrt{\frac{2}{3}}\frac{U}{2}$	$-\sqrt{\frac{2}{3}}\frac{U}{2}$	$-j\sqrt{\frac{2}{3}}\frac{U}{2}$
0	0	1	$a^2\sqrt{\frac{2}{3}}\frac{U}{2}$	$-ja^2\sqrt{\frac{2}{3}}\frac{U}{2}$	$a\sqrt{\frac{2}{3}}\frac{U}{2}$	$ja\sqrt{\frac{2}{3}}\frac{U}{2}$
0	1	0	$a\sqrt{\frac{2}{3}}\frac{U}{2}$	$-ja\sqrt{\frac{2}{3}}\frac{U}{2}$	$a^2\sqrt{\frac{2}{3}}\frac{U}{2}$	$ja^2\sqrt{\frac{2}{3}}\frac{U}{2}$
0	0	0	0	0	0	0

Tab.4.1: Distribution of the components of the direct and opposite voltages in the reference frame (α β).

We studied the case of an imbalance in module of the electrical supply network voltages. Figure 4.1 represents the evolution of the continuous bus voltage in absence of a fuzzy controller as well as the voltages synthesized by the converter CR. The continuous bus voltage is fluctuating in module and frequency.

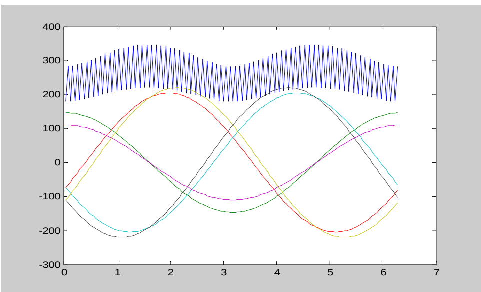

Fig. 4.2: The unbalanced network voltages.

Figure 4.3 illustrates the evolution of the homopolare component of the unbalanced network voltages system.

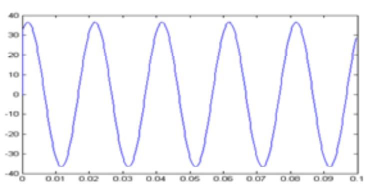

Fig. 4.3: The homopolar component in mode unbalanced.

The component on the direct axis of the V_α noted $V_{\alpha d}$ provided by the converter CR to the network evolves as indicates it figures 4.4 [1].

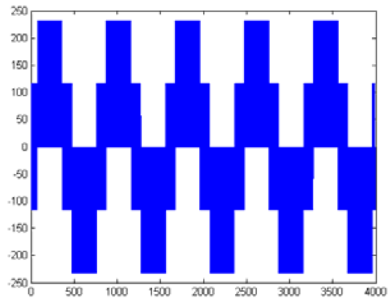

Fig.4.4: Vαd voltage in the case of an unbalanced system's module.

The flow chart of figure 4.5 summarizes the numerical procedure of calculation developed during simulations [6].

V-Conclusion

The adaptation of a doubly fed asynchronous generator with an unbalanced electrical supply network requires a logical procedure of converters control.

We granted a capital interest to the operating mode of the generator which does not have, to in no case of defect, to see imbalance affecting the network. What lets foresee a physical insulation of the generator and converter CM by the supervision of the continuous voltage bus.

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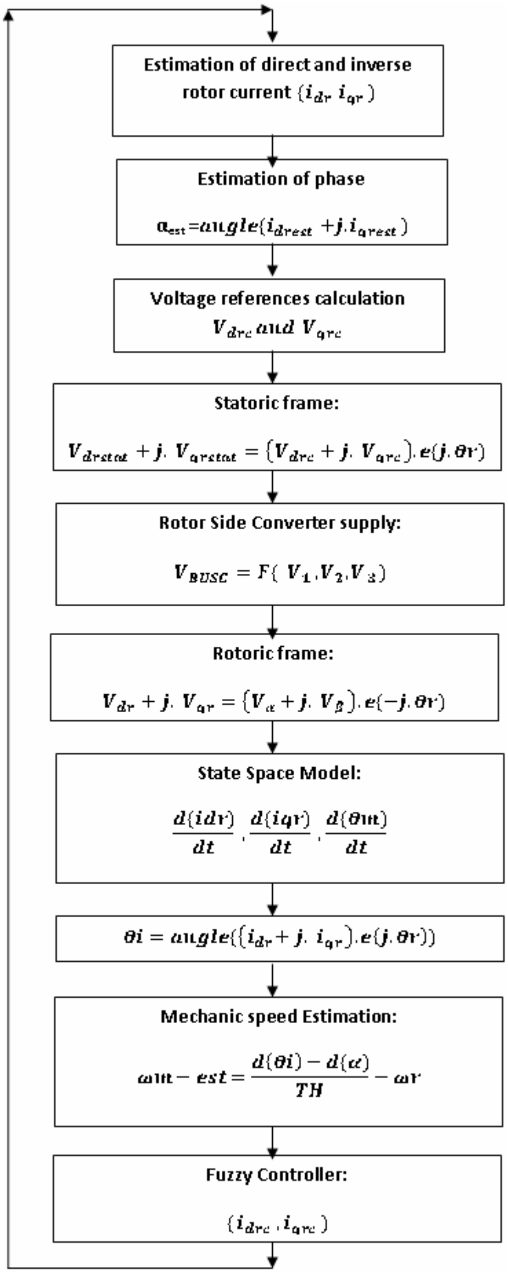

Fig.4.5 : Simulation flow chart.