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Design of Robust Controller of a Doubly-fed Induction Generator for Wind Energy Conversion System with different controllers

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***Abstract*— The aim of this paper is to propose a control method for a doubly-fed induction generator used in wind energy conversion systems. The active and reactive powers exchanged between the generator and the grid are controlled by the way of the generator inverter with the algorithm of control based on vector control concept (with stator flux orientation), with three different controllers: classical PI controller (proportional–integral), Sliding Mode Controller(SMC), Fuzzy Logic Controller (FLC). Finally the Simulations results are presented and discussed. Therefore, we conclude which is a suitable controller of DFIG in Wind Energy Conversion System.**

***Keywords*— Doubly fed induction generator, Power control, proportional integral controller, sliding mode controller, fuzzy logic controller.**

I. INTRODUCTION

Wind energy is one of the most promising renewable energy sources due to the progress experienced in the last decades. Governments are attracted by the Wind Energy Conversion System (WECS) with its simple structure, easy maintenance and management. With an average global annual growth rate of 14% for the period 2002-2006. Wind energy is playing a major role in the effort to increase the share of renewable energy sources in the world energy mix [1], [2], helping to satisfy global energy demand, offering the best opportunity to unlock a new era of environmental protection [3], the world energy crises can be solved in future.

DFIG has recently received much attention as one of preferred technology for wind power generation. Compared to a full rated converter system, the use of DFIG in a wind turbine offers many advantages, such as reduction of inverter cost, the potential to control torque and a slight increase in efficiency of wind energy extraction. The wind turbines variable-speed operation has been used for many reasons. Among these are the decrease of the stresses on the mechanical structure, acoustic noise reduction and the possibility of active and reactive power control [1,3].

Many papers have been presented, with different control schemes of WT to extract a maximum power from wind speed variable, based on fuzzy controller as it is commonly done in literature [4-5]. The DFIG control schemes are generally based on vector control concept (with flux orientation) with Sliding Mode Control (SMC) as proposed in [7-8]. SMC of active and reactive power of a DFIG and extracting maximum power for Variable Speed by WECS in [7-9]. Many works are done about decoupled control of DFIG to improve power quality for WECS. In [10,11] have studied an advanced control of DFIG and power quality improvement.

This paper presents a control method based on oriented field control with active and reactive powers as variables to be controlled in a WECS using three different controllers (PI, SMC, and FLC). Such an approach does not manage easily the compromise between dynamic performances and robustness or between dynamic performances and the generator energy cost. These compromises cannot easily be respected with classical PI controllers proposed in most DFIG control schemes. Due to external perturbations, such as random wind fluctuations, wind shear and tower shadows, variable speed control seems to be a good option for optimizing the operation of wind turbines.

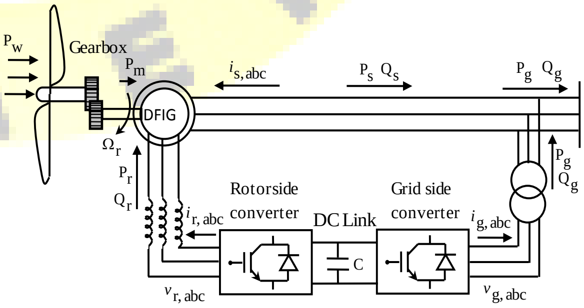

Fig. 1 Scheme of a DFIG equipped wind turbine.

II. GENERATOR MODELING:

A typical configuration of DFIG wind turbine is shown in Fig1. The DFIG consists of a stator and rotor windings, for the simple reason that both rotor and stator can control it, with its the stator is directly connected to the grid while the rotor is connected to the grid through the power electronic converters. Using faraday's law and ohm's law, the expressions relating the voltages with the currents and fluxes across the stator winding in the PARK frame are written as follows [10, 11]:

$$\begin{cases} V_{ds} = R_s.I_{ds} + \frac{d}{dt}\phi_{ds} - \omega_s\phi_{qs} \\ V_{qs} = R_s.I_{qs} + \frac{d}{dt}\phi_{qs} - \omega_s\phi_{ds} \end{cases} \quad (1)$$

$$\begin{cases} V_{dr} = R_r.I_{dr} + \frac{d}{dt}\phi_{dr} - (\omega_s - \omega)\phi_{qr} \\ V_{qr} = R_r.I_{qr} + \frac{d}{dt}\phi_{qr} - (\omega_s - \omega)\phi_{dr} \end{cases}$$

Where R_s and R_r are, respectively, the stator and rotor phase resistances, $\omega = p \cdot \Omega_{mec}$ is the electrical speed and p is the pair pole number.

The stator and rotor flux can be expressed as:

$$\begin{cases} \phi_{ds} = L_s I_{ds} + M I_{dr} \\ \phi_{qs} = L_s I_{qs} + M I_{qr} \\ \phi_{dr} = L_r I_{dr} + M I_{ds} \\ \phi_{qr} = L_r I_{qr} + M I_{qs} \end{cases} \quad (2)$$

Where I_{ds} , I_{qs} , I_{dr} , and I_{qr} are, respectively, the direct and quadrate stator and rotor currents.

The active and reactive powers at the stator, as well as those provide for grid are defined as:

$$\begin{cases} P_s = V_{ds}.I_{ds} + V_{qs}.I_{qs} \\ Q_s = V_{qs}.I_{ds} - V_{ds}.I_{qs} \end{cases} \quad (3)$$

The electromagnetic torque is expressed as:

$$T_{em} = P_{dfig}\,(\phi_{ds} I_{qs} - \phi_{qs} I_{ds}) \quad (4)$$

III. CONTROL STRATEGY OF THE DFIG

A. *Decoupling of the active and reactive powers*

When the DFIG is connected to an existing grid, this connection must be established in the following three steps. The first step is the synchronization of the stator voltages with the grid voltages, which are used as a reference. The second step is the stator connection to this grid. After that, the connection can be effectively established. Once this connection is achieved, the third step is the regulation of the transit of the power between the DFIG and the grid a d–q reference-frame synchronized with the stator flux is employed [8]. By setting the quadratic component of the stator flux to the null value as follows:

$$\phi_s = \phi_{ds} \quad \Rightarrow \quad \phi_{qs} = 0 \quad (5)$$

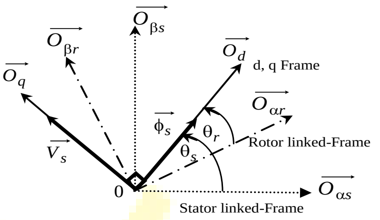

Fig. 2 Stator flux orientation.

Using the condition above, supposing that the grid system is steady, having a single voltage V_s that leads to stator's constant flux ϕ_s , we can easily deduce the voltages as:

$$\begin{cases} v_{ds} = 0 \\ v_{qs} = \omega_s \cdot \phi_s = V_s \end{cases} \quad (6)$$

If per phase stator resistance is neglected, which is a realistic approximation for medium power machines used in WECS, the stator voltage vector is consequently in quadrate advance in comparison with the stator flux vector.

Rotor voltages can be expressed by:

$$\begin{cases} v_{dr} = \sigma L_r \frac{di_{dr}}{dt} + R_r i_{dr} - \sigma L_r \omega_r i_{qr} + \frac{M}{L_s}\frac{d\phi_{ds}}{dt} \\ v_{qr} = \sigma L_r \frac{di_{qr}}{dt} + R_r i_{qr} + \sigma L_r \omega_r i_{dr} + s\frac{M}{L_s}V_s \end{cases} \quad (7)$$

Where V_s is the stator voltage magnitude assumed to be constant and s is the slip range, we can rewrite the rotor voltages as follows:

$$\begin{cases} v_{dr} = \sigma L_r \frac{di_{dr}}{dt} + R_r i_{dr} + fem_d \\ v_{qr} = \sigma L_r \frac{di_{qr}}{dt} + R_r i_{qr} + fem_q \end{cases} \quad (9)$$

With fem_d and fem_q are the crosses coupling terms between the $d-$axis and $q-$axis:

$$\begin{cases} fem_d = -\sigma L_r \omega_r i_{qr} \\ fem_q = \sigma L_r \omega_r i_{dr} + s\frac{M}{L_s}V_s \end{cases} \quad (10)$$

The active and reactive powers of the DFIG can be expressed with function of rotor currents by:

$$\begin{cases} P_s = -V_s \cdot \frac{M}{L_s}\frac{1}{(\sigma L_r \cdot s + R_r)}\left(v_{qr} - fem_q\right) \\ Q_s = -V_s \cdot \frac{M}{L_s}\frac{1}{(\sigma L_r \cdot s + R_r)}\left(v_{dr} - fem_d\right) + V_s \cdot \frac{\phi_{ds}}{L_s} \end{cases} \quad (11)$$

Field oriented control of the DFIG can then be applied with the active and reactive power considered as variables to be controlled. And, we consequently the bloc diagram is presented in Fig. 3.

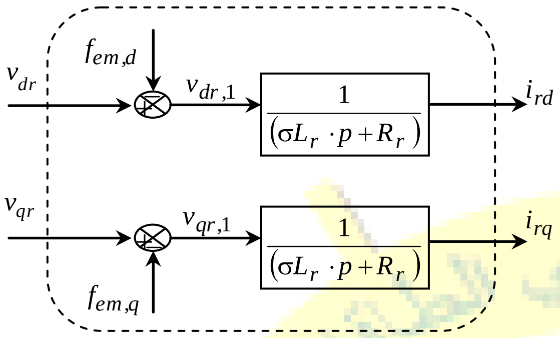

Fig. 3 The coupled model of active and reactive stator powers.

B. *Controllers synthesis*

In order to choose the robust controller we have compared the performances of DFIG with three different controllers. The proportional-integral will be first tested and will be reference compared to the others: Sliding Mode Controller and Fuzzy Logic Controller. Before synthesizing these controllers, we will make two considerations:

The first one will introduce the cross coupling terms between the $d-$axis and $q-$axis (fem_d and fem_q).

The second one will be to consider the constant term $V_s \cdot \frac{\phi_{ds}}{L_s}$ as a perturbation which will have to be rejected by the control law.

These simplifications allow us to consider the multi-variable models as two mono variable models as shown in Fig. 7 where C1 and C2 represent the d- and q-axis controllers.

We will measure the perturbation $V_s \cdot \frac{\phi_{ds}}{L_s}$ in order to improve the behavior of d-axis controller.

Field oriented control of the DFIG can then be applied with the active and reactive power considered as variables to be controlled.

1) *PI controller synthesis*

The design of this controller is simple. Fig. 4 shows the block diagram of the system with PI controller.

It is possible to generate the reference voltages from given reference currents.

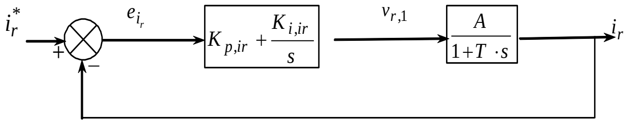

Fig. 4 Current-control loop of generator inverter.

In fact, the ($i_{qr}^* - i_{qr}$) and ($i_{dr}^* - i_{dr}$) errors are processed by PI controller to give v_{qr} and v_{dr} .

Using the Laplace Transform, the plant can be represented by the transfer function below:

$$\frac{i_r}{v_{r,1}} = \frac{1/R_r}{1+\sigma T_r \cdot s} \qquad (12)$$

The controller terms are calculated with a pole-compensation method. The time response of the controlled system will be fixed at 10 ms, this value is sufficient for our application and a lower value might involve transients with important overshoots. The calculated terms are in these tables:

TABLE. I.THE CALCULATED PI GAINS FOR THE DIRECT AXIS:

	$K_{p,id}$	$K_{i,id}$
PI controller	$(2\xi\omega_0\sigma T_r - 1)R_r$	$\omega_0^2\sigma T_r R_r$
Value	0.0331	3.7576

TABLE. II.THE CALCULATED PI GAINS FOR THE QUADRATE AXIS:

	$K_{p,iq}$	$K_{i,iq}$
PI controller	$(2\xi\omega_0\sigma T_r - 1)R_r$	$\omega_0^2\sigma T_r R_r$
Value	0.0331	3.7576

The pole- compensation in not the only method to calculate PI Controller but it is simple to elaborate with first-order transfer-function and it is sufficient in our case to compare with other controllers.

2) *Sliding Mode Controller (SMC)*

The rotor currents (which are linked to active and reactive powers by equation (12), quadrate rotor current i_{qr} linked to stator active power P_s and direct rotor current i_{dr} linked to stator reactive power Q_s have to track appropriate current references, so, a sliding mode control based on the above Park reference frame is used.

The sliding surfaces representing the error between the measured and references rotor currents are given by this relation:

$$\begin{cases} S_d = \lambda\left(i^*{}_{dr} - i_{dr}\right) \\ S_q = \lambda\left(i^*{}_{qr} - i_{qr}\right) \end{cases} \qquad (13)$$

V_{dr} and V_{qr} will be the two components of the control vector used to constraint the system to converge to $S_{dq} = 0$.

The control vector U_{dqeq} is obtain by imposing $\dot{S}_{dq} = 0$ so the equivalent control components are given by the following relation:

$$U_{eqdq} = \begin{bmatrix} -\begin{pmatrix} -R_r b\left(L_r \sigma I_{dr} + \dfrac{M}{L_s \omega_s} V_{qs}\right) \\ + R_r c \phi_{ds} + \omega_r (L_r \sigma I_{qr} + \dfrac{M}{L_s \omega_s} V_{ds}) \end{pmatrix} \\ -\begin{pmatrix} -R_r b\left(L_r \sigma I_{qr} + \dfrac{M}{L_s \omega_s} V_{qs}\right) \\ + R_r c \phi_{qs} - \omega_r (L_r \sigma I_{dr} + \dfrac{M}{L_s \omega_s} V_{qs}) \end{pmatrix} \end{bmatrix} \qquad (14)$$

To obtain good performances, dynamic and commutations around the surfaces, the control vector is imposed as follows:

$$U_{dq} = U_{eqdq} + K.sign\left(S_{dq}\right) \qquad (15)$$

The sliding mode will exist only if the following condition is met:

$$S(x,t) \cdot \dot{S}(x,t) < 0 \qquad (16)$$

The block-diagram of the variable structure control of the DFIG is presented on Fig. 7. The stator active and reactive powers are controlled.

3) *Fuzzy Logic Controller (FLC)*

To regulate the DFIG wind turbine, Fuzzy Logic Control (FLC) is used because of the nonlinearity of the system. The basic formation of a FLC is consisted of four parts: Fuzzification block determining inputs membership values. The Fuzzy Inference System FIS evaluates at each time which control rules are appropriate, using the fuzzy knowledge based block. The deffuzification block calculates the crisp output of the rules leading to the optimal plant control.

Fig. 5 shows the block diagram of the fuzzy control.

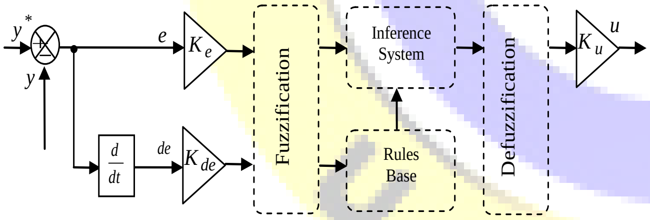

Fig. 5 Fuzzy logic structure.

Where the error e and its rate of change de are the input variables; K_e, K_{de} and K_u are inputs and outputs scaling gains. For the proposed FLC, The inputs to the direct and quadrate axis rotor current fuzzy controllers are the d- and q-axis rotor current errors [5]:

$$\begin{cases} e_{i_{dr}}(n) = i^*_{dr}(n) - i_{dr}(n) \\ e_{i_{qr}}(n) = i^*_{qr}(n) - i_{qr}(n) \end{cases} \qquad (17)$$

And their changes in error:

$$\begin{cases} \Delta e_{i_{dr}}(n) = i^*_{dr}(n) - i_{dr}(n-1) \\ \Delta e_{i_{qr}}(n) = i^*_{qr}(n) - i_{qr}(n-1) \end{cases} \qquad (18)$$

Respectively, the outputs of the two fuzzy controllers are i_{dr} and i_{qr}. The input and output linguistic variables of the two fuzzy controllers have been quantized in the following five fuzzy subsets:

TABLE. III THE FUZZY CONTROL RULE BASES.

e de	NL	NS	ZE	PS	PL
NL	NL	NL	NL	NS	ZE
NS	NL	NS	NS	ZE	PS
ZE	NL	NS	ZE	PS	PL
PS	NS	ZE	PS	PS	PL
PL	ZE	PS	PL	PL	PL

The fuzzy sets have been determined as: NL, Negative Large, NS, Negative Small and ZE, Zero, PS, Positive Small, PM positive medium, PL, Positive Large, respectively. The input/output variables used in this paper are fuzzified by seven symmetrical and triangular membership functions (MFs) (Fig. 6(a), (b) and (c)) normalized in the universe of discourse between -1 and +1.

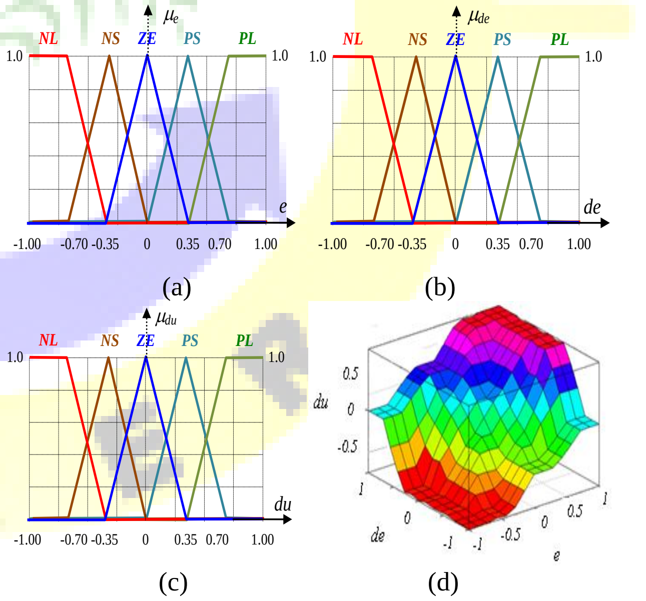

Fig. 6 The memberships of the: a – Error, b - Error variation, c - Command variation, d - Control surface.

The overall control system can be designed as shown in Fig.7. The blocks C_1 and C_2 represent rotor current controllers, respectively i_{dr} and i_{qr} .

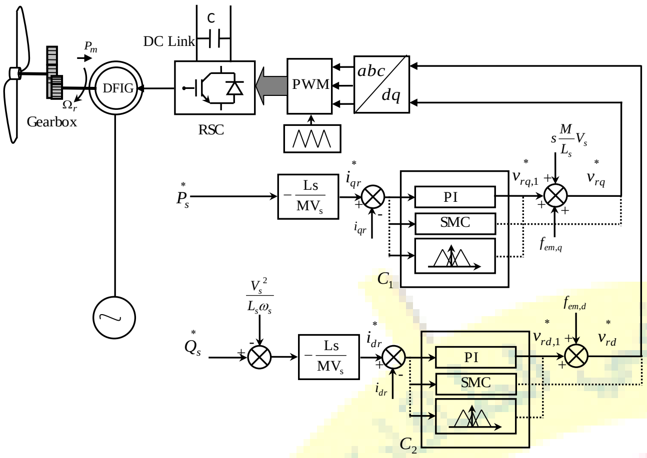

Fig. 7 Overall oriented field control of DFIG in WECS with different controllers.

IV. RESULTS AND DISCUSSION

In this part, simulations are investigated with a 7.5kW generator connected to a 220V/50Hz grid. The machine's parameters are presented below:

Three pole pairs, Rs = 0.455Ω, Ls = 0.084 H, M = 0.078 H, Rr = 0.62 Ω, Lr = 0.081 H

The simulations are done in purpose to study the responses of wind turbine and its control with different controllers to analyze the influence of a speed variation of the DFIG on active and reactive powers. The active and reactive power references are maintained to $5\,kW$ and $-5\,kVAR$ and at $t = 0.5\,s$ the speed varies from $1350\,rpm$ to $1450\,rpm$. At time= 1.5 s the speed varies also from $1450\,rpm$ to $1300\,rpm$. A variable step solver is used with an automatic step size and with a relative tolerance of 1e-3.

We notice that, those figures represent a good tracking and performances in terms of dynamics and responses. The classical PI controller is limited, which is only based on the machine's parameters and their eventual variations are not taken into account. In fact, for this controller, a speed variation induces an important peak value of the active and reactive powers. The Sliding Mode Controller contains the presence of perturbations in its synthesis, so it shows better disturbance rejection than PI controller. This rejection is still imperfect because the synthesis of the controller includes parameters, which have an influence on its performance. Nevertheless, SMC has an approximately perfect speed disturbance rejection with a very small power variation. Likewise, The Fuzzy Logic Controller satisfies the system dynamics, which presents no disturbances in during the variation of speed. The dynamics of FLC react quickly and without exceeding. Indeed, FLC doesn't pose a problem for the machine exploitation. It can ensure the stability and the good quality of the generated power when the speed is varying.

V. CONCLUSION

In this paper, we have presented Wind Energy Conversion System based Double Fed Induction Generator. The control of the generator inverter has been presented in order to control the active and reactive powers exchanged between the generator and the grid. Field oriented control is applied, is based on the calculated rotor currents from the active and reactive powers and measuring the rotor currents (Indirect Power Control). Three different controllers are synthesized and compared. Under the generator's speed variation, this represents a perturbation for system, the impact on the active and reactive powers values is important for PI and Sliding Mode controllers whereas it is almost absent for Fuzzy Logic controller. Consequently, FLC is capable to reduce the over current in the rotor circuit during transient period, besides increasing the transient stability margin as well as improving the overall DFIG time domain performance.

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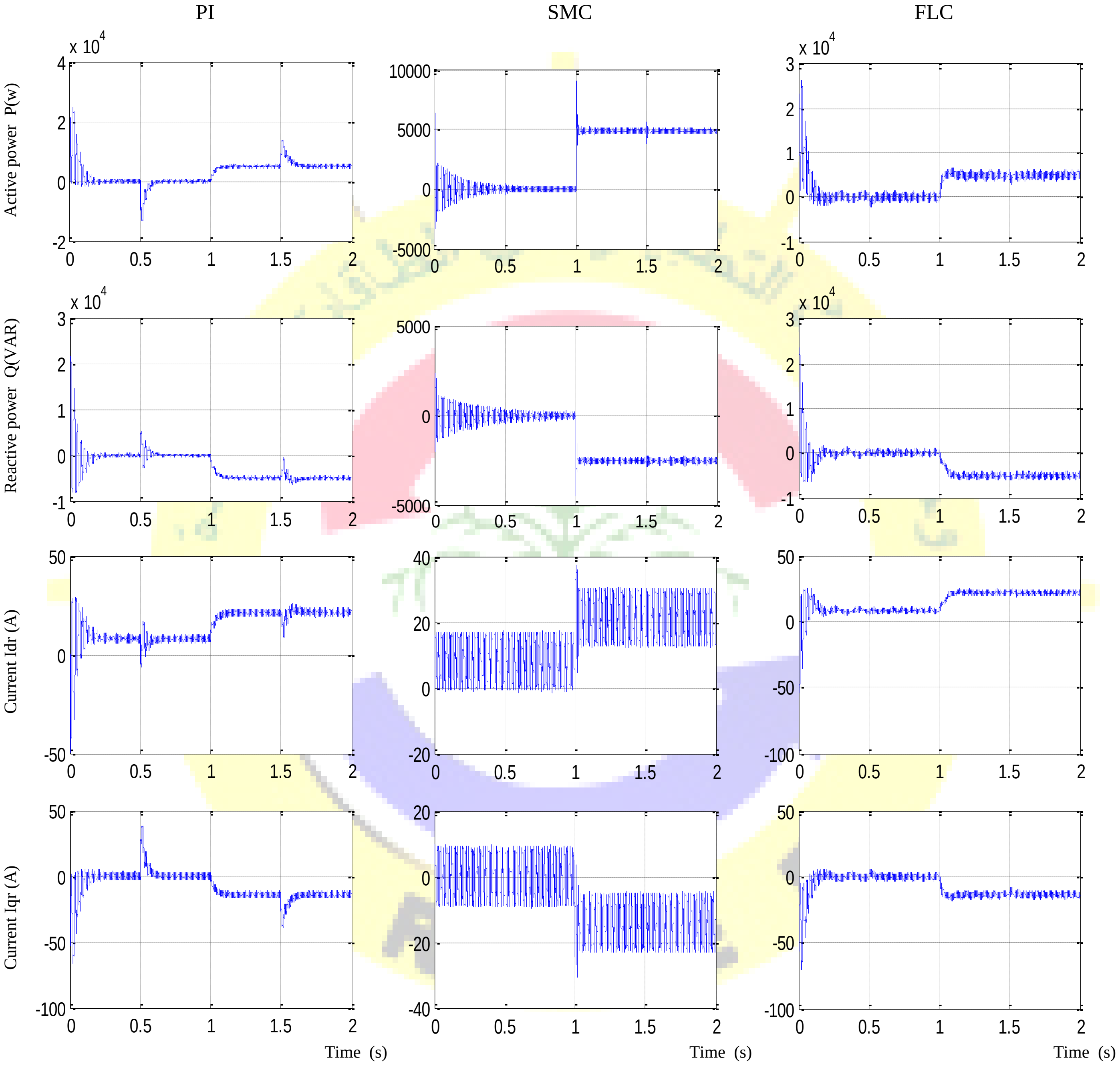

Fig. 8 Effect of a speed variation