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# Stabilization of A Small Power System with the Integration of A Wind Turbine using A Permanent Magnets Synchronous Generator

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*Abstract*—**When wind turbines are connected to electrical power systems, they constitute a fluctuating load which can lead to voltage variations, responsible for flicker and harmonic phenomena and also to variations in reactive power. In addition to these problems due to random variations of the wind source, there are problems related to unexpected incidents such as voltage dips and brief outages. Indeed, the power generation centers in developing countries are generally based on synchronous machines (hydroelectric and/or thermal power stations) unlike wind sources using other types of machines (asynchronous, synchronous with wound rotor or permanent magnets, variable reluctance, etc.), and stability becomes a major issue. In this article, it is a question of contributing to the stabilization of the whole of the network following the integration of the wind sources in the electrical networks of small size. For this, the multi-model approach and its control by Parallel Distributed Compensation (PDC) have been implemented for the modeling of a simplified electrical network called Single Machine Infinite Bus (SMIB) as well as a Permanent Magnets Synchronous Generator (PMSG) used in wind energy conversion. Both systems use the PDC control. Indeed, multiple models are recognized for their ability to take into account changes in the mode of operation of the system and to reproduce its behavior accurately over a wide operating range. It's a way to bring control problems back to a linear context. Initially, the SMIB system operates on its own. At t equal 180s, the wind turbine is integrated. At t equal 600s, a short-circuit type disturbance is introduced and the evolutions of the various variables as well as of the command are assessed. It was found that the PDC control law always makes it possible to bring the system back to the operating points in the nominal regime in the simulations considered, despite the disturbances due to the integration of the wind turbine due to the irregularity of its source which is the wind.**

***Keywords***— ***SMIB, GSAP; wind turbine integration; multiple model approach; PDC control***

## I. INTRODUCTION

Whether in industrialized countries or in developing countries, because of global warming and the pricing of fossil resources and with a view to protecting the environment, we are currently turning to renewable and alternative energy sources. The installation of such a system is already mastered on a small scale and in independent use. On the other hand, if they must be connected to an existing network of finite power, their integration is not at all won in advance. One of the main reasons is the different nature of the sources.

The integration of renewable energy sources into electrical networks is more generally decentralized production, if it presents an indisputable interest from various points of view, it also implies compliance with technical constraints to ensure citizens and businesses a power supply reliable and quality electrical energy. Wind energy is currently growing in island networks. However, island networks are more fragile than interconnected networks and the massive insertion of wind turbines is accompanied by specific characteristics that can degrade the operation of the electrical system. In distribution networks that were not originally designed to accommodate wind generation, the problems to be solved depend on the penetration rate decentralized production (Koumba, 2013).

To describe the dynamic behaviours of real physical systems, engineering sciences make extensive use of nonlinear models which are able to correctly describe the nonlinear behaviours of a system. They can nevertheless turn out, according to their mathematical complexity, to be difficult to exploit in a context of synthesis of a control law.

The multiple model approach constitutes an interesting analytical alternative and is currently widely used for the modelling of nonlinear systems. The approach focuses on the analysis of stability and the synthesis of correctors/observers. Following numerous studies such as (Orjuela et al., 2013), it has experienced renewed interest, particularly in applications such as simulation and control. It can also be seen as a certain type of fuzzy modeling (Takagi and Sugeno, 1985).

In control, an associated approach is that known as Distributed Parallel Compensation (PDC) (Wang et al. 1995). This method is based on linear controllers designed for each of the interconnected linear models, and the closed-loop stability of the whole is guaranteed via a Lyapunov function common to all the sub-models, combined with a Linear Matrix Inequalities (LMI) approach. The gains of the fuzzy controller are obtained by solving a set of LMIs.

In this article, a simplified electrical network is used. Said network can easily be rewritten in TS type multiple model form. A control study of this type of system by the PDC approach is proposed.to ensure the stabilization of the SMIB system during disturbances such as short-circuit, integration of a PMSG used in the conversion of wind energy, etc.

In the following, the presentation of the multiple model approach, the SMIB system and the PMSG considered, the implementation of the method, the results of simulations of the wind turbine integration and the related discussions will be respectively approached and the article will end with a conclusion and some perspectives.

## II. MATERIALS AND METHODS

### A. *Electrical Network*

The electrical network is made up of a set of structures for the production, transport and distribution of electrical energy. To ensure its stability, good monitoring and real-time control of its operation is necessary. It is considered among the most complex systems and actually, the major flows of electricity from renewable sources and the essential solidarity between territories are the main vectors for the development of the power system in France and Europe. (K. Bedoud et al. 2013)

Much work has been done on the study of wind turbines and their integration into the grid (Dong et al. 2020; Briceno Vicente et al. 2017). Different types of wind turbines are discussed: asynchronous generators (Aimani et al. 2003), PMSG (Omar et al. 2011), etc.

As part of this work, the center of interest is the integration of a wind turbine based on a 2.5MW PMSG on a 15MW SMIB system in order to visualize the behavior of the whole system in steady state. Then, the multiple model approach and its control by PDC to ensure the stabilization of the SMIB system against the integration of the wind turbine and other types of disturbances are introduced. Modeling and simulation of the whole system will be discussed.

A SMIB system like the one used in (Tachum et al., 2018) is made up of a synchronous machine which feeds a power system of infinite power (that is to say the power is much higher than that of the synchronous generator) through lines and a transformer. The synchronous machine is modeled by a constant electromotive force E behind a reactance x'd. The infinite node is a point where the voltage is constant and fixed in modulus and in phase (very high inertia of other machines) (Roosta Ali-Rèza, 2003). The following figure illustrates the basic elements and principle of an SMIB system.

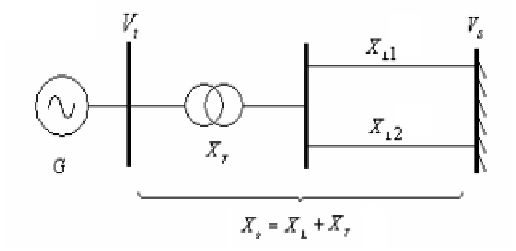

Fig. 1 : SMIB system

**Model in (δ, ω, Eq)**

On this part, the one-axis model of the synchronous machine is used and the system can be represented by the nonlinear model (δ, ω, Eq) of order 3 of the form (Rafanotsimiva, 2013):

$$\begin{cases} \dot{\delta}(t) = \omega(t) \\ \dot{\omega}(t) = -\frac{D}{H}\omega(t) - \frac{\omega_0}{2H}\frac{1}{x_{ds}}V_s sin\delta(t) E_q(t) + \frac{\omega_0}{2H}P_{m0} \\ \dot{E}_q(t) = \frac{x_d - x'_d}{x'_{ds}}V_s sin\delta(t)\omega(t) - \frac{1}{T'_{do}}\frac{x_{ds}}{x'_{ds}}E_q(t) + \frac{x_{ds}}{x'_{ds}}\frac{k_c}{T'_{do}}u_f(t) \end{cases} \tag{1}$$

Where δ, ω, Eq, Td0, Pm, D, H, Vt and Vs are respectively power angle, relative speed of electrical rotation, quadrature transient internal voltage, time constant of open d and D axis winding excitation, mechanical power, mechanical damping coefficient, inertia coefficient, generator terminal voltage and infinite bus voltage. xd, x'd, xds, x'ds are the electrical parameters representing the different reactances of the generator, the lines and the transformer.

And the outputs:

$$V_t^2(t) = \frac{x_s^2}{x_{ds}^2}\left[E_q^2(t) + V_s^2 + \frac{2x_d}{x_s}V_s cos\delta(t) E_q(t)\right] \tag{2}$$

$$P_e(t) = \frac{1}{x_{ds}}V_s sin\delta(t) E_q(t) \tag{3}$$

### B. *Model of the PMSG*

Several models exist in relation to the modelling of PMSG according to the approaches discussed and the hypotheses posed by the authors. (EIM Youness, 2017; M. S. Camara et al., 2014)

The model in (M. S. Camara et al., 2014) is used in this work with: Ld = Lq

$$\begin{cases} \frac{d\omega_r}{dt} = -\frac{f_v}{J}\omega_r + \frac{3p}{2J}\varphi_f i_q + \frac{1}{J}C_r \\ \frac{di_d}{dt} = p\omega_r i_q - \frac{RS}{L_d}i_d + \frac{1}{L_d}V_d \\ \frac{di_q}{dt} = -\frac{\varphi f}{L_q}p\omega_r - \frac{RS}{L_q}i_q - p\omega_r i_d + \frac{1}{L_q}V_q \end{cases} \tag{4}$$

With :
*fv* : viscous coefficient of friction,
*J* : inertia total moment of the machine,
*p* : pole pairs number of the machine,

$\varphi_f$ : excitation flux of permanent magnets,
*Lq* : quadratic inductance,
*Ld* : direct inductance,
*Rs* : stator resistance,
*wr* : electrical rotation speed of the machine,
*id* : d axis component of the stator current,
*iq* : component of the q axis of the stator current,
*Cr* : electromagnetic torque of the machine,
*Vd* : d-axis component of the stator terminal voltage,
*Vq* : q-axis component of the stator terminal voltage,

### C. *Multiple model approach*

The representation of nonlinear systems constitutes an interesting alternative in the field of control, observation and diagnosis of nonlinear systems. The multiple model structure makes it possible to simplify and easily study the stability of a nonlinear system, thanks to the numerical tool linear matrix inequalities (LMI) which makes it possible to find solutions to the equations of Lyapunov, the synthesis of the correctors consisting for example of a state feedback for each local model. It is also possible to link the multiple model to the physics of the nonlinear system in order to give meaning to the multiple model and more precisely to associate a particular behaviour of the nonlinear system with a sub-model.

The TS multiple model structure (Takagi and Sugeno, 1985; Murray-Smith and Johansen, 1997), used in this work, is composed of a finite set of linear models interconnected by nonlinear functions satisfying the convex sum property. In most works, local models of affine structure are used because of their simplicity. However, if the system has strong nonlinearities, the number of local models can be very large, which increases the complexity of the model.

The TS modelling approach therefore makes it possible to represent a nonlinear system by an interconnection of affine and linear models around different operating points through normalized weighting functions called activation functions. These functions can either be identified from a real process, or on the basis of a knowledge model in order to arrive at an exact representation of it in a compact space of the state space.

In (D. Orjuela et al. 2008a) and (D. Orjuela et al. 2008b), the authors develop that the multiple model approach has the advantage of the fact that multiple models constitute universal approximators, any nonlinear system being able to be approximated with an imposed precision by increasing the number of sub-models. In practice, however, a relatively small number of sub-models suffices to obtain a satisfactory approximation. The linear systems analysis tools can be used, at least partially, on the multiple models if the sub-models are of the linear type.

The activation function must satisfy the following conditions:

$$\begin{cases} \sum_{i=1}^{M} \mu_i(z(t)) = 1, \forall t \\ 0 \le \mu_i(z(t)) \le 1, \quad \forall i = 1, \dots, M, \forall t \end{cases} \tag{5}$$

z(t) represents the decision variable or premise variable, allows to pass from one sub-model to another.

If the dynamic model of the studied system is presented in the following form:

$$\begin{cases} \dot{x}(t) = Ax(t) + Bu(t) \\ y(t) = Cx(t) \end{cases} \tag{6}$$

Continuously, the corresponding TS multiple model is represented by:

$$\begin{cases} \dot{x}_i(t) = \sum_{i=1}^{M} \mu_i(z(t))(A_i x(t) + B_i u(t)) \\ y(t) = \sum_{i=1}^{M} \mu_i(z(t)) C_i x(t) \end{cases} \tag{7}$$

The corresponding theories are synthesized in (R. Murray-Smith and TA Johansen, 1997).

The idea of PDC control associated with multiple models is to build a regulator by state feedback relating to each local Linear Time Invariant (LTI) model. Similar to the technique used to interpolate the local models, the global control law is obtained by interpolation of the local linear control laws. Determining a control law amounts to determining for each local model matrix gains, for example by using a synthesis in the form of LMI or by minimizing a quadratic criterion.

The construction of the equivalent multiple model associated with the SMIB is discussed in (Rafanotsimiva et al., 2013). The same approach is used for the equivalent multiple model associated with the PMSG. They are no longer reproduced in this paper.

## III. RESULTS

To carry out the simulation, we considered Diego-Suarez city (Madagascar) power system whose peak power is approximately 12MW, we then used a 15MVA generator. Then, we inserted a 2.5MW wind turbine that is to say with a penetration rate of about 20% if we assume that the wind turbine is operating at full speed. The block diagram of the connection is as follows:

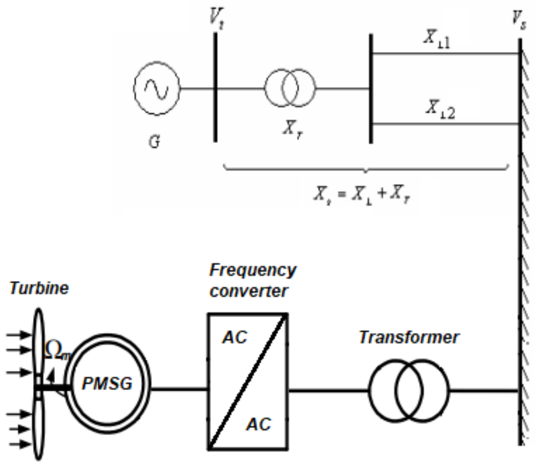

Fig. 2 : Connecting a wind turbine to the network

Numerical applications (Razafindrakoto et al. 2020):

The main parameters are:

For the wind turbine:

P=2.5MW; cos φ=0.7162; Rs=0.00517pu; Ld =Lq=0.7029pu; p=8; Cpmax=0.35 ;rho=1.22 ; λopt=7.07 ;R=55m
For the SMIB system:
S=15MVA ; ω0=314.159 rad/s; D=5pu; H=4pusec; Td0’’=0.022s ; kc=200pu; xd=1.25pu; xd’=0.205pu; Td0’=0.708sec; Xt=0.708pu; xl1=0.5pu; xl2=0.93pu; Kt=1pu; f0=50Hz; xds=1.7258pu; xds’=0.6808;xs=0.47578pu
max|kc Uf (t)|=7pu; max|Uf (t)|=0.035pu; 0<XE<1.5 pu
δ0=1.18rad ; Pm0=0.9pu ; Vt0=1.0pu
The control problem is then reduced to solving two LMIs, respectively functions of A1 and A2.

$$A_1 = \begin{pmatrix} 0 & 1 & 0 \\ 0 & -1.25 & 0.0227546 \\ 0 & -0.0015350 & -3.2499 \end{pmatrix}$$

$$A_2 = \begin{pmatrix} 0 & 1 & 0 \\ 0 & -1.25 & -22.7546 \\ 0 & 1.535 & -3.2499 \end{pmatrix}$$

$$B = B_1 = B_2 = \begin{pmatrix} 0 \\ 0 \\ 649.9895 \end{pmatrix}$$

$$K = \begin{pmatrix} 0 \\ 35.3429 \\ 0 \end{pmatrix}$$

And the system activation functions are :

$$\mu_1\big(z(t)\big) = \tfrac{1}{2}\big(1 - \sin x\,(t)\big)$$

(8)

$$\mu_2\big(z(t)\big) = \frac{1}{2}\big(1 + \sin x\,(t)\big) \qquad (9)$$

### A. *Application of a PDC control law*

$$\textstyle\sum_{i=1}^{2} \mu_i\big(z(t)\big)(XA_i^T - M_i^T B_i^T + A_i X - BM_i) < 0 \qquad (10)$$

After implementing the method, the following results are obtained by solving the LMI of this equation:

$$X = \begin{pmatrix} 4.6343 & -5.7111 & 0.3695 \\ -5.7111 & 7.0530 & 0.1713 \\ 0.3695 & 0.1713 & 32.0554 \end{pmatrix}$$

$$P = X^{-1} =$$
$$\begin{pmatrix} 602.2011 & 487.8641 & -9.5485 \\ 87.8641 & 395.3776 & -7.7363 \\ -9.5485 & -7.7363 & 0.1826 \end{pmatrix}$$

$$M_1 = (-0.0010 \quad -0.0020 \quad -0.1199)$$
$$M_2 = (-0.0145 \quad -1.1064 \quad -0.1194)$$
$$\Rightarrow$$
$$F_1 = M_1 X^{-1} = (-0.4645 \quad -0.3765 \quad 0.0036)$$

$$F_2 = M_2 X^{-1} =$$
$$(-547.3901 \quad -443.6166 \quad 8.6765)$$

from which the PDC control can be calculated.

### B. *Shapes of the curves*

In this present article, the centers of interest relate to the behavior of the network via the integration of the wind mill, the presence of a fault (short-circuit) on the system, and especially the reaction of the control used.

The following figures show the behavior of the power system in the presence of a short-circuit and wind turbine integration fault.

- For input variables : δ, ω and Eq

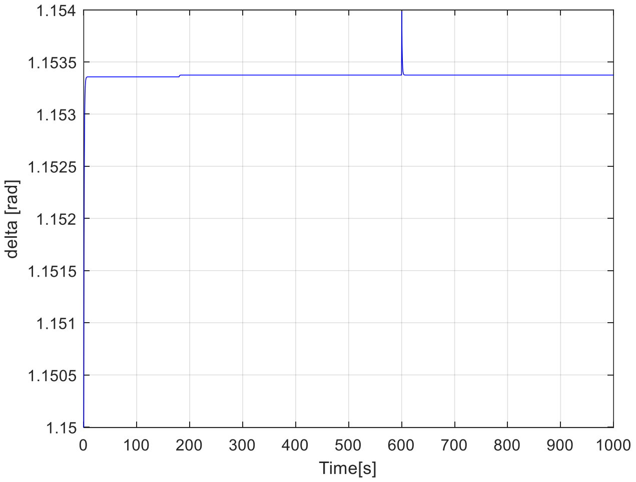

Fig. 3 : Power angle δ of generator SMIB

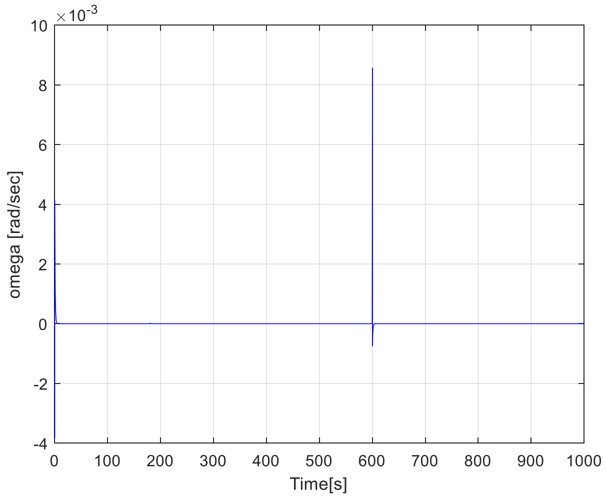

Fig. 4 : Relative speed of electrical rotation ω

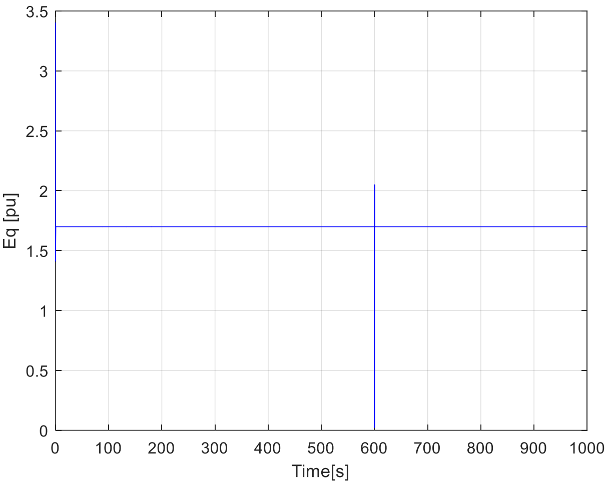

Fig. 5 : Quadrature transient internal voltage Eq

- For output variables : Vt and Pe

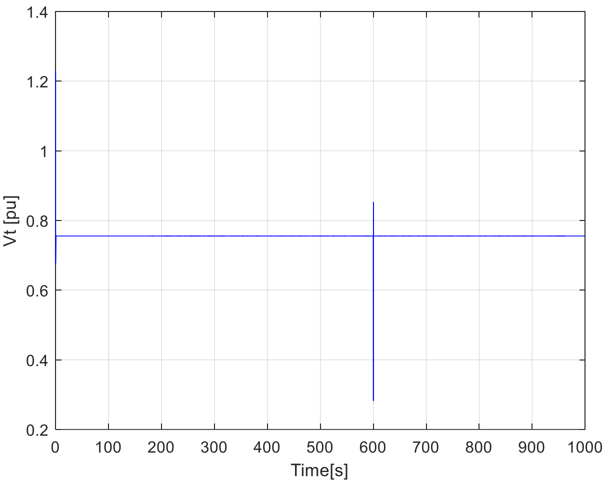

Fig. 6 : SMIB network output voltage Vt

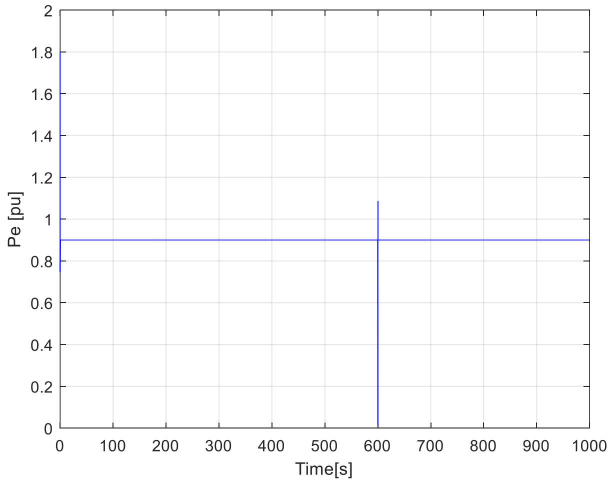

Fig. 7 : SMIB network power Pe

*1) Zoom on the effects to the integration of the wind turbine at t equal 180s.*

*a) For input variables : δ, ω and Eq*

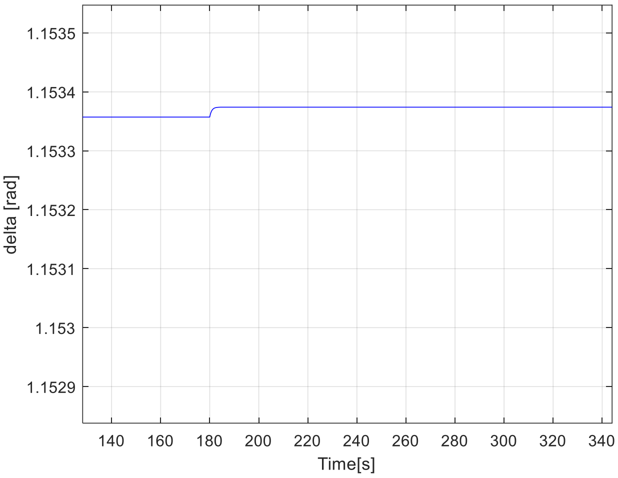

Fig. 8 : Power angle δ of generator SMIB

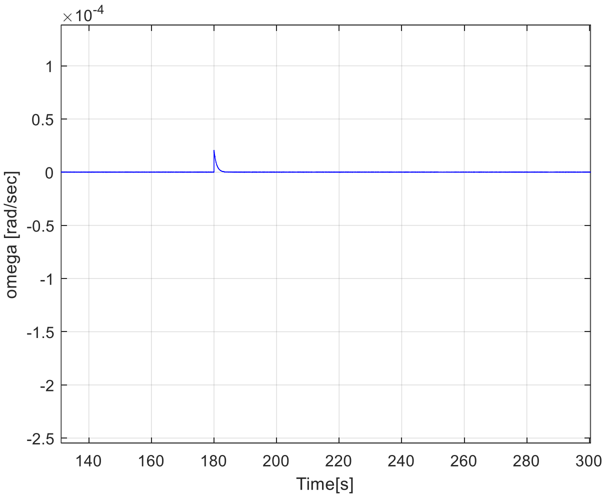

Fig. 9 : Relative speed of electrical rotation ω

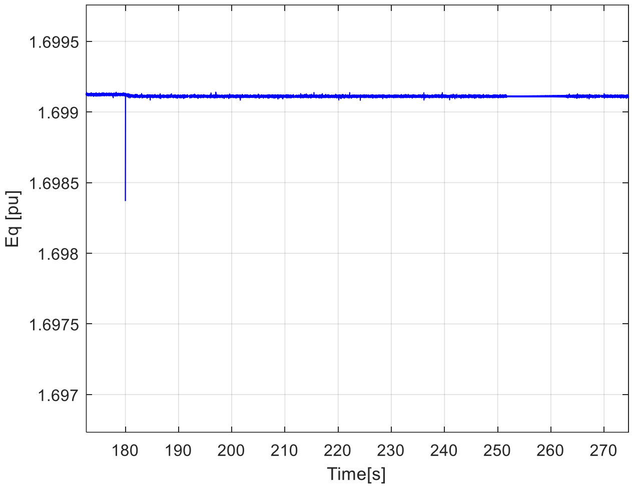

Fig. 10 : Quadrature transient internal voltage Eq

### *b) For output variables : Vt et Pe*

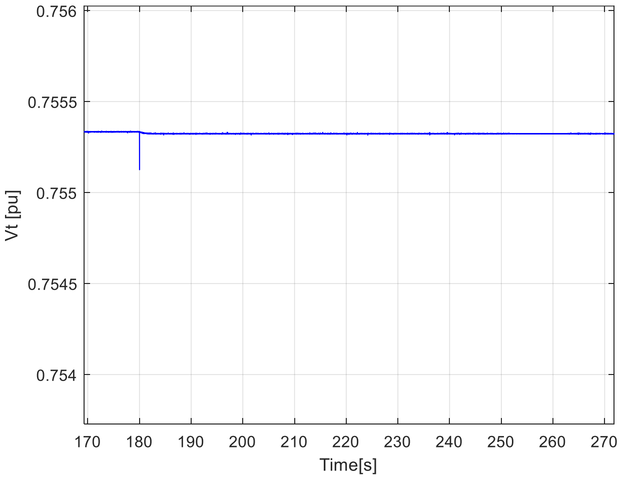

Fig. 11 : SMIB network output voltage Vt

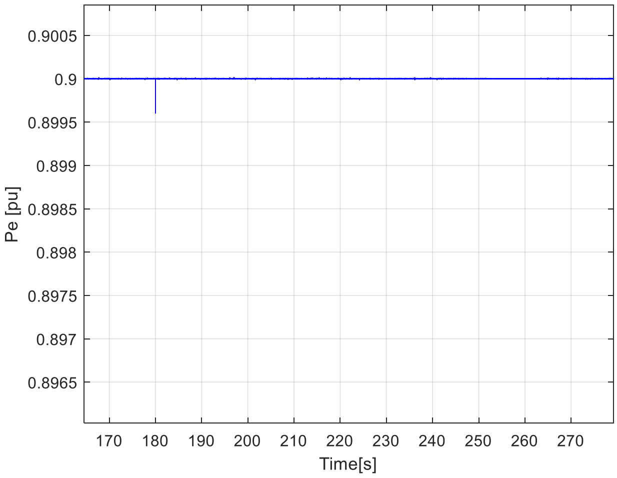

Fig. 12 : SMIB network power Pe

## *2) Zoom of the short_circuit fault on the SMIB network*

### *a) For input variables : δ, ω and Eq*

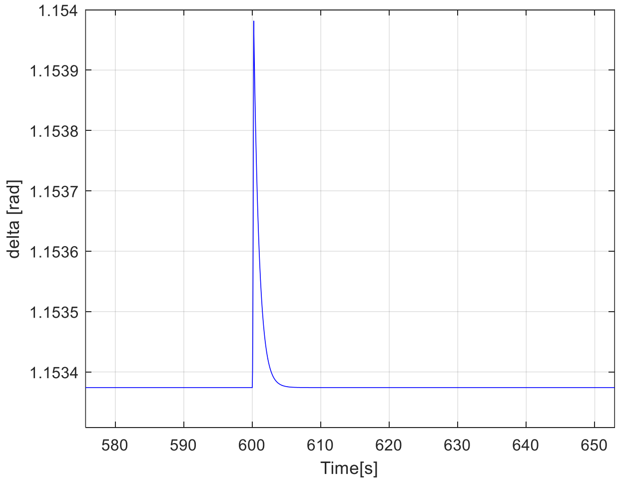

Fig. 13 : Power angle δ of generator SMIB

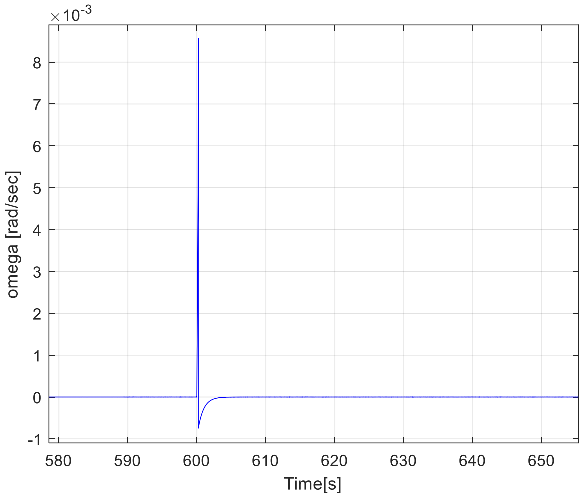

Fig. 14 : Relative speed of electrical rotation ω

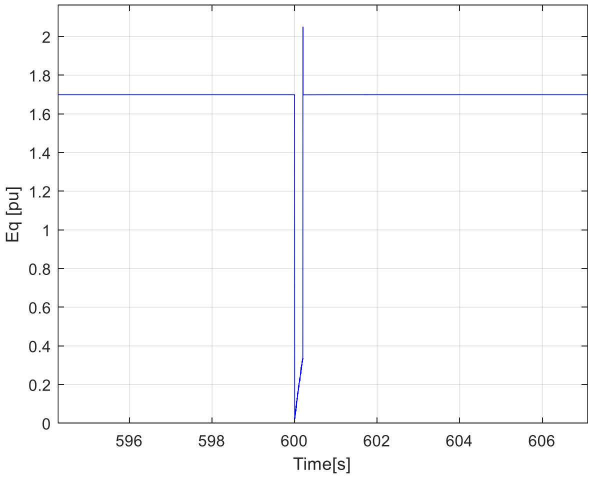

Fig. 15 : Quadrature transient internal voltage Eq

### *b) For output variables : Vt et Pe*

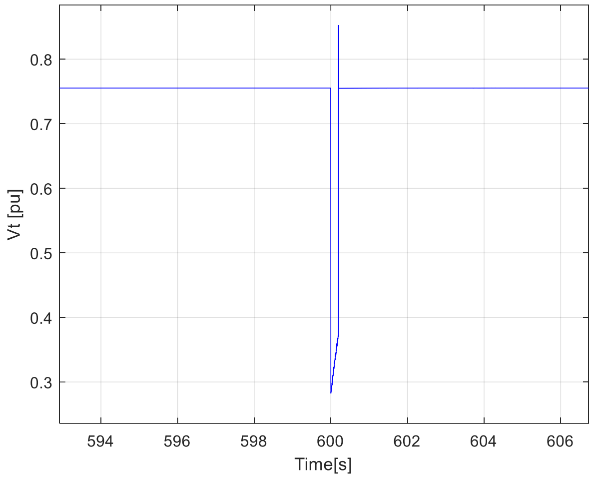

Fig. 16 : SMIB network output voltage Vt

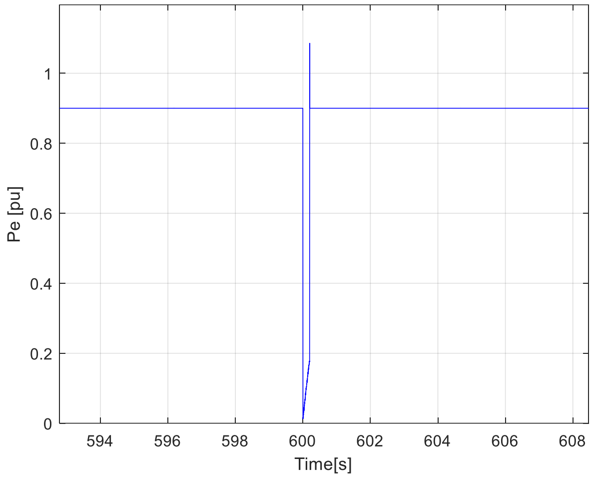

Fig. 17 : SMIB network power Pe

The following figures show the behavior of the wind turbine in the presence of a short-circuit fault.

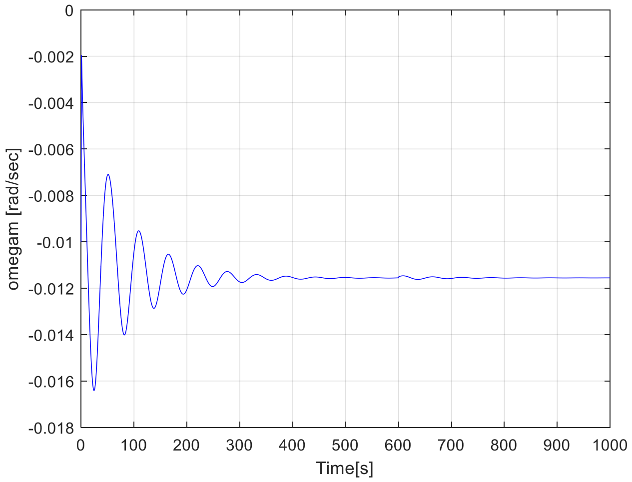

Fig. 18 : Speed of electrical rotation

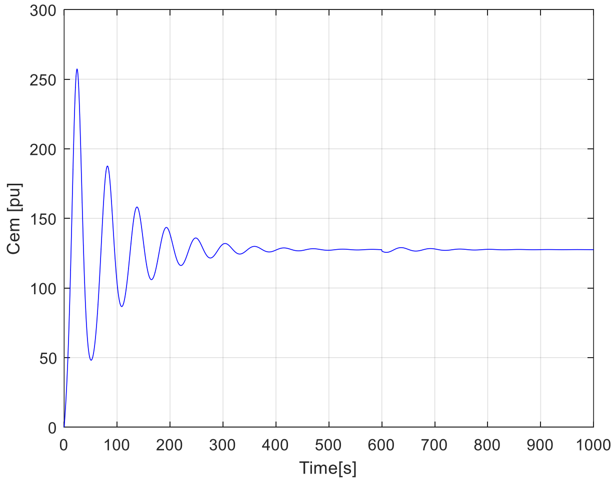

Fig. 19 : Electromagnetic torque of the wind turbine

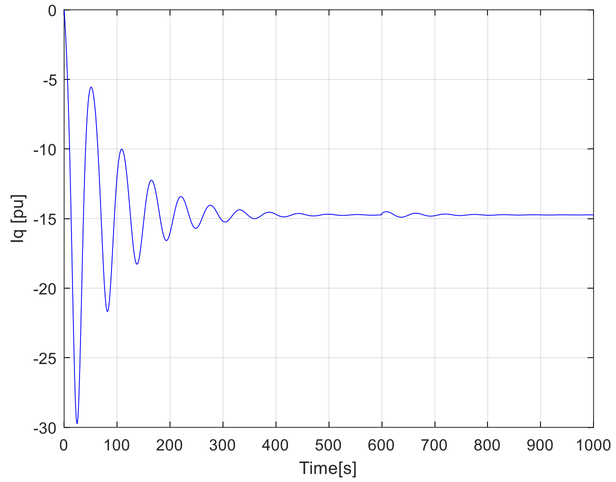

Fig. 20 : Quadrature currents

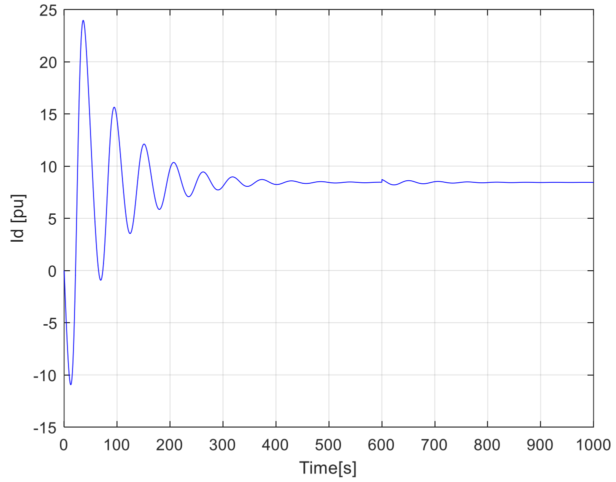

Fig. 21 : Direct currents

## IV. DISCUSSIONS

On these different figures, it is clear that the network is stable on a well-defined operating point. The wind turbine is inserted on the network at t equal to 180s and the short-circuit fault in the interval 600s to 600.2s on the common node Vs.

It is noted from these curves the presence of a very small change (see Fig.8, Fig.10 and Fig.11) and of the peak on certain parameters (see Fig.9 and Fig.12) during the integration of the wind turbine on the SMIB system. These various changes will not influence the power system operation unlike the short-circuit fault and also its size.

The PDC command always brings the power system back to its stable operating point as quickly as possible (see Fig.13, Fig.14, Fig.15, Fig.16 and Fig.17).

In the case of the wind turbine, when these parameters reach the point of their stability, the introduced short-circuit fault has changed their behavior. Compared to the quantities of instability due to the short-circuit on the power system (see Fig.18, Fig.19, Fig.20 and Fig.21), the wind turbine also needs to be controlled to bring this instability as quickly as possible to the point of stability and also for its good functioning.

## V. CONCLUSIONS

This present article is based on the integration of a wind turbine into an island electrical power system and their behavior in the face of a short-circuit fault. For the accomplishment of this work, the Diego-Suarez (Madagascar) city power system was considered. The peak electrical power is about 12MW considering stable network operation. A 15MVA synchronous generator for the SMIB and a 2.5MW wind turbine for the integration were used. The Matlab programming and simulation tool was used to simulate existing mathematical models, whether for the wind turbine or the SMIB.

The interest in this work lies in the contribution to the use of nonlinear models up to the design of control laws. The multiple model approach based on the TS fuzzy model and its PDC control have been implemented to develop a control law for the system. The insertion of a short-circuit fault on the power system made it possible to assess that the control used reacts well to this disturbance.

In the integration part, the insertion of the wind turbine has not at all changed the behavior of the power system, since the power of the latter is largely greater than that of the wind turbine.

As a very short-term perspective of this work, the gradual increase in the power of the wind turbine to be integrated is considered as well as its effect on the behavior of the entire network. In the medium term, an extension of this work may be the consideration of another type of generator used in wind energy conversion such as Asynchronous Generators and Double-Feed Asynchronous Generators as used in (Bedoud et al., 2013).

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