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Robust Nonlinear Backstepping Controller for a Tidal Stream Generator Connected to a High Power Grid

非线性鲁棒控制器反推用于发电机潮汐耦合到高功率网络中

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Abstract - **Increasing global energy requirements and the emergence of renewable energy involve some efficient Smart Grids deployment in order to prevent disturbances that may occur on electrical grid. In recent years, to enhance the stability and the sustainability of power systems, a great deal of attention has been paid to nonlinear power controllers. Indeed, they could be used to maintain steady voltage and frequency under normal and dysfunctional operations. Among various nonlinear controllers, we have chosen in this paper to design a controller based on the backstepping method, which can apply to our dynamical system. These advantages of this procedure are the smoothness and robustness with respect to external disturbances. It will be applied to a tidal stream system connected to a high - power electrical network called infinite bus. Dynamics of angular speed, active power and terminal voltage of our system without controller have been compared to those obtained with a nonlinear backstepping controller and with a classical linear controller named AVR-PSS (Automatic Voltage Regulator - Power System Stabilizer). Simulations on a single machine connected to an infinite bus power system will prove that our backstepping controller achieves the convergence of the system states. Robustness is demonstrated in transient and permanent behaviours when occur a mechanical perturbation and short-circuit on the transmission line. Furthermore, the effectiveness of the proposed controller compared to classical controller allows overcome the stall phenomena of synchronous generators directly connected to a high power grid.**

Keywords - **High Power Network, Backstepping Control, Power Systems Stability, Robustness**

I. INTRODUCTION

Nowadays, robust nonlinear control strategies development is an important challenge to ensure the stability of interconnected generators to high power grids. Indeed, the emergence of renewable terrestrial and tidal current energies [1] leads us progressively to a reversible network in terms of production and consumption. Hence it is necessary to develop resilient Smart Grids capable of self-regulation in the event of long or short power failures. As a result our research area requires transversal skills such as mathematical modelling of complex nonlinear systems, electrical and control engineering. The direct high-power grid connection requires a permanent regulation of terminal voltage and frequency with a quick rejection of mechanical or electrical disturbances. In this context, the controller design must take into account the inherent nonlinear properties of synchronous generators. So far the linearized Heffron-Philips model of a Single Machine Connected to an Infinite Bus (SMIB) associated with an AVR-PSS had been improved and shown their efficiency only around operating points [2]. But, in effect, this control strategy could disconnect synchronous generator the power grid under severe disturbances. Until now few implementations of nonlinear controllers have been done on benchmarks. For this reason, our team has developed, simulated and implemented robust nonlinear controllers [3, 4, 5].

In this paper a nonlinear controller will be designed by a backstepping method. Next, the robustness of this controller was improved under disturbances such as short-circuit and permanent turbine mechanical power drop - Fig. 1.

The paper is organised as follows: in Section II, we used third order dynamic model of SMIB elaborated in [6]. The advantage of this nonlinear state representation is that two state variables, relative angular speed of the generator (ω) and active power of the generator (P_e), are directly measurable. The power angle (δ) is obtained by integrating relative angular speed. The terminal voltage (V_t) of the synchronous generator is measurable and could be obtain by an algebraic equation. Our nonlinear system is already in a strict-feedback form, which allows design the backstepping control in Section IV. This method will achieve our control objectives summarized in Section III. We will check by simulations in section V our backstepping control law and compare this one with AVR-PSS controller.

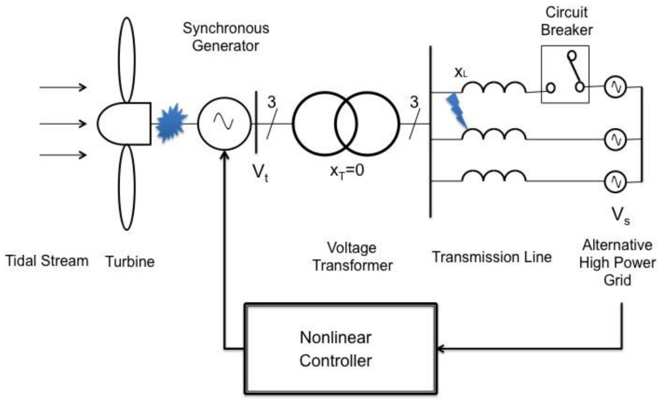

Fig 1, Tidal stream generator and his nonlinear controller connected to a high power grid

II. Problem Formulation

2.1. Assumptions

These following assumptions are based on the fact that tidal phenomena are predictable.

① The velocity of the tidal current is considered as a constant.

② The turbine mechanical power, P_m, evolves as a fast response first order system. Its steady state value is 0.8 pu.

③ It is assumed that all system parameters are known.

2.2. Synchronous generator dynamics model

Our nonlinear system is of the general form $\dot{x} = f(x, u)$. $x^T = [\delta\ \omega\ P_e]$ is the vector of state variables and $u = E_{fd}$ is the command. Our nonlinear system comes from formulations written in [8, 9].

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = \alpha_2 . x_2 + \gamma_2 + \beta_2 . x_3 \\ \dot{x}_3 = x_2 x_3 . \cot x_1 + \alpha_3 x_2 \sin^2 x_1 + \gamma_3 x_3 + \beta_3 \sin x_1 u \end{cases} \tag{1}$$

with:

$$x_1 = \delta \qquad x_2 = \omega = \omega_g - \omega_s \qquad x_3 = P_e$$

$$\alpha_2 = -\frac{D}{M} \qquad \beta_2 = -\frac{\omega_s}{M} \qquad \gamma_2 = -\beta_2 . P_m$$

$$\alpha_3 = \frac{x_d - x'_d}{x_{ds} . x'_{ds}} V_s^2 \qquad \gamma_3 = -\frac{1}{T'_{do}} . \frac{x_{ds}}{x'_{ds}} \qquad \beta_3 = -\frac{1}{T'_{do}} . \frac{V_s}{x'_{ds}}$$

$$M = 2.H \qquad x_{ds} = x_d + x_s \qquad x'_{ds} = x'_d + x_s$$

System parameters are defined in Table 1.

Table 1, system-grid parameters

Designation	Symbol	Value	Unit
Root mean square high power voltage	V_s	1	*pu*
Mechanical power turbine	P_m	0.8	*pu*
Transmission line parameters + voltage transformer			
Voltage transformer reactance	x_T	0	*pu*
Transmission line reactance	x_L	0.294	*pu*
Broken Transmission line reactance	x_s	$x_T + \frac{1}{2} x_L$	*pu*
Synchronous generator parameters			
Synchronous angular speed	ω_s	1	*pu*
Rotor angular speed	ω_g	–	*pu*
Damping constant	D	0.1	*pu*
Inertia constant	H	0.576	*sec.*
Synchronous direct axis reactance	x_d	0.894	*pu*
Synchronous direct axis transient reactance	x'_d	0.64	*pu*
Direct axis transient open-circuit time constant	T'_{do}	0.44	*sec.*

Let's write the previous system in strict–feedback form:

$$\begin{cases} \dot{x}_1 = \varphi_1(x_1) + \psi_1(x_1) x_2 \\ \dot{x}_2 = \varphi_2(x_1, x_2) + \psi_2(x_1, x_2) x_3 \\ \dot{x}_3 = \varphi_3(x_1, x_2, x_3) + \psi_3(x_1, x_2, x_3) u \end{cases} \tag{2}$$

In our case, by identification, we have:

$$\varphi_1 = 0 \qquad \psi_1 = 1$$

$$\varphi_2 = \alpha_2 x_2 + \gamma_2 \qquad \psi_2 = \beta_2$$

$$\varphi_3 = x_2 x_3 . \cot x_1 + \alpha_3 x_2 \sin^2 x_1 + \gamma_3 x_3 \qquad \psi_3 = \beta_3 \sin x_1$$

$$0 < x_1 < \frac{\pi}{2}$$

2.3. Terminal voltage

Since the terminal voltage of the synchronous generator does not appear in our system Eq. (1), we get it algebraically by the following direct relation [7]:

$$V_t = \left[\left(\frac{x_s P_e cot\delta}{V_s} + \frac{x_d . V_s}{x_{ds}} \right)^2 + \frac{(x_s . P_e)^2}{V_s^2} \right]^{1/2} \tag{3}$$

III. Control Objectives

Control law objectives are describe as follows:

- The power angle δ must converge to its reference value δ_{ref} define by equation Eq. (4).

- The relative speed ω of the synchronous generator must converge quickly towards zero. This means that rotor angular speed converges towards the synchronous angular speed.
- The terminal voltage of the synchronous generator V_t must converge quickly to the high power grid reference voltage V_s of 1 *pu*.

These control objectives can be summarized as follows:

$$\lim_{t\to+\infty}\begin{bmatrix}\delta\\ \omega\\ V_t\end{bmatrix}=\begin{bmatrix}\delta_{ref}\\ 0\\ V_s\end{bmatrix}$$

with :

$$\delta_{ref} = \operatorname{arcot}\left[\frac{V_s}{x_s P_m}\left(-\frac{x_d V_s}{x_{ds}}+\sqrt{{V_s}^2-\frac{{x_s}^2{P_m}^2}{{V_s}^2}}\right)\right] \quad (4)$$

The developed control law must reject electrical and mechanical disturbances as quickly as possible.

IV. Backstepping Controller Design

Backstepping is a systematic and recursive method used to design nonlinear controllers using the second stability principle of Lyapunov. This technique was inspired by the research works of Feurer, Morse [10] in the seventies and by Kokotović and Sussmann in the eighties. Works of Krstić, Kokotović and Kanellakopoulos [11, 12] made a great contribution to the development of this technique to a very large class of nonlinear systems. The block diagram in Fig. 2 illustrates the development of the backstepping control law for our nonlinear system. This method consists in designing a controller recursively by considering state variables as virtual controls. Then, we design some intermediate virtual control laws called stabilizing functions σ_i (i = 1,2,3). This control strategy will have to achieve the objectives of stabilization and tracking of desired trajectory. For this purpose, at each step we designed control Lyapunov functions, called **clf**, including estimated states z_i also called error variables: $z_1 = x_1 - \delta_{ref}$, $z_2 = x_2 - \sigma_1$ and $z_3 = x_3 - \sigma_2$. Under the theorem of Lassalle-Yoshizawa [13] these new coordinates z_i obtained in the new state space converge asymptotically to zero - Fig 3a.

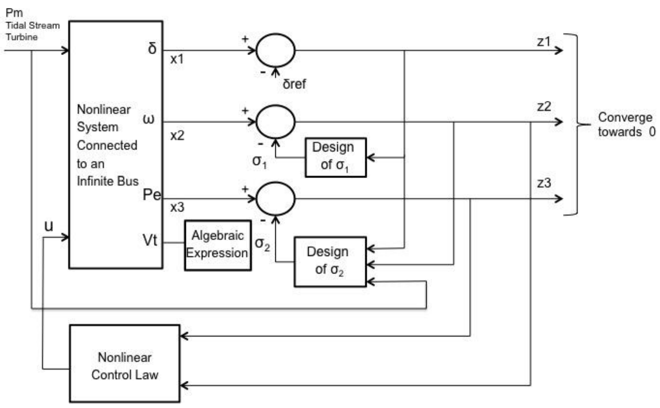

Fig 2, Block diagram of backstepping controller system

Step 1

Consider the following coordinate changes:

$$z_1 = x_1 - x_{1r} \quad (5)$$

$$z_2 = x_2 - \sigma_1 \quad (6)$$

with $x_{1r} = \delta_{ref}$ given by equation Eq. (4).

We derivate equation Eq. (5):

$$\dot{z_1} = \dot{x}_1 - \dot{x}_{1r} = x_2 \qquad (\dot{x}_{1r} = 0)$$

From Eq. (6), we get the expression of x_2 – first virtual control variable – and it is injected into $\dot{z_1}$, which gives:

$$\dot{z}_1 = z_2 + \sigma_1 \,. \quad (7)$$

Let us choose a first **clf**:

$$V_1 = \frac{1}{2}{z_1}^2$$

The time derivative of V_1 is:

$$\dot{V}_1 = z_1 . \dot{z}_1$$

We inject Eq. (7) into the previous expression:

$$\dot{V}_1 = z_1 z_2 + z_1 . \underbrace{\sigma_1}_{-c_1 z_1} \quad (8)$$

We deduce the first stabilizing function σ_1:

$$\sigma_1 = -c_1 z_1 \quad (9)$$

where c_1 is a positive constant.

Its time derivative, useful for the second step, is written:

$$\dot{\sigma_1} = -c_1 \dot{x_1} = -c_1 x_2 \quad (10)$$

Conclusion of step 1

Then the time derivative of V_1 becomes:

$$\dot{V_1} = -c_1 z_1^2 + z_1 z_2 \ . \quad (11)$$

Clearly, if $z_2 = 0$, then $\dot{V_1} = -c_1 z_1^2$ and $z_1$is guaranteed to converge toward zero asymptotically.

Step 2

Consider the following coordinate changes:

$$z_3 = x_3 - \sigma_2 \,. \quad (12)$$

The time derivative of Eq. (6) is:

$$\dot{z_2} = \dot{x_2} - \dot{\sigma_1} \,.$$

In the previous equation we inject the second equation of our nonlinear system Eq. (1) and Eq. (10):

$$\dot{z_2} = \alpha_2 x_2 + \beta_2 x_3 + \gamma_2 + c_1 x_2$$

From Eq. (12) we get the expression of x_3 – second virtual control variable – and it is injected into $\dot{z_2}$, which gives:

$$\dot{z_2} = (\alpha_2 + c_1)x_2 + \beta_2 z_3 + \beta_2 \sigma_2 + \gamma_2 \quad (13)$$

Let us choose a second **clf** of the form:

$V_2 = V_1 + \frac{1}{2} {z_2}^2$.

The time derivative of V_2 is:

$\dot{V_2} = \dot{V_1} + z_2.\dot{z_2}$.

We inject Eq. (13) and Eq. (11) into the previous expression:

$$\dot{V_2} = -c_1 {z_2}^2 + \beta_2 z_2 z_3 + z_2[z_1 + (\alpha_2 + c_1)x_2 + \beta_2\sigma_2 + \gamma_2] \quad (14)$$

with $[z_1 + (\alpha_2 + c_1)x_2 + \beta_2\sigma_2 + \gamma_2] = -c_2 z_2$.

We deduce the second stabilizing function σ_2:

$\sigma_2 = -\frac{c_2}{\beta_2} z_2 - \frac{1}{\beta_2} z_1 - \frac{\alpha_2 + c_1}{\beta_2} x_2 - \frac{\gamma_2}{\beta_2}$.

Substituting α_2, β_2 and γ_2 by their expressions we have:

$$\sigma_2 = \frac{M}{\omega_s}\left[c_2 z_2 + z_1 - \left(c_1 - \frac{D}{M}\right) x_2\right] + P_m \quad (15)$$

where c_2 is positive constant.

Its derivative, useful for the third and last step, is written:

$$\dot{\sigma_2} = \frac{\partial\sigma_2}{\partial x_1}\dot{x_1} + \frac{\partial\sigma_2}{\partial x_2}\dot{x_2}$$

$$= \frac{M}{\omega_s}[(1 + c_1 c_2)x_2 + (c_1 + c_2 - \frac{D}{M})\dot{x_2}] \quad (16)$$

where $\dot{x_2}$ is the second equation of our nonlinear system Eq. (1).

CONCLUSION OF STEP 2

Then the time derivative of V_2 becomes:

$$\dot{V_2} = -c_1 {z_1}^2 - c_2 {z_2}^2 + \beta_2 z_2 z_3 = -\sum_{i=1}^{2} c_i {z_i}^2 + \beta_2 z_2 z_3 \quad (17)$$

Clearly, if $z_3 = 0$, we have $\dot{V_2} = -\sum_{i=1}^{2} c_i {z_i}^2$, and thus both z_1 and z_2 are guaranteed to converge to zero asymptotically.

STEP 3

In this step we will determine the control law u.

We derivate the error dynamic z_3 Eq. (12):

$$\dot{z_3} = \dot{x_3} - \dot{\sigma_2} . \quad (18)$$

In the previous equation we inject the third equation of our nonlinear system Eq. (2) in which u appears:

$$\dot{z_3} = \varphi_3(x) + \psi_3(x)u - \dot{\sigma_2} \quad (19)$$

Let us choose a third **clf** of the form:

$V_3 = V_2 + \frac{1}{2} {z_3}^2$.

The time derivative of V_3 is:

$\dot{V_3} = \dot{V_2} + z_3.\dot{z_3}$.

We inject Eq. (19) and Eq. (17) in the previous expression:

$$\dot{V_3} = -\sum_{i=1}^{2} c_i {z_i}^2 + z_3[\beta_2 z_2 + \varphi_3(x) + \psi_3 u - \dot{\sigma_2}] \quad (20)$$

with $[\beta_2 z_2 + \varphi_3(x) + \psi_3 u - \dot{\sigma_2}] = -c_2 z_2$

We are able to design the control law u ensuring $\dot{V_3} \leq 0$.

$$u = \frac{-c_3 z_3 - \beta_2 z_2 - \varphi_3(x) + \dot{\sigma_2}}{\psi_3(x)} \qquad \psi_3(x) > 0$$

where c_3 is positive constant. Substituting β_2 and β_3 by their expression we have:

$$u = T'_{do} \frac{x'_{ds}}{V_s} \frac{-c_3 z_3 + \frac{\omega_s}{M} z_2 - \varphi_3(x) + \dot{\sigma_2}}{\sin x_1} \quad 0 < x_1 < \frac{\pi}{2} \quad (21)$$

$\dot{\sigma_2}$ is given by equation Eq. (16). Positives constant c_i is the tuning parameters of the nonlinear controller and $\varphi_3(x)$ is the nonlinear function resulting from the third equation of the nonlinear system Eq. (2).

CONCLUSION OF STEP 3

So, the time derivate of V_3 becomes:

$$\dot{V_3} = -\sum_{i=1}^{3} c_i {z_i}^2 \leq 0$$

CONCLUSION

The stability criterion of LYAPUNOV leads to $\lim_{t\to\infty}(z_1, z_2, z_3) \to 0$ – Fig 3a. This results in, $x_1 = \delta \to \delta_{ref}$, $x_2 = \omega \to 0$ and $x_1 = P_e \to P_m$. This last convergence implies the convergence of V_t toward V_s. Then we have just shown that the control law satisfies the convergence objectives given in the Section III.

V. SIMULATION RESULTS

Generator dynamics connected to the high power grid was simulated using MATLAB®R2016b with Simulink® environment.

5.1.TUNING PARAMETERS

We performed the simulations with synchronous generator parameters given in [3-5]. Controllers tuning parameters are given in Table 2.

TABLE 2, CONTROLLERS TUNING PARAMETERS

Backstepping	AVR-PSS
$c_1 = 1$ $c_2 = 10$ $c_3 = 0.5$	$K_A = 500$ $K_{PSS} = 0.5$ $T_W = 10s$ $T_1 = 0.2s$ $T_2 = 0.1s$ $T_R = 0$

5.2. ROBUSTNESS TEST

Our system will be tested by the following robustness test: combination of a short circuit on the transmission line lasting 500 *ms* occurring at 40 *s* after generator start-up and a permanent drop of the mechanical power of 50% of its nominal value occurring 80 *s* after the start of the generator.

5.3. Discussion

Temporal responses show that the implemented nonlinear regulator, called BCKSTP, gives satisfactory results. The AVR-PSS linear regulator ensures a good tracking of the reference trajectories. However, with the linear regulator, transient overrun appears in the dynamic of the power angle - Fig. 3c- while with the nonlinear regulator we can easily damp this transient overrun and improve the quickness of the dynamics of δ by playing on the parameter c_i. We note that during the short circuit, playing on these same parameters – Fig. 3e and Fig. 3f – can reduce the peaks of voltages and powers in transient state. After a mechanical power drop, the power angle does not return to its reference value since δ_{ref} depends on P_m in the expression Eq. (4) – Fig. 3c. The equilibrium point of the power angle has changed but remains stable because $0 < \delta < \frac{\pi}{2}$. Hence, the generator will not be subject to stall phenomena and the network will remain stable. We can see that the dynamics of ω regulated by our nonlinear controller reject the mechanical disturbance more quickly than the AVR-PSS regulator – Fig. 3d. The major disadvantage of the AVR-PSS is that the power has transient overrun and a peak overshoot during the short circuit – Fig. 3e. The control voltage of the BCKSTP regulator is smoother compared to the AVR-PSS signal – Fig. 3b. Indeed, a too high value of the gain of the voltage regulator K_A of the AVR-PSS regulator needed to obtain the convergence of V_t toward V_s degrades the control signal while the BCKSTP regulator does not have this disadvantage.

VI. Conclusion and Perspectives

In this paper, a nonlinear backstepping control has been developed for synchronous generator excitation driven by tidal stream turbine. This proposed nonlinear controller regulates simultaneously terminal voltage and frequency making possible direct connection to electrical grid. Numerical results show a better convergence, reliability, transient stability and robustness compared to AVR-PSS. Indeed, the nonlinear controller designed with nonlinear equations system avoids a degradation of dynamics in transient and steady states with respect to a classical linear regulator. Soon, our research will focus on simulations and implementations of robust nonlinear controllers in multimachine configuration in order to anticipate tidal stream generators production parks development.

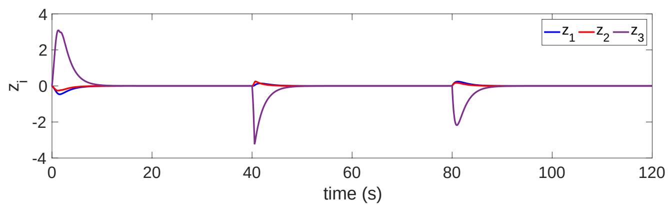

Fig 3a, Errors variables

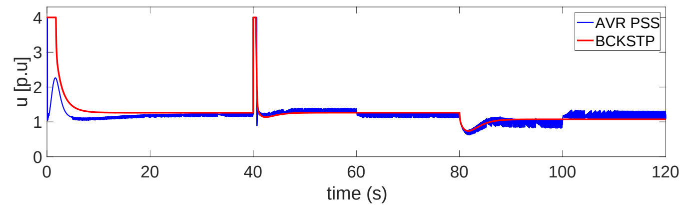

Fig 3b, Control signal

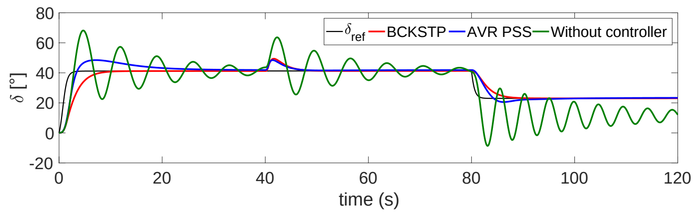

Fig 3c, Rotor angle

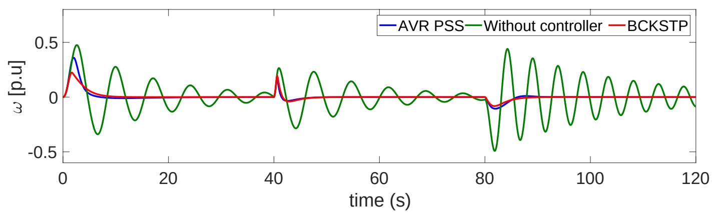

Fig 3d, Relative angular speed

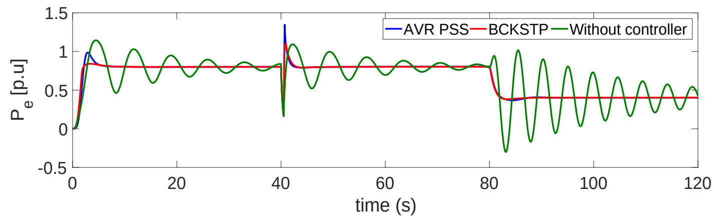

Fig 3e, Active electrical power

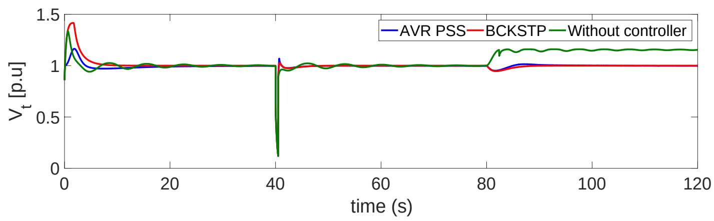

Fig 3d, Terminal voltage

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