

Nonlinear Multiple Model Control of A Simplified Electrical Power System Incorporating A TCSC FACTS Device

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Abstract— The power system operator faces major problems on increasing the power transfer capacity of the existing transmission system. The emergence of new technologies and the increase in the number of populations generate the increase of electric energy needs which imposes new requirements on the stability and security condition of an electric power system.

Flexible Alternating Current for Transmission Systems (FACTS) device of the Thyristor Controlled Series Capacitor (TCSC) type is used in order to design new nonlinear multiple model control laws called Parallel Distributed Compensation (PDC) for the system. The multiple model representation is obtained using a Takagi-Sugeno multiple model approach obtained by the non-linear sectors transformation. The TCSC is placed in series in the middle of the power line.

The methodology adopted is the use of the classical second-order equation of Single Machine Infinite Bus (SMIB) system or single machine system connected to an infinite bus with the injection model of TCSC.

Simulations and results obtained under MATLAB environment, for a SMIB system have shown the effectiveness of a serial FACTS type TCSC, which improves the stability of the transmission angle of the injected power and gives a new margin to the active power transited by injecting the reactive power at the consumption point, to make the electrical network robust that can be used up to its admissible thermal limit.

Keywords— SMIB; FACTS devices; TCSC; T-S multiple model; PDC control

I. INTRODUCTION

An electrical network includes lines, substations and transformers. It is a set of equipment that transports energy from the place of production to the consumers. By providing this interface, the network not only ensures a physical link for the circulation of energy flows, but also makes services available to the community it serves.

The rate of subscriber connection and the emergence of electrical equipment due to high rates of subscriber growth, the integration of renewable energy and the legalization of the

electricity market make power generation unpredictable. The increase in transit capacity in the grid by new power plants is prompting grid operators to build new power lines.

Precisely, the control devices based on power electronics components (Gate Turn Off - GTO, Insulated Gate Bipolar Transistor - IGBT) known under the acronym FACTS open a new approach to improving the operating conditions of electrical networks, among other things, the postponement of the investment related to the installation of new network infrastructures. These devices have various functions such as maintaining voltage, controlling power flows, improving network stability, increasing the maximum transmittable power, ... (Morsali et al. 2016)

Among these devices, the TCSC, the subject of this article, is often through the power line. However, the other important aspect of these controllers is their use during large disturbances such as faults because of their ability to improve the transient stability condition of a power system.

The Takagi-Sugeno fuzzy model is used to represent our electrical network. The advantage of this T-S fuzzy model is the flexibility, simplicity and efficiency of representing complex nonlinear processes by a very small number of fuzzy rules. A study has been done on multiple model modeling and PDC control of a power system with an application to the SMIB system (Rafanotsimiva et al. 2013). The originality in this paper lies on the integration of a FACTS device as the TCSC type.

In the case of a dynamic system, the loads can vary greatly depending on the environment to which the system is subjected, or depending on its use at a given time. The model is used to represent the behavior of the power system and the generators connected to it. The nonlinear control method of an electrical network will be established in order to improve its transient stability and that of the synchronous machines connected to it. To achieve the objectives of this study, the modeling and simulation of the whole system (SMIB as multiple model form, PDC Control and FACTS) have been

performed in the MATLAB environment and the results are presented by the curves obtained by these simulations.

In this paper, we will discuss FACTS devices of the TCSC type that will be connected in the middle of a power line in order to control the flow of reactive power exchanged in the electric power system. However, the association of these devices to an electrical power system generates a complex model with strong nonlinearities. (Bésanger et al. 2000), (Bouarar T. 2009)

After this introduction, we will discuss the materials and methods, then the simulation results with their interpretation. And we will end with a brief conclusion.

II. MATERIALS AND METHODS

A. Electrical Network

In this work, the materials considered are the electrical power system, the FACTS device and the Matlab/Simulink simulation software. While the methods used concern the modelling of the different elements of the considered power system, the calculation and implementation of the PDC multiple model control law and their simulation.

Electrical power system with FACTS device

In general, a power system consists of the generation plant, the transmission and distribution lines and the consumers. In a very general concept, an electrical power system is made up of multiple electrotechnical equipment (lines, cables, transformers, switchgear and control) associated in a coordinated manner.

In power system operation, the voltage U and Frequency f (and thus the relative electrical speed ω) must remain within permissible margins of 5% in Low Voltage (LV), 10% in Medium Voltage (MV) and 1% in High Voltage (HV) respectively. FACTS devices control the flow of reactive power exchanged in the electrical power transmission network.

A better load distribution is needed, which ensures the voltage and phase amplitude for given operating conditions to allow the calculation of transmitted and generated power and losses.

The active power P transited between two networks of voltage V_1 and V_2 has a transport angle δ connected by a link of impedance X which is given by the following equation:

$$P = \frac{V_1 V_2}{X} \sin \delta \quad (1)$$

From this equation, it is possible to increase the active power transited by acting either on the voltage amplitude, on the transport angle or on the line impedance.

In this work, we will use the model of a synchronous machine feeding an infinite network through lines and a transformer as used in Rafanotsimiva et al, 2013.

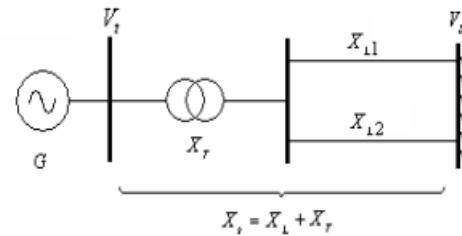


Fig. 1 : Model of a machine connected to an infinite node

We use a model that is valid for moderate disturbances whose state variables are the power angle δ , the relative electrical rotation speed ω and the internal quadrature voltage E_q of the generator.

Model in (δ, ω, E_q)

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, E_q) of order 3 of the form (Rafanotsimiva, 2013):

$$\begin{aligned} \dot{\delta}(t) &= \omega(t) \\ \dot{\omega}(t) &= -\frac{D}{H} \omega(t) - \frac{\omega_0}{2H} \frac{1}{x_{ds}} V_s \sin \delta(t) E_q(t) + \frac{\omega_0}{2H} P_{m0} \\ \dot{E}_q(t) &= \frac{x_d - x'_d}{x'_{ds}} V_s \sin \delta(t) \omega(t) - \frac{1}{T'_{d0} x'_{ds}} E_q(t) + \frac{x_{ds}}{x'_{ds} T'_{d0}} \frac{k_c}{k_f} u_f(t) \end{aligned} \quad (2)$$

Where δ , ω , E_q , T'_{d0} , P_m , D , H , V_t and V_s 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. x_d , x'_d , x_{ds} , x'_ds are the electrical parameters representing the different reactances of the generator, the lines and the transformer.

With the output voltage of the generator and the electrical power flowing through the lines as outputs:

$$V_t^2(t) = \frac{x_{ds}^2}{x_{ds}^2} \left[E_q^2(t) + V_s^2 + \frac{2x_d}{x_s} V_s \cos \delta(t) E_q(t) \right] \quad (3)$$

$$P_e(t) = \frac{1}{x_{ds}} V_s \sin \delta(t) E_q(t) \quad (4)$$

$$Q_e = V_s (\cos \delta) \frac{E_q}{x_{ds}} - V_s^2 / x_{ds} \quad (5)$$

B. Model of the FACTS (TCSC)

FACTS can work as a Current Source Converter (CSC) or as a Voltage Source Converter (VSC).

By definition, the Thyristor Controlled Series Capacitor (TCSC) is a series compensation device using power electronics as its basic element. It is connected in series with the grid to control the power flow. The roles of the TCSC are to balance the load currents and ensure the damping of power oscillations as well as the stability of the voltage. (N. Mojtaba 2001)

These TCSCs are among the FACTS devices used to increase the capacity of the power transmitted through the power line. It consists of a coil in series with thyristors in parallel with a bank of capacitors, which allow the regulation of the capacitive reactance at the initial frequency.

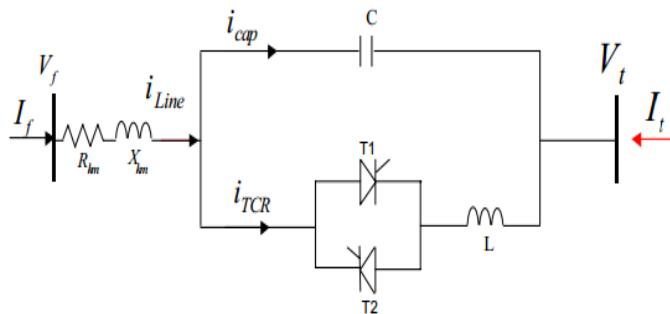


Fig. 2 : TCSC model

Paralleling, the capacitance and the variable inductance form the total equivalent impedance measured in the power line.

$$K = \frac{X_{TCSC}}{X_L} \quad (6)$$

$$X_{TCSC} = \frac{X_C X_{ind}}{X_C + X_{ind}} \quad (7)$$

With:

X_{TCSC} : is the series reactance of the TCSC

X_{Line} , X_{ind} , X_C : are the respective reactances of the power line and the TCSC (inductive and capacitive).

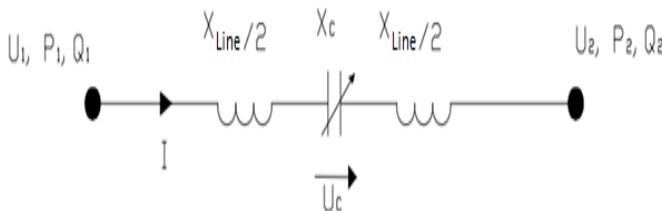


Fig. 3 : Equivalent diagram of a TCSC placed in the middle of a power line

Knowing that X_C represents the reactance of the TCSC capacitor, the equations for the transmitted active and reactive power become:

$$P = (V_1 * V_2) * \sin \delta / (X - X_C) \quad (8)$$

$$Q = V_1 * (V_1 - V_2) * \cos(\delta) / (X - X_C) \quad (9)$$

The dynamic equation for the variable reactance of the TCSC is given by the following relationship:

$$X_C(t) = (-X_C + K_C * X_{ref} + K_C * U_C) / T_C \quad (10)$$

The methodology adopted is the application of the electrical power system of dynamic models, the TCSC and the multiple model control laws that will be programmed for the dynamic study of the power system including the FACTS

device considered to ensure the stabilization of these non-linear system following a disturbance.

Application of the multiple model approach and the associated PDC control law

For several years, many works have been interested in the stability and stabilization of nonlinear systems described by Takagi-Sugeno fuzzy models. It is often performed by the Lyapunov technique which imposes restrictive requirements and gives sufficient stability conditions. One of the first ideas for stabilizing these fuzzy modes was to use linear state feedbacks. These were soon superseded by a control law that allows for the non-linearities of fuzzy models and is known as PDC (Parallel Distributed Compensation). (Wang et al. 1995)

The study of the stability of Takagi-Sugeno fuzzy relies on the choice of a candidate Lyapunov function:

$$\begin{aligned} \|x\| \rightarrow \infty &\Rightarrow V(x) \rightarrow \infty \\ \alpha(\|x\|) \leq V(x) \leq \beta(\|x\|) \end{aligned} \quad (11)$$

Where $\alpha, \beta \in \mathbb{C}^1$ are positive definite functions.

Let the following continuous free-running Takagi-Sugeno fuzzy model be used:

$$\dot{x}(t) = \sum_{i=1}^M h_i(z(t)) A_i x(t) \quad (12)$$

Quadratic stability is studied by calculating the derivative of the function $V(x)$.

$$\frac{d}{dt} V(x(t)) = \dot{x}(t)^T P x(t) + x(t)^T P \dot{x}(t) \quad (13)$$

The PDC control law is given by:

$$u(t) = - \sum_{i=1}^M h_i(z(t)) F_i x(t) \quad (14)$$

Where F_i is the local return gain relative to the i -th model.

The principle of this method is to elaborate a state feedback control for each local model, then to perform a fuzzy interconnection in a similar way to the technique used for the local models.

The major advantage of this control law is that it respects the same non-linearity partitioning structure as that used to obtain the T-S fuzzy model. (Takagi-Sugeno 1985)

To obtain the closed-loop fuzzy model, the PDC control to the T-S fuzzy model was applied.

Thus, the resulting fuzzy model is as follows:

$$\dot{x}(t) = \sum_{i=1}^M \sum_{j=1}^M h_i(z(t)) h_j(z(t)) G_{ij} x(t) \quad (15)$$

With:

$$G_{ij} = A_i - B_i K_i \quad (16)$$

In this paper, noting that a simplified power system model (corresponding to the classical SMIB case, a single machine connected to an infinite bus) can easily be re-written in a multiple model T-S form, and in view of the issues that have

become evident around energy management, we propose a study of the control of this type of system by PDC approach. (Lendek et al. 2015)

Multiple models have three structures : coupled-state or T-S, decoupled-state and hierarchical. (Orjuela et al. 2006)

In this work, the T-S multiple models used can be written as:

$$\begin{cases} \dot{x}(t) = \sum_{i=1}^M \mu_i(z(t))(A_i x(t) + B_i u(t)) \\ y(t) = \sum_{i=1}^M \mu_i(z(t))C_i x(t) \end{cases} \quad (17)$$

Where $x \in \mathbb{R}^n$ is the state vector, $u \in \mathbb{R}^m$ the control vector and $y \in \mathbb{R}^p$ the measurement vector.

The matrices $A_i \in \mathbb{R}^{n,n}$, $B_i \in \mathbb{R}^{n,m}$ and $C_i \in \mathbb{R}^{p,n}$, $\forall i = 1, \dots, M$ are constant and assumed to be known.

The activation function $\mu_i(z(t))$ determines the degree of activation of the i -th associated local model. It allows a gradual transition from this model to the neighbouring local models.

$$\begin{aligned} \sum_{i=1}^M \mu_i(z(t)) &= 1, \forall t \\ 0 \leq \mu_i(z(t)) &\leq 1, \quad \forall i = 1, \dots, M, \forall t \end{aligned} \quad (18)$$

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

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

$$\begin{cases} \dot{x}(t) = Ax(t) + Bu(t) \\ y(t) = Cx(t) \end{cases} \quad (19)$$

Three approaches are widely used in the literature to obtain a T-S model : by identification, by linearization or by transformation by non-linear sectors (Ichalal D. 2009). We focus on the third approach by transformation by non-linear sectors.

Given the continuous T-S model in equation (16), a control law from a PDC synthesis will therefore be the combination of laws for each sub-model, given by equation (13).

Given a continuous T-S mode, the PDC control law and the γ_{ij} , if there exists a positive definite matrix X and matrices M_i , $i = 1, \dots, M$, such that the above conditions are satisfied, then the closed loop is globally asymptotically stable. Moreover, if the problem has a solution, the gains of the PDC control are given by:

$$F_i = M_i X^{-1} \quad (20)$$

And the PDC control by:

$$u(t) = - \sum_{i=1}^M \mu_i(z(t)) F_i x(t) \quad (21)$$

If $F_i = F$, $\forall i = 1, \dots, M$, we find a linear control law in the state.

From the solution of a set of Linear Matrix Inequalities (LMIs), to find the matrix P and the control gains F_j such that $j=1, \dots, M$, the closed-loop multiple model system is written without cross terms:

$$\dot{x}(t) = \sum_{i=1}^M F_i(x(t))(A_i x(t) + B_i u(t)) \quad (22)$$

$$\dot{x}(t) = \mu_1(z(t))A_1 x(t) + \mu_2(z(t))A_2 x(t) + B u(t) \quad (23)$$

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.

III. RESULTS

The data used for the comparison of the result obtained are that in Rafanotsimiva et al. 2013. The parameters describing the elements of the system are as follows:

$$\begin{aligned} \omega_0 &= 314.159 \text{ rad/s}; D = 5 \text{ pu}; H = 4 \text{ pusec}; T'_{d0} = 8 \text{ sec}; \\ k_c &= 200 \text{ pu}; x_d = 1.81 \text{ pu}; x'_d = 0.3 \text{ pu}; x_T = 0.15 \text{ pu}; \\ x_{L1} &= 0.5 \text{ pu}; \delta_0 = 67, 5^\circ; f_0 = 50 \text{ Hz} \\ x_{L2} &= 0.93 \text{ pu}; x_{ds} = x_T + x_d + \frac{x_{L1}x_{L2}}{x_{L1} + x_{L2}} = 2.28518; \\ x'_{ds} &= x_T + x'_d + \frac{x_{L1}x_{L2}}{x_{L1} + x_{L2}} = 0.77518; \\ x_s &= x_T + \frac{x_{L1}x_{L2}}{x_{L1} + x_{L2}} = 0.47518; \quad \max|k_t u_f(t)| = 7 \text{ pu}; \\ P_{m0} &= 0.9 \text{ pu}; V_s = 1.0 \text{ pu}. \end{aligned}$$

Firstly, we will study a SMIB system which comprises a synchronous machine connected to an infinite busbar through two parallel transmission lines, and a TCSC is installed in the middle of the second line. The reactance of the TCSC is varied from 0pu to -0.5pu to $t=8$ s, then from -0.5pu to 1.2pu to $t=15$ s, to illustrate the conduction of thyristors in both directions.

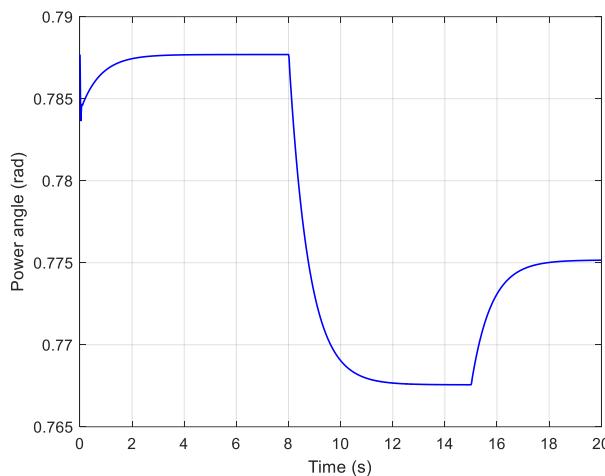


Fig. 4 : Variation of the generator power angle (delta) according to the reactance of the TCSC

For the TCSC:

$$\text{deltaxc} = 0;$$

$$xc = xc0 + \text{deltaxc};$$

$$xs = xT + ((xL1 + xc) * xL2) / (xL1 + xc + xL2);$$

$$xds = xd + xs;$$

$$xdsp = xdp + xs;$$

$$xL1 = 0.5;$$

$$xL2 = 0.93;$$

$$Vs = 1.$$

The control problem is then reduced to solving two LMIs, respectively functions of A_1 , A_2 .

$$A_1 = \begin{pmatrix} 0 & \frac{1}{D} & 0 \\ 0 & -\frac{D}{H} & -\varepsilon \frac{\omega_0}{2Hx_{ds}} V_s \\ 0 & \varepsilon \frac{x_d - x'_d}{x'_{ds}} V_s & -\frac{x_{ds}}{T'_{do} x'_{ds}} \end{pmatrix} \quad (24)$$

$$A_2 = \begin{pmatrix} 0 & \frac{1}{D} & 0 \\ 0 & -\frac{D}{H} & -\frac{\omega_0}{2Hx_{ds}} V_s \\ 0 & \frac{x_d - x'_d}{x'_{ds}} V_s & -\frac{x_{ds}}{T'_{do} x'_{ds}} \end{pmatrix} \quad (25)$$

$$B = \begin{pmatrix} 0 \\ 0 \\ \frac{K_C x_{ds}}{T'_{do} x'_{ds}} \end{pmatrix} \quad (26)$$

And the system activation functions are:

$$\mu_1(z(t)) = \frac{1}{2}(1 - \sin x(t)) \quad (27)$$

$$\mu_2(z(t)) = \frac{1}{2}(1 + \sin x(t)) \quad (28)$$

A. Application of a PDC control law

$$\sum_{i=1}^2 \mu_i(z(t)) (X A_i^T - M_i^T B_i^T + A_i X - B M_i) < 0 \quad (29)$$

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

$$F_1 = M_1 X^{-1} \quad (30)$$

$$F_1 = M_1 X^{-1} \quad (31)$$

$$F_1 = (0.2202 \ 0.1677 \ 0.0218) \quad (32)$$

$$F_2 = (18.0185 \ 13.689 \ -1.56) \quad (33)$$

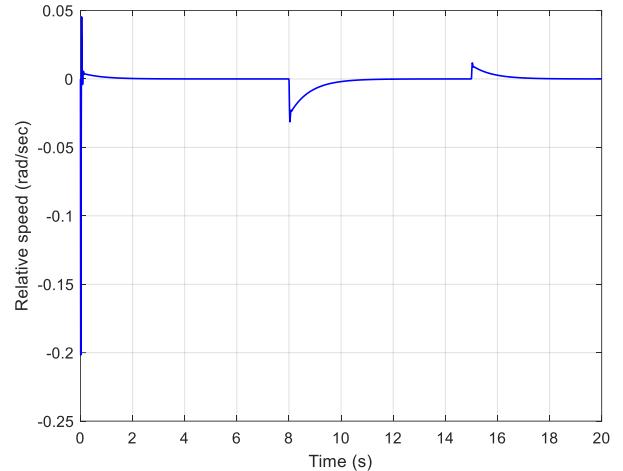


Fig. 5 : Variation of the generator relative speed (omega) according to the reactance of the TCSC

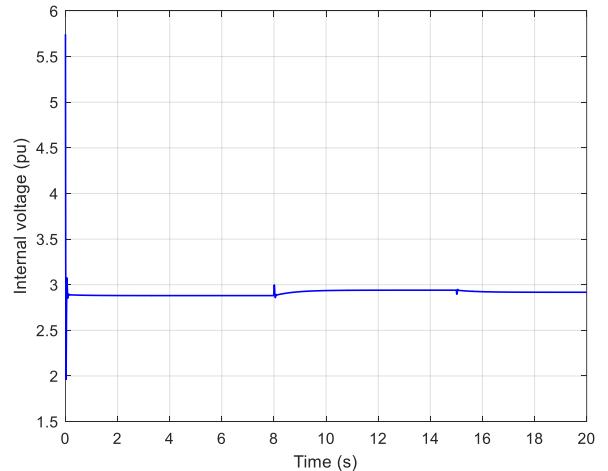


Fig. 6 : Variation of the generator internal voltage in quadrature (Eq) according to the reactance of the TCSC

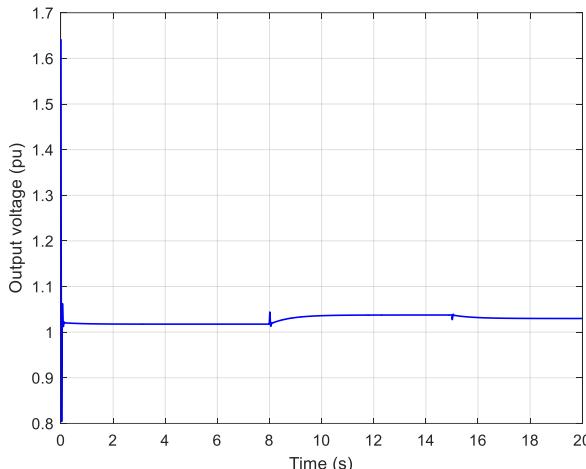


Fig. 7 : Variation of the generator output voltage (Vt) according to the reactance of the TCSC

- For output variable Pe

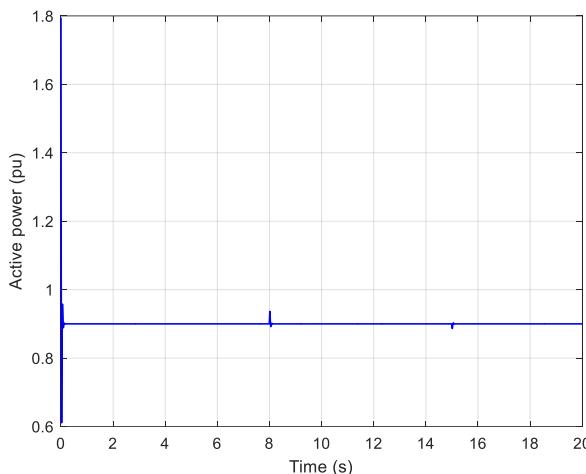


Fig. 8 : Variation of the active power transited in the power system (Pe) according to the reactance of the TCSC

- For output variables Q

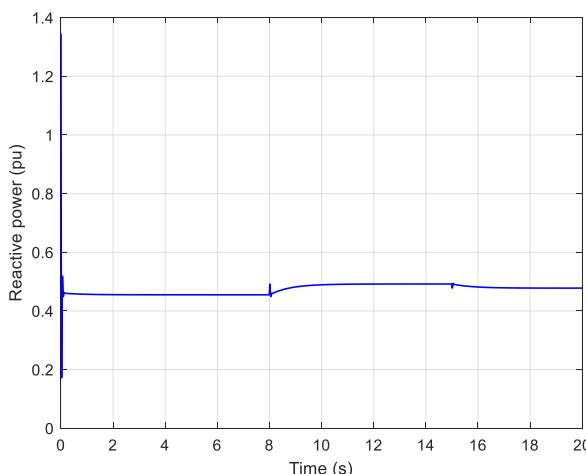


Fig. 9 : Variation of the reactive power (Q) transited in the power system according to the reactance of the TCSC

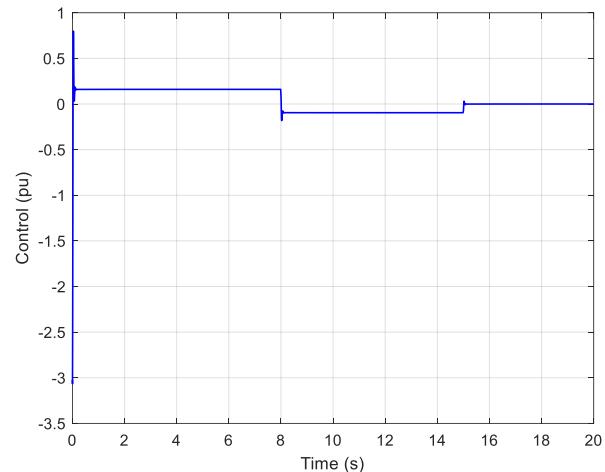


Fig. 10 : Variation of the PDC control variable (uf) according to the reactance of the TCSC

We can well see the effect of reverse conduction of the two thyristors of the TCSC dimmer on the variation of the different variables (Fig. 4, 5, 6, 7, 9, 10). The transited active power in Fig. 8 is the only variable that is not infected by the change in TCSC reactance, which is perfectly normal. On the other hand, the compensation of the reactive power can be seen in Fig. 9. Fig. 10 shows that the command responds well in accordance with the change in network behavior at t=8s and t=15s.

IV. DISCUSSIONS

The value of the TCSC reactance was varied : a decrease at t=8s from 0pu to -0.5pu, then an increase from -0.5pu to 1.2pu at t=15s. The results are shown in figures 4 to 10.

The TCSC used rapidly changes the reactive power transfer capability, Fig. 9, in the SMIB system and also varies the internal quadrature voltage of the machine as well as the voltage at the output of the infinite busbar, Fig. 6 and 7.

When the TCSC acts at t=8s and t=15s, the reactive power changes from 0.45pu to 0.49pu, then from 0.49pu to 0.47pu with oscillation signal (Fig. 9), while the T-S fuzzy control leads to the stabilization of the non-linear system. The reactive power flow is oscillatory and damped.

Since the (δ, ω, Eq) model has been used, the PDC control acts faster and ensures that the network operating point is maintained.

V. CONCLUSIONS

In this work, we simulated the behaviour of a simplified power system incorporating a serial FACTS device of the TCSC type in the presence of disturbances and the reaction of the multiple model PDC control. FACTS allow precise control, optimization of power flows on existing installations and improvement of the dynamic stability of the power system. They also allow industrial consumers to reduce load imbalances and control voltage fluctuations created by rapid changes in reactive power demand.

As a result, they increase production, reduce losses, lower costs and extend the life of equipment.

The structure of the model is necessary to represent the behavior of the electrical network, and finally to study their behavior in the face of various disturbances. It is from the illustrated models that we could distinguish the synthesis of control laws.

Reactive power compensation in a power line reduces power losses, improves the transport angle and the load voltage profile and allows for a reduction in reactive power. The implementation of TCSC with T-S fuzzy multiple model control has allowed greater flexibility in the operation and control of the system. The transport angle of the transient power improves and becomes stable after 3s when using the TCSC with the control.

Series compensation of line parameters by the TCSC reactance or by capacitors and phase shifting transformers are conventional means of controlling the power flow.

In the context of the insertion of FACTS systems in transmission and interconnection networks, it has been found that static simulations have shown the undeniable contribution of FACTS to the improvement of voltage stability. Serial FACTS have a better local behavior.

An extension of this work can be considered for the case of a multimachine power system, or taking into account the presence of other types of FACTS devices.

Our perspective is to consider a more complete model of the network (2-axis model of the generator), a hybrid FACTS and the addition of disturbances.

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