Decentralized Hybrid Fuzzy-Sliding Mode Control of Multi-machine Power System

Seddik BENHADOUGA*, Abdelhakim BELKAID**‡, Ilhami COLAK***, Djamel BOUKHETALA****, Farès BOUDJEMA****, Mounir MEDDAD*, Riad KHENFER*, Adil EDDIAID*****

* Laboratoire d'Electronique et de la Télécommunication Avancé (ETA), Université de Mohamed el Bachir el Ibrahimi, Bordj Bou Arreridj, Algeria

** Laboratoire de Technologie Industrielle et de l'Information, Université de Bejaia, Algeria

*** Department of Electrical & Electronics Engineering, Nisantasi University, Istanbul, Turkey

****Laboratoire de Commande des Processus (LCP), ENP, El Harrach, Algeria

*****Laboratoire de Physique de la Matière Condensée, Faculté des Sciences Ben M'sik, Université Hassan II de Casablanca, Morocco

(s.benahdouga@univ-bba.dz, belkaid08@yahoo.fr; ilhcol@gmail.com; djamel.boukhetala@g.enp.edu.dz; fares.boudjema@g.enp.edu.dz; meddadmounir@gmail.com; riadh_kh05@yahoo.fr; aeddiai@gmail.com)

‡ Corresponding Author; Abdelhakim BELKAID, Laboratoire de Technologie Industrielle et de l'Information, Université de Bejaia, Algeria, belkaid08@yahoo.fr

Received: 18.05.2022 Accepted: 28.05.2022

Abstract- The first advantage property of sliding mode control (SMC) system is the robustness about internal/external disturbances, but the main inconvenient of this control theory it's the chattering phenomenon caused by a non-ideal switching action. The main objective of this paper is to develop a decentralized hybrid fuzzy-sliding mode controller (DHFSMC) applied for nonlinear multi-machine power system. The hybrid fuzzy logic controller with sliding mode controller used to exploit the advantage of each controller and to eliminate the chattering phenomenon inconvenient characteristics of SMC. The main purpose is overcome the problem of the equivalent control computation. The feedback linearization method used at first step study in order to overcome the difficulty of the nonlinear and to decentralize the excitations signals controller. Each generation unit have a local hybrid fuzzy sliding mode stabilizer designed to control the speed angle under high-level external disturbances test. The proposed method illustrated and tested with a three synchronous nonlinear generators power system. Simulations results show that the decentralized hybrid fuzzy-sliding mode controller provides high-performances dynamic characteristics and their robustness regard to eternal/external disturbances.

Keywords power system multi-machine stability, feedback linearization approach, hybrid fuzzy sliding mode stabilizer.

1. Introduction

The power system automatic regulation is tested by its ability to return to normal operation or to maintain its stability (Dynamic stability and transient stability) after being subjected to some form of disturbance, such as slow and fast disturbances[1,2].

Dynamic stability can be ensured by conventional linear devices such as AVRs (Automatic Voltage Regulator) and PSSs (Power System Stabilizers), when the disturbances acting on the system; the operating point are not moving it away from these linearity limits. These disturbances are generally fast and of low amplitude [1,2].

In the case of the study of transient stability, the power system is subject to strong and rapid disturbances going so far as to bring the system beyond the capacities of the conventional control devices, because this one enters the zone of non -linearity. Faced with this situation, researchers in the field of power systems and automatic have been interested in the development of new control structures well suited to ensure transient stability and improve the performance of the power system [1,2].

Among the modern control techniques used for the power systems stability, we can distinguish backstepping control [3], fuzzy logic control [4-6, 16], standard sliding mode control [7-9], adaptive control [10-12], higher order sliding mode control [12], and decentralized sliding mode control (DSMC) [13-15].

The SMC considered as a discontinuous control law. The main role is to drive the trajectory state to a specified sliding surface and maintain its motion along that surface [7-9],[17-19]. Due to switching and delays of the system dynamics, it is difficult for the control to achieve the ideal sliding mode, and thus unwanted high frequency motion describes the chattering phenomenon [7-9],[17,18]. The integration a hybrid control methods considered to eliminate the chattering problem, although there has been no perfect solution. Many research works have proposed to combine two or three types of robust controls, like Fuzzy sliding [5], Adaptive Fuzzy Sliding [10].

Guaranteeing the robustness and solve the chattering problem of SMC, can be ensured by the use of a hybrid fuzzy sliding mode controller [5],[16]. The fuzzy control has many advantages such as the control of poorly systems modelling by the possibility of using information and experts' knowledge.

The proposed system consists of three generating units of synchronousness machines. Each unit is considered as a subsystem which is connected to the rest of the system through voltage transmission lines. Each subsystem is modeled by a nonlinear dynamic model. The objectives of the design control are to decentralize the controllers firstly, and to regulate the machine angle of each synchronous generator. The basic idea here is to use a feedback linearization approach to ensure the linearization of the overall system by considering each term of the interconnect generator as a disturbance for the rest of the system [12,13],[20].

Sliding mode control law as it is known, it consists of two terms, the equivalent control and the switching term. The latter, and for the purpose of eliminating the main drawback of SMC and which will be replaced by fuzzy logic control in order to eliminate the sudden discontinuity of the switching term (phenomenon of chatter), and it's the main objective of our study.

The present paper is organized as follows:

The global nonlinear mathematical model of the system is decomposed into two parts, electrical and mechanical, where they are described in the first section. The feedback linearization approach is applied to each subsystem model to linearize the system and consequently to develop mathematical models of interconnection terms [12,13],[20], will be described in the second section. These coupling terms are approximated by local measurements for use by each controller [12,13].In the third section, we start by applying the SMC to show the chattering effect due to the discontinuous parts of the controller's laws. The fuzzy logic control method has been applied to the excitation signals to make them smoother.

2. Mathematical Power System Model

The mathematical formulation of a power system with n-generating units interconnected has been developed in this section. The final model of the system decomposed by the mechanical part and the electrical part of the ith synchronous machine and which given by the following equations [1,2],[12-16],[20] :

2.1 Mechanical equations:

$$\begin{cases} \dfrac{d\delta_i}{dt} = \omega_i - \omega_0 \\ \dfrac{d\omega_i}{dt} = \dfrac{\omega_0}{2H}(P_{mi} - P_{ei}) - \dfrac{D_i}{2H}(\omega_i - \omega_0) \end{cases} \tag{1}$$

2.2 Generator Electrical equation:

$$\frac{dE'_{qi}}{dt} = \frac{1}{T_{doi}}\left(E_{fdi} - E'_{qi} + \left(x_{di} - x'_{di}\right)I_{di}\right) \tag{2}$$

2.3 Electrical equations:

$$P_{ei} = E'_{qi} I_{qi} + \Delta xd_i \cdot I_{qi} I_{di} \tag{3}$$

$$V_{di} = x_{qi} I_{qi} \tag{4}$$

$$V_{qi} = E'_{qi} - x'_{di} I_{di} \tag{5}$$

$$V_{ti} = \sqrt{\left(V_{di}^2 + V_{qi}^2\right)} \tag{6}$$

$$\begin{aligned} I_{di} &= \sum_{j=1}^{n} E'_{qi}(B_{ij} \cdot sin(\delta_{ij}) - G_{ij} \cdot cos(\delta_{ij})) \\ I_{qi} &= \sum_{j=1}^{n} E'_{qi}(B_{ij} \cdot cos(\delta_{ij}) + G_{ij} \cdot sin(\delta_{ij})) \end{aligned} \tag{7}$$

Where

I_d , I_q : d and q axis stator circuit currents

E'_d ,E'_q : d and q components of transient EMF

V_d ,V_q : d and q components of the terminal voltage

V_t : Terminal voltage

ω, ω_0 : Rotor speed and rated rotor speed of the generator

δ, δ_{ref} : Machine angle and the reference machine angle

x_d , x_q : d and q axis synchronous reactance

$x_d{}', x_q{}'$: d and q axis transient reactance

r : Armature resistance

H : Inertia constant

D : Damping constant

E_{fd} : Exciter voltage

P_m : Mechanical power

P_e : Electrical power

3. Nonlinear Feedback linearization

This section presents the linearization method witch transforms the nonlinear system into an equivalent linear [12,13],[20]. The decentralized of the controllers ensured by the consideration of the interconnected terms as disturbances of each machine. The first step is to transform the nonlinear multi-machine power system into a linear system controllable.

The system studied in this paper is composed of three nonlinear synchronous generators, each machine considered as a subsystem and it is given by the following equations [12-13],[20]:

$$\begin{cases} \dot{x}_{1i} = x_{2i} \\ \dot{x}_{2i} = \dfrac{\omega_0}{2H_i}\left(P_{mi} - P_{ei}\right) - \dfrac{D_i}{2H_i}\left(\omega_i - \omega_0\right) \\ \dot{x}_{3i} = \dfrac{1}{T'_{doi}}\left(E_{fd_i} - x_{3i} - \Delta x d_{1i} I_{d1i}\right) \end{cases} \quad (8)$$

When

$x_i = [x_{1i} \;\; x_{2i} \;\; x_{3i}]^T = \left[\delta_i \; \omega_i \; E'_{qi}\right]^T$: The state vector for synchronous machine i.

Where $i = 1,2,3$

3.1. Relative degree

A dynamic system given by the following form:

$$\dot{x} = g(t,x) + b(t,x)u \quad , \quad y = h(t,x) \quad (9)$$

Where

$x \in R^n, u \in R$: control law

y : output

g, b and y are smooth functions.

Where the output variable coincides with the surface of the SMC:

$$s^{(r)} = g(t,x) + b(t,x)u \; , \; \frac{\partial s^{(r)}}{\partial u} = b \neq 0 \quad (10)$$

Where r is the relative degree given by the conditions

$$L_f h = L^2{}_f h = \ldots = L_f^{r-2} h = 0 \; , \; L_g L_f^{r-1} h \neq 0$$

We choose the rotor angle as output for calculate the relative degree and we pose:

$$h_i = x_{1i} - xd_{1i} = \delta_{1i} - \delta d_{1i}$$

The first derivatives of h_i are given by [12-14],[21]:

$$\frac{dh_i}{dt} = \frac{dx_{1i}}{dt} = x_{2i}$$

$$\frac{d^2 h_i}{d^2 t} = \frac{\omega_0}{2H_i}\frac{d}{dt}\left(P_{mi} - P_{ei}\right)$$

$$\frac{d^3 h_i}{d^3 t} = -\frac{\omega_0}{2H_i}\left[\frac{1}{T'_{d0i}}\left(E_{fdi} - x_{3i} - \Delta x_{di} I_{di}\right) I_{qi} + x_{3i} \cdot \dot{I}_{qi}\right] + \frac{\Delta x_{di} \cdot \omega_0}{2H_i}\left(\dot{I}_{qi} \cdot I_{di} + I_{qi} \cdot \dot{I}_{di}\right) \quad (11)$$

The relative degree obtained $(r = n = 3)$, where the subsystem exactly linearized.

3.2. Canonical form

The nonlinear transformation calculated given by:

$$\begin{aligned} Z_{1i} &= h_{1i}(x) \\ Z_{2i} &= L_f h_{1i}(x) = x_{2i} \\ Z_{3i} &= L_f^2 h_{1i}(x) = \frac{\omega_0}{2H_i}\left(P_{mi} - x_{3i} I_{qi}\right) - \frac{D_i}{2H_i}\left(\omega_i - \omega_0\right) \end{aligned} \quad (12)$$

$Z_i = [Z1_i \; , Z_{2i} \; , Z_{3i}]$: The new state variable vector.

The system canonical form with new variables stats given by the following stats equations:

$$\begin{bmatrix} \dot{Z}_{1i} \\ \dot{Z}_{2i} \\ \dot{Z}_{3i} \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{bmatrix} \cdot \begin{bmatrix} Z_{1i} \\ Z_{2i} \\ Z_{3i} \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} v_{1i} + \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} w_i \quad (13)$$

3.3. Linearization control law

The linearized and decoupled control law given by:

$$E_{fd_i} = -\frac{1}{L_g L_f^2 h_{i1}(x)}\left[-L_f^3 h_{1i}(x) - wi + v_i\right] \quad (14)$$

Where

$$L_g L_f^2 h_{i1}(x) = \frac{2H_i T'_{d0i}}{\omega_0 I_{qi}} \quad (15)$$

The virtual control vi as defined by:

$$v_i = \alpha_i + \beta_i E_{fdi} \quad (16)$$

Where

$$\alpha_i = \frac{\omega_0}{2HT'_{d0i}} E'_q I_{qi} \text{ and } \beta_i = \frac{-\omega_0}{2HT'_{d0i}} I_{qi}$$

The interconnected terms w_i given by :

$$w_i = \frac{\omega_0}{2H}\left[x_{3i} \cdot \dot{I}_{qi} + \Delta x_{di}\left(\dot{I}_{qi} \cdot I_{di} + \dot{I}_{di} \cdot I_{qi} \right)\right] \quad (17)$$

In this work, a decentralized controller achieved by by supposing w_i as disturbances.

The following variables:

I_{qi} and E'_q obtained through a local measurements and $\dot{I}_{qi}$ and $\dot{I}_{di}$ obtained by Euler approximation approach.

4. Sliding Mode Control Design

The sliding mode control objective consists of calculating the equivalent control and a switching control law [7-8],[13],[22-23].

Consider the linearized system presented in equation (13):

$$\dot{Z}_i = A_i.Z_i + B_i.V_i + B_{pi} w_i \quad (18)$$

$$Y_{1i} = C_i Z_{1i}$$

A pole placement approach used in order to calculate a state feedback controller.

We propose the following sliding surfaces:

$$S_i(z) = \begin{bmatrix} K_{1i} & K_{2i} & K_{3i} \end{bmatrix} \cdot \begin{bmatrix} Z_{1i} \\ Z_{2i} \\ Z_{3i} \end{bmatrix} + K_{1i} W_i = 0 \quad (19)$$

4.1. Equivalent control

The first step for determining the equivalent control V_{eqi} is:

-Selecting sliding surface $\dot{S}_i(Z) = 0$

Where V_{eqi} calculated by:

$$\dot{S}_i = 0 \quad \Leftrightarrow \quad K_i \dot{Z}_i + K_{1i} \dot{Z}_{di} = 0 \quad (20)$$

$$\Rightarrow V_{eqi} = -[K_i B_i]^{-1} K_i A_i Z_i - [K_i B_i]^{-1} K_i B_p Z_{di}$$

$$\Rightarrow V_{eqi} = \text{-(k1/k3)}.Z_{2i} \text{ - (k2/k3)}.Z_{3i} \quad (21)$$

4.2. States feedback vector

Replace V_{eqi} in equation (18)

$$\dot{Z}_{eqi} = \left[A_i - B_i[K_i B_i]^{-1} K_i A_i\right] Z_i + \left[I - B_i[K_i B_i]^{-1} K_i\right] B_p w_i \quad (22)$$

$$A_{eqi} = \left[A_i - B_i[K_i B_i]^{-1} K_i A_i\right] \quad (23)$$

Where

A_{eqi} : a dynamic matrix

$$A_{eq} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & -K_{1i}/K_{3i} & -K_{2i}/K_{3i} \end{bmatrix} \quad (24)$$

The characteristic polynomial equation given by:

$$P_i(\lambda) = \lambda_i\left[\lambda_i^2 + (K_{2i}/K_{3i})\lambda_i + K_{1i}/K_{3i}\right] \quad (25)$$

The gains are determined as follows:

$$K_{3i} = Cont$$
$$K_{1i} = 2\rho_i^2 K_{3i}$$
$$K_{2i} = 2\rho_i K_{3i}$$

So, finally the feedback vector Ki is given by [13]:

$$K_i = \left[2.\rho_i^2 Cont \;\; 2.\rho Cont \;\; Cont\right] \quad (26)$$

The switching controls terms Vci are given by the following equation:

$$V_{ci} = -g_i \, sign(s_i) \quad (27)$$

Where

g_i : positive constants.

Consider the intermediate control signal given by:

$$v_i(Z) = Veqi - g_i sign(s_i) \quad (28)$$

Now the excitations controllers' laws applying in the multi-machine power system are given by:

$$E_{fd_i} = -\frac{1}{L_g L_f^2 h_{i1}(x)}[-L_f^3 h_{1i}(x) - wi + (V_{eqi} - g_i sign(s_i))] \quad (29)$$

5. Design Decentralized Hybrid Fuzzy-Sliding mode Controller

In this part, we propose a new robust 'hybrid' control scheme that we will apply to the multi-machine power system in question. It is a question of using a fuzzy supervisor allowing the gradual switching between two control laws: the first by sliding mode which acts essentially during the transient state, and the second by fuzzy logic activating during the steady state. The use of this hybrid control scheme not only preserves the robustness guaranteed by the sliding modes, but also the reduction or cancellation of the 'Chattering' phenomenon [4-6], [16], [24].

The basic configuration presentation of the fuzzy logic systems rules [4-6]:

$$R(l): IF.x_1\ is.F_1^l and...and.x_n\ is.F_n^l.THEN.y.is.G^l \quad (30)$$

Lets i=1, 2,...,n indicates the number of input for fuzzy logic system.

Where l=1,2,…,M indicates the fuzzy IF-THEN rules number. The fuzzy system output value based on the singleton fuzzification and with a centre average defuzzification given by [1-3]:

$$y(\underline{x}) = \frac{\sum_{l=1}^{M}\theta_l\left(\prod_{i=1}^{n}\mu_{F_i^l}(x_i)\right)}{\sum_{l=1}^{M}\left(\prod_{i=1}^{n}\mu_{F_i^l}(x_i)\right)} \quad (31)$$

Where

$\mu_{F_i^l}(x_i)$: the membership function value of x_i in F_i^l.

θ_l : the gravity centre of the membership function of the output to the lth rule, equation (31) can be rewritten as:

$$y(\underline{x}) = \sum_{l=1}^{M}\theta_l\xi_l(\underline{x}) = \underline{\theta}^T\underline{\xi}(\underline{x}) \quad (32)$$

Where

$\underline{\theta}_l = [\underline{\theta}_1...\underline{\theta}_M]^T$ and $\underline{\xi}(\underline{x}) = [\xi_1(\underline{x})...\xi_M(\underline{x})]^T$ the fuzzy basis functions defined as [13]:

$$\xi_l(\underline{x}) = \frac{\prod_{i=1}^{n}\mu_{F_i^l}(x_i)}{\sum_{l=1}^{M}\left(\prod_{i=1}^{n}\mu_{F_i^l}(x_i)\right)} \quad (33)$$

5.1. Proposed structure of controller

The controller signal (28) results a high frequency switching in its outputs, this problem known as a chattering phenomenon. The most solution to reduce or eliminate this chattering is to combine the SMC by other controllers, such as a fuzzy logic control [4-6].

One of the most important points for the design of FSMC is the determination of the number of fuzzy subsets for the input/output of the controller, as well as the form of the corresponding membership functions. Here, the ufuzzy input/output variables are chosen respectively by the sliding surface and by 5 linguistic labels. A fuzzy variables membership functions chosen to be fully overlapped, triangular and symmetric. However, it has been noticed that, for the switching term, a triangular and symmetric rule table is very appropriate to this problem and very simple [16],[24-25].

The proposed structure based on the fact that the chattering term Vc replaced by fuzzy rule. The fuzzy controller design begins with extending the crisp sliding surface S = 0 to the fuzzy sliding surface and defined by the following linguistic expression [1-3]:

$$\tilde{S}\ is\ Zero$$

Where

$\tilde{S}$: the sliding surface (S) linguistic variable

The fuzzy sets introduced by:

$$(\tilde{S}) = \{NB, NM, ZR, PM, PB\} = \{Fs^1,\ldots, Fs^5\} \quad (34)$$

where

$T(\tilde{S})$: the term set of $\tilde{S}$.

The terms set fuzzy control output ufuzzy defined similarly by:

$$T(\tilde{u}_c) = \{NB, NM, ZR, PM, PB\} = \{Fu^1,\ldots,Fu^5\} \quad (35)$$

The design fuzzy controller sets by The membership functions presented in Fig. 1 and in Fig.2.

Where Φ is the switch surface boundary layer

To normalize the switching surfaces Φ= [-1,1], we devised all surfaces sliding its maximum.

$$\tilde{S}_1 = S_1/400 \\ \tilde{S}_2 = S_2/80 \\ \tilde{S}_3 = S_3/80 \quad (36)$$

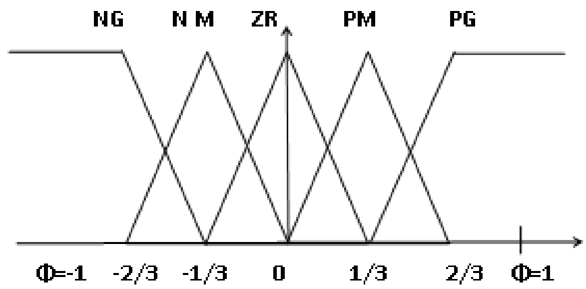

Fig. 1. Fuzzy partition of the universe of discourse of S

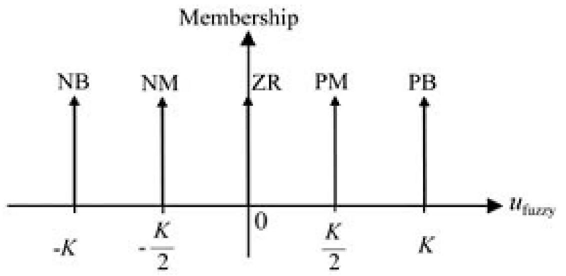

Fig. 2. Fuzzy partition of the universe of discourse of u_{fuzzy}

From these two term sets, we can build the following fuzzy rules [1-3]:

1 :If S is NB then *ufuzzy* is PB
2: If S is NM then *ufuzzy* is PM
3: If S is ZR then *ufuzzy* is ZR (37)
4: If S is PM then *ufuzzy* is NM
5: If S is PB then *ufuzzy* is NB

The defuzzification procedure allowing to determine a crisp control for the fuzzy, takes place last, after the membership functions and the fuzzy rules are determined. Several defuzzification strategies exist like the mean of maximum, the maximum criterion, the center of area, and the weighted average method [4.6]. Last method is used here to get the crisp control for fuzzy. Then

$$u_{\text{fuzzy}} = \frac{\sum_{i=1}^{5} C_{f_i}\ \mu_i(S)}{\sum_{i=1}^{5} \mu_i(S)} \quad (38)$$

Where

C_{fi} : the associated singleton membership function of *ufuzzy*. In which case the corresponding control law of the FSMC using the rules in form of Equation (37) becomes:

$$u_{fuzz} = -K_{fuzz}(|s|)sgn(s) \quad (39)$$

where $0 < K_{fuzz} < u_{max}$

Finally, the sliding fuzzy control law is given by:

$$v_i(z) = v_{eqi} + U_{Fuzzyi} \quad (40)$$

5.2. Fuzzy Sliding Mode Control Performance

The signals excitations Hybrid fuzzy sliding mode controllers' laws applying in the multi-machine power system are given by Eq. 29 cited in section 4.

6. Simulation Results for DSMC Control

In this part, the proposed DSMC technique is applied to the global interconnected system which has been linearized via the feedback linearization method. The design control is aiming to regulate the rotor angle and the terminal voltage of each synchronous generator in the system around them initials conditions. Robustness tests are carried out in order to demonstrate the proposed control method performances [12-13],[20].

The multi-machines power system study shown in Fig.3, is decomposed of three synchronous generators connected with infinit bus.

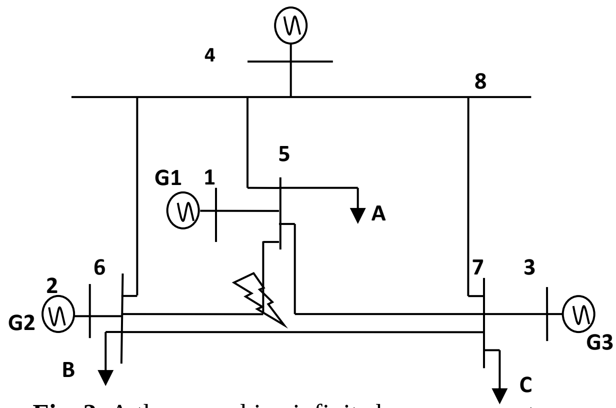

Fig. 3. A three machine infinite bus power system

Figures 4-7 below, show the simulation results of the application of decentralized sliding mode control on a multi-machine power system with the tracking and robustness test against an extreme three-phases short-circuit occurring at t=0.1 s with a duration of 0.05 s. The desired outputs of the internal angles chosen around the operating point of each generator. Our goal is to control the internal angles and stabilize the terminal tensions near 1(pu).

The reference angles, the nominal parameters for initial conditions are specified in [5] and all parameters of the controls laws are set in Appendix.

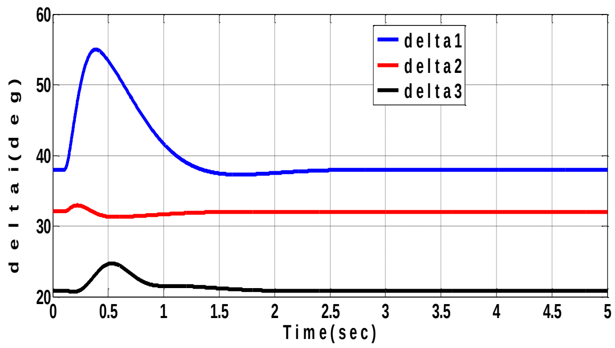

Fig. 4. Controlled Machine Angle under fault with DSMC

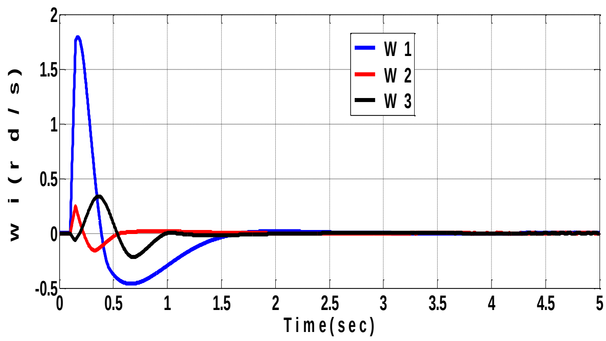

Fig. 5. Speed deviation response of under fault with DSMC

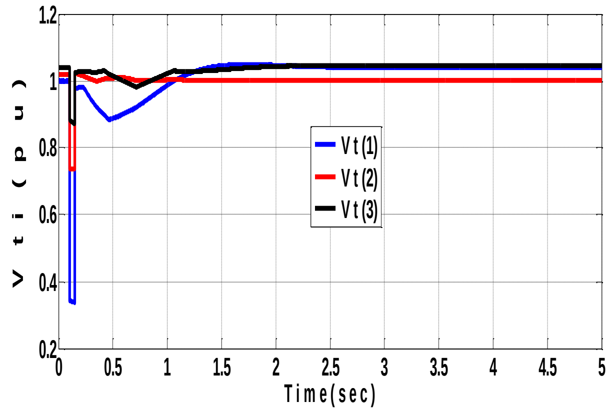

Fig. 6. Terminals voltages responses under fault with DSMC

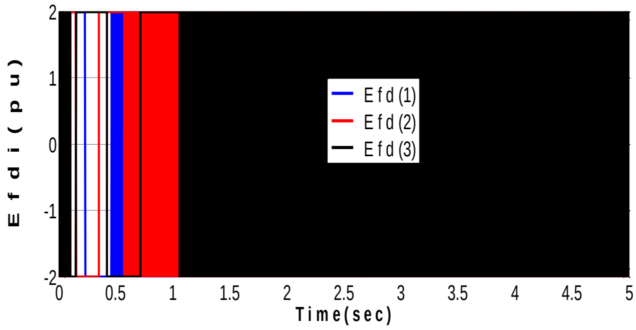

Fig. 7. Excitations voltages field responses with DSMC

From these results, we can notice that the decentralized control by sliding mode has a very good attenuation of damping of the oscillations at the time of the application of three-phase short-circuit, which confirms the robustness of the control against this type of disturbance, as well as the regulation of the internal angles and terminal voltages around 1 (pu). And the synchronism is restored at t=2.5 s.

As expected, the Chattering phenomenon is clearly observed in the Efdi excitation signals. This is due to the presence of the discontinuous sign function in the global control law. To remedy this problem, we will then apply a hybrid fuzzy-sliding contril.

7. Simulation Results for DHFSMC Control

In order to justify and show the robustness of the proposed fuzzy-sliding controller. The system is subjected to the same robustness tests presented in the previous control part (DSMC). Figures (8-12) below gives the simulation results of the dynamics of the system controlled by the hybrid fuzzy sliding control.

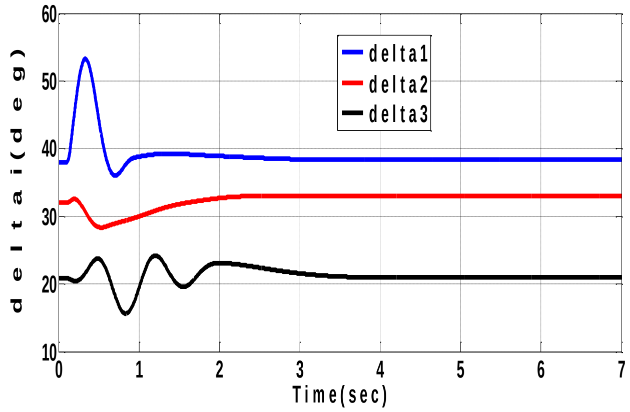

Fig. 8. Machine angle evolution under fault with DHFSMC

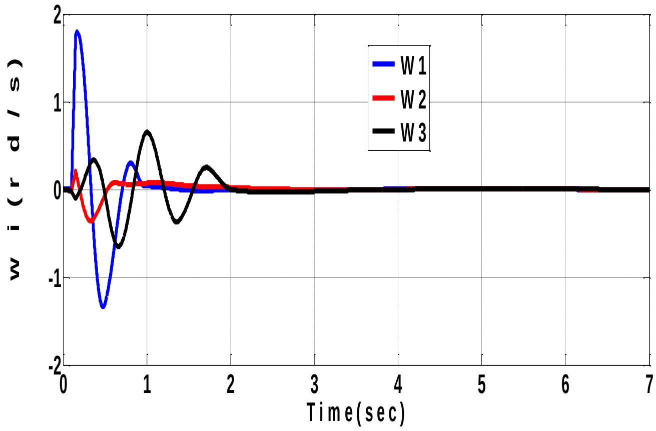

Fig. 9. Speed deviation evolution under fault with DHFSMC

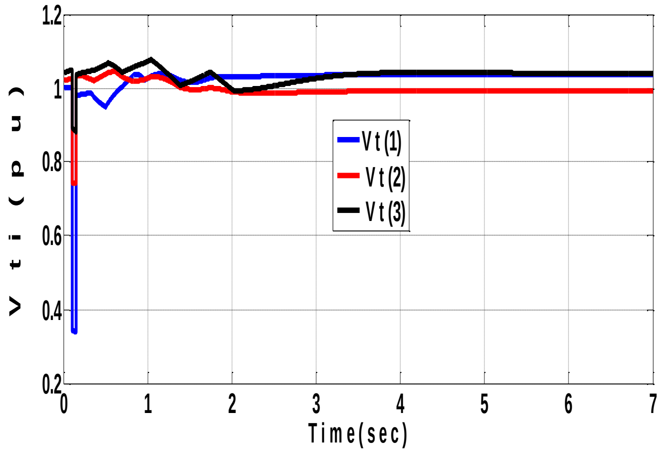

Fig. 10. Terminal voltage evolution under fault with DHFSMC

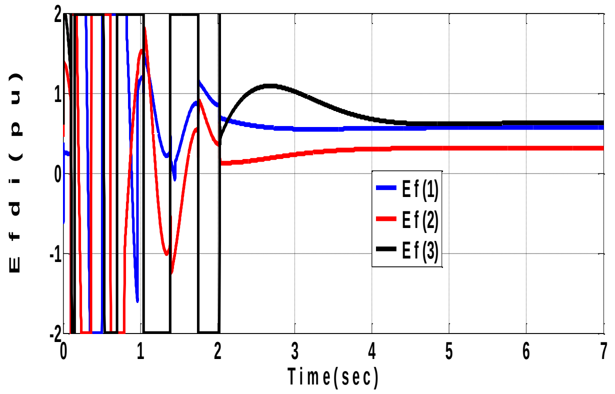

Fig. 11. Excitation voltage field responses with DHFSMC

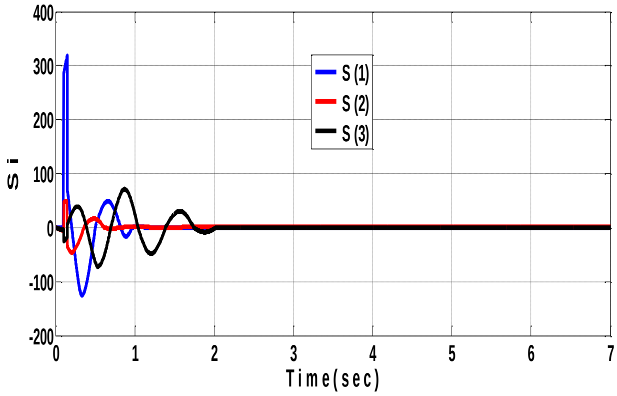

Fig. 12. Switching surfaces dynamics

In terms of regulation, we notice that the internal angles of the generators in Fig.8 correctly follow their references. The excitation commands, applied to the generators, are illustrated in Fig.11, It can be seen that the Chattering phenomenon is practically removed in the excitation voltage field responses signals. The controllers are physically acceptable.

To better understand the difference between the two controllers used, we have compared the dynamics of the system controlled by these two techniques DSMC and DHFSMC.

Figure 13, presents the result of comparison of the responses of the internal angles of the two commands DSMC and DHFSMC.

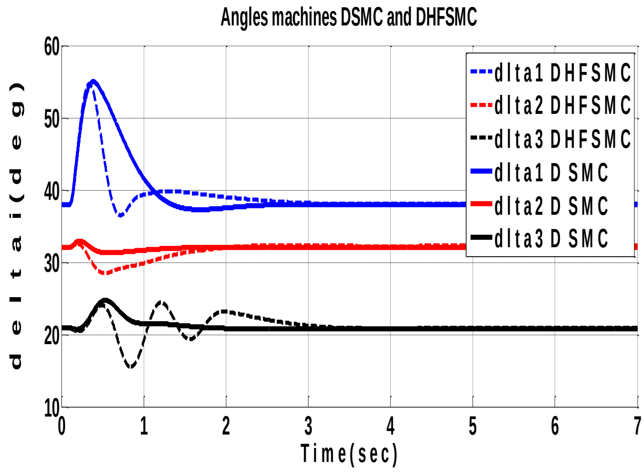

Fig. 13. Machines angles evolution under fault of two controllers DSMC and DHFSMC

According to the result of Fig.13, it can be concluded that the two decentralized controls of the sliding mode and the fuzzy logic present a very good attenuation of damping of the oscillations during the application of the three-phase short-circuit, which confirms our choice of the hybrid command. Both controls are robust against strong disturbances. But the difference between them is in synchronism time, for DSMC synchronism time is restored at t=2.5 s, while DHFSMC synchronism time is restored at t=4 s.

8. Conclusion

In this paper, two controllers were applied to a nonlinear multi-machine power system. Our goal is to improve the transient stability of power systems in order to regulate the internal angles machines and to stabilize the terminal voltage around a nominal value. The first controller was the DSMC, it can be directly employed to control the system. However, feedback linearization has been used in order to deal with nonlinearity and to decentralize the control law. The results showed that the direct decentralized sliding mode controller can ensure the complete stability below extreme situations (three phases short-circuit) and demonstrate here its very effectiveness. However, the main problem was the Chattering phenomenon. For this reason, the second controller applied, was the fuzzy sliding mode controller. The principal design is to replace the corrective term in the sliding mode controller law by a continuous fuzzy logic control. The simulation results showed that the Chattering problem was perfectly eliminated with guarantied the sliding mode control robustness.

Appendix A

The switching surfaces gains

$$\rho = 1.5$$

$$k_{13} = 8,\ k_{11} = 2.\rho^2.k_{13}\ \text{ and }\ k_{12} = 2.\rho.k_{13}$$

$$k_{23} = 10,\ k_{21} = 2.\rho^2.k_{23}\ \text{ and }\ k_{22} = 2.\rho.k_{23}$$

$$k_{33} = 12,\ k_{31} = 2.\rho^2.k_{33}\ \text{ and }\ k_{32} = 2.\rho.k_{33}$$

The correctives gains

Sliding mode case

$$g_1 = 50,\ g_2 = 50\ \text{ and }\ g_3 = 70$$

Fuzzy Sliding mode case:

Table 1. The rules bases parameters

S_i	NB	NM	NZ	PM	PB
u_{1fuzzy}	-9000	-4500	0	4500	9000
u_{2fuzzy}	-5000	-2500	0	2500	5000
u_{3fuzzy}	-5000	-2500	0	2500	5000

Appendix B:

The Excitation voltages boundary:

$$-2 \le E_{fdi} \le 2$$

The References rotor angles are around the initials conditions:

$$\delta_{1ref} = 37.92^o,\ \delta_{2ref} = 32^o\ \text{and}\ \delta_{3ref} = 20.8^o$$

Loads Parameters

A=0.4257-j2.038 p.u

B=0.1121-j1.176 p.u

C=0.4218-j1.475 p.u

Table 2. Parameters Machines [12-13]

Machine	$x_d(p.u)$	$x_d'(p.u)$	$T_{d0}'(p.u)$	$H\ (s)$	D
1	1.68	0.32	4.0	2.31	0
2	0.88	0.33	8.0	3.40	0
3	1.02	0.20	7.76	4.63	0

Table 3. Initials conditions machines [12-13]

Machine	δ (deg)	$P_m(p.u)$	$Ef(p.u)$	$Vt(p.u)$
1	37.93	0.8005	0.3770	0.9999
2	32.07	0.6863	0.4513	1.0200
3	20.88	0.5004	0.6077	1.0399

Admittances Matrix before fault

$$Bbd = \begin{bmatrix} 0.1827 & 0.0281 & 0.0193 & -0.1161 \\ 0.0281 & 0.1462 & 0.0386 & -0.1161 \\ 0.0193 & 0.0386 & 0.2633 & -0.1382 \end{bmatrix}$$

$$Gbd = \begin{bmatrix} -1.5941 & 0.3818 & 0.5030 & 1.1017 \\ 0.3818 & -1.8560 & 0.5227 & 1.3949 \\ 0.5030 & 0.5227 & -2.0235 & 1.5809 \end{bmatrix}$$

Admittances Matrix during fault

$$Bdd = \begin{bmatrix} 0.1023 & 0.0017 & 0.0115 & -0.0245 \\ 0.0017 & 0.1382 & 0.0381 & -0.0564 \\ 0.0017 & 0.1382 & 0.0381 & -0.0564 \end{bmatrix}$$

$$Gdd = \begin{bmatrix} -2.4492 & 0.0227 & 0.1688 & 0.3384 \\ 0.0227 & -2.0067 & 0.3826 & 1.0757 \\ 0.1688 & 0.3826 & -2.1535 & 1.2871 \end{bmatrix}$$

Admittances Matrix after fault

$$Bad = \begin{bmatrix} 0.2137 & 0.0017 & 0.0129 & -0.1134 \\ 0.0017 & 0.1682 & 0.0434 & -0.1022 \\ 0.0129 & 0.0434 & 0.2637 & -0.1367 \end{bmatrix}$$

$$Gad = \begin{bmatrix} -1.1909 & 0.0875 & 0.4899 & 0.9830 \\ 0.0875 & -1.6413 & 0.5322 & 1.4816 \\ 0.4899 & 0.5322 & -2.0232 & 1.5849 \end{bmatrix}$$

References

[1] P. M. Anderson, A. A. fouad, Power System Control And Stability, the IOWA state university press, Ames, IOWA.1977.

[2] L.Qiang, S.Yuanzhang, M. Shengwei, Nonlinear Control Systems and Power System Dynamics, Kluwer Acadimic Publishers, USA, 2001.

[3] M. Mokhlis, M. Ferfra, K. Chennoufi, "Experimental Test Bench of Photovoltaic Panel Under Partial Shading Effect Using the SLG-Backstepping technique",

International Journal of Renewable Energy Research (IJRER), Vol. 11, N°.2, pp. 585–594, 2021,

https://dorl.net/dor/20.1001.1.13090127.2021.11.2.9.8.

[4] **A. Belkaid**, I. Colak, K. Kayisli, R. Bayindir *« Improving PV System Performance using High Efficiency Fuzzy Logic Control», pp: 152-156,* 8th International Conference on Smart Grids, Paris/France, 17-19 June 2020. **DOI:** 10.1109/icSmartGrid49881.2020.9144817.

[5] S. Bououden, M. Chadli, H. R. Karimi, "Fuzzy Sliding Mode Controller Design Using Takagi-Sugeno Modelled Nonlinear Systems", Mathematical Problems in Engineering, DOI:10.1155/2013/734094, Vol. 2013, Article ID 734094, 7 pages, 2013.

[6] E.H. Mamdani, "Application of Fuzzy Algorithms for Control of a Simple Dynamic Plant", Proc. of the IEEE Control and Science, pp. 1585-1588, 1974.

[7] V. I. Utkin, Sliding Modes in Control and Optimization, Vol. 116. Berlin: Springer-Verlag, 1992.

[8] V. I .Utkin, "Variable Structure System With Sliding Mode", IEEE Transaction on Automatic Control,Vol.22, iss.2, pp212–221,1977.

[9] U. Itkis, Control Systems of Variable Structure , Wiley, New York, 1976.

[10] Sinn-Cheng Lin, Yung-Yaw Chen, "Design of Adaptive Fuzzy Sliding Mode for Nonlinear System Control", Fuzzy Systems,. IEEE World Congress on Computational Intelligence, Proceedings of the Third IEEE Conference on Dept. of Electr. Eng., National Taiwan Univ, 1994.

[11] Shuanghe Yu, Xinghuo Yu and M. O. Efe, "Modeling-error based adaptive fuzzy sliding mode control for trajectory-tracking of nonlinear systems", IECON'03, 29th Annual Conference of the IEEE Industrial Electronics Society, DOI:: 10.1109/IECON.2003.1280726, Vol.3, pp. 3001-3006, 2003.

[12] S. Benahdouga, D. Boukhetala, F. boudjema, R. Khanfer, M. Meddad, "Decentralized Adaptive Sliding Mode Exciter Controller of Power Systems", International Review of Automatic Control, vol.5, N.6, pp. 790-797, November 2012.

[13] Seddik Benahdouga, Djamal Boukhetala, Farés Boudjema, "Decentralized high order sliding mode control of multimachine power systems", International Journal of Electrical Power & Energy Systems, DOI: 10.1016/j.ijepes.2012.06.018, Volume.43, Issue.1, pp. 1081-1086, 2012.

[14] J. W. Chapman, M. D. Ilic, C. A. King, L. Eng and H. Kaufman, "Stabilizing a multimachine power system via decentralized feedback linearizing excitation control", in IEEE Transactions on Power Systems, DOI: 10.1109/59.260921, vol. 8, no. 3, pp. 830-839, Aug. 1993.

[15] Zairong Xi, G. Feng, Daizhan Cheng and Qiang Lu, "Nonlinear decentralized saturated controller design for power systems", in IEEE Transactions on Control Systems Technology, DOI: 10.1109/TCST.2003.813404, Vol. 11, no. 4, pp. 539-547, July 2003.

[16] K. Ben Meziane, F. Dib, I. Boumhidi, "Fuzzy Sliding Mode Controller For Power System SMIB", Journal of Theoretical and Applied Information Technology, 20th August, Vol. 54 No.2, 2013.

[17] S.Benhadouga, A.Belkaid, I.Colak, M. Meddad and A. Eddiai, "Experimental Validation of The Sliding Mode Controller to Improve The Efficiency of The MPPT Solar System", 2021 10th International Conference on Renewable Energy Research and Application (ICRERA), doi:10.1109/ICRERA52334.2021.9598584, pp. 333-337, 2021.

[18] Benhadouga, S., Meddad, M., Eddiai, A. et al. "Sliding Mode Control for MPPT of a Thermogenerator", Journal of Elec Materi, DOI: 10.1007/s11664-019-06997-y, Vol. 48, pp. 2103–2111, 2019.

[19] H. Benbouhenni, "Neuro-Second Order Sliding Mode Field Oriented Control for DFIG Based Wind Turbine", International Journal of SMART GRID, Vol. 02, No. 4, pp. 209-217, 2018.

[20] Lingling Fan, A. Feliachi and A. Davari, "Decentralized control of power systems using-disturbance accommodation techniques", Proceedings of the 2001 American Control Conference. DOI: 10.1109/ACC.2001.945813, pp. 799-804 vol.2, 2001.

[21] D. Cheng, T.J. Tarn, A. Isidori, "Global external linearization of nonlinear systems via feedback", IEEE Trans. Autom. Control AC, Vol. 30, iss.8, 1985.

[22] A.Isidori, Nonlinear Control Systems (3rd edn) , Springer: Berlin, 1995.

[23] J.J. E. Slotine et W. Li, Applied Nonlinear Control , Prentice Hall, N.J., 1991.

[24] Touil, S., Bekakra, Y. & Ben Attous, D. "Influence of Fuzzy Power System Stabilizer using Different Membership Functions for Single and Multi-machine", J Control Autom Electr Syst, DOI: 10.1007/s40313-021-00739-4, Vol. 32, pp.1269–1278 2021.

[25] A.Anilkumar and N. V. Srikanth, "Teaching-Learning Optimization Based Adaptive Fuzzy Logic Controller for Frequency Control in an Autonomous Microgrid", International Journal of Renewable Energy Research (IJRER), Vol. 07, No. 4, pp. 1842-1849, 2017.