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On-line Fuzzy sliding mode controller for Hybrid Power System

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Abstract

This paper concerns the control design of Hybrid Power System(HPS). Dynamic equations describing the coupling of buck converters are derived and a robust fuzzy sliding mode dynamic controller is designed. The aim is to show that the proposed control leads to good results in terms of robustness and stability according to the fluctuations of renewable sources and the load variations, without the use of cascade structure commonly used in literatures. The proposed control method is stable, good behavior to external disturbances, and does not request to know the system parameters exactly. Simulation results show good dynamic performances in term of response time of the DC bus voltage and robustness according to the load and the input voltage variations.

Keywords: DC/DC converter, hybrid power system, energy conversion, fuzzy logic, renewable energy, sliding mode.

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1 Introduction

Electrical energy is an essential factor for the development of the human societies. The limited reserves of fuel oils and their unstable prices have significantly increased the interest in renewable energy sources (photovoltaic modules, wind turbine, etc). Combining renewable energy and conventional energy sources with a storage system, can reduce pollution and enhance energy security and reliability.

That's why the design of hybrid power systems has received considerable attention in the last decade [1].

As in any isolated multi-sources power system, the key issue is the balance of energy. For this aim power electronics are widely used to manage power hybrids systems according to the variation of the sources and the load [2].

An accurate model for the coupling of DC/DC power converters on a DC bus has been developed to take full advantage of renewable energy [21].

In comparison with the related works [3]-[9], the proposed model is useful to explain the physical phenomena relating to the coupling of the DC/DC power converters on the DC bus as well as the energy flow control provided by each source.

To perform the hybrid systems, a control strategy has to be design and implement to the system. The literature in the domain [10]-[12] is mainly concerned with the sizing, economics and power flow management of the system devices, while paying little attention to dynamic control aspects. However, the development of robust controller is necessary to ensure stability and robustness of a multi-sources renewable energy system. Particularly, the variable structure systems (VSS) theory [13], [14] can be extremely helpful in the study of the control of powers converters as DC/DC buck converters. The switched mode DC/DC converters are non-linear and it is not suitable to application of linear control theory.

A different approach, which complies with the non-linear nature of switch-mode power supplies, is proposed. In this context, the sliding mode control, which is derived from the variable structure systems (VSS) theory appears as a powerful control technique that offers several advantages: stability even for large supply and load variations, robustness, good dynamic response and simple implementation. Their capabilities emerge especially in application to high-order converters, yielding improved performances as compared to usual control techniques.

However, during the reaching phase, the controlled system uncertainties influence negatively on the performances (chattering problem). Numerous techniques have been proposed to eliminate this fact [8] [9], such that replacing the discontinues control by a saturating approximation [10], and integral sliding control [11].

Recently, Fuzzy SMC (FSMC) has also been used for this purpose. This combination (i.e., FSMC) provides the mechanism for designing robust controllers for nonlinear systems with uncertainty.

In this paper, in order to guarantee the robust behavior of the system (eliminate the chattering problem), fuzzy system is used for reaching phase.

This paper is organized as follows. Firstly, we will present the multisource renewable energy system. The second part presents the system configuration. The third part describes the model of several DC/DC power converters coupled on the DC bus. The last part is an application to the fuzzy sliding mode control to manage power of two renewable energy sources.

2 System Configuration

The HPS under consideration is shown in Figure 1. It consists of a Combustion Engine (CE), a renewable energy sources (RES: photovoltaic module and wind turbine), an Energy Storage System (ESS: Batteries and Ultracapacitors) and a variable load. All these elements are connected onto a DC bus through DC/DC power electronic converters.

The DC bus accumulates the generated energy and sends it to the variable load and, if necessary, to the energy storage system. In this configuration, renewable sources take over as main energy source.

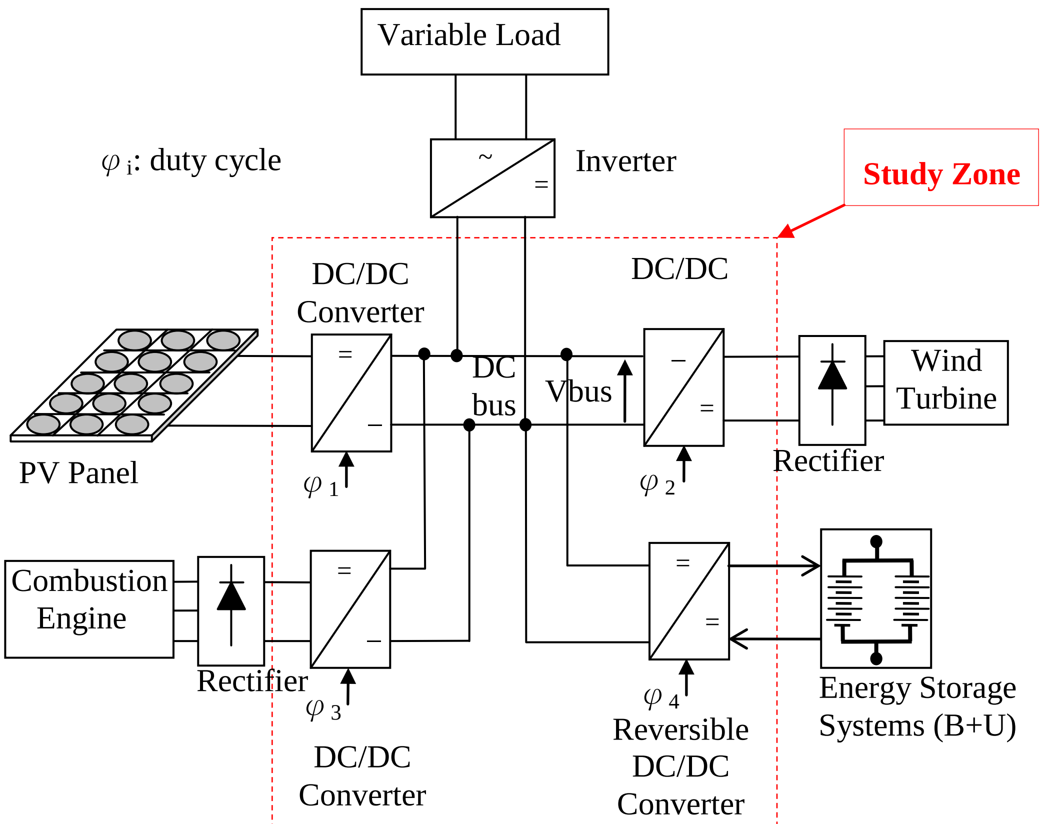

Figure 1: HPS Scheme

3 Hierarchical Controller for Hybrid Power System

Based on reviews of multisource power, the block diagram of the global control strategy is illustrated in Figure 2.

Two hierarchical levels are required to control and manage the *HPS*.

The high level is performed by the online supervisor unit. This unit uses the data about the load, the meteorological conditions and the charge state of energy storage system (*ESS*) and combustion engine (*CE*), to correctly and efficiently share the load demand according to the availability of conventional and renewable energy, in other words, to decide whether to charge or discharge the *ESS*, to turn on or off the *CE*, to reduce the renewable sources power production or not, and so forth. Such control level is designed by applying on-line Takagi-Sugeno fuzzy logic principles [25].

The low level is performed by a local control unit (*DC/DC* converters controller) of the different power sources. This level manipulates the duty cycle converter according to the variation of the sources and the load.

In this paper, emphases are put on the Low level controller. In my previous works [25], the sliding mode controller is applied to *DC/DC* converters. In order to improve the robustness and performance under the uncertainty of this controller, we apply in this section a fuzzy sliding mode approach.

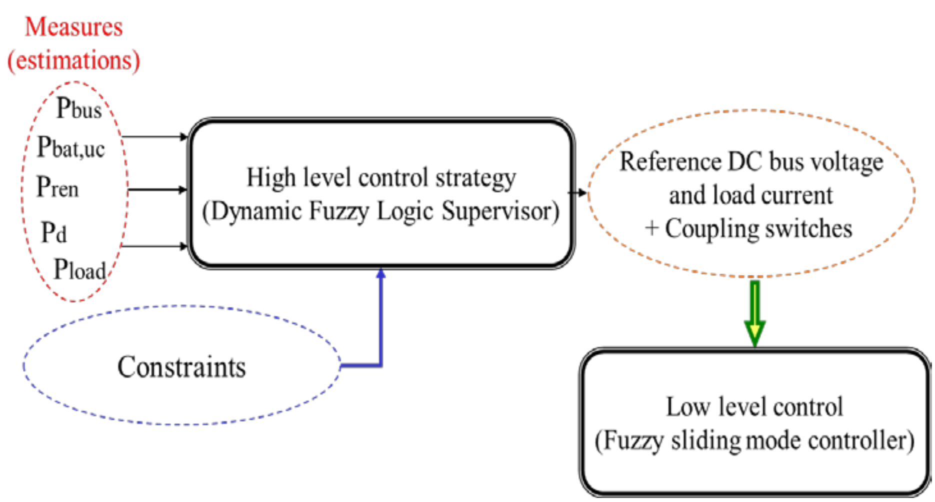

Figure 2: Block diagram of hierarchical controller for HES

3.1 Modeling of DC/DC Converters

The *DC/DC* converters are basic constituents of the multisource system. The aim of these converters is to regulate the *DC* component of the output voltage to its reference by controlling the current provided by each source in spite of the voltage variations on their inputs.

The *ZVS* full bridge isolated *DC/DC* converter [15], [16], [17], studied in this paper, is represented on Figure 3.

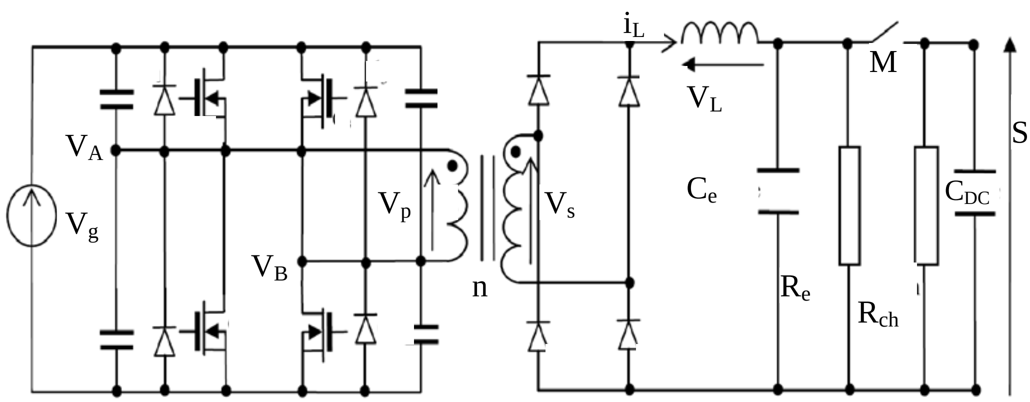

Figure 3: Structural diagram of the ZVS full bridge isolated buck converter

It supposed that it runs in a continuous conduction mode. The full bridge control (*Q1* to *Q4*) is realized by a phase shift controller UC3879. The duty cycle value φ is modified by the phase shift between *VA* and *VB* voltages.

Four basic structures of operation may be distinguished.

Phase 1: (Q1Q4) On and (Q2Q3) Off. **Phase 2:** (Q1d3) On.

Phase 3: (Q2Q3) On and (Q1Q4) Off. **Phase 4**: (Q2d4) On.

The structural diagram corresponding to the operation phases 1 and 3 is depicted in Figure 4 and the one corresponding to the operation phases 2 and 4 is represented on Figure 5. r_p and r_s are respectively, the transformer primary and secondary resistances. L_M is the transformer magnetizing inductance. C_{DC} is the *DC* bus capacity and the load R_{ch} is supposed resistive.

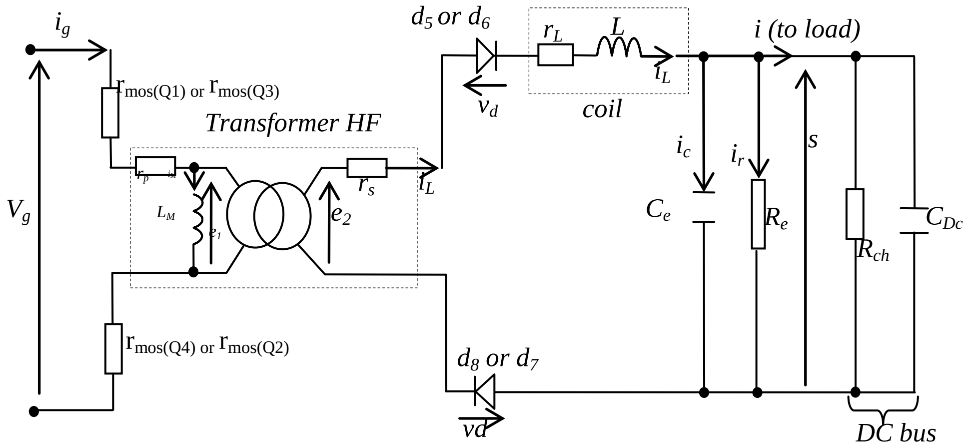

Figure 4: Phases 1 and 3

The voltage source (V_g) is disconnected during phases 2 and 4 which correspond to the transformer demagnetization (Figure 5), so $i_g=0$.
Each phase leads to a following state space model:

$$\dot{x} = A_i x + B_i u \tag{1}$$

where $x = \begin{bmatrix} i_M & i_L & V_{\text{bus}} \end{bmatrix}^T$ is the state vector, and $u = \begin{bmatrix} V_g & V_{\text{d}} \end{bmatrix}^T$ is the control vector. $i_{M,}$ $i_{L,}$ V_{bus}, V_g and V_d respectively represent the transformer magnetizing current, the inductance current, the DC/DC power converters output voltage, the source and the diode voltage. It is assumed that diodes are not ideal.

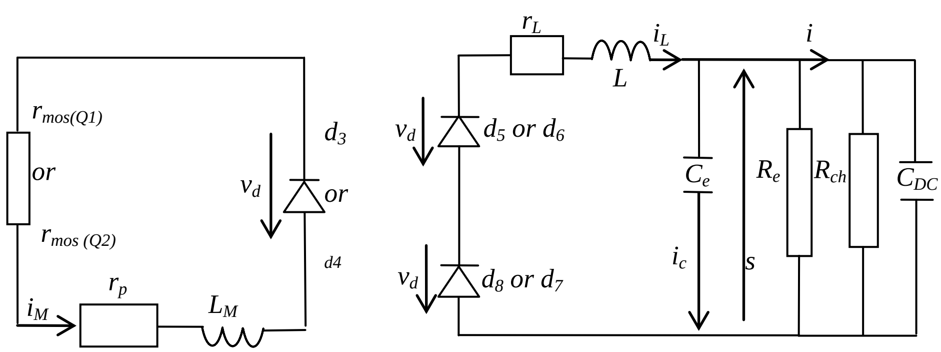

Figure 5: Phases 2 and 4

$$A_1 = \begin{bmatrix} \dfrac{-(2R_{mos}+r_p)}{L_M} & \dfrac{-n\,(2R_{mos}+r_p)}{L_M} & 0 \\ \dfrac{-n\,(2R_{mos}+r_p)}{L} & \dfrac{-n^2\,(2R_{mos}+r_p)-(r_s+r_L)}{L} & \dfrac{-1}{L} \\ 0 & \dfrac{1}{C_{eq}} & -\dfrac{1}{R_{eq}C_{eq}} \end{bmatrix}$$

$$B_1 = \begin{bmatrix} \dfrac{1}{L_M} & \dfrac{n}{L} & 0 \\ 0 & \dfrac{-2}{L} & 0 \end{bmatrix}^T$$

$$A_3 = \begin{bmatrix} \dfrac{-(2R_{mos}+r_p)}{L_M} & \dfrac{+n\,(2R_{mos}+r_p)}{L_M} & 0 \\ \dfrac{-n\,(2R_{mos}+r_p)}{L} & \dfrac{-n^2\,(2R_{mos}+r_p)-(r_s+r_L)}{L} & \dfrac{-1}{L} \\ 0 & \dfrac{1}{C_{eq}} & -\dfrac{1}{R_{eq}C_{eq}} \end{bmatrix},$$

$$B_3 = \begin{bmatrix} -\dfrac{1}{L_M} & \dfrac{n}{L} & 0 \\ 0 & \dfrac{-2}{L} & 0 \end{bmatrix}^T$$

$$A_{2/4} = \begin{bmatrix} \dfrac{-(R_{mos}+r_p)}{L_M} & 0 & 0 \\ 0 & \dfrac{-r_L}{L} & \dfrac{-1}{L} \\ 0 & \dfrac{1}{C_{eq}} & -\dfrac{1}{R_{eq}C_{eq}} \end{bmatrix}, \quad B_{2/4} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}^T$$

Combining the above phase states model, the average model of the DC/DC converter shown in Figure 3 can be derived as follows [18-20]:

$$\dot{x}(t) = f(x,u) + g(x,u)\varphi(t) \tag{2}$$

Where

$$f(x,u) = ax(t) + bu(t), \qquad g(x,u) = Ax(t) + Bu(t), \qquad A = \frac{1}{2}(A_1 - A_2 + A_3 - A_4),$$

$$a = \frac{1}{2}(A_2 + A_4),\ B = \frac{1}{2}(B_1 - B_2 + B_3 - B_4),\ b = \frac{1}{2}(B_2 + B_4).$$

3.2 Coupling of several DC/DC power converters on a DC bus

The average model of the buck converter developed above can be extended to the coupling of many renewable sources [21]. We suppose that the DC /DC power converters are identical. Thus, the partial structural diagram of the coupling of *m* DC/DC power converters is represented on Figure 6.

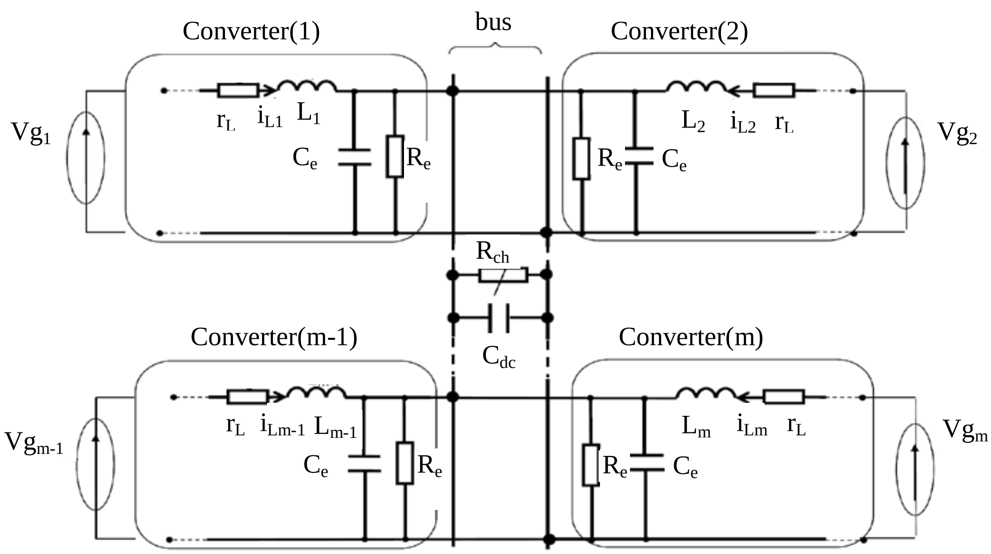

Figure 6: Structural diagram of the coupling of m DC/DC power converters

The multimodel for *m* DC/DC converters coupled on a DC bus is express as follow:

$$\dot{X}(t) = F(X,u) + G(X,u)\varphi(t) \tag{3}$$

Where

$$F(X,U) = [f_1(x_1,u_1),\dots f_m(x_m,u_m)]^T,\ \ G(X,U) = diag[g_1(x_1,u_1),\dots g_m(x_m,u_m)],$$

$$X = [x_1,\dots x_m]^T,\ \ U = [u_1,\dots u_m]^T,\ \ \varphi = [\varphi_1,\dots \varphi_m]^T.$$

The multimodel parameters (*F* and *G*) change according to the DC/DC power converters coupled on the DC bus.

For simplicity of presentation, in this subsection, only two coupling sources are considered ($m=2$).

3.3 Dynamic controller design for DC/DC converter

In this section, we design a sliding mode dynamic controller "SMDC" which regulates the voltage level on the DC bus by controlling the current provided by each source.

In various works in the literature, a cascade control structure with two control loops for DC/DC converters control is usually adopted [22], [23]. In this structure, an inner current loop regulates the buck inductor current, whereas an external control loop keeps a constant output voltage.

However, this structure has some drawbacks such as the value of reference current that may be poorly estimated because of quick variations of the load and the sources. The current estimation error introduces a bus voltage error compared to the reference one. This affects the controller performances in terms of robustness.

To overcome this issue, we adopt in this paper, a MIMO fuzzy sliding mode robust control device (Figure 7).

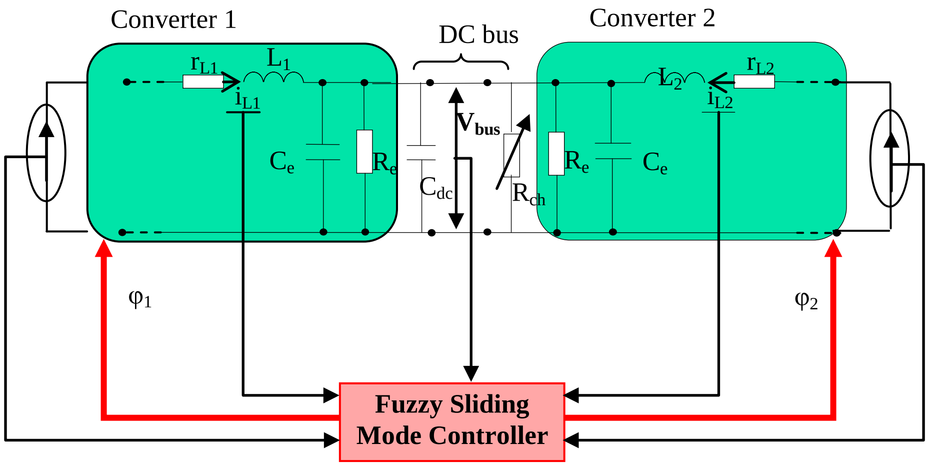

Figure 7: MIMO fuzzy sliding mode robust control scheme

The development of the sliding mode control scheme consists of two phases. The first is to design a sliding surface where the DC/DC converter exhibits desired properties. The second is to design a control law to drive and maintain the system on the sliding surface [22-23].

In order to act simultaneously on all state variables, let us define the following PI-type sliding surface

$$\delta_i(t) = e_i(t) + \alpha \int_0^t e_i(\tau)\, d\tau, \quad i = 1,2 \tag{4}$$

where:

$$e_i(t) = k_i\left(I_{Li} - I_{Li\_ref}\right) + k_3\left(V_{bus} - V_{bus\_ref}\right) \tag{5}$$

I_{Li_ref}, V_{bus_ref} are the references of inductor current and voltage DC bus. $k_{1,2,3}$ are the tracking weight factor error and $\alpha > 0$ is the sliding-surface integral parameter.

In the following, a bounded control input is designed to force $\delta_i(t)$ to converge to zero or make its absolute value smaller.

We obtain the equivalent control $\varphi_{eq1,2}$ by applying the invariance condition.

$$\delta_i(t) = \dot{\delta}_i(t) = 0, \quad \text{with} \quad \varphi_i(t) = \varphi_{eqi}(t), \quad i = 1,2\,.$$

From (4), the time derivative of $\delta_i(t)$ along system (3) is given as

$$\begin{aligned} \dot{\delta}_i &= k_i(A_{2-}x_i + B_{2-}u_i)\varphi_{eqi} + k_i\left(a_{2-}x_i + b_{2-}u_i - \dot{I}_{Li\_ref}\right) - \\ & k_3\left(A_{3-}x_i + B_{3-}u_i - \dot{V}_{bus-ref}\right) + \alpha e_i = 0 \end{aligned} \tag{6}$$

The notation A_{2-} refers to the second column of the A matrix.

Thus, the equivalent control-input is given as

$$\varphi_{eqi} = -R_i/H_i\,, \quad i = 1,2 \tag{7}$$

where

$$R_i = k_i\left(a_{2-}x_i + b_{2-}u_i - \dot{I}_{Li\_ref}\right) - k_3\left(A_{3-}x_i + B_{3-}u_i - \dot{S}_{ref}\right) + \alpha e_i \, (32)$$

$$H_i = k_i\left(A_{2-}x_i + B_{2-}u_i\right) \tag{8}$$

It is well known that the exact value of the external disturbance and the parameter variations of the system, such as internal resistance and magnetizing current, are difficult to measure in advance for practical applications. Therefore, I propose a non-linear switching control-input φ_{si} to estimate the upper bound of uncertainties and external disturbance.

$$\varphi_{si}(t) = -\frac{\gamma_i(t)}{H_i(t)}\, sign(\delta_i(t)) \tag{9}$$

In the presence of parameter uncertainties and external disturbances the dynamic equation (3) becomes

$$\dot{X}(t) = F(x) + G(x)\varphi + \Delta(t) \tag{10}$$

where Δ includes the uncertainties and perturbations.

In order to reduce chattering, the most common method is to replace the sign function by the saturation function $sat(\delta(t), \zeta)$ [26].

where

$$sat(\delta(t),\zeta)=\begin{cases} sign(\delta), & |\delta|>\zeta>0 \\ \dfrac{\delta}{\zeta}, & |\delta|\le\zeta \end{cases} \tag{11}$$

and ζ is a small positive constant.

Hence, the SMDC rule can be designed as

$$\varphi_i(t)=\varphi_{eqi}(t)-\frac{\gamma_i(t)}{H_i(t)}sat(\delta_i(t),\zeta) \tag{12}$$

In order to improve the robustness and performance under the uncertainty of the SMDC and to eliminate the chattering effect, we apply in this section a fuzzy logic approach.

The control law of the proposed adaptive robust fuzzy sliding-mode control is given as

$$\varphi_i(t)=\varphi_{eqi}(t)-\frac{\gamma_i(t)}{H_i(t)}f(\delta) \tag{13}$$

where δ is the sliding surface and $f(\delta)$ is a fuzzy switch system.

By using the singleton fuzzifier and center-average defuzzifier, the output of the fuzzy system is given as follows [26]:

$$f(\delta)=\frac{\sum_{j=1}^{5}b_i\phi_i(\delta)}{\sum_{j=1}^{5}\phi_i(\delta)}=\frac{\sum_{i=1}^{2}b_i\left(e^{-\frac{(\delta+a_i)^2}{\sigma^2}}-e^{-\frac{(\delta-a_i)^{2^2}}{\sigma^2}}\right)}{\sum_{j=1}^{5}\phi_i(\delta)} \tag{14}$$

where $\phi_i(\delta)$ (i = 1, . . . , 5) are the input Gaussian membership functions (Figure 9) and b_{ij} (i,j = 1, . . . , 5) are the center values of output membership functions defined as $b1=-b5$, $b2=-b4$ and $b3=0$ (Figure 10).

Gaussian center values are defined as: a1 = −a5, a2 = −a4, a3 = 0, and widths of the input membership function are defined as $\sigma_i=\sigma$.

The linguistic labels used to describe the fuzzy sets were {NB, NM, Z, PM, PB} negative big, negative medium, zero, positive medium and positive big, respectively.

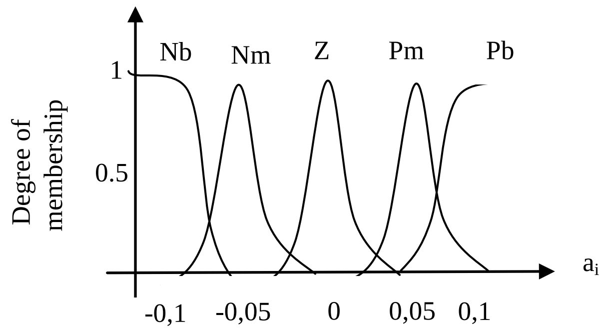

Figure 8: Input membership function for δ

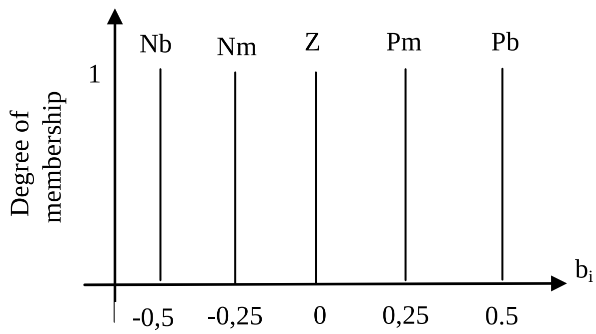

Figure 9: Output membership function

The fuzzy rules (Table 1) are designed in such a way that the stability of the system would be satisfied such as proven below.

Table 1: FSMDC rule base

	S				
	Pb	Pm	Z	Nm	Nb
$f(\delta)$	Nb	Nm	Z	Pm	Pb

The main theorem, stated and proved below, provides sufficient conditions to ensure the stability and robustness of the multi-sources system.

Theorem 3.1 *Let the nonlinear multi-sources system given by equation (10) and sliding surface given by equation (4), and suppose that the Lyapunov function is defined by*

$$V(t)=\frac{1}{2}\delta_1(t)^2+\frac{1}{2}\delta_2(t)^2 \tag{15}$$

Then, the sufficient stability condition for the FSMDC in the sense of Lyapunov should satisfy the following range of switching gains:

$$\gamma_i(t)\leq\frac{|\Delta(t)|}{f\left(\delta_i\right)},\quad i=1,2 \tag{16}$$

where $|\Delta|$ *represent the upper bound of the uncertainties and perturbations.*

Proof. If $V(t)$ is a Lyapunov function candidate defined as in (15), the asymptotic stability will be satisfied if $\dot{V}(t)\leq 0$, with

$$\dot{V}(t)=\delta_1(t)\dot{\delta}_1(t)+\delta_2(t)\dot{\delta}_2(t) \tag{17}$$

Using the equations (10) and (4) and substituting the control law equation (13) into the above equation becomes

$$\dot{V}(t)=\delta_1(t)\left(H_1\varphi_{eq1}+R_1-\gamma\ f(\delta_1)+\Delta\right)+\delta_2(t)\left(H_2\varphi_{eq2}+R_2-\gamma\ f(\delta_2)+\Delta\right)$$

From (6),

$$\dot{V}(t)=\delta_1(t)[-\gamma_1(t)f(\delta_1)+\Delta(t)]+\delta_2(t)[-\gamma_2(t)f(\delta_2)+\Delta(t)] \tag{18}$$

Notice that $ai<0$ for $i=1,2$

$$\text{if}\begin{cases}\delta<0, then\ f(\delta)>0\\ \delta=0, then\ f(\delta)=0\\ \delta>0, then\ f(\delta)<0\end{cases}$$

Therefore, it can be derived that $\delta_i f(\delta_i)\leq 0$, for $i=1,2$

Then

$$\dot{V}(t)\leq-\sum_{i=1}^{2}\delta_i(t)f(\delta_i(t))\left(\gamma_i-\frac{|\Delta(t)|}{f\left(\delta_i(t)\right)}\right)$$

As a conclusion, to satisfy the condition $\dot{V}(t) \leq 0$, and to compensate the bounded parametric uncertainties and disturbances, we must restrict to the sufficient condition (16).

4 Simulation Results

To illustrate the control design and performance evaluation of our structure, a hybrid power systems coupled to two sources through a similar buck converter is considered. The characteristics of the full bridge buck converters are:

Rmos=0.005*Ω*, *Rl*=2 *Ω*, *n*=12, *Vd*=0.3*v*, *L*=1e-3*H*, *Lm*=20e-6*H*, *rp*=0.05*Ω*, *rs*=0.05Ω, *Ce*=20e-6*F*, *Re*=56e3*Ω*, *CDC*=10e-6*F*.

The DC bus voltage reference is set at *100V*. Simulations are obtained with sampling interval $Te = 50\mu s$. We suppose that, 40 % of the load demands are supplied with the first source and 60 % with the second one.

Responses obtained with our algorithm are compared with ones resulting from the PI algorithm with cascade structure. The linearization techniques are applied to the converters in order to deduce linear parameters [24].

The simulation conditions are identical for both controllers.

To compare the global performances of our algorithm with PI one, let us consider the Mean Square Error (*NMSE*, Table 2), that is interpreted as the overall deviations between output plant and desired values, and is defined as:

$$NMSE = \sum_{l} \left(V_{bus} - V_{bus\_ref}\right)^2 \Big/ \sum_{l} \left(V_{bus\_ref}\right)^2 \qquad (19)$$

In order to test the capacity of FSMDC to reject disturbances, and to investigate the robustness of the control scheme, the load and sources dynamics of the hybrid system are supposed fast. The sources and load profiles are represented by the Figures 10 and 11.

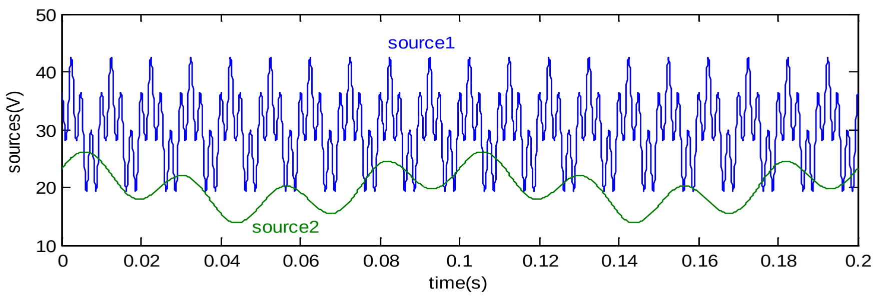

Figure 10: Sources profiles

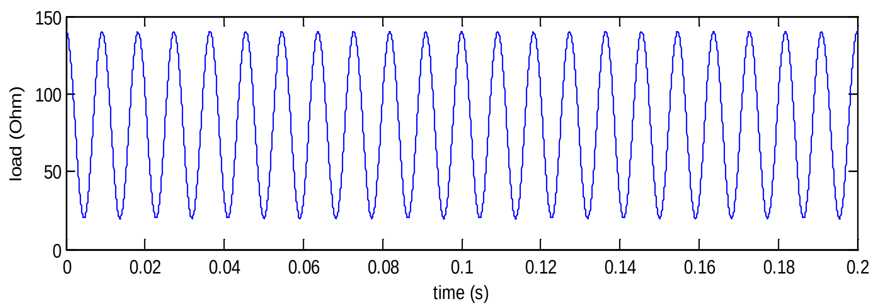

Figure 11: Load profiles

The closed-loop responses of load current DC bus voltage, tracking voltage error and load current obtaining with PI controller, sliding mode controller and fuzzy sliding mode controller are shown in Figures 12, 13 and 14 respectively.

Table 2: *NMSE*

PI	SMDC	FSMDC
1.2483	0.0075	2.3e-4

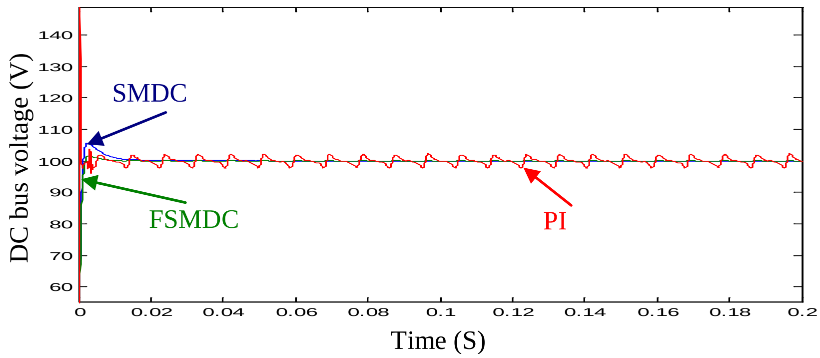

Figure 12: DC bus voltage plot obtained with PI controller, sliding mode controller and fuzzy sliding mode controller

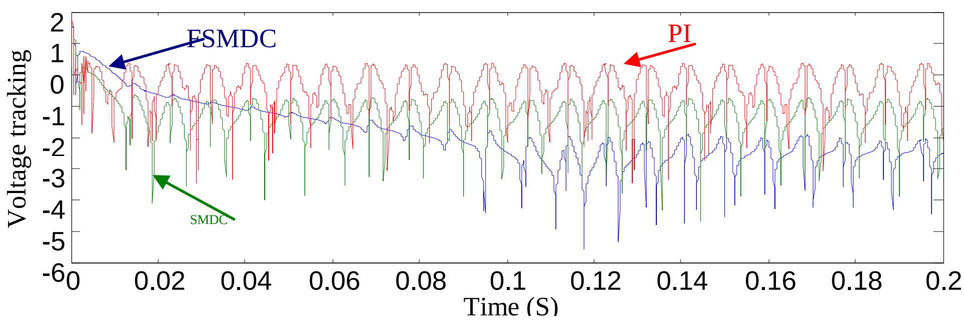

Figure 13: Tracking voltage error plot (logarithmic scale) obtained with PI controller, sliding mode controller and fuzzy sliding mode controller

Given the fast dynamics imposed on the sources and the load as evident from Figure 10 and 11, the simulation results reveal that the FSMDC is advantageous in providing negligible steady-state errors (*NMSE* = 2.3e-4), to adjust the flow source that meets the load demand and guaranteed stable system (Figure 12). It can also be seen that the responses are satisfactory in terms of overshoot, settling time, and fall time. This shows an excellent behavior of the sliding mode controller in comparison with PI controllers which does not run correctly for wide variations of operating point.

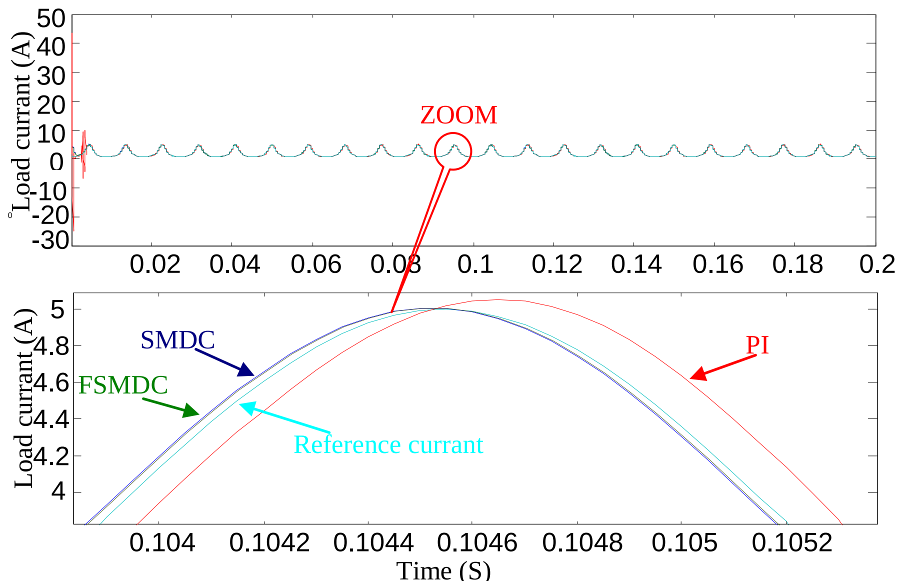

Figure 14: Load current plot obtained with PI controller, sliding mode controller and fuzzy sliding mode controller.

5 Conclusion and Prospects

The application of the sliding mode control technique to Full bridge DC-DC converters is analyzed in this work. Mathematical proof for the stability and convergence of the system parameters is presented. In order to reduce the chattering phenomenon, which is inherent in a sliding mode control, a fuzzy logic approach is used. This control technique provides good overall performances compared to standard current control and good robustness against load and input voltage variations.

The proposed control scheme avoids current overshoots and so contributes to the optimal design of multi-sources power system.

The value of the system tracking error has related to controller parameters. Since the inappropriate controller parameters affect the performances of the control system, it is important to adapt in real time the whole parameters according to the controlled system. This issue and the application of the proposed control scheme to large scale renewable multi-source power systems will be considered in our future work.

The neural-based adaptive observer, in order to identify unknown functions in the multi-source system and to estimate the unmeasured states, will be also studied in our further works.

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