Fuzzy Sliding Design of Chopper Controller in Wind Turbine

Ahmed TAHOUR [1], Abdel Ghani AISSAOUI [2], Mohamed ABID[2], Najib ESSOUNBOULI[3],, Frédéric NOLLET[3]

Abstract:
In this paper, a fuzzy logic controller (FLC) is designed, based on the similarity between the FLC and the sliding mode control (SMC), for a class of nonlinear system to tackle the nonlinear control problems with modelling uncertainties, plant parameters variations and external disturbances.
The purpose is therefore to make the voltage and the current control resist to speed variations, because the variation of speed degrades the performance of the voltage pruducted to the networks. The use of the nonlinear sliding mode method provides very satisfactory performance for chopper control of synchronous generator, and the chattering effect is also eliminated by fuzzy function. Simulation study was done to prove the validation of the strategy and the method of control used in power control. Conclusions are summarized in the last section.

Keys words: synchrone generator, wind turbine, fuzzy sliding mode control and voltage control.

I. INTRODUCTION

The use of wind energy is increasing these last years. The power generated by the wind varies greatly throughout the day; it depends on the power available in the wind and has the same variation. The need of energy has increased significantly. The use of renewable energies is indispensable. Renewable energies are clean and constitute an alternative to meet the needs of today's society. These energies neglected in the past, find their proper place, obtained through research and studies that are increasingly diverse and multidisciplinary. Consumption of energy has increased in recent years because of massive industrialization which tends to grow more and more, specifically in certain geographic areas as Asian countries [1]. The consequence of the increasing consumption affects significantly the environment and the World reserves of fossil fuel. [2].

Several sources of renewable energy are object of advanced researches, which aim to develop techniques for extracting power with high reliability, lower cost and increase energy efficiency [2-3].

In this paper, we focus on the conversion of wind energy into electrical energy that has became competitive due to three main factors [4]:

- Wind energy is clean, renewable and naturally replenished by nature,
- The development of the wind turbine industry,
- The evolution of semiconductor technology, and new methodologies for control of variable speed turbines.

However, several problems, related in part to the complexity of wind conversion systems as the need for speed multiplier between the turbine and generator, and the instability of wind speed on the other hand [5].

The use of wind turbine structures with synchronous generator of high poles number make of wind conversion systems with variable speed more attractive than those with fixed speed, because of the possibility of extracting the optimal energy for different wind speed, reducing mechanical stresses by eliminating the multiplier which improves system reliability, and reduce the maintenance costs [1, 6]. This paper deals with a variable-speed system consisting of synchronous generator, diode rectifier and thyristor inverter. The advantages of the synchronous generator and a diode rectifier are the high efficiency of the rectifier and the low price. There are two disadvantages that can be important in wind turbine generator systems. Motor start of the turbine is not possible without auxiliary equipment and the torque control is normally not faster. The aim of this report is to describe an efficient variable-speed system and to model the generator and converter losses [1].

In this context, the present study focuses on wind energy, which seems to be one of the most promising. The aim of this paper is to present a comprehensive model of a synchronous generator based on a proposed structure and control strategies to optimize power output, to regulate the DC bus voltage, and to control voltage transmitted to the network [1, 7].

To control the Wind Energy Conversion System (WECS) we need robust controller. Sliding Mode Control (SMC) is a nonlinear control technique derived from variable structure control system theory and developed by Vladim UTKIN. Such control solution has several advantages such as simple implementation, robustness and good dynamical response. Moreover, such control complies with the nonlinear characteristic of the switch mode power supplies [4, 11, 12].

Recently, the synthesis algorithms of modern control theory and artificial intelligent (AI) have been studied to upgrade the performance of SMC. In this paper, a methodology of FLC based on SMC is presented. The fuzzy sliding mode control (FSMC) takes the features of both SMC and FLC to overcome the disadvantage of chattering and enhance the robustness of the controllers.

[1] *University of Mascara, 29000, Algeria*
Corresponding author e-mail: tahourahmed@yahoo.fr
[2] *IRECOM Laboratory, University of Sidi Bel Abbes, 22000, Algeri.*
[3] *CReSTIC Laboratory, IUT de Troyes, 9 Rue du Québec, B.P. 396, 10026 Troyes cedex-France.*

The motivation of this study is to design an FSMC control scheme in order to control the voltage of chopper.

The organization of this paper is as follow: in the first section, we establish the model of the turbine. The second section is devoted to modeling the synchronous machine with their equivalent electrical model. Global model of the chain of wind conversion device and associated controller are developed in an equivalent continuous model that takes into account relevant parts of the voltages at the generator, the DC bus and the network is started at third section. In four sections, FSMC will be applied to the chopper.

The last section is devoted to the simulation results. All models developed in this study are simulated by the Matlab-simulink.

II. WIND CONVERSION SYSTEM MODEL

The WECS described in this article includes the wind turbine, synchronous generator, a transformer, a diode rectifier, a filter and an inverter. In this system, the wind energy is transmitted through the turbine to the three-phase synchronous machine and generated in electrical form. This energy is transmitted directly through a transformer, a bridge rectifier and inverter to the electrical network (Figure 1). We consider in this study that the transformer is perfect. The main assumption in this simplified study is that the currents are sinusoidal and semiconductors are ideal [6-7]. Figure (1) shows the equivalent diagram of the WECS.

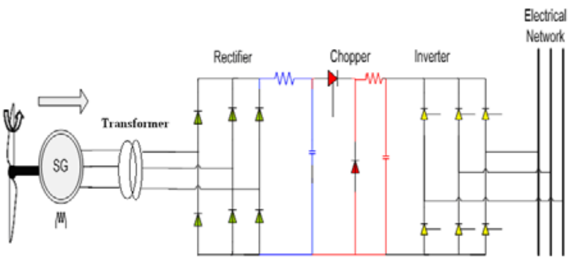


Fig.1. Wind electrical conversion system based on synchronous machine

A. Turbine Model

The turbine model is to present the power and the torque developed by the turbine, and which can be defined by the following equations [2-3, 8]:

$$P_m = \frac{1}{2}\rho\pi R^2 v^3 C_p(\lambda) \quad (1)$$

$$T_m = \frac{P_m}{\Omega} = \frac{1}{2\lambda}\rho\pi R^3 v^2 C_p \quad (2)$$

Which λ presents the ratio between the turbine angular speed and the wind speed. This ratio called the tip speed ration and is defined as:

$$\lambda = \frac{\Omega R}{v} \quad (3)$$

Where: ρ is the air density, R is the blade length, v is the wind speed, C_p is the power coefficient, Ω is the turbine angular speed.

The power coefficient (C_p) presents the aerodynamic efficiency of the turbine and depends on the specific speed λ and the angle of the blades.

It is different from a turbine to another, and is usually provided by the manufacturer and can be used to define a mathematical approximation. A model of wind turbine is developed and it's presented on figure (2).

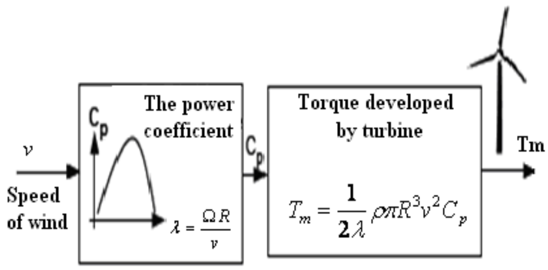


Fig.2. Model of Wind

Figure (3) represents the power coefficient C_p as a function of β and λ.

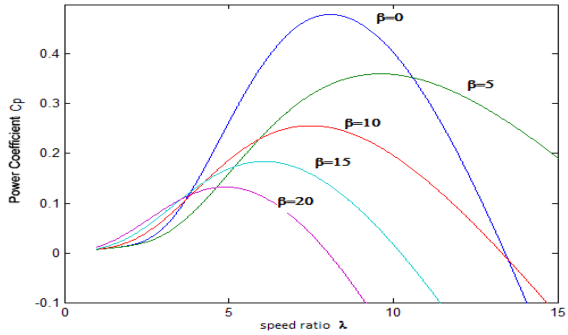


Fig.3. Power coefficient C_p as a function of β and λ

Figure (4) shows the mechanical power as a function of rotor speed of the turbine for different values of wind speed [4].

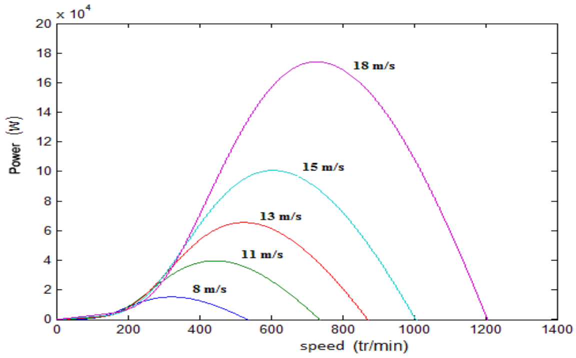


Fig.4. The characteristics of the mechanical power as function of the turbine speed.

B. Generator Model

The generator chosen for the conversion of wind energy is the synchronous generator [6, 9-10]. The dynamic model of synchronous generator in d-q frame can be represented by the following equations:

Electrical equations:

$$V_{ds} = -R_s i_{ds} - \omega\varphi_{qs} + \frac{d\varphi_{ds}}{dt}$$
$$V_{qs} = -R_s i_{qs} - \omega\varphi_{ds} + \frac{d\varphi_{qs}}{dt} \qquad (4)$$
$$V_{fd} = R_f i_{fd} + \frac{d\varphi_{fd}}{dt}$$

The flux linkage equations are:

$$\varphi_{ds} = -L_d i_{ds} + M_{fd} i_{fd}$$
$$\varphi_{qs} = -L_q i_{qs} \qquad (5)$$
$$\varphi_f = L_f i_f - M_{fd} i_{ds}$$

The dynamic behavior of synchronous generator can be defined by:

$$T_m - T_{em} - f\omega = J\frac{d\omega}{dt} \qquad (6)$$

Where R_s – stator resistance, R_f is the field résistance, L_{ds}, L_{qs} – respectively direct and quadrature stator inductances, L_f is field inductance, T_W – Wind torque applied to SG rotor, T_{em} – electromagnetic torque, p – pair number of poles, f – is the damping coefficient, J – is the moment of inertia, ω – electrical angular speed of motor.

III. SLIDING MODE CONTROLLER

A. Sliding mode principle

Consider a nonlinear system which can be represented by the following state space model in a canonical form [3, 18]:

$$x^n(t) = f(x(t),t) + g(x(t),t)u + d(t)$$
$$y(t) = x(t) \qquad (7)$$

Where $x = [x(t)\ \dot{x}(t) .... x^{n-1}(t)]^T$ is the state vector, $f(x(t),t)$ and $g(x(t),t)$ are nonlinear functions, u is the control input, $d(t)$ is the external disturbances. The objective of the control is to determine a control law $u(t)$ to force the system output $y(t)$ in (7) to follow a given bounded reference signal $y_{ref}(t)$, that is, the tracking error $e(t) = y_{ref}(t) - y(t)$ and its forward shifted values, defined as

$$e^i(t) = y^i_{ref}(t) - y^t(t)$$
$$= x^i_{ref}(t) - x^t(t) \qquad (i = 1,.......n-1) \qquad (8)$$

should be small. The design of SMC involves two tasks. The first one is to select the switching hyperplane to prescribe the desired dynamic characteristics of the controlled system. The second one is to design the discontinuous control such that the system enters the sliding mode and remains in it forever [3, 14].

In this paper, we use the sliding surface proposed par J.J. Slotine,

$$S(x,t) = (\lambda + \frac{\partial}{\partial t})^{n-1}.e(t) \qquad (9)$$

In which $e(t) = x_{ref}(t) - x(t)$, λ is a positive coefficient, and n is the system order .

It remains to be shown that the control law can be constructed so that the sliding surface will be reached. Then, a sliding hyperplane can be represented as . $S(x,t) = 0$

Consider a Lyapunov function:

$$V = \frac{1}{2}.S^2 \qquad (10)$$

From Lyapunov theorem we know that if $\dot{V}$ is negative definite, the system trajectory will be driven and attracted toward the sliding surface and remain sliding on it until the origin is reached asymptotically [6]: V

$$\dot{V} = .S.\dot{S} \qquad (11)$$

The simplified 1st order problem of keeping the scalar $S(x,t)$ at zero can be achieved by choosing the control law $u(t)$. A sufficient condition for the stability of the system is :

$$\frac{1}{2}.\frac{d}{dt}S^2 \leq -\eta|S| \qquad (12)$$

where η is a positive constant.

The equation (12) is called reaching condition or sliding condition. $S(t)$ verifying (12) is referred to as sliding surface, and the system's behaviour once on the surface is called sliding mode.

If the control input is so designed that the inequality (12) is satisfied, together with the properly chosen sliding hyperplan, the state will be driven toward the origin of the state space along the sliding hyperplane from any given initial state. This is the way of the SMC that guarantees asymptotic stability of the systems. The process of sliding mode control can be divided in two phases, that is, the approaching phase and the sliding phase. The sliding mode control law $u(t)$ consists of two terms, equivalent term $u_{eq}(t)$, and switching term $u_s(t)$.

In the sliding phase, where $x(t) = 0$ and $\dot{x}(t) = 0$, the equivalent term $u_{eq}(t)$ is designed to keep the system on the sliding surface. In the approaching phase, where , the switching term $u_s(t)$ is designed to satisfy the reaching condition (12). While in sliding phase we have :

$$\dot{S}(x,t) = 0 \qquad (13)$$

By solving the above equation formally for the control input, we obtain an expression for u called the equivalent control u_{eq}, which can be interpreted as the continuous control law that would maintain $\dot{S}(x,t)=0$ if the dynamics were exactly known. In order to satisfy sliding conditions (13) and to despite uncertainties on the dynamic of the system, we add a discontinuous term across the surface , so the sliding mode control law $u(t)$ has the following form:

$$u = u_{eq}(t) + u_s(t)$$
$$u_s(t) = k_f \sin g(S(x,t)) \tag{14}$$

where k_f is the control gain.

B. Control Strategy

It is possible to control the load voltage, by the control of the converter associated. The all system is shown in Figure (5). The control of the system is based on the control of the PWM inverter and the chopper [15-16].

The DC-Link is made by using buck DC/DC converter.

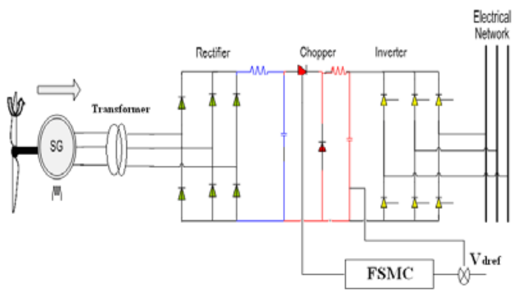


Fig.5. Control of the WECS

For the Buck converter we consider the following sliding surface S :

$$S = (\lambda + \frac{\partial}{\partial t}).e \tag{15}$$

where k is the sliding coefficient and e is the output voltage error defined as follows :

$$e = V_{dcref} - V_{dc} \tag{16}$$

By considering the mathematical model of the Buck converter, the surface can be expressed by the following expression [12-13].:

$$S = \frac{\partial V_{ref}}{\partial t} - \frac{1}{C}.i_l + \lambda.(V_{dcref} - V_{dc}) \tag{17}$$

and its derivative is given by :

$$\frac{\partial S}{\partial t} = \lambda.\frac{\partial V_{ref}}{\partial t} + \frac{\partial^2 V_{ref}}{\partial t^2} - \frac{1}{C}.i_L + (\frac{1}{L.C}).V_{dc} - (\frac{V_{red}}{L.C}).u \tag{18}$$

The next step is to design the control input so that the state trajectories are driven and attracted toward the sliding surface and then remain sliding on it for all subsequent time. The SMC signal u consists of two components a nonlinear component u_s and an equivalent component u_{eq} , [13].

$$u_{eq} = \frac{\lambda.L.C}{V_{red}}.\frac{\partial V_{ref}}{\partial t} + \frac{L.C}{V_{red}}.\frac{\partial^2 V_{ref}}{\partial t^2} - \frac{L}{V_{red}}.i_L + (\frac{1}{V_{red}}).V_{dc} \tag{19}$$

Let us consider the positive definite Lyapunov function V defined as follows:

$$V = \frac{1}{2}.S^2 \tag{20}$$

The derivative of V must be negative definite $\frac{\partial V}{\partial t} < 0$ to insure the stability of the system and to make the surface S attractive. Such condition leads to the following inequality:

$$S.\frac{\partial S}{\partial t} = S.(\frac{-V_{red}}{L.C}.u_s) < 0 \tag{21}$$

To satisfy such condition, the nonlinear control component can be defined as follows:

$$u_s = k_f.sign(S)$$

Where V_{dc} output voltage of chopper, V_{red} intput voltage of chopper, V_{dref} reference voltage, L and C is the inductance and capacitance of chopper.

V. FUZZY SLIDING MODE CONTROLLER FOR CHOPPER CONVERTER

As SMC, Fuzzy Logic Control (FLC) is known to be robust. Moreover, it is considered to be an alternative to the chattering problem. FLC is an intelligent control complying with complex or uncertain systems. Some researchers show that FLC is a general form of variable structure control. Thus, some attempts have been made in order to use both the SMC and FLC to have a robust controller called Fuzzy Sliding Mode Control (FSMC). However, the design of a fuzzy sliding mode controller for nonlinear system is a difficult problem. There have been quite a lot of researches on the combination of sliding mode control with fuzzy logic control techniques for improving the robustness and the performances of nonlinear systems with uncertainty [17]. The control consists of the set of fuzzy control algorithms which approximate the input-output map of traditional sliding mode control [18].

A Stability using Lyapunov function in FSMC

The second class of FSMC uses the surface S and its variation $\dot{S}$ to define the changes on the control signal. The aim of this kind of FSMC is to insure the Lyapunov stability condition $S\,\dot{S} < 0$.

Let us consider the sliding surface S . The proposed fuzzy sliding mode controller forces the derivative of the Lyapunov function to be negative definite. So, the rule base table is established to satisfy the inequality (21).

Intuitively, suppose that $S>0$ and $\dot{S}<0$, the duty cycle must increase. Also, if $S>0$ and $\dot{S}<0$ the duty cycle must decrease. Thus, the surface *S* and its variation $\dot{S}$ are the inputs of the proposed controller. The output signal is the control increment $\Delta U(k)$ which is used to update the control law. As for the Fuzzy boundary layer SMC the control signal is defined by equation (22). The proposed Fuzzy Sliding Mode Controller is a Sugeno fuzzy controller which is a special case of Mamdani fuzzy inference system. Only the antecedent part of the Sugeno controller has the "fuzzyness", the consequent part is a crisp function. In the Sugeno fuzzy controller, the output is obtained through weighted average of consequents.

As the proposed approach have to be implemented in practice, such choice can be motivated by the fact that Sugeno fuzzy controller is less time consuming than the Mamdani one Trapezoidal and triangular membership functions, denoted by N (Negative), Z (Zero) and P (Positive), were used for both the surface and the surface change. They are respectively presented in Fig. 8 and Fig. 9 in the normalized domain [-1 1].

For the output signals, five normalized singletons denoted by NB (Negative Big), NM (Negative Middle), Z (Zero), PM (Positive Middle), PB (Positive Big) are used for the output signal $\Delta U(k)$, Fig. 9.

The output signal is the control increment $\Delta U(k)$ which is used to update the control signal defined as follows:

$$U(k)=\Delta U(k)+U(k-1) \qquad (22)$$

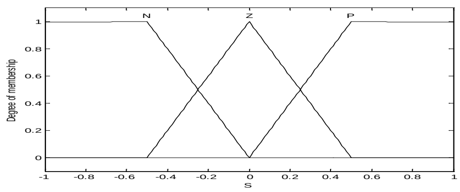


Fig.7 Membership functions attributed to S

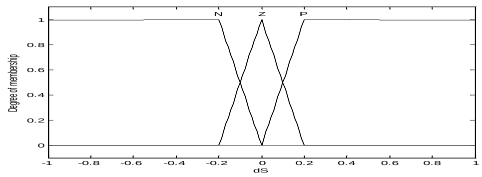


Fig.8 Membership functions attributed to dS

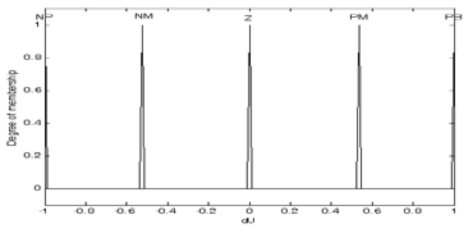


Fig.9 Output variable

Table I shows one of possible rules of Fuzzy.

dU		S		
		N	Z	P
dS	N	NB	NM	Z
	Z	NM	Z	PM
	P	Z	PM	PB

Table.1 rules bases of FSMC

V. SIMULATION AND RESULTS

In order to validate the control strategies as discussed above, digital simulation studies were made the system described in figure (5).

The wind speed taken variable (Fig. 10). The reference DC-link voltage taken is $V_{dcref}=580v$ and which corresponds to the voltage applied in the network with a value of 220*v* and a frequency of $50Hz$. The global system is simulated using matlab/simulink software.

Figures 11.a and 11.b present the simulation results using a fuzzy sliding mode controller voltage.

It can be shown that the voltage generated will influence the energy consumption figure (11.a). In figure (11.b), the voltage given by the chopper follows the reference voltage needed for the voltage requested by the network.

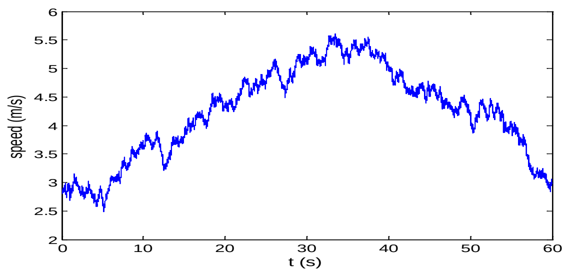
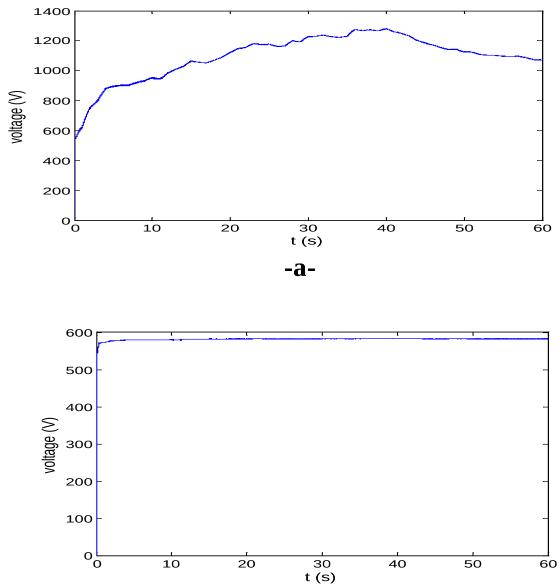


Fig. 10. The curve of wind speed



-b-

Fig. 11. The voltages in the output of: a- Rectifier, b- Chopper

Figure (12) shows the voltages in three grid phases. The use of FSMC gives good result in control of voltages transmitted to the grid.

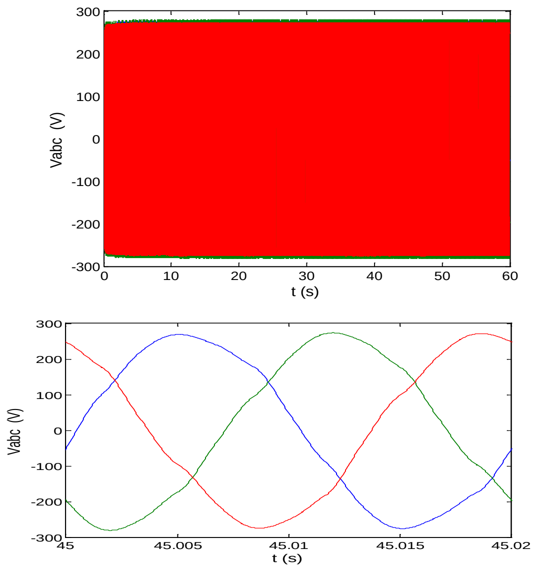


Fig. 12. The voltage in the grid phase with controller,

Figure (14) shows the current in the load. We observe that current varies with the variation of wind (fig.14) and the voltage remains constant (fig.13).

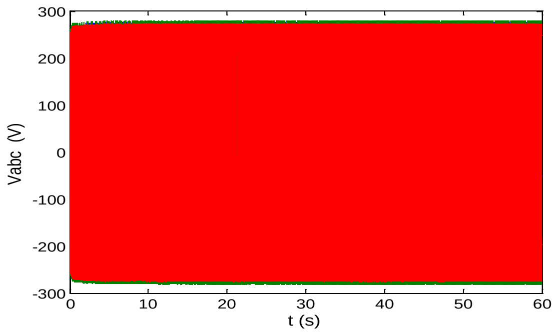


Fig. 13. The votage in the three phases grid,

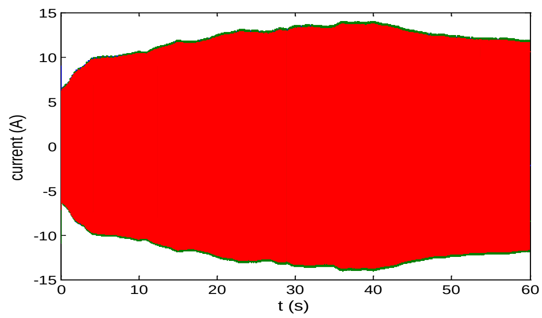


Fig. 14. The current in the three phases grid,

V. CONCLUSION

This paper suggests a fuzzy sliding mode control method that is used for control the voltage of chopper.

After modelling the system we have developed controller using fuzzy sliding mode. In order to eliminate the chattering effect we have used the fuzzy mode.

Simulation results have show robustness and good performances.

Furthermore, this regulation presents a simple robust control algorithm that has the advantage to be easily implantable in calculator.

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