



Stator Voltage Control of a Wound Rotor Synchronous Generator- A Sliding Mode Approach

Hemilda Carmel¹, Sreedevi R C²

Electrical and Electronics Dept., Lourdes Matha College of Science & Technology Trivandrum, India^{1,2}

Abstract: This paper presents the stator voltage control of a wound rotor synchronous generator which is treated as a standalone generator. The stand alone Wound Rotor Synchronous Generators is most commonly used for the stand-alone generation emulating the power grid for emergency and security reasons. They found their applications in electric vehicles, renewable energies etc. The standard dq model of the machine is connected to a resistive load. A switching function is defined in order to fulfil control objective. A sliding mode control algorithm is proposed to obtain a very simple controller which ensures stability. The obtained control laws regulate the stator voltage amplitude irrespective of the load value. The design of control law requires only voltage measurements and is easily implementable.

Keywords: Wound rotor synchronous generator (WRSG), Sliding mode control (SMC), synchronous machine (SM), Stand-alone generation

I. INTRODUCTION

The worldwide demand for electrical energy is increasing in a large scale and is widely studied around the world due to the advantages of transmission possibilities, flexibility and control capacity among others. Electrical energy is mainly generated by interconnecting wound rotor synchronous generators (WRSG) driven by prime movers which are basically wind, hydro, steam turbines or internal combustion engines. When Wound Rotor Synchronous Generators (WRSG) are connected in parallel it will set up a theoretical infinite bus^[10]. In this configuration the the own grid determines the stator voltage and frequency and the rotor voltage helps to improve the power factor and to compensate the reactive power at the connection point.

But when a WRSG is isolated from the grid and kept as stand alone the configuration is different. In this configuration neither the stator voltage amplitude nor frequency is fixed. For this stand alone configuration, the mechanical speed determines the frequency, and the rotor voltage is used to regulate the stator voltage amplitude. In the stand-alone case it is not possible to neglect the transients of the machine

The synchronous machines can be controlled by several techniques. The most common are linear techniques^[4] and hysteresis regulators. However, decoupling methods are also used to the synchronous machine control. Modern control techniques, such as passivity-based control optimal torque control^[5] or predictive control are also used for synchronous machines speed regulation. From literature examples it is clear that normally industry applications use linear controllers which cannot ensure stability as the electrical machines are highly interconnected non linear electromechanical systems. Therefore it is necessary to design a nonlinear controller which takes care of the

system dynamics. Sliding Mode Controller (SMC) is one of the best nonlinear controllers for which is designed to control the stator voltage amplitude. Apart from other linear controllers the Sliding mode controller only requires voltage measurements, and is easily implementable. The robustness and ease of implementation make this approach particularly attractive.

II. SYSTEM DESCRIPTION

Fig 1 shows the proposed system scheme. A prime mover drags the WRSG which is feeding a continuously varying resistive load. ω_m is the mechanical speed. V_{abc} V_f are the stator and field voltages. I_{abc} and I_f are the stator and field currents. As explained earlier in this configuration the frequency is determined by the mechanical speed given by the prime mover and the stator voltage amplitude is regulated by the rotor field voltage.

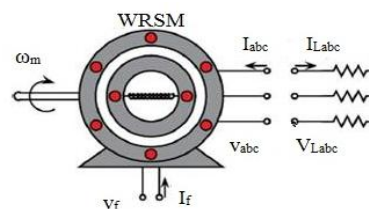


Fig 1 Scheme of a standalone WRSG

III. SYSTEM MODELLING

An electrical machine is a highly interconnected non linear electromechanical system. A three-phase wound rotor synchronous machine is composed by a set of three-phase



stator and field windings. At the stator side, the voltages, currents and fluxes are three-phase variables, while the rotor variables are one dimensional. The dq-transformation allows simplifying the study [12]. This transformation eliminates the θ dependent coefficients of the inductance matrix and reduces the three-phase system into a two-phase system.

A. Dynamic model

A WRSG can be represented by means of dq coordinate dynamic equations. The electrical part of a wound rotor synchronous machine can be described using the state space form as

$$L \frac{dx}{dt} = \begin{bmatrix} -R_s & \omega L_s & 0 \\ -\omega L_s & -R_s & -\omega L_m \\ 0 & 0 & -R_f \end{bmatrix} x + \begin{bmatrix} v_d \\ v_q \\ v_f \end{bmatrix} \quad (1)$$

Where L is the inductance matrix and is given

$$L = \begin{bmatrix} L_s & 0 & L_m \\ 0 & L_s & 0 \\ L_m & 0 & L_f \end{bmatrix}$$

In dq coordinate system the stator voltages are given by

$$v_q = \frac{2}{3} \left\{ v_a \cos \theta_r(t) + v_b \cos \left(\theta_r(t) - \frac{2\pi}{3} \right) + v_c \cos \left(\theta_r(t) - \frac{4\pi}{3} \right) \right\} \quad (2)$$

$$v_d = \frac{2}{3} \left\{ v_a \sin \theta_r(t) + v_b \sin \left(\theta_r(t) - \frac{2\pi}{3} \right) + v_c \sin \left(\theta_r(t) - \frac{4\pi}{3} \right) \right\} \quad (3)$$

Where L_s , L_m , L_f are the stator, magnetizing, and field inductances. ω is the electrical speed. v_d and v_q are the dq stator voltages; and v_f is the field voltage which will be used as a control input. In order to design the control law, let us first obtain the complete model of a WRSM connected to a resistive load R_L .

By connecting the resistive load to the system the system can be represented in the form as

$$L \frac{dx}{dt} = Ax + Bv_f \quad (4)$$

Where L is the inductance matrix defined before and A and B are given by

$$A = \begin{bmatrix} -(R_s + R_l) & \omega L_s & 0 \\ -\omega L_s & -(R_s + R_l) & -\omega L_m \\ 0 & 0 & -R_s \end{bmatrix} \quad B = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}$$

B. Control objective

As mentioned before, this machine must ensure stator voltage amplitude and frequency. For a synchronous generator, the stator frequency is directly given by the mechanical speed, which, in this paper it is assumed to be constant and externally regulated. Then, the system output is the stator voltage amplitude V_s , which can be represented in a dq-coordinates as,

$$V_s = \sqrt{v_d^2 + v_q^2} \quad (5)$$

By using state variables V_s can be represented as

$$V_s = R_L \sqrt{i_d^2 + i_q^2} \quad (6)$$

From (3) and (5), where V_s was replaced by its desired value V_r , at the equilibrium point (i_d^* , i_q^* , i_f^*) and the control input V_f^* is obtained. Using cylindrical coordinates system, the equilibrium control input is obtained as

$$v_f^* = -\frac{R_f}{\omega L_m R_L} V_r (\omega L_s \cos \delta^* + (R_s + R_L) \sin \delta^*) \quad (7)$$

Where δ is the load angle.

IV. CONTROLLER DESIGN

In this Section the Sliding Mode Control technique is developed to regulate an isolated wound rotor synchronous generator. The purpose of the switching control law is to drive the nonlinear plant's state trajectory onto a pre specified surface in the state space and to maintain the plant's state trajectory on this surface for subsequent time. The surface is called a switching surface. When the plant state trajectory is "above" the surface, a feedback path has one gain and a different gain if the trajectory drops "below" the surface. This surface defines the rule for proper switching.

This surface is also called a sliding surface or sliding manifold. For sliding mode controller, Lyapunov stability method is used to keep the nonlinear system under control. Therefore simple control algorithm can be developed. Sliding mode control is an important robust control method.

A. Sliding mode controller

The switching function is directly derived from the stator voltage amplitude, and assuming a bang-bang control action According to the control objective a switching function is to be defined as follows

$$s(x) = V_s^2 - V_r^2 \quad (8)$$

By using state variables the switching function can be written as



$$s(x) = R^2_L (i^2_d + i^2_q) - V^2_{ref} \tag{9}$$

Instead of classical error difference square error of the voltage amplitude is chosen because both equilibrium points are achievable. The equivalent control satisfies S=0. By considering eq(4)

$$\frac{\partial s}{\partial x} L^{-1} (Ax + Bu_{eq}) = 0 \tag{10}$$

Now, solving for u_{eq} and replacing the matrices and partial derivatives we get u_{eq} as

$$u_{eq} = R_F i_F - \frac{L_F}{L_m} (R_s + R_L) i_d + \omega L_m i_q - \frac{m}{L_s} \left(\frac{(R_s + R_L)}{L_m} i_q + \omega i_F \right) i_d \tag{11}$$

Where $m = L_s L_F - L_m^2$, which is always positive. The closer to zero i_d , the higher the equivalent control. Lyapunov method is usually used to determine the stability properties of an equilibrium point without solving the state equation. Let $V(x)$ be a continuously differentiable scalar function defined in a domain D that contains the origin. A function $V(x)$ is said to be positive definite if $V(0)=0$ and $V(x)>0$ for x . It is said to be negative definite if $V(0)=0$ and $V(x)<0$ for x . Lyapunov method is to assure that the function is positive definite when it is negative and function is negative definite if it is positive. In that way the stability is assured. Consider the following Lyapunov function which is positive.

$$V = \frac{1}{2} s^2$$

To stabilize the closed loop system, the derivative of Lyapunov function must be negative. that is the sliding mode controller must ensure that,

$$s \frac{ds}{dt} < 0$$

This is equivalent to,

$$s \frac{\partial s}{\partial x} L^{-1} (Ax + Bv_f) < 0 \tag{12}$$

Adding and subtracting Bu_{eq} and considering u_{eq} ,

$$s \frac{\partial s}{\partial x} L^{-1} B (v_f - u_{eq}) < 0 \tag{13}$$

The control action is defined by

$$v_f = u_{eq} - k \text{sign} \left(s \frac{\partial s}{\partial x} L^{-1} B \right) \tag{14}$$

The control action can be simplified as

$$v_f = u_{eq} - k \text{sign} (-s i_d) \tag{15}$$

With a positive 'k' fulfills the stability condition $s \frac{ds}{dt} < 0$. The stability condition is simplified to

$$(v_f - u_{eq}) s i_d < 0 \tag{16}$$

The control rotor voltage is given by

$$\begin{cases} + v_f, & \text{if } s i_d < 0 \\ - v_f, & \text{if } s i_d > 0 \end{cases} \tag{17}$$

The proposed control scheme is shown in Fig 2.

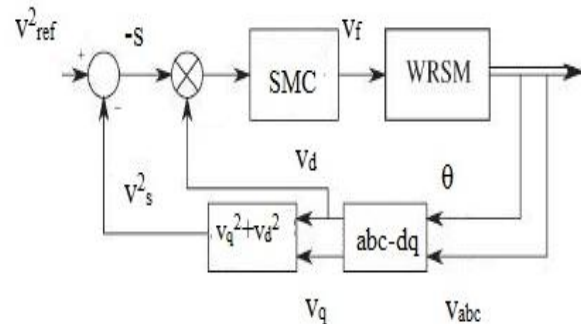


Fig 2: control scheme

V. SIMULATION RESULTS

In this section the simulation results of the designed sliding mode controller controllers for the stand-alone wound rotor synchronous generator is presented. The simulations were performed using Matlab/Simulink. The simulation parameters are shown in table1. The various results correspond to the load change with respect to time. The load is taken as a function of time and is continuously varying. The variation of the switching function with respect to load change is plotted. Moreover the regulated three phase stator voltage wave form is also plotted. The results are used to validate the performance of the controller.

Table1: WRS simulation parameters

Parameters	Value with units
Power rating ,p	2.4 kVA
Frequency,f	50 Hz
Speed ,N	1500 rpm
Field voltage,V _f	100V
Field current ,I _f	2.4 A
Stator current,I _s	6.3 A
Stator resistance,R _s	3.06 Ω
Mutual inductance,L _m	0.31 H
Stator inductance,L _s	0.48H



Field inductance, L_f	3.87 H
Field resistance, R_f	39.65 Ω
Number of poles	4

The variation of stator voltage with the change of load resistance at time $t=4$ sec is plotted fig 3.

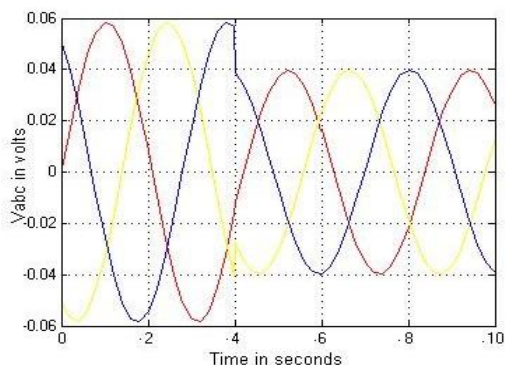


Fig3. Change in stator voltage with respect to R_L

The variation of switching function with respect to continuous load change is shown in fig4.

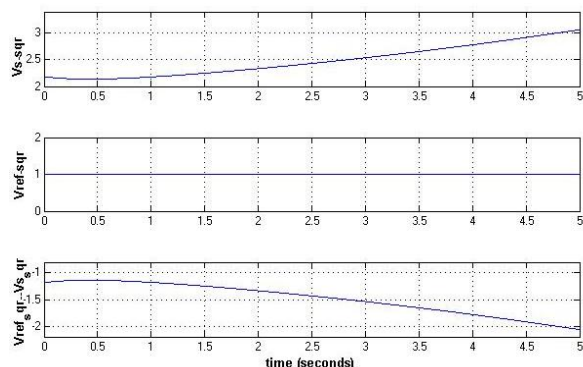


Fig4. Change in V_s^2 , V_r^2 , S with respect to R_L

The bang bang control action is depicted in fig 5. from the plot it is clear that s^*id is negative the equivalent control action is positive value.

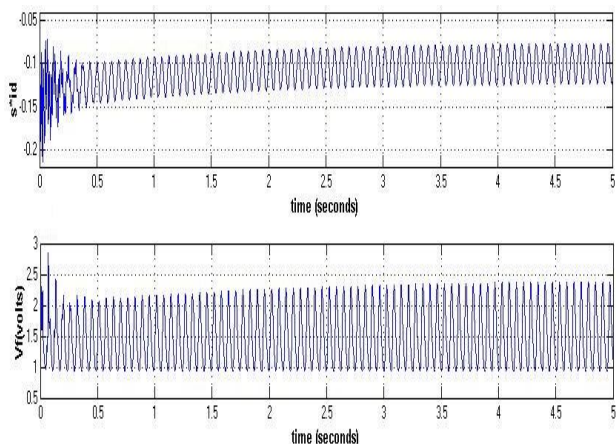


Fig 5: variation of field voltage (vf) with S^*id

Fig 6 shows the regulated outputs after control action. The P_{gen} and Q_{gen} are the real and reactive components of generated power. up to time $t=0.5$ sec there is some disturbances in the output. After that due to the control action it is settled.

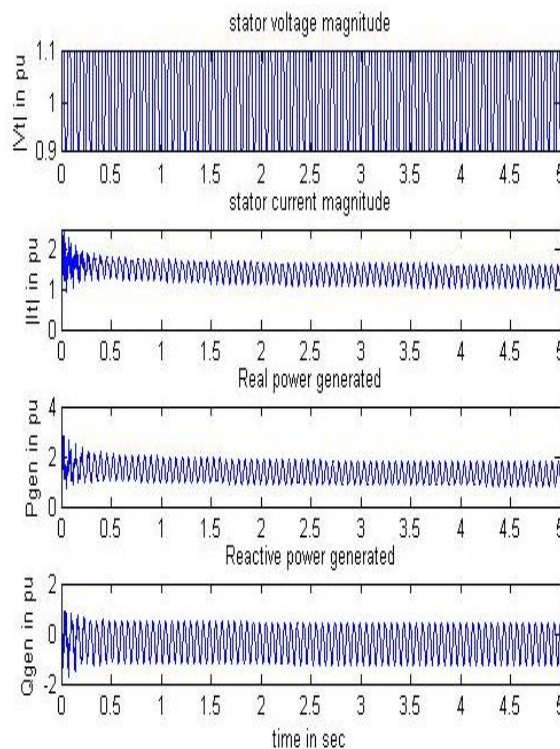


Fig 6. Regulated output parameters with respect to R_L

Fig7. Shows the regulated three phase stator voltage wave form.

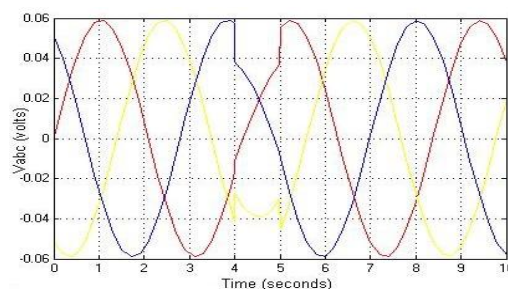


Fig 7: Regulated three phase stator voltage .

From the simulation result it is clear that the stator voltage amplitude settled to its actual value within a few seconds because of the sudden control action.

VI. CONCLUSIONS

A sliding mode controller is designed for a stand alone wound rotor synchronous generator which is feeding resistive load. The obtained control law regulates the stator voltage amplitude irrespective of the load value. and the



closed loop system is invariant to machine parameters. Only voltage and rotor position measurements are required to compute the dq-transformation. The simulation results are provided to validate the performance of the controller.

REFERENCES

- [1] A. G. Loukianov, J. M. Cañedo, L. M. Fridman, and A. Soto-Cota, "Highorder block sliding-mode controller for a synchronous generator with an exciter system," *IEEE Transactions on Industrial Electronics*, vol. 58, no. 1, pp. 337–347, Jan. 2011.
- [2] Xiaoguang Zhang, Lizhi Sun, Ke Zhao, Li Sun, "Nonlinear Speed Control for PMSM System Using Sliding-Mode Control and Disturbance Compensation techniques" *IEEE Transactions On Power Electronics*, Vol. 28, No. 3, March 2013.
- [3] G. Foo and M. F. Rahman, "Sensorless sliding-mode MTPA control of and IPMSM drive using a sliding-mode observer and HF signal injection," *IEEE Transactions on Industrial Electronics*, vol. 57, no. 4, pp. 1270–1278, April 2010.
- [4] F. Genduso, R. Miceli, C. Rando, and G. R. Galluzzo, "Back EMF sensorless-control algorithm for high-dynamic performance PMSM" *IEEE Trans. Ind. Electron.*, vol. 57, no. 6, pp. 2092–2100, June 2010.
- [5] A. Dòria-Cerezo, C. Battle, and G. Espinosa-Pérez, "Passivity-based control of a wound rotor synchronous motor," *IET Control Theory Appl.*, vol. 4, no. 10, pp. 2049–2057, Oct. 2010.
- [6] H. Huerta, A. G. Loukianov, and J. M. Cañedo, "Multimachine powersystem control: Integral-SM approach," *IEEE Transactions on Industrial Electronics*, vol. 56, no. 6, pp. 2229–2236, Jun. 2009.
- [7] Raúl Santiago Muñoz-Aguilar, Arnau Dòria-Cerezo, Enric Fossas, Member, IEEE, and Rafel Cardoner Papa" Sliding Mode Control of a Stand-Alone Wound Rotor Synchronous Generator " *IEEE Transactions On Industrial Electronics*, Vol. 58, No. 10, October 2011.
- [8] A. Girardin and G. Friedrich. Optimal control for a wound rotor synchronous starter generator. In *Proc. of the IAS Annual Meeting. Industry Applications Conference*, 2006. 2.
- [9] A.E. Magri, F. Giri, A. Abouloifa, and M. Haloua. Nonlinear control of wound rotor synchronous-motor. In *Proc. of the IEEE International Conference Control*, pages 3110–3115, 2006. 2
- [10] P. M. Anderson and A. A. Fouad, *Power System Control and Stability*. Ames, IA: Iowa State Univ. Press, 1977. W. Leonhard, *Control of Electric Drives*. Berlin, Germany: Springer-Verlag, 1995
- [11] Peter Vas. *Vector Control of AC Machines*. Oxford Clarendon Press, 1990.
- [12] E. Mouni, S. Tnani, and G. Champenois, "Improvement of synchronous generator's transient state by using voltage source and sliding mode control," in *Proceedings of the IEEE International Symposium on Industrial Electronics*, Jun./Jul. 2008.