# Gaussian Radial Basis Function Neural Network Controller of Synchronous Reluctance Motor in Electric Motorcycle Applications

Chien-An Chen[1], Huann-Keng Chiang[2] and Wen-Bin Lin[3]
[1] *Electronic Vehicle and System Verification Group R & D Division, Automotive Research and Testing Center, Changhua 50544, Taiwan*
[2] *Department of Electrical Engineering, National Yunlin University of Science & Technology, Taiwan*
[3] *Graduate School of Engineering Science & Technology, National Yunlin University of Science & Technology, Taiwan*
*Fax :+886-5-5312065*
*E-mail: chianghk@yuntech.edu.tw*

***Abstract***: In this paper, a sliding mode control (SMC) design based on Gaussian radial basis function neural network (GRBFNN) is proposed for the synchronous reluctance motor (SynRM) system in electrical motorcycle applications. The conventional sliding mode control is assumed that the upper lumped boundary of parameter variations and external disturbances is known and the sign function is used. It causes high frequency chattering and high gain phenomenon. In order to avoid above drawback, the proposed method utilizes the Lyapunov stability method and the steep descent rule to guarantee the convergence asymptotically and reduce the magnitude of the chattering or avoid the chattering. Finally, numerical simulations are shown to illustrate the good performance of our controller design.

***Keywords***: Sliding mode control, Radial basis function neural network, Synchronous reluctance motor, Electric m otorcycle, Lyapunov stability method.

## I. INTRODUCTION

In recent years, the discussion of environmental protection such as reducing air pollution and to avoid gasoline depletion, some countries require their automotive industries to develop electric vehicles in place of gasoline-powered automobiles gradually [1,2]. In Asia, motorcycles are much more widespread than automobiles for individual transportation, so we attention on the development and research of electric motorcycles. SynRM [3,4] has been a renewed interesting research subject, due to the rotor circuit of the SynRM is opened such that the flux linkage of SynRM is directly proportional to the stator currents.

The fast and error-free dynamic response is a primary topic in control systems. Recently, many researches have focused on designing the electric motors. The parameters of electric motors may be changed in working circumstances. Therefore, the robust control technology can be solved in parameter variations and external disturbances.

One of the famous methods about robust control of the parameter variations system is the so-called variable structure control [5,6] in modern control theories. The sliding mode control has been proven as an effective and robust control technology to overcome the uncertainties when the upper lumped uncertainty boundary of the systems is known.

The GRBFNN control1er is an effective method when the systems mathematical model is unknown, or known with uncertainties. It is a three-layer feedforward neural network structure [7] which has the nonlinear transformation of Gaussian basis function in the hidden layer and output layer is the linear combination of hidden layer responses.

According to the RBFNN advantages, we proposed the SMC design based on GRBFNN concept of SynRM system. The GRBFNN doesn't use the signum function control element hence this system reduces chattering phenomenon and has the response smoother.

## II. MOTORCYCLE MODEL

The model of the electric motorcycle propulsion system is shown in Figure 1. This model describe is based on the principles of mechanics and aerodynamics. The load torque of motorcycle is shown in Figure 2, it is composed of $F_r$ , $F_a$ and $F_g$ . The total load of the motorcycle is given by

$$F = F_r + F_a + F_g \tag{1}$$

where the $F_r$ , $F_a$ and $F_g$ are rolling resistance, aerodynamic drag and grading resistance, respectively. They are the function of rotational speed as follows.

$$F_r = MgC_r \cos\theta \quad \text{: rolling resistance}$$

$$F_a = \frac{1}{2}\rho C_d A_f v^2 \quad \text{: aerodynamic drag}$$

$$F_g = Mg\sin\theta \quad \text{: grading resistance}$$

where, $\rho$ is the air density, $C_d$ is the aerodynamic drag coefficient, $A_f$ is the orthographic projection area which is composed of the driver and the travel direction of the vehicle, $v$ is the linear speed of the motorcycle, $M$ is the mass of the motorcycle, $g$ is the gravitational constant, $C_r$ is the rolling resistance coefficient, $\theta$ is the grade angle. The linear speed $v$

is proportional to the rotor speed of SynRM as

$$v = \frac{R_t}{i_o}\omega_r \qquad (2)$$

where $R_t$ is the radius of the tire, $i_o$ is the total ratio between the motor shaft and the differential axle of the vehicle, respectively. Hence, the total load torque is represented as follows.

$$\begin{aligned} T_L &= \frac{R_t}{i_o}(F_r + F_g + F_a) \\ &= \frac{R_t}{i_o}(MgC_r\cos\theta + Mg\sin\theta + \frac{1}{2}\rho C_d A_f v^2) \end{aligned} \qquad (3)$$

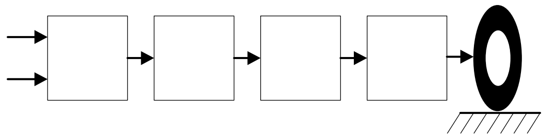



Fig. 1. Configuration of the electric motorcycle propulsion system.

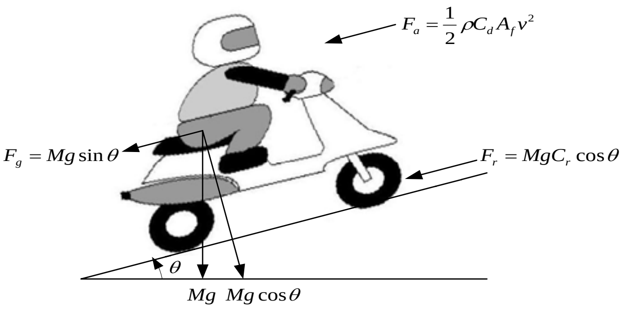



Fig. 2. Elementary forces acting on the motorcycle.

## III. MODELING OF THE SYNRM

The model of the SynRM is shown in Figure 3. The d-q equivalent voltage equations of the SynRM with the synchronously rotating rotor reference frame are represented as

$$V_{ds} = R_s i_{ds} + L_{ds}\frac{di_{ds}}{dt} - \omega_r L_{qs} i_{qs} \qquad (4)$$

$$V_{qs} = R_s i_{qs} + L_{qs}\frac{di_{qs}}{dt} + \omega_r L_{ds} i_{ds} \qquad (5)$$

where the $V_{ds}$ and $V_{qs}$ are direct and quadrature axis terminal voltages, respectively. The $i_{ds}$ and $i_{qs}$ are, respectively, direct axis and quadrature axis terminal currents or the torque producing current. The $L_{ds}$ and $L_{qs}$ are the direct and quadrature axis magnetizing inductances, respectively. The $R_s$ is the stator resistance and $\omega_r$ is the speed of the rotor.

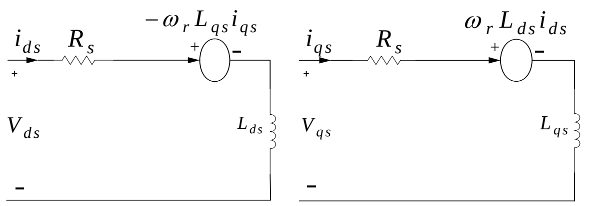



**Fig. 3.** The model of synchronous reluctance motor

The corresponding electromagnetic torque $T_e$ and motor dynamic equation are given as following

$$T_e = \frac{3}{2}P(L_{ds} - L_{qs})i_{ds}i_{qs} \qquad (6)$$

$$T_e - T_L = J\frac{d\omega_r}{dt} + B\omega_r \qquad (7)$$

where $P$, $T_L$, $J$ and $B$ are the pair of poles, the torque load, the inertia moment of rotor and the viscous friction coefficient, respectively. If both $i_{ds}$ and $i_{qs}$ are suitable selected values, we can control the electromagnetic torque in (6) and (7) to satisfy the torque of load and the speed command.

A comparative study of different control methods of the SynRM was done by Betz et. al. [3]. We adopt the maximum torque control (MTC) strategy [4].

## IV. SLIDING MODE CONTROL (SMC)

We can rewrite the motor dynamic equation of (7) as follows:

$$\begin{aligned} \dot{\omega}_r &= (-\frac{B_m}{J_m})\omega_r + (\frac{1}{J_m})(T_e - T_L) \\ &= a\omega_r + b(T_e - T_L) \\ &= a_o\omega_r + b_o(u(t) + f) \end{aligned} \qquad (8)$$

where

$$a \equiv -\frac{B_m}{J_m} = a_o + \Delta a\,; \qquad b \equiv \frac{1}{J_m} = b_o + \Delta b$$

$$u \equiv T_e\,; \qquad f \equiv \frac{1}{b_o}(\Delta a\omega_r + \Delta bu(t) - bT_L)$$

$$J_m \equiv J_{mo} + \Delta J_m\,; \qquad B_m \equiv B_{mo} + \Delta B_m$$

The subscript index "o" indicates nominal system value; "$\Delta$" symbol expresses uncertainty, and $f$ is the lump uncertainty. Defining the velocity error $e(t) = \omega_{ref} - \omega_r$, $\omega_{ref}$ is the velocity command.

The sliding function is defined as

$$S = e(t) + c\int e(\tau)d\tau,\ c > 0 \qquad (9)$$

The input control $u(t)$ (the electromagnetic torque $T_e$) can be defined

$$u(t) = u_{eq}(t) + u_n(t) \qquad (10)$$

To satisfy equivalent control concept $\dot{S}(e) = 0$, we get

$$\dot{S} = (\dot{\omega}_{ref} - a_o\omega_r - b_o u_{eq} + ce) - b_o(u_n + f) \qquad (11)$$

We set

$$u_{eq} = \frac{1}{b_o}(\dot{\omega}_{ref} - a_o\omega_r + ce) \qquad (12)$$

To satisfy the sliding condition $S(e)\dot{S}(e) < 0$, we have

$$S\dot{S} = -S[b_o(u_n + f)] \qquad (13)$$

Let $|f| \le K$, the uncertain nonlinear switching control input can be defined as

$$u_n = Ksign(S) \qquad (14)$$

where

$$sign(\upsilon) = \frac{\upsilon}{|\upsilon|}$$

Hence, the sliding condition $S(e)\dot{S}(e) < 0$ can be guaranteed. To avoid the chattering phenomenon, the $sign(\cdot)$ is replaced by saturation function $sat(\cdot)$. Therefore, $u_n$ becomes

$$u_{nM} = Ksat(S) \quad \textbf{(15)}$$

This method has a steady state error.

## V. SLIDING MODE CONTROLLER BASED ON GRBFNN

In real world, the physical systems always have certain nonlinear and various uncertainties. The error back propagation NN has the disadvantages of slower learning speed and local minimal convergence. Hence, we use the GRBFNN to solve these problems and develop a model-free controller structure based on GRBFNN. The structure of the SMC based on GRBFNN model is shown in Fig. 4. The RBFNN model has $j$ receptive field units. We select the Gaussian function $\varphi_j(S) = \exp\left(-\left(S - c_j\right)^2/(2b_j^{\,2})\right)$ as the receptive field units, where $S$ is the sliding surface function and $c_j, b_j$ are the spread factor and central position of the Gaussian function, respectively. $j$ is the number of hidden layer neurons. The output $u$ of the RBFNN is the sum of weights which the output can be described as

$$u = \sum_{j=1}^{5} w_j \varphi_j(S) \quad \textbf{(14)}$$

$$\varphi_j(S) = \exp\left(-\frac{\left(S - c_j\right)^2}{2b_j^{\,2}}\right), \quad j = 1, \cdots, 5 \quad \textbf{(15)}$$

where

$$\theta = \left[\varphi_1(S), \varphi_2(S), \cdots, \varphi_5(S)\right]^T, \quad W = [w_1, w_2, \cdots, w_5]^T$$

$$c_1 = \frac{2000\pi}{6}, c_2 = \frac{2000\pi}{12}, c_3 = 0, c_4 = -\frac{2000\pi}{12}, c_5 = -\frac{2000\pi}{6}$$

$$b_1 = b_2 = b_3 = b_4 = b_5 = 500\pi/6$$

According the SMC reaching condition $S\dot{S} < 0$, the adaptive rules of this structure derive from the steep descent method to minimize the value of the performance index $S\dot{S}$ with the weight $w_j$ as follows:

$$\dot{w}_j = -\eta \frac{\partial S\dot{S}}{\partial w_j} = -\eta \frac{\partial S\dot{S}}{\partial u}\frac{\partial u}{\partial w_j} \quad \textbf{(16)}$$
$$= \eta \cdot S \cdot b_o \cdot \varphi_j(S)$$

where $\eta$ is the learning rate.

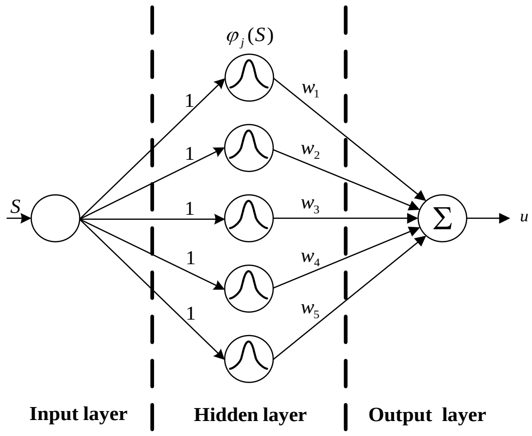



Fig. 4. The structure of the RBFNN model

## VI. NUMERICAL SIMULATION RESULTS

System parameters for the motor and the motorcycle are setting as shown in Table 1 and 2, respectively, and the proposed controller parameters are in Table 3. The sampling period of control rules is set as 0.3 $m$sec . To investigate the effectiveness of the proposed controllers, two conditions are provided in the numerical simulation, In Fig. 5, the response under grade angle $\theta = 0^\circ$ is depicted. In Fig. 6, shows the same speed control command under grade angle $\theta = 5^\circ$ is presented. From Fig. 5 and 6, the proposed controller has good velocity performance.

Table 1. The parameters of SynRM

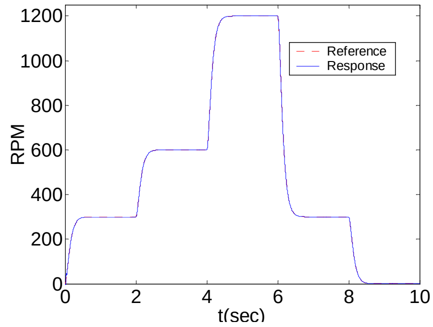
| | |
|---|---|
| $R_s = 4.2\Omega$ | $P = 1$ |
| $L_{ds} = 0.328$ H ( $f = 60$Hz) | $L_{qs} = 0.181$ H ( $f = 60$Hz) |
| $J_{mo} = 0.00076\ kg\text{-}m^2$ | $B_{mo} = 0.00012\ Nt\text{-}m/rad/sec$ |

Table 2. The parameters of motorcycle

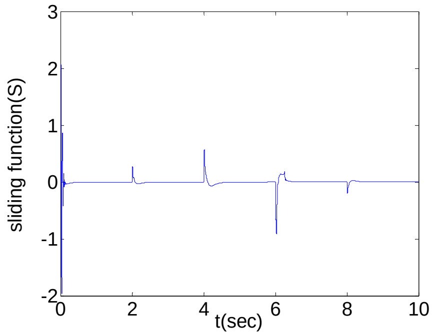
| | | |
|---|---|---|
| $R_t = 0.2m$ | $i_o = 8$ | $\rho = 1.2\,kg/m^3$ |
| $A_f = 1m^2$ | $C_d = 0.4$ | $C_r = 0.015$ |
| $M = 30kg$ | $g = 9.81m/\sec^2$ | |

Table 3. The parameters of proposed controller

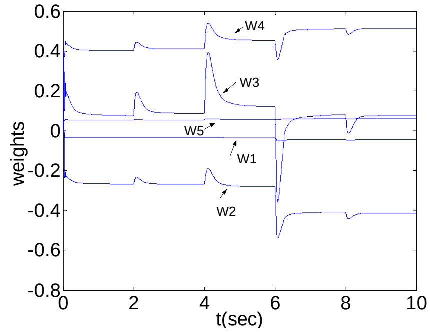
| | |
|---|---|
| $c = 6$ | $\eta = 0.0086$ |




(a)

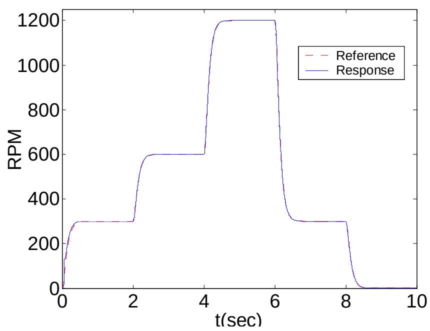



(b)

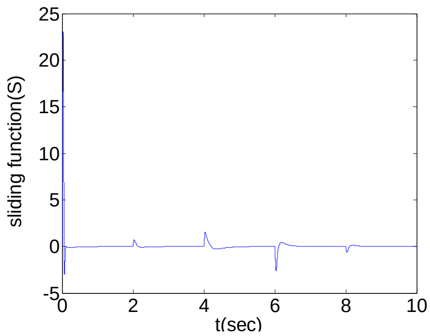



(c)

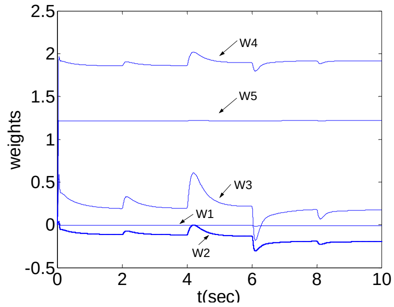
Fig. 5. simulation results of the SMC based on RBFNN under grade angle $\theta = 0^{\circ}$ (a) rotor velocity (b) sliding function (c) weights




(a)




(b)




(c)

Fig. 6. simulation results of the SMC based on RBFNN under grade angle $\theta = 5^{\circ}$ (a) rotor velocity (b) sliding function (c) weights

## VII. CONCLUSION

A SynRM of the electric motorcycle using the sliding mode control based on GRBFNN is proposed in this paper. It derives from the steep descent method to minimize the value of the performance index $S\dot{S}$. Hence, the chattering problem can be minimized with the proposed control and has the better smooth response. Finally, we employ the numerical simulation results to validate the proposed method.

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