A Neural Network Approach to Sensorless Control of Synchronous Reluctance Motor

M.Sadeghierad [(1)] B.Ganji[(1)] H.ImanEini[(1)] S.Afsharnia[(2)]
1:Ph.D. Student – 2: Associate professor
Electrical & computer engineering faculty
University of Tehran

Abstract : To control Synchronous Reluctance Motors (SYRM) without using position sensors has been , challenging task for some time. This paper presents a new approach to the problem based on neural network methods Instead of using position sensors, neural networks are used to identify the rotating angles of the rotor. Neural networks are trained to associate between the measured phase voltages and currents and the rotor positions. Once this association is established, the networks perform independently to identify the rotor positions based on the measured voltages and currents. The background, theoretical analysis and the results obtained are described in this paper.

Key Words : Vector control, Synchronous Reluctance Motors, neural networks, sensorless

1. Introduction

Increasing Interest has been shown in the Synchronous Reluctance Motor in recent years, particularly in the axially – laminated design first introduced by Cruickshank in 1966 and further developed by El – Antably[1]. The later axially laminated designs do not have a starting squirrel Cage; this improves the saliency – ratio and hence torque and efficiency . Without the starting cage the synchronous reluctance motor cannot be used for direct–on–line starts, but requires to be driven by an inverter to keep the rotor and flux in synchronism. Most inverter drives use a sensor to measure the rotor position to achieve this. However, the rotor position sensor has been a major complaint in variable speed inverter drives as it is expensive, fragile, and can prevent use in hostile environments.

The position information is traditionally provided by measurements using costly transducers. Such as optical encoders or magnetic resolvers. In order to make the SYRM drive less expensive and more robust compared to its induction machine counterpart, recent work has focused on investigating various position estimation techniques that would allow the removal of shaft position sensors.

An additional motivation for the renewed interest in SYRM is undoubtedly its inherent saliency and, thus, amenability to sensorless operation.

The basic principle used by most techniques [2] is the variation of stator inductances with rotor position which allows position estimation down to zero speed. This variation is enhanced with larger saliency ratios and can be detected in the switching ripples on the current waveforms [3] or by the magnetic coupling coefficients between windings. These two approaches are combined in [2] for both low and high speeds. A Kalman filter is then used to obtain the optimal position and velocity estimates. An effective flux – oriented speed controller based on the torque vector control principle is described in [4]. Unlike the previous techniques, It does not require a rotor position in formation at all, but only needs to know the flux position. Reference [5] outlines the versatile sensorless scheme potentially applicable to all salient ac machines.

2. The Mathematical Model

A synchronous reluctance motor is typically equipped with three – phase symmetrical sinusoidal distributed windings. The vector diagram of a synchronous reluctance machine is shown in Figure 1.

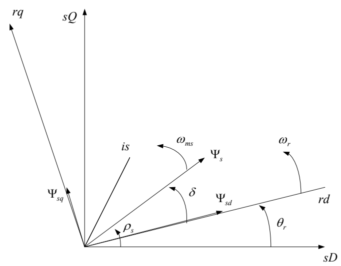

Figure 1. Vector diagram of a Synchronous Relustance Motor Source

The equations that describe the behavior of the motor can be adapted from the conventional equations of a wound field synchronous machine based on Park's equations. Since the rotor currents are zero, the equations related to the rotor are omitted. The flux harmonics in the air gap contribute only an additional term to the stator leakage inductance. The d–q equations for a Synchronous Reluctance Motor are given by

$$v_{ds} = r_s i_{ds} + \frac{d}{dt}\lambda_{ds} - \omega_r \lambda_{qs} \quad (١)$$

$$v_{qs} = r_s i_{qs} + \frac{d}{dt}\lambda_{qs} - \omega_r \lambda_{ds} \quad (٢)$$

Where

$$\begin{aligned} \lambda_{ds} &= L_{is} i_{ds} + L_{md} i_{ds} \\ \lambda_{qds} &= L_{is} i_{qs} + L_{md} i_{qs} \end{aligned} \quad (٣)$$

L_{is}, L_{md}, and L_{mq} are the stator leakage inductance, direct axis magnetizing inductance, and quadrature axis magnetizing inductance, respectively; r_s is the stator resistance per phase .

The electromagnetic torque is given by

$$T_e = \frac{3}{2}\frac{p}{2}[\lambda_{ds} i_{qs} - \lambda_{qs} i_{ds}] \quad (٤)$$

Based on the steady – steady – state equations and including the core losses of the machine, the d – q equivalent circuit of the synchronous reluctance machine is given in Figure 2.

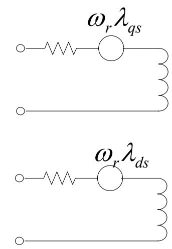

Figure 2 Equivalent circuit of a synchronous reluctance machine

3. Vector Control Principle

The machine is supplied by a PWM voltage source inverter and is current – current – controlled along the direct (d) and quadrature (q) axes of the rotating reference frame fixed to the rotor. It is assumed that the drive operates in both constant – torque and constant – power regions. Figure 3 shows the block diagram of the drive system.

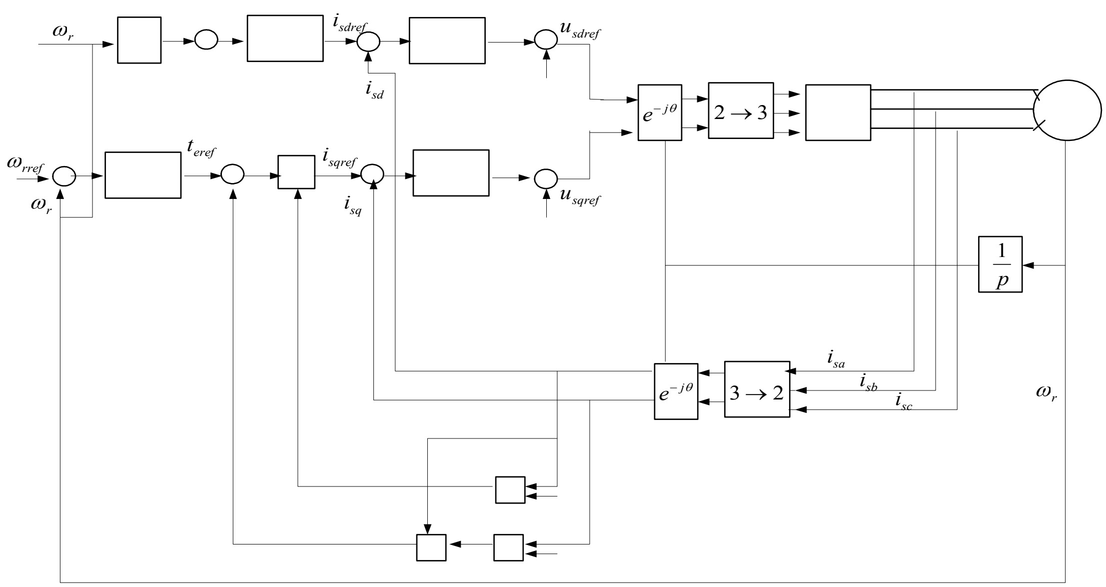

Figure 3 Vector control of a synchronous reluctance machine

The monitored rotor speed is fed into the function generator FGl, the output of which is the direct – axis stator flux reference (ψ_{sdref}). During field weakening, this reference signal is a function of the rotor speed.

The direct – axis stator flux linkage ψ_{sd} is obtained with the stator flux – estimation circuit surrounded with the dashed lines. Below base speed, the direct – axis stator flux loop is current controlled. The difference between ψ_{sdrdf} and ψ_{sd} is fed into a flux loop is current controlled, a P1 controller, and the output is the direct – axis stator current reference i_{sdrdf}. The error $\Delta i_{sd} = i_{sdref} - i_{sd}$ is fed into a current controller, also a P1 controller, and the output signal of this controller is added to the rotational voltage component, $\omega_r \psi_{sq}$, *where* ψ_{sq} is the quadrature – axis stator flux linkage expressed in the reference frame fixed to the rotor. Thus d- axis stator voltage reference u_{sdref} is obtained and it should be noted that it is expressed in the rotor reference frame.

The speed error ω_{rref} - ω_r is fed into a speed controller to produce the reference signal for the electromagnetic torque(t_{efef}). It is possible to obtain the reference torque as

$$t_{eref} = \psi_{sd} i_{sqref} - \psi_{sq} i_{sd} \qquad (5)$$

and thus the quadrature –axis stator current reference i_{sd} is obtained as

$$i_{sdref} = \frac{t_{dref} + \psi_{sq} i_{sd}}{\psi_{sd}} \qquad (6)$$

The error $\Delta i_{sq} = i_{sqref} - i_{sq}$ fed into the quadrature – axis current controller (a P1 controller) and the output signal together with the rotational voltage component $\omega_r \psi_{sd}$ is added to yield the q- axis stator voltage reference u_{sq} which is expressed in the reference frame fixed to the rotor.

The voltage components u_{sdref} are transformed in to their stationary – axes components u_{sDref}, u_{sQref} via the complex transformation e and these components are finally transformed into the three – Phase to three phase transformation shown in the block labeled $2 \rightarrow 3$. These are the reference voltages for the inverter

It has been necessary to use the stator current components i_{sd}, i_{sq} which correspond to the rotor reference frame. In Fig. 3 these are obtained from the monitored three – phase stator currents (i_{sA}, i_{sB}, i_{sB}) by the application of the three – phase to two – phase and e complex transformations. Because of the absence of the zero – sequence currents, it is possible to obtain i_{sd} *and* i_{sq} by utilizing only two monitored stator currents.

The stator flux components are obtained by the stator flux estimator circuit shown in Fig. 3, which uses $\psi_{sq} = L_{sq} i_{sd}$ *and* $\psi_{sq} = L_{sq} i_{sd}$ and assumes L_{sd} and L_{sq} to be known; they can even vary with i_{sd} and i_{sq} It is also possible to implement other flux estimators, e.g. those which involve monitored machine terminal voltages and currents.

Like the permanent magnet brushless motor, the synchronous reluctance motor also needs an absolute rotor position sensor for starting, running, and closed loop control. Using the rotor angular position, the stator currents are transformed from the stationary reference frame to the rotating reference frame (of d-q components). The position sensor is also used for speed measurement. Based on the speed value, the desired values of i_{ds} and i_{qs} are established. These desired values are compared with the actual values of i_{ds} and i_{qs} and the errors are amplified and integrated in PI controllers. The voltage outputs of the PI controllers are converted back to the stationary reference frame using the rotor angular position signals. The resulting components define the PWM switching pattern for the power devices of the voltage source inverter feeding the motor.[6]

4. Neural Network Algorithm

The proposed feedforward neural network is indicated in figure 4.The network has three layers, Input layer, Hidden layer, and the Output layer. The circles in the network represent the neurons. The input and output layers have neurons equal to the respective number of signals, where has the hidden layer in the present design has 20 neurons. The topology can be defined as eight-twenty-one network. The network is fully connected, the output of each neuron is connected to all the neurons in the forward layer. The hidden layer neuron has hyperbolic-tan type nonlinear transfer function. The feedforward neural network is usually trained by a back-propagation training algorithm.(first proposed by Rumelhart, Hinton, and William in 1986)

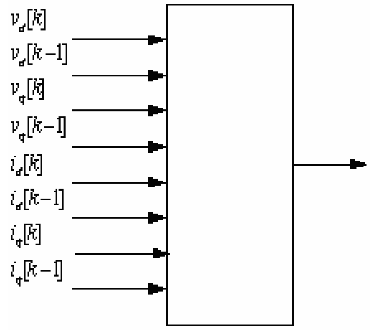

Figure 4 the neural network used for estimation

Once the training is finished, the neural networks establish the relationship between the input voltages/currents and the speed of rotor, hence can be used as a estimator for speed of rotor.

5. Simulations and Results

To verify the proposed approach of the position estimation, digital simulations were carried out. The required phase voltages and currents were measured directly from an existing Synchronous Reluctance Motor drive system. This system consists of a Synchronous Reluctance Motor, an incremental encoder, a PI controller and a PWM current controller.. The parameters of the SYRM are listed in Table 1. [7]

Power	5.8KW
Voltage(rms)	415V
Current(rms)	14.3V
Speed	1500rpm
Poles	4
Ld/Lq unsaturated	9.1
Ld/Lq saturated	7.8
Lq	9.8mH
Rdc(ohm)	0.6
J(kgm2)	0.23

Table 1: The SYRM motor parameters

The simulation results at no-load and 1500rpm are given in Figure 5-8. Figure 5 shows the measured motor phase current, Figure 6,7 present the measured and estimated rotor speed. The speed can get to Steady state during 0.7s. The Speed estimated Error after 0.7s is shown in figure 8.

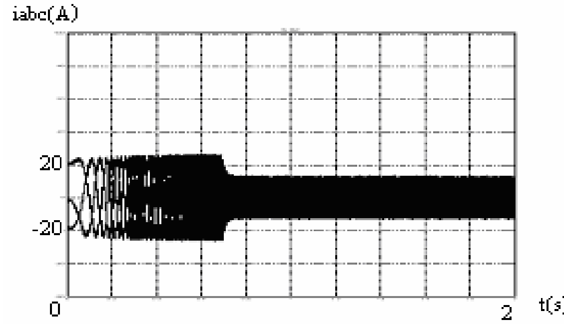

Figure 5 SYRM Current

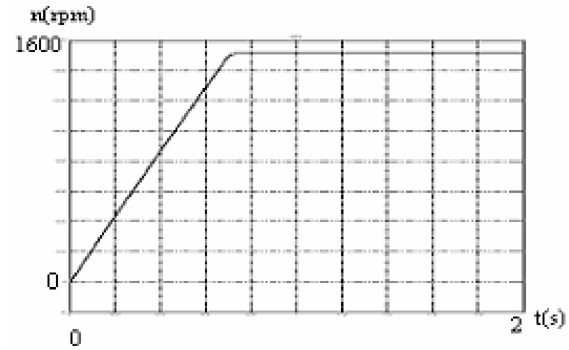

Figure 6 Real Speed

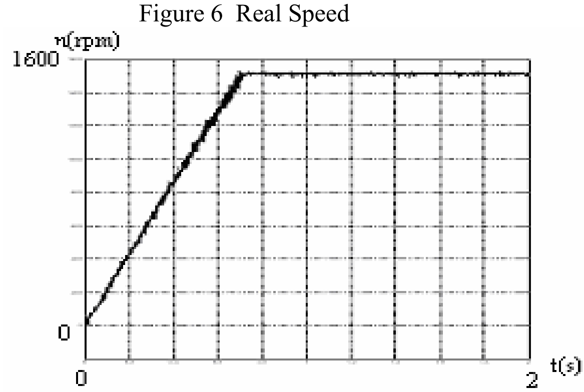

Figure 7 Stimated Speed with Neural Network

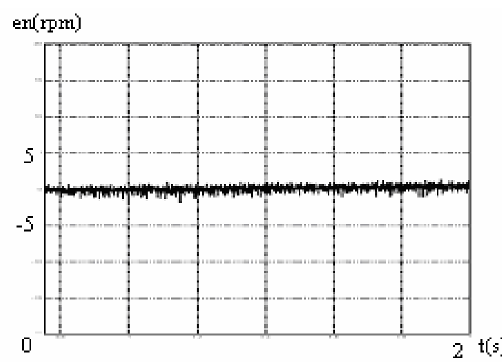

Figure 8 SYRM Speed estimated Error in Steady State

We studied many condition and get results, and consider them. For example , another examine in low speeds (300rpm)

The simulation results at no-load and 300rpm are given in Figure 9-12 (for the first second). Figure 9 shows the measured motor phase current, Figure 10,11 present the measured and estimated rotor speed. Figure 12 shows the measured Torque of motor

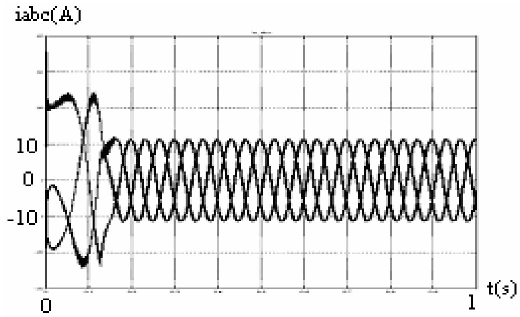

Figure 9 SYRM Current

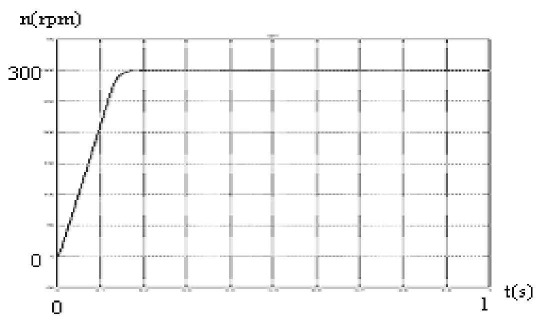

Figure 10 Real Speed

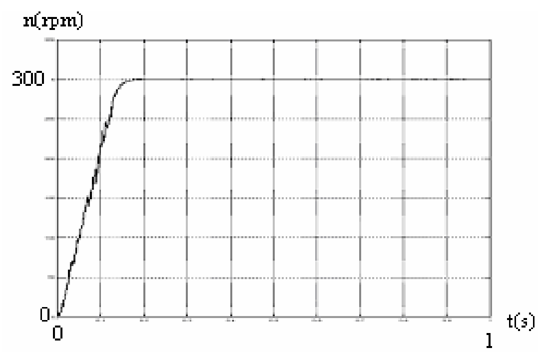

Figure 11 Stimated Speed with Neural Network

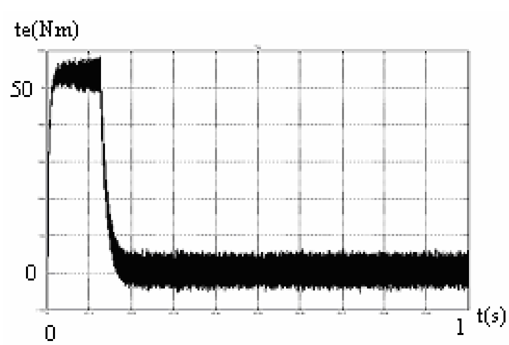

Figure 12 SYRM torque

In many of methods we didn't have good result at low speeds, but in this method we can reached to accurate stimated speed. (at 0.15 s). At the starting the torque of motor is about 50NT and after that disappear (become zero – between +5,-5)

6. Conclusions

A neural network approach to sensorless control of synchronous reluctance motor was proposed. The simulation result shows that stator voltages and currents can be used to estimate the speed of rotor. Although the estimator performance was demonstrated for a Sensorless vector-controlled SYRM drive, it can be extended to scalar or indirect vector control of any type of drive system. The estimator can be implemented either by hardware or by microprocessor software. The neural network has distinct advantages when compared to the conventional DSP-based estimator and promises to be the future choice for application in industrial drives.

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