COMPARISON OF FLUX LINKAGE ESTIMATORS IN POSITION SENSORLESS SWITCHED RELUCTANCE MOTOR DRIVES

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ABSTRACT

There are some proposed methods in the literature about position sensorless Switched Reluctance Motor (SRM) drives based on using current and flux linkage of active phase. Although all conventional SRM drives include highly precise and robust phase current sensing systems, the same statement is not correct for the flux linkage. Besides that, flux linkage is not a quantity that can be explicitly measured at the SRM electrical terminals. It must be estimated by measuring phase winding voltage in addition to the phase current and using Faraday's Law. This paper compares the performance of digital and analog flux linkage estimators used in a position sensorless SRM drive. The position estimation scheme adopted here is an Artificial Neural Network (ANN) based rotor position estimator. But the comparison results can be fully extended to other SRM rotor position estimators which utilize phase current and flux linkage information.

I.INTRODUCTION

The Switched Reluctance Motor has been receiving attention for industry applications due to its low cost in mass production, reduced maintenance requirements, rugged behavior and large torque output over very wide speed range. On the other hand, torque ripple, acoustic noise and rotor position sensor requirements are main disadvantages of the motor[1,2].

A large number of methods have been introduced to accomplish position sensorless drive of the SRM during the last fifteen years. The fundamental principle used in position estimation is the extraction of rotor position information from stator circuit measurements or their derived parameters. Flux linkage is a function of the rotor position and the current through the phase winding. The magnetization characteristic which establishes relation between electrical and mechanical variables of an SRM is shown in Figure1. Compared to other types of electric machines, it is an advantage for an SRM not to have a rotor field disturbing the stator field. On the other hand, the nonlinear relationship between the electrical and mechanical terminals of the machine makes analytic calculation of rotor position impossible for a given flux linkage and current value.

All of the proposed rotor position estimation techniques try in one way or another to use the SRM as its own sensor[3]. Some of these techniques require manipulating the unexcited phase[4,5,6]. Another group of methods use active phase quantities for position estimation. In [7], magnetization data are used for position estimation. The data are stored in a look-up table and interpolation is used to estimate rotor position. The major difficulty in their approach is the accurate modelling of SRM since they used simulated data instead of real time experimental data.

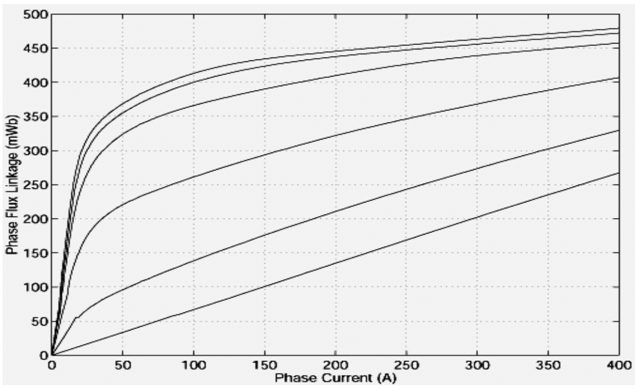

Figure.1 Magnetization curves for a 20kW 6/4 SRM.

In [8], magnetization data of only aligned and unaligned positions are used from the measurements, then fuzzy reasoning is used to construct magnetization curves for the intermediate positions . It is also suggested in [8] to use fuzzy-logic for position estimation along with a coarse position estimator which is using the dynamic equation of the motion. In another fuzzy reasoning based method proposed in [9], measured magnetization data for several rotor positions are stored in fuzzy rule base tables, the position information is then retrieved from the tables during the online operation. Another artificial intellegence based method using ANN is proposed in [10]. This method is fundamentally similar to fuzzy reasoning based methods in terms of utilizing the current and flux linkage information of active phase.

As can be seen from this review of the rotor position estimation schemes in SRM drives, the availability of the phase current and flux linkage information plays an important role in most of the proposed methods. This paper presents a comparison between different flux linkage estimation schemes. In Section II, Position sensorless operation of a SRM by using ANN is introduced. In Section III, flux linkage estimation is discussed from general perspective. Section IV and Section V are about the details of digital and analog flux estimation schemes, respectively. Finally, Section VI compares the performance of two methods based on experimentally acquired data.

II. POSITION SENSORLESS OPERATION OF AN SRM BY USING ANN

The basic premise of an Artificial Neural Network based position estimation method is to form a very efficient mapping structure for the nonlinear SRM. Through measurement of the phase flux linkages and phase currents the neural network is able to estimate the rotor position, thereby facilitating elimination of the rotor position sensor. The ANN training data set is comprised of magnetization characteristic of the SRM of which flux linkage λ and phase current i as inputs and the corresponding position θ as output in this set. Given a sufficiently large training data set, the ANN can build up a correlation among λ, i and θ for an appropriate network architecture[10,11]. Figure.2 and Figure.3 show how the ANN is trained off-line and then used as an on-line position estimator, respectively.

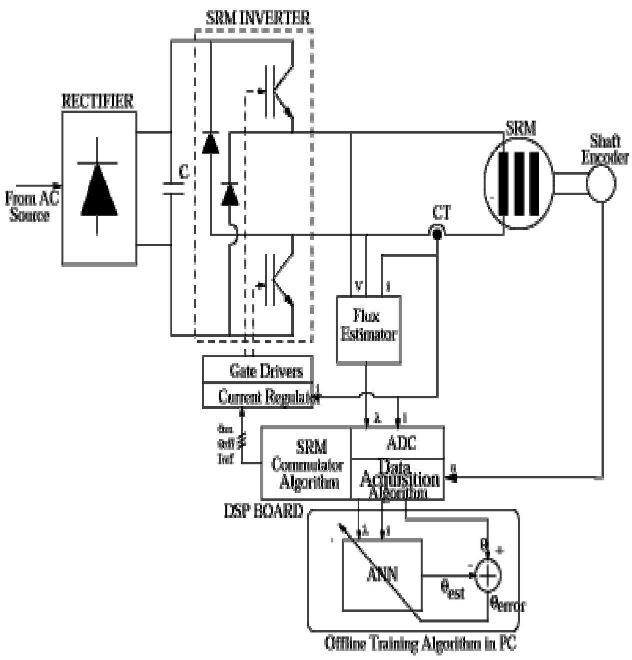

Figure.2 Collecting data and training an ANN.

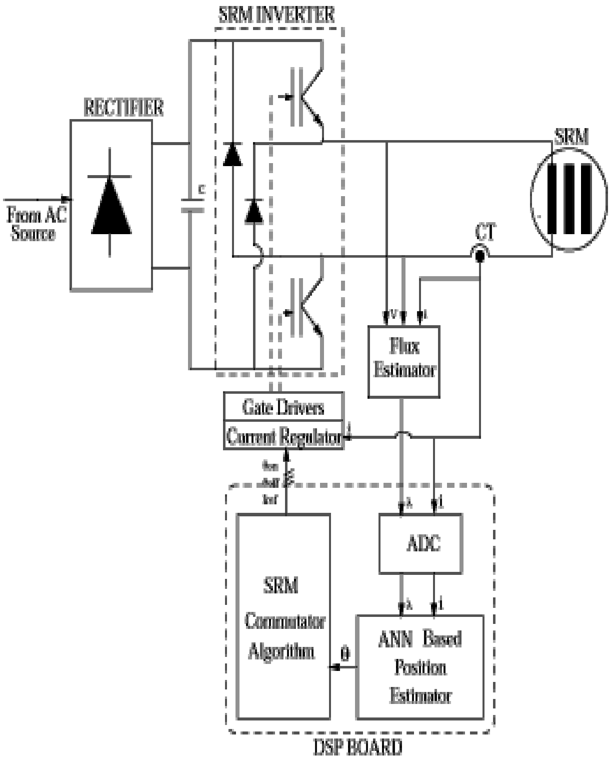

Figure.3 Usage of the trained ANN as a position estimaton.

III. FLUX LINKAGE ESTIMATION

It was previously stated that the ANN estimator is driven by phase current and phase flux linkage information to obtain estimated rotor position. Although all conventional SRM drives include phase current sensing systems, the same statement is not correct for the flux linkage. Besides that, flux linkage is not a quantity that can be explicitly measured at the SRM electrical terminals. It must be estimated by measuring phase winding voltage in addition to the phase current and using Faraday's Law,

$$\lambda = \int (v - Ri)dt \qquad (1)$$

where,

λ: Phase winding flux linkage (Wb.)

v: Voltage across the phase winding (V)

R: Phase winding resistance (Ω)

i: Phase current (A)

This estimation algorithm can be implemented either through a software algorithm or through an analog circuit. Both methods have been investigated and our studies have shown that both methods have their own drawbacks as well as some benefits.

IV. DIGITAL IMPLEMENTATION FOR THE FLUX LINKAGE ESTIMATION

By using the trapezoidal rule, the discretized version of the Faraday's law given by Equation.1 can be obtained as,

$$\lambda(k)=\lambda(k-1) + 0.5*T*(v(k)-R*i(k)+v(k-1)- R*i(k-1)) \quad (2)$$

where,

$\lambda(k)$: The most updated flux estimation (Wb).

$\lambda(k-1)$: The flux linkage estimation from the previous sampling interval (Wb).

v(k): The most updated phase voltage sensing (V).

v(k-1): The phase voltage sensing from the previous sampling interval (V).

i(k): The most updated phase current sensing (A).

i(k-1): The phase current sensing from the previous sampling interval (A).

R: The phase winding resistance (Ω).

T: Sampling period (s).

The digital implementation enjoys the extreme simplicity in the implementation and the flexibility in the tuning. On the other hand, the accuracy of the estimated flux linkage is limited by the sampling rate. In particular, the estimation error increases during the current regulation mode where relatively high frequency voltage pulses are needed to be sensed and integrated. Although the sampling theorem is employed and the voltage is sampled at a frequency 3-4 times higher than the PWM frequency, the resulting flux estimation error is large enough to get a high estimation error in the position. As a result, the available Digital Signal Processor (DSP) platform to implement whole algorithms during the sensorless SRM drive study is not capable of operating at a frequency that is sufficiently high to reduce the error resulting from the low sampling frequency.

V.ANALOG IMPLEMENTATION OF THE FLUX LINKAGE ESTIMATION

An analog circuit designed with precise elements and by considering certain precise circuit design rules was conceived to be a better solution to the flux linkage estimation problem. This circuit is basically analog implementation of Faraday's law given by equation.1 An analog integrator forms the core part of the analog flux estimator. This integrator basically implements the integral form of Faraday's law. Before the integration, sensing and isolation of phase voltage is accomplished by an isolation amplifier. After subtracting the resistive voltage drop from the sensed voltage, the resulting voltage which represents phase back emf is fed into the integrator. Theoretically, the voltage across the winding becomes zero after the flyback diode currents become zero. Since there is no voltage at the input of the integrator the output of it should stay at zero. This is not the case in practice because certain nonzero voltage exists at the integrator input and this causes drift in the integrator output. As a result, the drifting saturates the integrator output in a relatively short time period. This problem is solved by resetting the integrator after each time the phase current becomes zero. For this purpose, the available phase current sensing is used. An instrumentation amplifier amplifies the current and then this current is fed into a comparator which forms a zero current detection circuit. This circuit generates a pulse as long as the current stays at zero. This pulse is used to prevent the integrator from drifting.

Figure.4 shows the complete analog integrator built for one phase of the SRM. The AD210 is a precision isolation amplifier that is used to isolate the floating phase voltage from the rest of the system. A symmetrical voltage divider was used to step down the voltage before entering the isolation amplifier. On the other side of the circuit, sensed phase current is amplified with an AMP02 precision instrumentation amplifier and fed into an analog summer along with isolated phase voltage from the AD210. The summer circuit was implemented with a LT1056 high-precision low-offset operational amplifier. The output of the summer circuit represents the back emf of the SRM; and is fed into the integrator. The integrator was implemented with the MAX420, another high-precision and ultra low-offset operational amplifier. A specially built-in circuit in this IC keeps the offset voltage almost at zero, so sufficiently high precision integration is achieved. A simple auxiliary circuit across the feedback capacitor of the integrator periodically discharges the capacitor and prevents it from being recharged as long as the phase current stays at zero. As shown, this can be achieved with 100 Ohm resistor in series with a transistor used as switch. The transistor is turned on or off by a pulse generated by the zero current detection circuit. It is turned on once the phase current hits the zero level and stays on until the current starts to build up for the next electrical cycle. The zero current detection circuit is formed by an LM311 comparator[12].

VI. COMPARISON BETWEEN DIGITAL AND ANALOG FLUX ESTIMATOR

It has been stated that flux estimation error increases the position estimation error and the analog flux estimator has relatively better performance than the digital flux estimator. The cause of the poor performance in the digital version of the flux estimator is insufficient sampling rate. Although this problem can be solved by using a faster processor, the available DSP does not allow a sampling rate above 10 kHz. Figure.5 and Figure.6 show the performance of position estimator using the digital flux and analog flux linkage estimators, respectively. Figure.7 compares the two flux estimators at 800rpm shaft speed. As seen from Figure.7, the estimation error is bounded by a much narrower band in the analog flux estimator case and improvement in the position estimator performance is achieved.

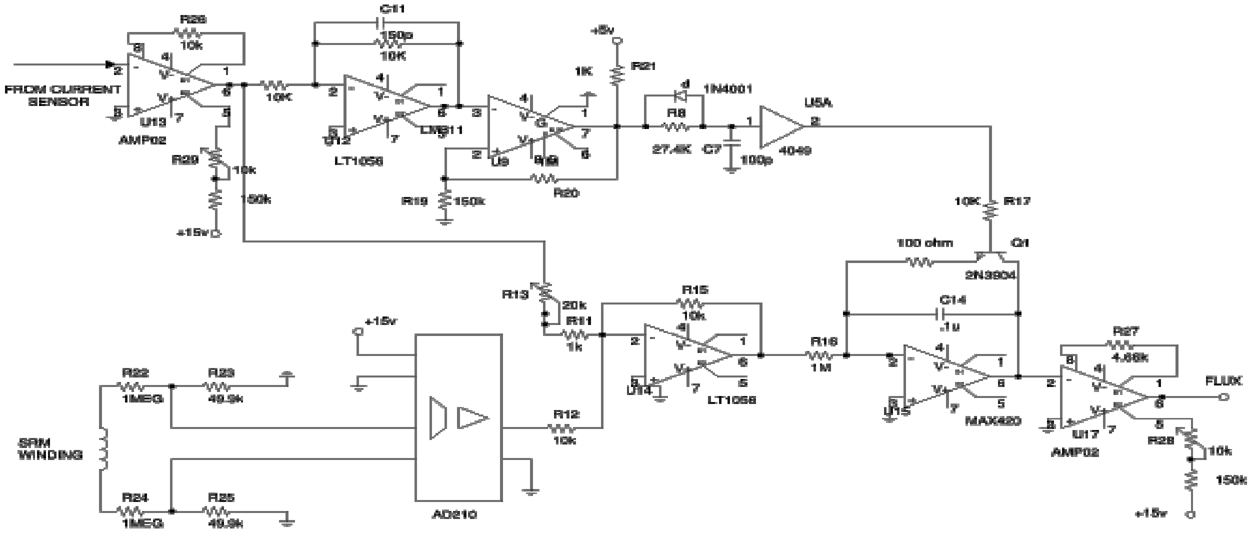

Figure.4 The circuit showing the analog implementation of flux linkage estimator

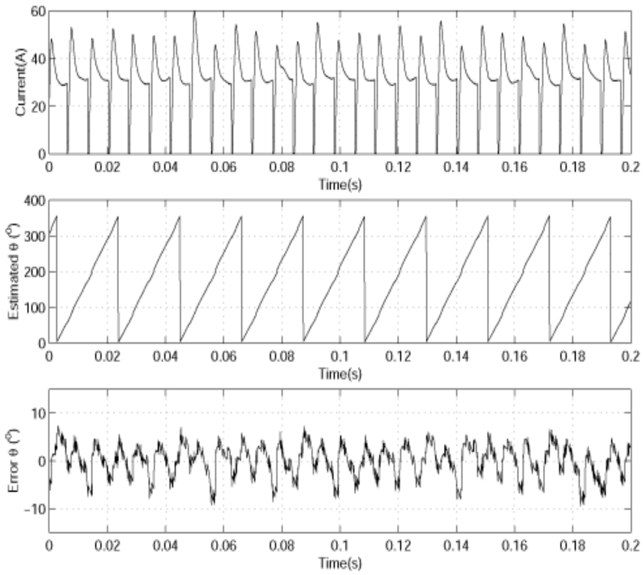

Figure.5 Phase current, estimated position and estimation error waveforms for the position estimator using the digital flux estimator at 1000rpm.

Showing the analog flux estimator as absolutely superior over the digital flux estimator would not be fair. There are certainly some disadvantages associated with using the analog estimator. Although great effort has been spent to make the analog estimator very accurate, Electromagnetic Interference (EMI) has considerable distorting effect over the circuit, particularly above 50-60A current level of the SRM. This issue has two effects over the position estimator: One is the generation of outliers in the training data set and the other is generation of outliers during the online operation which is a cause for the wrong position estimation. The cost is another disadvantage of the analog flux estimator. In particular, accuracy requirement makes the cost higher. The trade-off between the accuracy of the analog estimator and the simplicity of the digital estimator should be carefully made.

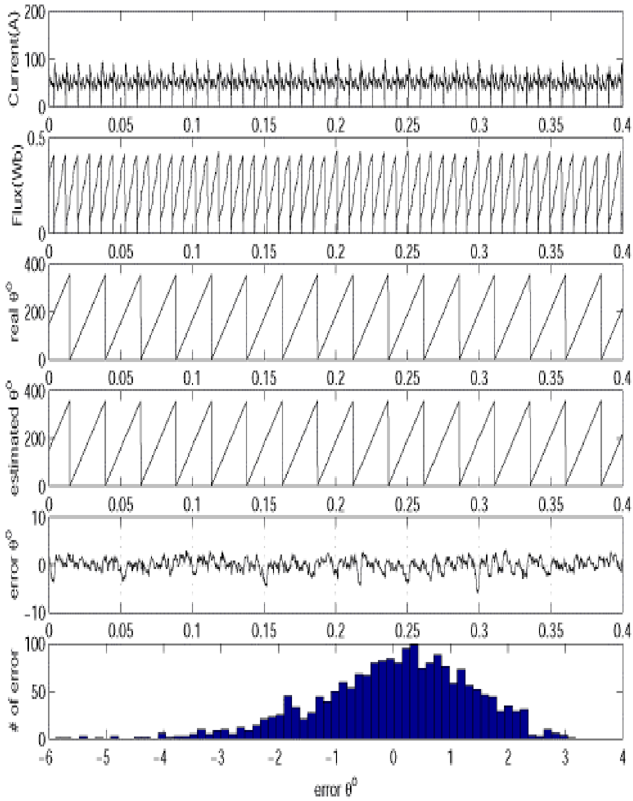

Figure.6 Phase current, flux linkage, real and estimated rotor position, position estimation error and error distribution with analog flux linkage estimator at 600rpm.

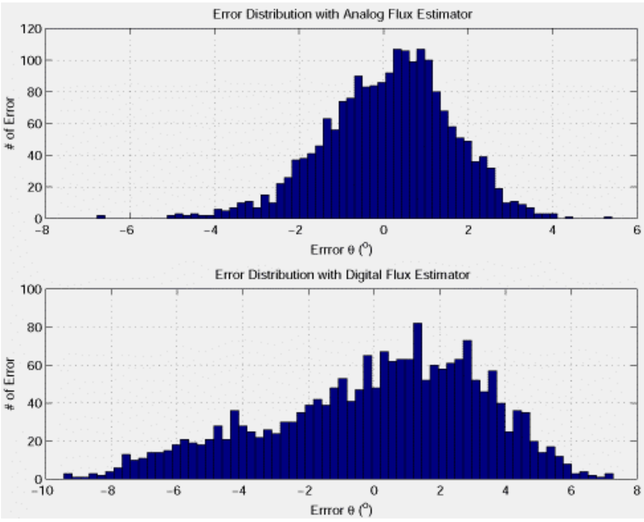

Figure.7 Position estimation error distributions for two different flux estimators at 800rpm.

VII. CONCLUSION

In this study, a comparison between digital and analog flux estimators which are used in a position sensorless SRM drive is presented. Experimental results show that digital scheme can estimate flux linkage with less accuracy but in simpler and more flexible manner. Low accuracy in digital flux estimator is a result of limitation in sampling rate of voltage waveform especially in PWM chopping mode. This problem can be overcome by using faster DSP. Analog flux estimator is more superior over digital scheme in terms of accuracy as long as it is built by considering some precision circuit design issues. However, analog flux estimation scheme is not as flexible as digital scheme. Moreover, the susceptibility to EMI and the cost are other disadvantages of analog flux linkage estimation scheme.

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APPENDIX: EXPERIMENTAL SRM DRIVE

A conventional SRM drive system has been constructed by the following subsystems: SRM, two switches per phase inverter, IGBT gate drive circuits, Hall effect current sensors, an analog current regulator for chopping mode operation and DSP. Following tables summarize the details of SRM and DSP system.

SRM

PARAMETER	VALUE	UNITS
DC Bus Voltage	150	V
Base Speed	3000	rpm
Rated Continous Power	11.5	kW
Number of Phases	3	
Number of Stator Poles	6	
Number of Rotor Poles	4	
Stator Pole Arc	32	degrees
Rotor Pole Arc	45	degrees
Turns per Pole	13	
Aligned Phase Inductance	18	mH
Unaligned Phase Inductance	0.67	mH

DSP-TMS320C30

Clock Speed	33MHZ
ADC	16 channel, 3μs conversion time
DAC	32 Channel
Sampling Rate	100 μs
Programming	C Language