CHAPTER 3

LOW COST DIGITAL MEASUREMENT SYSTEM FOR SRM

3.1 INTRODUCTION

SRM drives have entered the market with applications already developed or being developed for industries, consumer products, aerospace and automobile industries. The SRM drives have attractive features of fault tolerance, excellent speed torque characteristics and the absence of magnets. However, the control of an SRM depends on the commutation of the stator phases in synchronism with the rotor position. Rotor position sensing is an integral part of SRM control because of the nature of reluctance torque production. A shaft position sensor is usually employed to determine the rotor position. However, these discrete position sensors not only add complexity and cost to the system, but also tend to reduce the reliability of the drive system.

Besides, there are certain other applications, such as compressors, where the ambient conditions do not allow the use of external position sensors. The position-sensing requirement increases the overall cost and calls for extra space and complexity. This drawback excludes the SRM from many cost sensitive industrial applications. Sensorless operation is a key requirement for the success of SRM drives in various industries. Several sensor-less control methods have been reported in the literature over the past two decades. Of these, a non-intrusive method involving magnetic
characteristics and inductance profile are mostly used to find the rotor position indirectly. Therefore, it is necessary to have an accurate knowledge of the motor’s magnetic characteristics in order to predict the motor’s performance for better control. It is also possible to calculate the magnetization curves without experimental measurement of the motor waveforms using finite element methods as shown by Moghbelli (1991) and Moghbelli et al (1988) and using active phase vectors (Ramani and Ehsani 1994). However, the accuracy of such methods varies according to the choice of the elements used, and in addition, the complexity of computation. Secondary effects, such as manufacturing irregularities, three-dimensional (3-D) fields, and non-uniform iron structure, are difficult to model. Hence, real-time experimental evaluation is absolutely necessary. Therefore, a number of measuring techniques, Adrian D Cheok (2001), Krishnan et al (1988, 1990) and Ferrero and Racati (1990) have been proposed in the literature:

(i) Measuring the flux linkage through magneto-resistive sensors.
(ii) Measuring the flux indirectly with op-amp circuits.
(iii) Measuring the inductance indirectly with op-amp circuits.
(iv) Measuring the flux linkage indirectly.

Among all the above methods, the last one, of measuring flux linkage is most widely accepted. Many papers have reported on the performance simulation of the SRM with experimental validation for different control strategies, such as feedback linearization control, variable structure control, fuzzy logic control and four-quadrant operation of the SRM. None of these papers have focused their discussion exclusively on a low cost digital measurement system, to acquire the parameters of the machine, which are very much required for the sensorless operation of an SRM drive.
3.2 SRM DESCRIPTION

A proto-type SRM having 6 stator poles and 4 rotor poles is shown in Figure 3.1; here the angle of the stator pole arc ($\beta_s$) and the angle of the rotor pole arc ($\beta_r$) are described. Figure 3.2 shows an idealized inductance profile of an SRM. From Figure 3.2 the phase inductance variation over one rotor pole pitch with constant current magnitude is determined. The phase inductance is maximum when the rotor pole is aligned with the stator pole, and the phase inductance is minimum when the rotor pole is aligned with the interpolar axis of the stator.

Figure 3.1 6/4 Pole proto-type SRM
Self Inductance $L$ (H)

\[
\frac{dL}{d\theta} = 0 \quad \frac{dL}{d\theta} > 0 \quad \frac{dL}{d\theta} = 0 \quad \frac{dL}{d\theta} < 0 \quad \frac{dL}{d\theta} = 0
\]

Figure 3.2 Inductance ($L$) variation over one rotor pole pitch with constant current magnitude

\[
L(\theta) = \begin{cases} 
L_{na} & \theta_0 \leq \theta < \theta_1 \\
L_{na} + p\theta & \theta_1 \leq \theta < \theta_2 \\
L_a & \theta_2 \leq \theta < \theta_3 \\
L_a - p(\theta - \beta_s) & \theta_3 \leq \theta < \theta_4 \\
L_{na} & \theta_4 \leq \theta < \theta_5 
\end{cases} \tag{3.1}
\]

Where

$L(\theta)$ - Inductance variation over one rotor pole pitch

$L_{na}$ - Unaligned inductance (H)

$L_a$ - Aligned Inductance (H)

$\beta_s$ - Stator pole arc (rad)

$\beta_r$ - Rotor pole arc (rad)

$\beta_r > \beta_s$ and $p = \frac{L_a - L_{na}}{\beta_r}$

The single phase equivalent circuit of the SRM can be described as shown in Figure 3.3.
Figure 3.3 Per phase electrical equivalent circuit of the SRM

\[ V(t) = Ri(t) + L(\theta, i) \frac{di}{dt} + i\omega \frac{dL(\theta, i)}{d\theta} \]  \hspace{1cm} (3.2)

where,

- \( V \) - Voltage applied to the phase
- \( r \) - Phase resistance
- \( Ri(t) \) - Resistive voltage drop
- \( L(\theta, i) \frac{di}{dt} \) - Static voltage
- \( i\omega \frac{dL(\theta, i)}{d\theta} \) - Speed voltage

Equation (3.2) is applicable only when the mutual inductances are neglected. From this equation (3.2), it is understood that the speed voltage of each phase is proportional to the actual speed of the motor and the rate of change of inductance is proportional with respect to rotor position. The instantaneous torque (\( T_d \)) produced in the SRM is given by the formula,

\[ T_d = \frac{1}{2} i \frac{dL}{d\theta} \]  \hspace{1cm} (3.3)

From the above non-linear equation, the motoring torque and braking torque can be obtained. The Motoring torque can be determined only when the phase current is switched on during the rising period of phase inductance and the braking torque can be determined from the switching off phase current during the decreasing period of phase inductance. It is obvious
from Figure 3.2 and the above equations (3.1-3.3) that rotor position sensors are used to have a better control on SRM drive and its essential to have a low cost digital measurement system.

3.3 REVIEW ON FLUX LINKAGE MEASUREMENTS

Nowadays, it’s very important that flux linkage, current and rotor position information are required for the successful operation of the SRM and any other motor drive, which eliminates the physical sensors and enhances the reliability of the motor drive systems. At present, there is no such low cost digital system, which can do these kinds of measurements with the desired accuracy. This has led to the search for various measurement techniques.

a) **Direct flux sensor:** In this type, the coils are physically mounted inside the motor; this is not usually preferred as it is very expensive and complex. Also, it was observed that this led to complicate the motor design and manufacturing process. In addition, the flux sensors were not able to measure a wide range of flux variations accurately due to high frequency switching.

b) **Direct inductance measurement system:** The other method for acquiring the motor characteristics is to measure the inductance (L) of the motor directly for various values of currents. Motor phase inductance can be measured by ac bridge methods (Acarnley et al 1985). But, these methods are not popular due to the injecting of high frequency signals into the phase winding of the machine. This method depends on the frequency of the signal that is being injected into the phase windings, which means that this measurement technique will not be valid for other frequencies.
c) **Analog flux measurement systems:** Here, the acquired voltage and current information are basically used to calculate the flux linkage (Ray and Al-Bahadly 1994, Ray and Erfan 1994). This leads to additional operational amplifier circuits, which are not dependable in hot environments, where the operational amplifier output will vary due to temperature variation on resistance in the feedback circuits. A small variation in flux linkage calculation will lead to an error in operation.

d) **Digital flux linkage calculation:** Digital flux linkage calculation requires phase current and voltage information, which will be measured through suitable sensors and fed into the ADC of a digital controller for digital flux linkage function implementation by software. The main advantage of calculating the flux linkage by digital techniques, is the elimination of the drifts, sags and swells, and component non-linearities found in analog integration. Also, digital flux linkage measurements can readily be used for indirect rotor position implementations, control and any other graphical representations. Digital integration schemes have been very well discussed in Adrian David Cheok and Nesimi Ertugrul (2001).

### 3.4 LOW COST DIGITAL MEASUREMENT SYSTEM DESCRIPTION

The basic step, which is being used by the algorithm of the Code Composer Studio (CCS) environment, is explained below.

i) Turn on the PC; ensure that the CCS environment drive is open, and download the digital measurement program for the SRM drive into the TMS320F2812 DSP.

ii) Start the machine by the soft start algorithm, which ensures that rotor stabilization is done and generates the necessary PWM signals to the SRM converter.
iii) Acquire all the phase voltages and currents through Hall
effect sensors and verify with reference to the set value.

iv) Self Calibration is done by comparing the acquired phase
information with the reference value.

v) Go to the normal mode once when self calibration is done.

vi) Measure the motor instantaneous phase voltages and
currents and calculate the flux linkage.

vii) Produce instantaneous graphical output using the CCS
graphical window for voltage, current, flux linkage.

viii) Repeat this measurement process till the motor stops.

The CCS environment is a very simple and cost-effective solution,
which can be used to define the software and the hardware, and added to a
personal computer so that the computer acts as a custom-designed instrument.
In the graphical window environment, the graph property dialog allows the
user to edit the display type, which gives more freedom for the developer to
implement any kind of parameter display, which is required to be displayed
for motor drive systems.

The main program of the software developed and reported in this
research study allows the user to enter/scale any essential parameters of the
SRM motor drive like phase currents, voltages, resistances, rotor angle,
number of rotor/stator phases. This low cost system is capable of displaying
instantaneous current, voltage, actual/measured rotor positions and flux
linkage versus time, after the soft start algorithm is executed. The data of
these parameters can be stored as a data file and can be used to display flux
linkage versus current graphs for various rotor positions and the same is given
in Figure 3.4.
3.5 HARDWARE SYSTEM DESCRIPTION

The SRM drive system is made up of several distinct subsystems and is illustrated in Figure 3.5. The subsystem consists of a 6/4 pole SRM, personal computer (PC), driving circuit, power converter, sensing circuitry and the eZdsp F2812 board from Texas Instruments as a development tool board. The SRM is equipped with a rotor position sensor. The three sensors are mounted on the shaft of the SRM, wherein a combination of an infrared LED (MLED930) and photo transistor (MRD5009) are used to sense the rotor position to indicate which of the three phases of the SRM is to be excited as the motor runs. One of the rotor position sensors’ outputs is used to calculate the actual speed of the SRM.
The controller is implemented by software and executed by an eZdsp F2812 board. The eZdsp kit provides a complete development environment, and includes the Digital Signal Processor (DSP) board, power supply for the board, on-board JTAG compliant emulator, and an eZdsp specific version of the CCS integrated development environment (full featured, including debugger IDE, and ANSI C and C++ compliant compiler). The DSP board itself has nearly all-peripheral signals available on the board headers, making it easy to interface the board with other system hardware. The program is completely contained in the DSP and the computer is only required to load new programs into the DSP.

Figure 3.5  Block diagram of digital measurement system for SRM
Additionally, it has an internal Analog-to-Digital Converter (ADC), which can accept up to sixteen analog inputs and two event managers, and is used to produce the necessary Pulse Width Modulation (PWM). Also, necessary protection circuits are used to prevent damage to the DSP. The control algorithm is written and loaded into the DSP using the PC. The driver circuit is constructed using the totem pole configuration, wherein NPN (3904) and PNP (2907) transistors are used. In order to maintain the current at its rated value, the DC bus current is measured through a current sensor (LEM25-NP). The inputs to the DSP are the rotor position information and dc bus current. The output of the switching logic section is a sequence of gating signals that are pulse-width modulated (PWM) gating signals, which are used to drive the classic bridge converter. The power converter is a classic bridge converter utilizing six MOSFETs (IRFP360) and fast recovery diodes (MUR3060). The output of the power converter is chopped to get the desired voltage.

3.5.1  eZdsp F2812 Board

The eZdsp F2812 board is available from Texas Instruments as a development tool. This eZdsp kit provides a complete development environment, and includes the DSP board, power supply for the board, on-board JTAG compliant emulator, and an eZdsp specific version of the Code Composer Studio (CCS) integrated development environment (full featured, including debugger IDE, and ANSI C and C++ compliant compiler). The DSP board itself has nearly all the peripheral signals available on the board headers, making it easy to interface the board with other system hardware. The eZdsp board requires that pins 17 and 18 on header P9 be connected, for the ADC to function properly (i.e., connect the ADCLO to analog ground on the DSP). This connection was done manually on the board.
3.5.2 Software

The entire SRM low cost digital measurement system consists of system initialization, followed by a single interrupt loop (the ADC end-of-conversion interrupt), which implements the speed Control algorithm. GP Timer 1 is used to clock the PWM output at a 4 kHz switching frequency. The function main() performs CPU and peripheral initialization, and then enters an endless loop that waits for the ADC end-of-conversion interrupt. The controller itself is implemented in the ADC interrupt-service routine in the file DefaultIsr.c. The clock frequency of the DSP is 150MHz. All timing calculations (e.g., sample rates, PWM frequencies etc.) have been performed, based on this clock speed. The ADC sampling rate and PWM switching frequency can be changed using the constant sample period and PWM_period found in the file srm.h. The PWM is of the asymmetric type. The actual position information forms one of the position sensors to the capture unit-1 and is used to calculate the actual speed of the motor. Actual phase currents, voltages and reference speed are fed through the ADC channel-0 to ADC channel-6. The values obtained from the ADC and Capture unit-1 will be an input to the speed control algorithm and low cost digital measurement system. The ADC channel to be used can be selected using the constant ADC channel in the file srm.h. The ADC channel configuration uses the adcina0 and adcina1 channels. The speed reference value is from 0-3.0 volts, which corresponds to 0-3000 rpm. This can be changed through ADCina0. All the variables pertaining to the SRM controller are contained in the structure srmdeclared in the file global variable defs.c. This structure of the controller and measurement system is defined in the file srm.h. In addition, the total controller output as well as the current control limit is independently assigned in the main(). All these values can be altered, if desired.
However, it was observed during experimentation that sampling the speed signal at the same time as the PWM was switched either on or off, induced noise in the converted actual speed-reading. To overcome this problem, it is desired to synchronize the triggering of the ADC (i.e., GP timer 2) with the PWM clock base (i.e., GP timer 1), and then to adjust the sampling instant so that the PWM is not switched at that moment.

### 3.6 SPEED CONTROL SYSTEM

The speed control of the SRM utilizes PID control algorithm. Figure 3.6 shows the block diagram of the speed control system. The input to the closed loop system is taken as the reference speed and the difference in the estimated speed from the reference speed is considered as the speed error. The speed error is processed through a proportional plus integral plus derivative controller. The PID controller output is given by

\[
 u(t) = k_p e(t) + \frac{1}{T_i} \int_0^t e(t) \, dt + T_d \frac{de(t)}{dt} \tag{3.4}
\]

where
- \( u \) - Controller output signal
- \( e \) - Controller input (error signal)
- \( k_p \) - Controller proportional gain
- \( T_i \) - Integral time
- \( T_d \) - Derivative time

![Figure 3.6 Block diagram of the SRM speed control system](image-url)
The speed controller with an inner current loop will generate the reference current for the current controller. The current command is compared with the motor current and their errors generate the required PWM control signals. These controls signals are steered to the corresponding base/gate of the power switches (MOSFET) of the power converter, which will maintain the desired speed of the SRM. Figure 3.7 shows the response of the speed controller in steady state at 1000 rpm.

![Figure 3.7 The response of the speed controller in steady state at 1000 rpm](image)

### 3.7 RESULTS AND DISCUSSIONS

The SRM drive was built and tested to plot its magnetic characteristics. The algorithm to plot the phase voltage, current and magnetic characteristics of the SRM, is implemented through the TMS320F2812 digital signal processor. Figure 3.8 illustrates the photographic view of the experimental setup. It consists of a 6/4 pole SRM with load, driving circuit, power converter, DSP board and measuring instruments.

The experimental results at 1000 rpm are shown in Figures 3.9 to 3.11. Figure 3.9 shows the experimental results of the phase voltage and current of the SRM drive at 1000 rpm, which was measured through a power quality analyzer. Figure 3.10 shows the experimental results of the phase voltage and current and flux linkage waveforms of the SRM drive at 1000 rpm. Figure 3.11 shows the experimental results of the actual rotor position, estimated rotor position and estimation error at 1000 rpm.
Figure 3.8 The photographic view of the experimental setup

![Experimental setup diagram](image)

Figure 3.9 Experimental results at 1000 rpm through the Power Quality Analyzer (PQA) (a) Phase Voltage (V), (b) Phase current (A)
Figure 3.10 Experimental results at 1000 rpm through the Code Composer Studio (CCS) Environment (a) Phase Voltage (V) (b) Phase current (A) and (c) Flux Linkage (V.s)
Figure 3.11 Experimental results at 1000 rpm through the Code composer studio (CCS) Environment (a) Actual rotor position, (b) Estimated rotor position (c) Estimation error
Table 3.1 Values of phase voltage and current were measured using a standard power quality analyzer and CCS environment through the TMS320F2812

<table>
<thead>
<tr>
<th>Sampling time</th>
<th>Voltage PQA</th>
<th>CCS</th>
<th>Error</th>
<th>Current PQA</th>
<th>CCS</th>
<th>Error</th>
<th>Flux Linkage PQA</th>
<th>CCS</th>
<th>Error</th>
<th>Rotor position Actual</th>
<th>CCS</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>55</td>
<td>128.320</td>
<td>127.900</td>
<td>0.420</td>
<td>9.916</td>
<td>9.918</td>
<td>-0.002</td>
<td>0.144</td>
<td>0.147</td>
<td>-0.003</td>
<td>5.320</td>
<td>5.300</td>
<td>0.020</td>
</tr>
<tr>
<td>70</td>
<td>142.260</td>
<td>142.780</td>
<td>-0.520</td>
<td>7.712</td>
<td>7.727</td>
<td>-0.015</td>
<td>0.516</td>
<td>0.531</td>
<td>-0.015</td>
<td>25.270</td>
<td>25.290</td>
<td>-0.020</td>
</tr>
<tr>
<td>85</td>
<td>-147.840</td>
<td>-147.260</td>
<td>-0.580</td>
<td>1.377</td>
<td>1.359</td>
<td>0.018</td>
<td>0.002</td>
<td>0.002</td>
<td>0.000</td>
<td>35.170</td>
<td>35.180</td>
<td>-0.010</td>
</tr>
<tr>
<td>100</td>
<td>-2.780</td>
<td>-2.290</td>
<td>-0.490</td>
<td>-0.275</td>
<td>-0.259</td>
<td>-0.016</td>
<td>-0.001</td>
<td>-0.001</td>
<td>0.000</td>
<td>50.220</td>
<td>50.230</td>
<td>-0.010</td>
</tr>
</tbody>
</table>
Figure 3.12 Flux Linkage Vs. Current for different rotor positions

magnetic characteristics of the SRM

Table 3.2 Values for magnetic characteristics of the SRM for five rotor positions

<table>
<thead>
<tr>
<th>Rotor position</th>
<th>Current</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.000</td>
</tr>
<tr>
<td>30.000</td>
<td>0.080</td>
</tr>
<tr>
<td>25.000</td>
<td>0.073</td>
</tr>
<tr>
<td>15.000</td>
<td>0.048</td>
</tr>
<tr>
<td>10.000</td>
<td>0.036</td>
</tr>
<tr>
<td>0.000</td>
<td>0.007</td>
</tr>
</tbody>
</table>

In this research study, 254 samples of instantaneous values of phase voltages and current were measured using a standard power quality analyzer and CCS environment through the TMS320F2812. A few sample measurements are tabulated in Table 3.1. Figure 3.12 shows the magnetic
characteristics of the SRM for few rotor positions, and their values are tabulated in Table 3.2. It has been observed from the Table 3.1 that the voltage, current, flux linkage and rotor position measured through a standard power quality analyzer and low cost digital measurement system using the TMS320F2812 with CCS environment are almost the same and their errors are very low. It is proved that this low cost digital measurement system is capable of accurately measuring various parameters of the SRM drive system. The cost of this system is approximately 10 times lesser than that of the system proposed in Adrian David Cheok and Nesimi Ertugrul (2001).

3.7 CONCLUSION

In this research study, a low cost digital measurement system for a switched Reluctance motor drive using a TMS320F2812 with CCS has been developed and implemented, based on a classic bridge converter. The controller employs a digital speed controller with a low cost digital measurement system. Experimental results in this research study show that a low cost digital measurement system for a switched Reluctance motor drive using a TMS320F2812 with CCS measures accurately the various parameters of the SRM drive in real-time. It was found during experimentation that the errors are very low compared to those of the standard power quality analyzer. It is shown that this is an almost perfect low cost digital measurement system for the SRM drive and this concept can be implemented in any motor control applications by adding proper algorithms in the programming environment. Most importantly, the implementation of this low cost measurement system needs a high speed DSP, a few logic IC’s, and a current and voltage sensor. There is no need for any data acquisition systems. It can be concluded that this digital low cost digital measurement system for the SRM drive is highly effective in dealing with the highly non-linear characteristics of the SRM drive system during steady state operation.