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Experimental Verification of Sensorless Rotor Position Estimation for 8/6 Pole Switched Reluctance Motor Drive Using Regression Technique

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Abstract: A proper prediction of the rotor position is essential for an effective and successful operation of the Switched Reluctance Motor (SRM). The proper control of speed, torque can be achieved by deciding the switching of power converter devices which in turn depends on the information of position of rotor in SRM drives. Several sensorless control prediction methods are available for SRM drives. In this paper, the flux current rotor position method using liner regression and fuzzy logic is used for prediction of the rotor position. The rotor position estimation at steady state conditions for an 8/6-pole SRM involving flux current method is implemented using TMS320F2812. The results show that the rotor position error is greatly reduced.

Key words: Regression technique · Rotor Position estimation · Switched Reluctance Motor (SRM) · Sensorless Control · Fuzzy Logic Control (FLC)

INTRODUCTION

Switched Reluctance Motor (SRM) is singly excited machine and doubly salient which avoids magnetic locking between the stator and rotor poles by designing with unequal number of rotor and stator poles [1]. For reliable and proper operation of SRM, it is crucial to predict rotor position accurately. SRM Drives is used in various industrial applications. A non-intrusive indirect rotor position estimation method can be used to achieve this. The concept of eliminating the position sensor for sensorless control by various techniques is discussed [2]. A variety of methods have been implemented by using different techniques [3-10]. Using Voltage measurements, position estimation is proposed by the authors of [11] and [12]. At different operating conditions, the rotor position estimation is proposed by ANN and ANFIS method [13]. The starting and running conditions are compared with actual values by ANFIS is proposed [14]. A resonant circuit whose associated resonant frequency depends on the rotor position is defined by the author, where in the circuit is defined by a combination of motor and power convertor driver circuits. Measurement of large amplitude voltages, robustness against temperature variation and high rates for position estimation are favorable characteristics for the proposed system. Based on the phase inductance vectors of SRM, new sensorless control method is presented by combining the vector orthogonal decomposition method and a new inductance sub regional method [15-16]. Significantly large error in rotor position is produced by the existing methods. In this paper, a method using regression techniques is used to predict the rotor position. The proposed method uses the Flux, Current and Rotor position (Ψ-i-θ) characteristics and constructs an input-output mapping based on Motor using Regression Techniques (MRT). The proposed MRT adaptive network is functionally equivalent to machine Ψ-i-θ characteristics and it efficiently predicts the rotor position of the SRM. Results are presented experimentally by comparing estimated values of rotor position with actual values.

Flux Current Method: The flux linkage (Ψ) in the flux current method of rotor position is estimation is calculated from the understanding of voltage (v) and phase current (i) of an energized phase of the SRM using the following relationship (1).

$$\psi = \int (v - ir)dt \tag{1}$$

Figure 1 illustrates the block diagram of the rotor position estimation. Figure 2 illustrates the characteristics of flux linkage with respect to current and voltage defined by (1) which used to estimate the rotor

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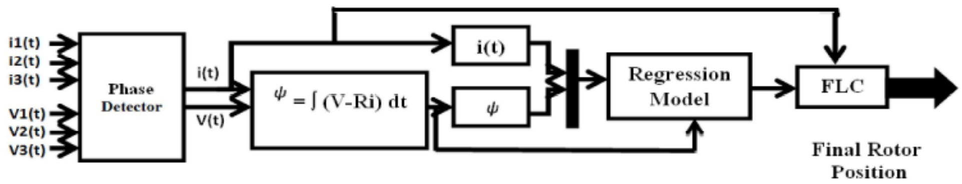


Fig. 1: Block Diagram of Rotor Position Estimation

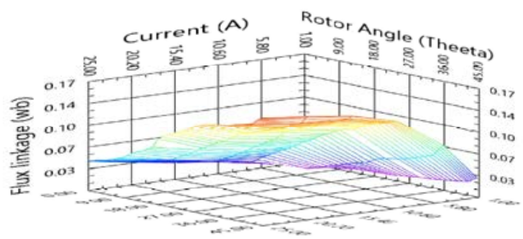


Fig. 2: Flux Linkage- Current and Flux Theta Characteristics of SRM

position. The implementation of flux linkage value found from the equation (1) is achieved by a simple arithmetic logic and integrator. According to the membership values of the flux linkage and current, Regression Model predicts the rotor position (Theta) of the SRM.

Rotor Position Estimation Algorithm

Step 1: To determine the accuracy of the measurements, energize all the phases with reduced voltage for a short period less than 1 ms and repeat the same 5 times.

Step 2: Read all the phase currents and voltages

Step 3: Start counting by setting the current comparison count = 5. Go to step 5, if the current comparison count is not equal to 5 and values are consistent in all measurements.

Step 4: Identify the phase which is carrying maximum current and set max current phase as active phase for starting the Motor

Step 5: Compute the flux linkage using equation (1).

Step 6: Using Regression model estimate the rotor position.

Step 7: The appropriate phase is energized with desired voltage.

Step 8: Go to Step 2.

Rotor Position Prediction at Start up and Running Conditions: To start and run the motor in the proper direction without any difficulties, rotor position prediction is very essential. A start up algorithm was developed and the same was used in order to predict the rotor position at start up. The instantaneous currents and voltages are measured for 5 times and the consistencies of all measurements were checked by applying a reduced voltage across all phases of the motor for a short duration (<1 ms). The active phase is detected by the phase detector by comparing all the phase currents. The active phase ie. the phase carrying maximum current, will be energized to start.

The rotor position prediction is done by feeding the flux linkage and current to the regression model. The initial rotor position is accurately predicted by the regression model. The appropriate phase will be sequentially energized with required PWM pulses and intern voltage according to the direction of rotation of the motor once the initial rotor position is predicted.

It is necessary to monitor the rotor position when the machine is running in order to get the smooth, continuous and trouble free operation. At each sampling instant, the phase voltage and current of the appropriate phase is measured and the corresponding flux linkage is calculated using equation (1). During the running condition regression model accurately predicts the rotor position by taking the flux linkage and current of the active phase in to it. To ensure the desired direction of rotation with desired torque and speed, the phase windings are switched ON and OFF at appropriate instances with the known rotor position during running condition.

Regression Model: Linear regression is the least squares estimator of a linear regression model with a single explanatory variable. Alternatively, simple linear regression fits a straight line through the set of n points in such a way that makes the sum of squared residuals of the model (that is, vertical distances between the points of the data set and the fitted line) as small as possible.

Table 1: Ψ-i-θ characteristics of a 8/6 pole SRM

	Current						
Flux linkage	1.25 A	5 A	10 A	15 A	20 A	25 A	Theeta (θ)
Flux Linkage	0.0025	0.0075	0.0175	0.025	0.0350	0.046	0.00
	0.0028	0.0077	0.0180	0.027	0.0360	0.047	0.50
	0.0030	0.0080	0.0185	0.028	0.0370	0.048	1.00
	0.0035	0.0083	0.0188	0.030	0.0380	0.049	1.50
	0.0038	0.0085	0.0190	0.030	0.0390	0.050	2.00
	0.0040	0.0088	0.0200	0.032	0.0410	0.051	3.33
	0.0045	0.0090	0.0220	0.033	0.0430	0.053	4.66
	0.0048	0.0093	0.0240	0.036	0.0450	0.056	6.00
	0.0050	0.0095	0.0260	0.039	0.0470	0.059	7.33
	0.0055	0.0098	0.0310	0.040	0.0490	0.062	8.66
	0.0058	0.0100	0.0370	0.041	0.0510	0.067	10.00
	0.0060	0.0130	0.0410	0.045	0.0560	0.072	11.33
	0.0065	0.0150	0.0460	0.049	0.0610	0.076	12.66
	0.0070	0.0170	0.0500	0.053	0.0650	0.080	14.00
	0.0075	0.0200	0.0550	0.058	0.0690	0.084	15.33
	0.0078	0.0230	0.0590	0.062	0.0750	0.088	16.66
	0.0080	0.0250	0.0630	0.067	0.0790	0.103	18.00
	0.0083	0.0280	0.0680	0.073	0.0840	0.107	19.33
	0.0085	0.0300	0.0740	0.077	0.0890	0.113	20.66
	0.0088	0.0330	0.0770	0.082	0.0930	0.117	22.00
	0.0090	0.0350	0.0820	0.087	0.0960	0.120	23.33
	0.0100	0.0370	0.0870	0.092	0.1020	0.124	24.66
	0.0110	0.0400	0.0920	0.098	0.1070	0.128	26.00
	0.0120	0.0450	0.0950	0.106	0.1130	0.133	27.33
	0.0130	0.0480	0.1000	0.110	0.1160	0.136	28.66
	0.0140	0.0500	0.1040	0.114	0.1190	0.139	30.00
	0.0150	0.0530	0.1090	0.118	0.1240	0.143	33.33
	0.0160	0.0550	0.1130	0.123	0.1280	0.144	34.66
	0.0170	0.0570	0.1160	0.127	0.1320	0.145	36.00
	0.0180	0.0600	0.1190	0.130	0.1340	0.148	37.33
	0.0190	0.0620	0.1230	0.133	0.1370	0.150	38.66
	0.0200	0.0650	0.1250	0.137	0.1400	0.152	40.00
	0.0210	0.0680	0.1280	0.1400	0.1440	0.154	41.33
	0.0220	0.0700	0.1300	0.142	0.1460	0.157	42.50
	0.0230	0.0750	0.1310	0.144	0.1480	0.160	43.00
	0.0250	0.0780	0.1320	0.146	0.1500	0.163	43.50
	0.0270	0.0815	0.1330	0.148	0.1550	0.165	44.00
	0.0290	0.0850	0.1350	0.152	0.1590	0.167	44.50
	0.0310	0.0885	0.1350	0.153	0.1615	0.168	45.00

The slope of the fitted line is equal to the correlation between y and x corrected by the ratio of standard deviations of the variables. The intercept of the fitted line is such that it passes through the center of mass (x, y) of the data points.

In particular, when one wants to do regression by eye, people usually tend to draw a slightly steeper line, closer to the one produced by the total least squares method. Regression analysis includes many techniques for modeling and analyzing several variables and the focus is on exploring the relationship between a dependent variable and one or more independent variables even if the physical process is unknown.

Table 1 shows the Ψ-i-θ characteristics of a 8/6 pole SRM and these Values were used to build multiple linear regression model where in data relating Ψ-i-θ which covers the entire machine magnetic characteristics.

Rotor Position Estimation Using Regression Technique: From the equation-2, rotor position was estimated and compared with actual values and the same are tabulated in Table-2. It is observed that there are huge errors during the non linear region of magnetic characteristics. To overcome this issue, an error corrector model was developed using Fuzzy logic controller with 7x7 triangular membership function and is shown in Figure 3.

Table 2: Estimated Rotor position compared with actual values

Current	Flux linkage	Actual theta	Estimated Theta	Error	Estimation by the error corrector	Actual Estimator after accounting Error corrector FLC	New Error
0	0.0000	0.00	15.610670	-15.610700	-14.8570	0.753667020	-0.75367
1.25	0.0025	0.00	14.811560	-14.811600	-13.9132	0.898364922	-0.89836
	0.0048	6.00	15.635900	-9.635900	-8.9075	6.728401590	-0.72840
	0.0065	12.66	16.245190	-3.585190	-3.1784	13.066793910	-0.40679
	0.0088	22.00	17.069530	4.930469	5.8688	22.938330580	-0.93833
	0.0140	30.00	18.933250	11.066750	11.3222	30.255448260	-0.25545
	0.0190	38.66	20.725280	17.934720	18.4679	39.193184500	-0.53318
	0.0310	45.00	25.026170	19.973830	20.9286	45.954771470	-0.95477
5	0.0075	0.00	11.518240	-11.518200	-11.2505	0.267740509	-0.26774
	0.0093	6.00	12.163370	-6.163370	-5.9133	6.250073554	-0.25007
	0.0150	12.66	14.206290	-1.546290	-0.6186	13.587694860	-0.92769
	0.0330	22.00	20.657630	1.342375	1.4110	22.068625310	-0.06863
	0.0500	30.00	26.750550	3.249451	3.5489	30.299448520	-0.29945
	0.0620	38.66	31.051440	7.608565	8.2002	39.251635480	-0.59164
	0.0885	45.00	40.549230	4.450772	4.6541	45.203327530	-0.20333
10	0.0175	0.00	8.3218320	-8.321830	-7.6859	0.635932116	-0.63593
	0.0240	6.00	10.651480	-4.65148	-3.8531	6.798379223	-0.79838
	0.0460	12.66	18.536440	-5.876440	-5.3747	13.161738660	-0.50174
	0.0770	22.00	29.647060	-7.647060	-6.9963	22.650763320	-0.65076
	0.1040	30.00	39.324060	-9.324060	-8.5281	30.795959000	-0.79596
	0.1230	38.66	46.133800	-7.473800	-7.2404	38.893396700	-0.23340
	0.1350	45.00	50.434680	-5.434680	-4.8339	45.600783660	-0.60078
20	0.0350	0.00	1.032997	-1.033000	-0.9205	0.112497212	-0.11250
	0.0450	6.00	4.617070	1.382930	1.8987	6.515769684	-0.51577
	0.0610	12.66	10.351590	2.308414	3.1462	13.497785640	-0.83779
	0.0930	22.00	21.820620	0.179382	1.1002	22.920817550	-0.92082
	0.1190	30.00	31.139210	-1.139210	-0.6410	30.498205980	-0.49821
	0.1370	38.66	37.590540	1.069464	1.3471	38.937636430	-0.27764
	0.1615	45.00	46.371510	-1.371510	-0.7190	45.652513980	-0.65251
25	0.0460	0.00	-1.805000	1.805004	2.7223	0.917296066	-0.91730
	0.0560	6.00	1.779069	4.220931	4.7307	6.509768538	-0.50977
	0.0760	12.66	8.947213	3.712787	4.6870	13.634213480	-0.97421
	0.1170	22.00	23.641910	-1.641910	-1.4446	22.197310620	-0.19731
	0.1390	30.00	31.526870	-1.526870	-1.4157	30.111170060	-0.11117

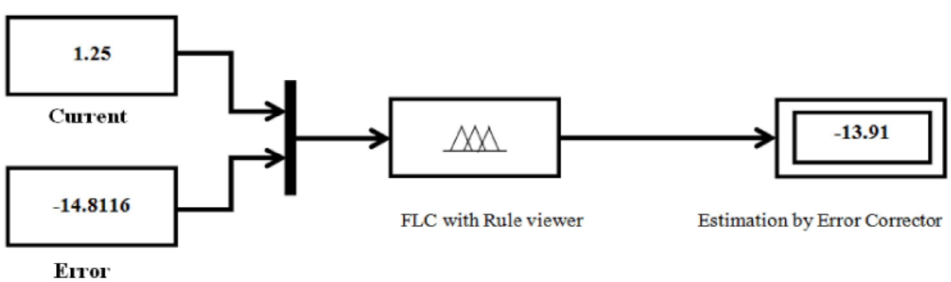


Fig. 3: FLC for Error estimation

Computer Simulation Results: The linear regression algorithms along with error corrector algorithm using Fuzzy logic controller (FLC) are discussed in this paper. It's observed from Table-2 that the error due to linear regression gives maximum absolute error of 19.97 electrical digresses and minimum absolute error of 0.179382 electrical degrees which is not desirable for accurate position prediction. Based on the error outcome from the table-2, it was proposed to introduce an FLC for error correction. 7X7 FLC was modeled with triangular membership function and is represented in Figure 3. It is observed from FLC that it predicts the error accurately with the knowledge of current (i) and flux linkage (si). The error which was found via FLC has been added with

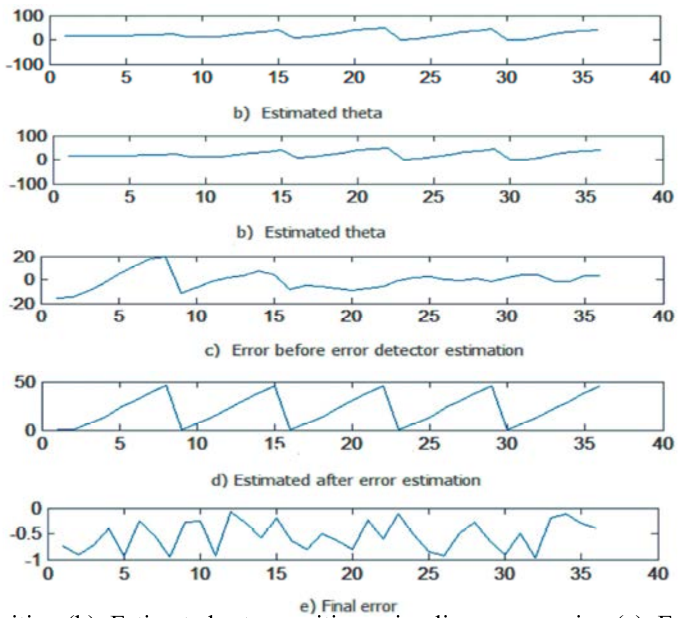


Fig. 4: (a).Actual Rotor position (b). Estimated rotor position using linear regression (c). Error due to linear regression (d). Estimated with linear regression and Fuzzy logic error corrector (e). Error between actual and estimated rotor position

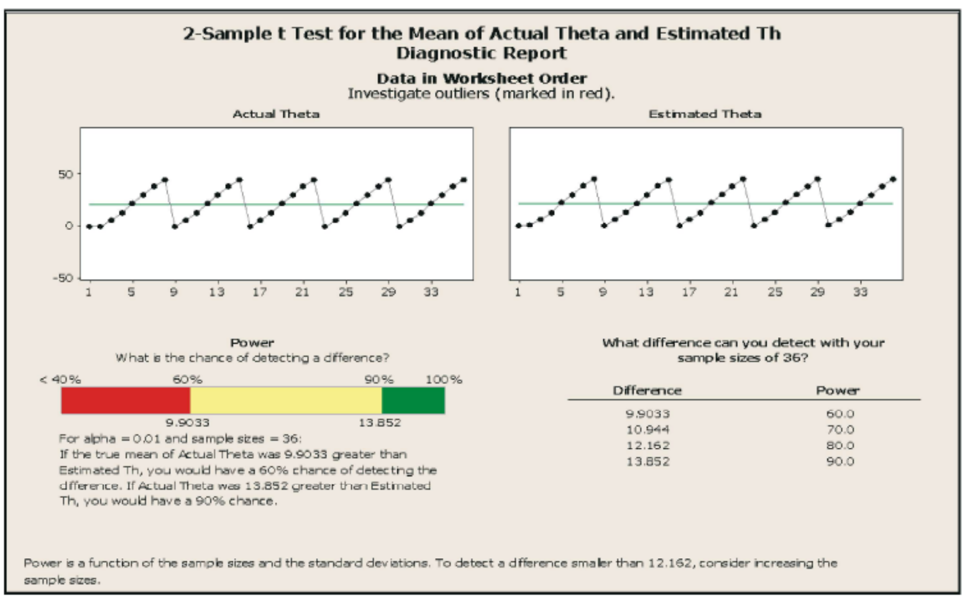


Fig. 5: 2- Sample t test for the mean of actual theta and estimated theta diagnostic report

linear regression predicted rotor position value and then new value arrived for rotor position which was named as "Actual Estimator after accounting Error corrector FLC". It's observed from the new prediction; maximum absolute error is within one electrical degree. This reveals that linear regression with FLC would be highly suitable for prediction of rotor position.

Figure 4 shows actual Rotor position, estimated rotor position using linear regression, Error due to linear regression, estimated with linear regression and Fuzzy logic error corrector and Error between actual and estimated rotor position. It gives the indication that the actual and estimated standard deviation and mean are very close to each other. This proves that this algorithm can be implemented for rotor position estimation. Figure5 shows 2 – Sample t test for the mean of actual theta and estimated theta diagnostic report using Minitab software. Figure 6 shows the Sample t test for the mean of actual

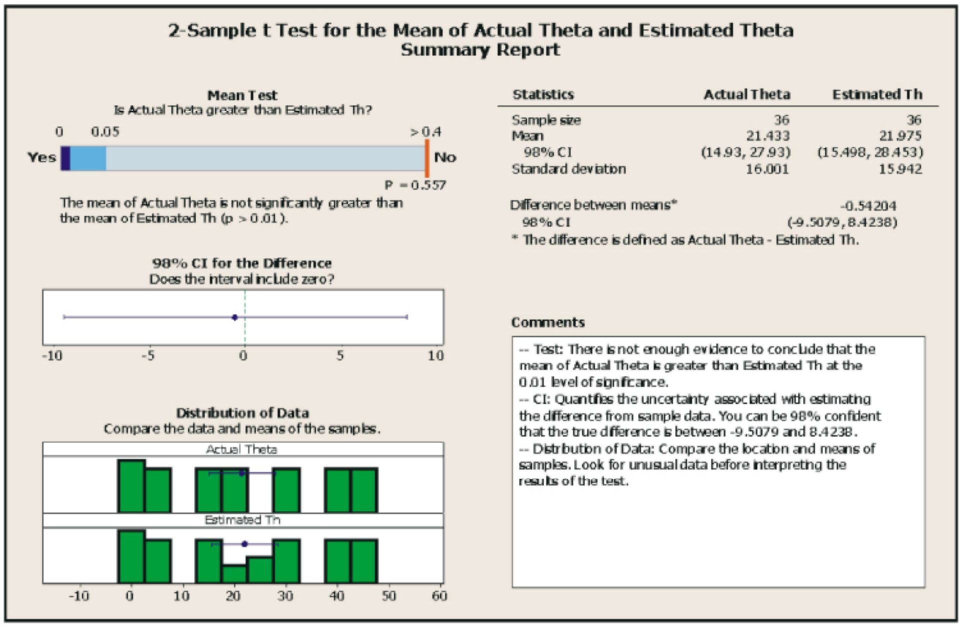
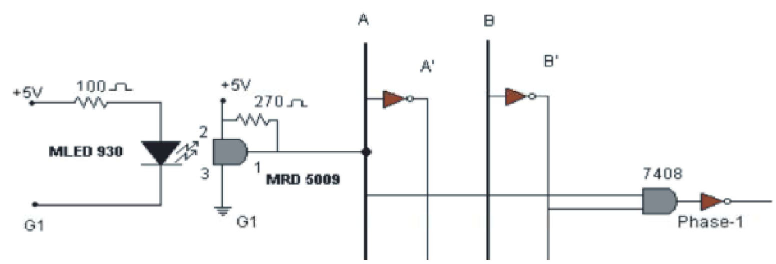
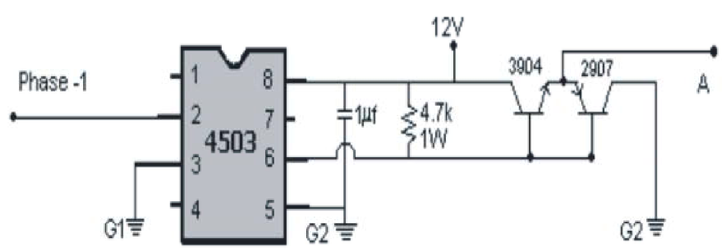


Fig. 6: 2 – Sample t test for the mean of actual theta and estimated theta summary report

(a)



(b)



(c)

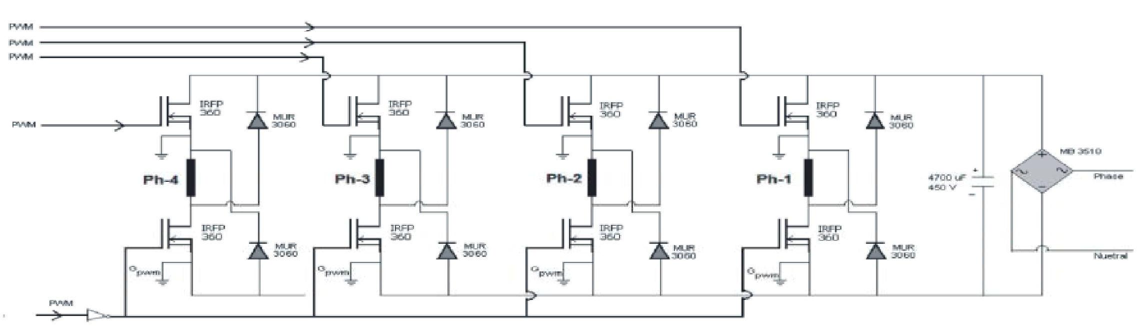


Fig. 7: (a).Rotor position sensor for one phase, (b). Opto-Isolator and Gate driver circuit and (c).Power converter of 8/6 pole SRM Drive

Fig. 8: (a).An actual rotor position estimation using Physical rotor position sensor, (b).Estimated rotor position and (c). Final error between actual vs. estimated rotor positions

theta and estimated theta summary report. It is observed from the Figure 5 and 6 that the two sam ple for actual and estimated theta gives the indication. The actual and estimated standard deviation and mean are very close to each other.This proves that this algorithm can be implemented for rotor positin estimation.

Experimental Description: The Switched Reluctance Motor drive (SRM) system consists of different subsystems which are SRM, driver circuit, Classic Bridge converter, circuit with voltage and current sensors and TMS320F2812 processor board from TI as a hardware and software tool.

Experimental Results: After assembling of all subsystems together, SRM drive was constructed as a system. Then subsequently an algorithm was developed using linear regression algorithms along with error corrector algorithm using Fuzzy logic controller using TI CCS and algorithm were verified in real time environment. Figure 7 shows Rotor position sensor for one phase, opto Isolator & Gate driver circuit and Power converter of SRM Drive respectively. Figure 8 shows experimental results of actual rotor position estimation using Physical rotor position sensor, estimated rotor position and final error between actual vs. estimated rotor positions. It’s clear from the conducted test case on experimental results that there is good agreement between simulation and experimental test results. This conveys that regression techniques along with fuzzy logic controller will be potential candidates for rotor position estimation. Fig 8.(a) through c shows that rotor position prediction provides an indication on its capability as an estimator to follow the actual rotor position. Fig 9 shows the voltage and current wave of SRM motor when the motor running at 1360 RPM at no load in soft chopping mode.

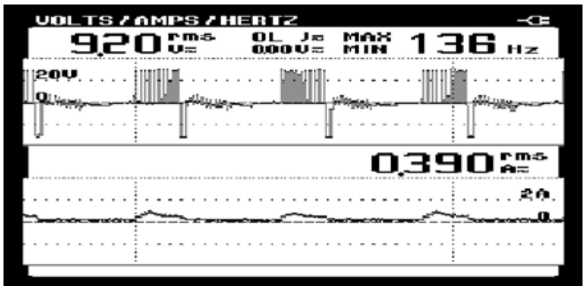


Fig. 9: Phase Voltage and Current waveforms when the machine running at 1360 RPM

CONCLUSIONS

An indirect method for rotor position estimation using linear regression algorithms along with error corrector algorithm using Fuzzy logic controller using TI CCS were implemented and tested in real time. An 8/6 Pole SRM proto type drive was built using necessary hardware's and used for the experimentation. As a part of algorithm implementation, TMS320F2812 was used to implement and test the algorithm. The complete set was run to verify the algorithm at 1360 RPM using soft chopping mode and observed that the simulated results and experimental results have very good agreement and hence linear regression algorithms along with error corrector algorithm using Fuzzy logic controller are the potential candidates for SRM rotor position estimation.

Formulae:

1. $\psi = \int (v - ir)dt$

2. *Theta* $(\theta) = -1.356096173\ x1 + 358.4072472\ x2 + 15.61066702$

REFERENCES

1. Miller T.J.E., 1989. Brushless Permanent Magnet and Reluctance Motor Drives, Oxford University Press,.
2. Mehrdad Eshani and Babak Fahimi, 2002. Elimination of position sensorless in SRM drives, State of the art and Future trend, IEEE Transaction in industrial Electronics, 49: 40-47.
3. Acarnley, P.P., R.J. Hill and C.W. Hooper, 1985. Detection of rotor position in stepping and switched motors by monitoring of current waveforms, IEEE Trans. Ind. Electron., 32: 215-222.
4. Ray, W.F. and I.H. Al-Bahadly, 1993. Sensorless methods for determining the rotor position of switched reluctance motors, in Conf. Rec. IEE EPE Conf., Brighton, U.K., pp: 7-13.K. Elissa,1993.
5. Xu, L. and J. Bu, 1997. Position transducerless control of switched reluctance machine with Minimum magnetizing input, in Conf. Rec. IEEE-IAS Annu. Meeting, New Orleans, LA, pp: 533-539.
6. Cheok, A. and N. Ertugrul, 1996. A model free fuzzy logic based rotor position sensorless switched reluctance motor drives, in Conf. Rec. IEEE-IAS Annual. Meeting, San Diego, CA, pp: 76-83.
7. Gallegos-Lopez, G., P.C. Kajr and T.J.E. Miller, 1997. A new sensorless method for switched reluctance motor drives, in Conf. Rec. IEEE-IAS Annual. Meeting, New Orleans, LA, pp: 564-570.
8. Ehsani, M., I. Husain and A.B. Kulkarni, 1992. Elimination of discrete position sensor and current sensor in switched reluctance motor drives, IEEE Trans. Ind. Applicat., 28: 128-134.
9. Ehsani, M., I. Husain, S. Mahajan and K.R. Ramani, 1994. New modulation encoding techniques for indirect rotor position sensing in switched reluctance motors, IEEE Trans. Ind. Application., 30: 85-91.
10. Lyons, J.P., S.R. MacMinn and M.A. Preston, XXXX. Flux/current methods for SRM rotor position estimation, in Conf. Rec. IEEE-IAS Annual Meeting, pp: 482-487.
11. MacMin, S.R., W.J. Rzesos, P.M. Szczensy and T.M. Jahns, 1992. Application of sensor integration techniques to switched reluctance motor drives, IEEE Trans. Ind. Application., 28: 1339-1344.
12. Geldhof, K.R., P. Sergent, A.P.M. Van den Bossche and J.A. Melkebeek, 2011. Analysis of hysteresis in resonance- based position estimation of switched reluctance drives, IEEE Trans. Magn., 47(5): 1022-1025.
13. Paramasivam, S., S. Vijayan, M. Vasudevan, R. Arumugam and Ramu Krishnan, 2003. Real Time Verification of AI based rotor osition estimation Technologies for 6/4 ole Switched Reluctance Motor, IEEE Transaction on Magnetics, 43: 3209-3222.
14. Paramasivam, S., R. Arumugam, B. Umamaheshwari, S. Vijayan, S. Balamurugan and G. Venkatesan, 2003. Accurate Rotor position estimation of switched reluctance motor using ANFIS,TENCON 2003, pp: 1493-1497.
15. Geldhof, K.R., A.P.M. Van den Bossche and J.A. Melkebeek, 2010. Rotor position estimation of switched reluctance motors based on damped voltage resonance, IEEE Trans. Ind. Electron., 57(9): 2954-2960.
16. Jun Cai and Zhiquan Deng, 2012. Sensorless Control of Switched Reluctance Motor Based on Phase Inductance Vectors, IEEE Transactions on Power Electronics, 27(7): 3410-3423.