

Advances in Intelligent Systems and Computing 1361

S. Chandramohan · Bala Venkatesh ·
Subhransu Sekhar Dash ·
Swagatam Das · C. Sharmeela *Editors*

Artificial Intelligence and Evolutionary Computations in Engineering Systems

Computational Algorithm for AI
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Preface

This volume contains the papers presented at the Sixth International Conference on Artificial Intelligence and Evolutionary Computations in Engineering System (ICAIECES 2020) held during 17–18 December 2020, at Anna University, Chennai, India. ICAIECES 2020 is the Sixth International Conference aiming at bringing together the researchers from academia and industry to report and review the latest progresses in the cutting-edge research on various research areas of artificial intelligence, evolutionary computing, image processing, computer vision and pattern recognition, machine learning, data mining and computational life sciences, management of data including big data and analytics, distributed and mobile systems including grid and cloud infrastructure, information security and privacy, VLSI, antenna, computational fluid dynamics and heat transfer, intelligent manufacturing, signal processing, intelligent computing, soft computing, web security, privacy and e-commerce, e-governance, optimization, communications, smart wireless and sensor networks, networking and information security, mobile computing and applications, industrial automation and MES, cloud computing, electronic circuits, power systems, renewable energy applications, and green IT and finally to create awareness about these domains to a wider audience of practitioners.

ICAIECES 2020 received 92 paper submissions, including three foreign countries across the globe. All the papers were peer-reviewed by the experts in the area in India and abroad, and comments have been sent to the authors of accepted papers. Finally, 32 papers were accepted for oral presentation at the conference. This corresponds to an acceptance rate of 34% and is intended to maintain the high standards of the conference proceedings. The papers included in this volume cover a wide range of topics in intelligent computing and algorithms and their real-time applications in problems from diverse domains of science and engineering.

The conference was inaugurated by Dr. S. Chandramohan, Professor and Head, DEEE, CEG Campus, Anna University, Chennai, India, on 17 December 2020. The conference featured distinguished keynote speakers as follows: Dr. P. Sanjeevikumar, Associate Professor, Aalborg University, Denmark, Dr. Bala Venkatesh, Professor and Director, Centre for Urban Energy, Ryerson University, Canada, Dr. Sridhar Krishnan, Professor, Associate Dean (Research), Ryerson University, Canada;

Dr. Lalit Singh, Scientist NPCIL-BARC, DAE, GOI; Dr. Swagatam Das, Associate Professor, ISC Kolkatta, India; and Dr. B. K. Panigrahi, Professor, IIT Delhi, India.

We take this opportunity to thank the authors of the submitted papers for their hard work, adherence to the deadlines and patience with the review process. The quality of a referred volume depends mainly on the expertise and dedication of the reviewers. We are indebted to the Technical Committee members, who produced excellent reviews in short time frames and Paper Scrutiny Committee In-charge Dr. B. Hemamalini, Teaching Faculty, DEEE, Anna University, Chennai. First, we are indebted to the honourable Vice-Chancellor Prof. Dr. M. K. Surappa and thank him wholeheartedly for the confidence he entrusted on us for organizing this International Conference ICAIECES 2020 in a virtual platform during the Covid-19 Pandemic. We sincerely thank Dr. S. Chandramohan, Professor and Head, DEEE, Anna University, Chennai, India; the Conference Programme Chair Dr. C. Sharmeela, Associate Professor, DEEE, Anna University, Chennai, India; Dr. S. S. Dash, HOD/DEE, Government Engineering College, Odisha, India; and the Professors and the staff members of the Department of Electrical and Electronics Engineering, Anna University, Chennai, India, for their valuable support for the success of this programme. We thank the International Advisory Committee members for providing valuable guidelines and inspiration to overcome the various difficulties in the process of organizing this conference. We would also like to thank the participants of this conference and Dr. P. Sakthivel, Professor, Anna University, Chennai, India, and Treasurer, IEEE Computer Society, Chennai chapter, for sponsoring generously towards the conference. We thank wholeheartedly the Aalborg University, Denmark, Ryerson University, Canada and IEEE Computer Society, Chennai chapter, India, for jointly collaborating with Anna University, Chennai, India, in organizing and conducting this prestigious International Conference ICAIECES 2020 during 17–18 December, 2020, in Virtual Platform during the Covid-19 pandemic. Finally, we thank all the volunteers who made great efforts in meeting the deadlines and arranging every detail to make sure that the conference could run smoothly. We hope the readers of these proceedings find the papers inspiring and enjoyable.

Anna University, Chennai
Anna University, Chennai
GCE Keonjhar, Orissa

Dr. S. Chandramohan
Dr. C. Sharmeela
Dr. Subranshu Sekhar Dash

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About the Editors

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Dr. Bala Venkatesh is the founding academic director of the Centre for Urban Energy (CUE) at Ryerson University. He is also Tenured Professor in the Department of Electrical and Computer Engineering. He specializes in electric power systems with interests in transmission and distribution systems, renewables, energy storage and smart grids. He works with industry partners such as Hydro One, Toronto Hydro, the Independent Electricity System Operator (IESO), Schneider Electric, eCAMION, Temporal Power, Alectra Utilities and Tata Power Delhi Distribution Limited. In total, his extramural funding is over \$18 million. In the last two decades, he has worked on over 30 consulting and research projects in India and Canada. With a Ph.D. from Anna University (India), Dr. Venkatesh is a registered professional engineer in Ontario, Canada. Since 1994, he has also taught at the University of New Brunswick, Multimedia University (Malaysia) and Anna University. Dr. Venkatesh has published over 230 journal papers, conference papers, technical reports and book chapters. He has supervised over 60 M.A.Sc., Ph.D. and PDF candidates.

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Dr. C. Sharmeela is Associate Professor and Professor-In-Charge, Power Engineering and Management, Department of Electrical and Electronics Engineering at C.E.G., Anna University, Chennai. She was also the assistant director, Centre for Entrepreneurship Development, C.E.G., Anna University, Chennai, during 2015–2018. She has done a number of consultancies for power quality measurements and design of compensators for industries. She has received in the year 2011 a grant from CTDT, Anna University, for a two-year project on “Energy Efficient Solar Based Lighting System for Domestic Application”. She has authored over 30 journal papers in refereed international journals and more than 60 papers in international and national conferences. Her areas of interest include power quality, power electronics applications to power systems, smart grid, energy storage systems and renewable energy systems. She is Fellow of the Institution of Engineers (India) and Life Member of ISTE, Central Board of Irrigation and Power (CBIP), New Delhi, India, and SSI, India. She has a teaching/research and consultancy experience of 18 years in the areas of power quality and power systems.

Design and Construction of a Dual-Axis Solar Tracking System by Astronomical Algorithm



C. Sharmeela, G. Kumaresan, Vidhya Sagar Devendran, Jasronita Jasni, and S. Balaji

Abstract Solar energy is an intermittent energy source that varies throughout the day and seasons, thereby affecting the overall power system stability. In order to reduce this impact, the solar tracking system can be incorporated, which increases the system energy yield with less silicon consumption. This paper deals with the design and construction of dual-axis solar tracking system based on an astronomical algorithm. The angle sensor is used as feedback in the solar tracking system, which is the combination of accelerometer and gyroscope to measure yaw and tilt angle of the panel. A dual-axis mounting structure is designed by using Solid Works software and constructed with DC motors and worm gear to drive the solar PV panel. The developed astronomical-based algorithm for dual axis solar tracking system has been verified with a sun path chart.

Keywords Solar tracker · Astronomical tracking · Dual axis · Real time clock · MEMS · Wiper motor

1 Introduction

It is evident that the sun-tracking systems are used to maximize the solar radiation that reaches the solar PV panel surface [1, 2]. For example, the tracking-equipped PV module delivers 40% more electricity in an average year than the non-tracking PV

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module. Solar tracking system based on orientation can be classified as single and dual-axis tracking systems. Single-axis tracking systems normally follow the sun's trajectory by only changing the altitude angle [3] while dual-axis tracking system follow the sun's trajectory by changing both, the azimuth and altitude angles [4, 5]. The solar tracking system is normally done either by using light sensors such as Light Dependent Resistor (LDR) or by computing sun's position by astronomical calculation and moving the collectors toward the sun's ray [6–10]. LDR are prone to false triggering during shadows due to flying birds or human movement around sensors, which may trigger the motor in an unwanted direction [11]. Moreover, in the astronomical calculation, without proper feedback, initial adjustment needed to be done in order to trigger the motor to align in exact angle; otherwise, initial angular adjustment of the PV panel has to be done manually. This may lead to tracking error [12]. Thus proper feedback is to be provided to the astronomical algorithm so that the initial angles of the solar PV panel are known accurately.

In order to track the sun's ray to improve energy yield from solar panel, the position of the sun at the particular time at the particular location is needed exactly. The position of the sun in the sky is found by calculating altitude angle and azimuth angle and these angles are programmed in a microcontroller (ATMEL) which provides up to date the position of the sun for aligning solar PV panel facing the sun in both the axes. In order to achieve this, a mounting structure for PV panel is designed which rotates around its axis, compensating azimuth angle and also tilts the panel compensating altitude angle of the sun.

2 Design of the Mounting Structure

A dual-axis mounting structure is designed using Solid Works software as shown in Fig. 1 by considering environmental (wind load) and operating conditions. The

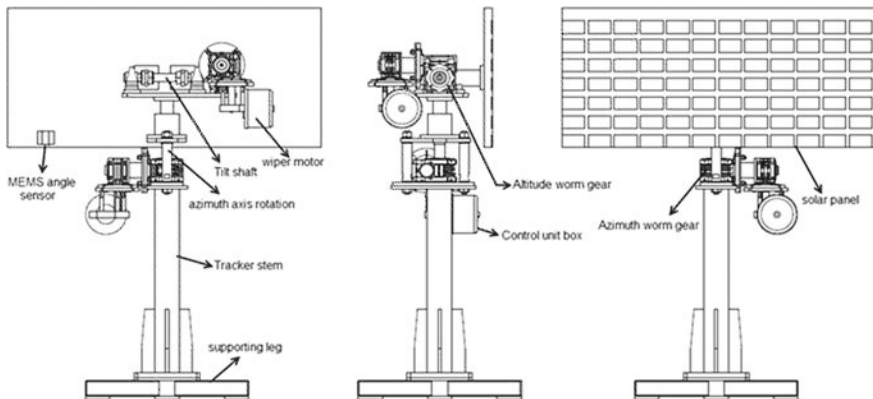


Fig. 1 Dual-axis solar PV panel mounting structure

mounting structure is designed in such a way that it with stands average daily maximum wind load of Chennai location 9 m/s [13]. The azimuthal shaft can rotate fully along its own axis and the solar panel mounted can be tilted slightly more than 90° so that the mounted solar PV panel can cover the whole movement of the sun with respect to the earth [14]. Since solar tracking is a low-speed application, a speed reduction worm gear set (gear ratio 450:1) is coupled to the DC motors of speed 20 rpm.

3 Astronomical Algorithm

Astronomical algorithms Intend to guide people who want to do calculations about astronomical bodies. An algorithm is a set of rules that can help in achieving a certain goal.

The writing of a program to solve some astronomical problem will require a study of more than one aspect of a celestial body. For instance, in order to create a program for the calculation of the altitude of the Sun for a given time on a given date at a given place, one must first convert the date and time to Julian Day, then calculate the sun's longitude for that instant, its right ascension and declination, the sidereal time and finally the required altitude of the sun.

In order to create a program for calculating altitude of sun for a given time on an a given date at a given place the following need to be calculated:

- Convert the date and time to Juliann day,
- Calculate the sun's longitude for instant,
- Sun's ascension and descension and altitude of sun, and
- Sidereal time.

3.1 Julian Day

Julian Day is a continuous count of day and fractions thereof from the beginning of the year—4712. A JD begins at Greenwich noon, that is, at 12 h universal time:

$$JD = \text{INT}(365.25(Y + 4716)) + \text{INT}(30.6001(M + 1)) + D + B - 1524.5 \quad (1)$$

where Y is the year,

M be the month number,

D be the day of the month If,

- (1) $M = 2$, leave Y and M unchanged,
- (2) $M = 1$ or 2 , replace Y by $Y-1$ and M by $M + 12$.

(i.e., if the date is in January or February, it is considered to be in the 13th and the 14th month of the year) In Gregorian calendar (Fig. 2),

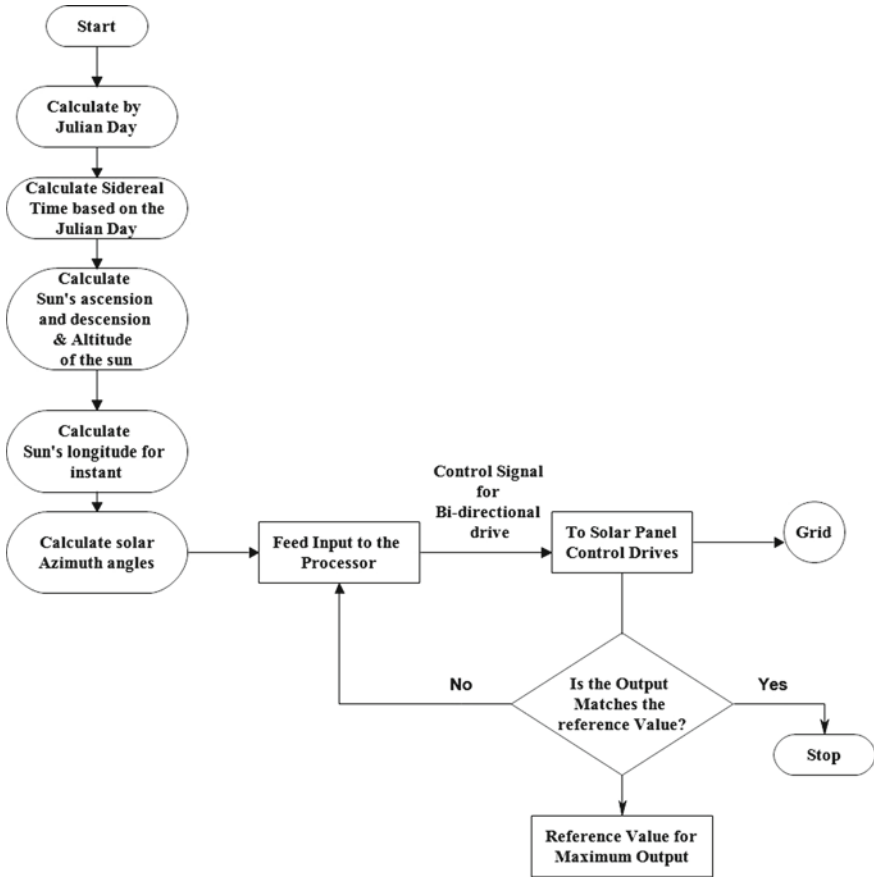


Fig. 2 Flow chart for the astronomical algorithm

$$A = \text{INT}(Y/100) \quad (2)$$

$$B = 2 - A + \text{INT}(A/4) \quad (3)$$

In Julian Calendar, take $B = 0$,
 30.6 will give the correct result, but 30.6001 is used to get a correct integer.

3.2 Siderial Time (T)

The sidereal time at Greenwich at 0 h UT of a given date (capital) The sidereal time at Greenwich for any given instant UT(o).

Calculate JD corresponding to that date at 0 h UT (this is a number ending on 0.5)
 T can be calculated by

$$T = (\text{JD} - 2451545.0/36525) \quad (4)$$

The mean sidereal time at Greenwich at 0 h UT is then given by the following expression (adopted in 1982 by the international Astronomical Union)

$$\begin{aligned} \theta_0 = & 6h41m50s.54841 + 8640184s.812866T \\ & + 0s.093104T^2 - 0s.0000062T^3 \end{aligned} \quad (5)$$

Expressing in degrees and decimals, the same formula can be written as

$$\begin{aligned} \theta_0 = & 100.46061837 + 36000.770053608T \\ & + 0.000387933T^2 - T^3/38710000 \end{aligned} \quad (6)$$

The sidereal time at Greenwich for any given instant UT(o).

The mean sidereal time at Greenwich, expressed in degrees, can also be found directly by the following JD is the Julian Day corresponding to the instant in UT (not necessarily 0 h). Find T as per the previous formula

$$\begin{aligned} \theta_0 = & 280.46061837 + 360.98564736629(\text{JD} - 2451545.0) \\ & + 0.000387933T^2 - T^3/38710000 \end{aligned} \quad (7)$$

For high accuracy, use of a computer working with a sufficient number of significant digits.

3.3 Solar Coordinates

To calculate the Sun's ascension and descension and altitude of the sun is given in the Eq. (8)

$$L = L_0 + DL, \quad (8)$$

where L_0 is the mean longitude

$$L_0 = 280.46645 + 36000.76983 * T + 0.0003032 * T * T \quad (9)$$

DL is the equation for the Sun at Center

$$DL = (1.914600 - 0.004817T - 0.000014T^2) \sin(\text{kM})$$

$$+ (0.019993 - 0.000101T) \sin(2 \text{ kM}) + 0.000290 \sin(3 \text{ kM}) \quad (10)$$

$$M = 357.52910 + 35999.05030 * T - 0.0001559 * T^2 - 0.00000048 * T^3 \quad (11)$$

$$k = 2 * PI/360 \quad (12)$$

where T is the Siderial Time.

3.4 Azimuth Angle

The azimuth angle is the compass direction from which the sunlight is coming. At solar noon, the sun is always directly south in the northern hemisphere and directly north in the southern hemisphere. The azimuth angle varies throughout the day, as shown in the animation below. At the equinoxes, the sun rises directly east and sets directly west regardless of the latitude, thus making the azimuth angles 90° at sunrise and 270° at sunset. In general, however, the azimuth angle varies with the latitude and time of year and the full equations to calculate the sun's position throughout the day are given on the following

$$\text{Azimuth Angle} = \cos^{-1} \left[\frac{\sin \delta * \cos \varphi - \cos \delta * \sin \varphi * \cos(HRA)}{\cos \alpha} \right] \quad (13)$$

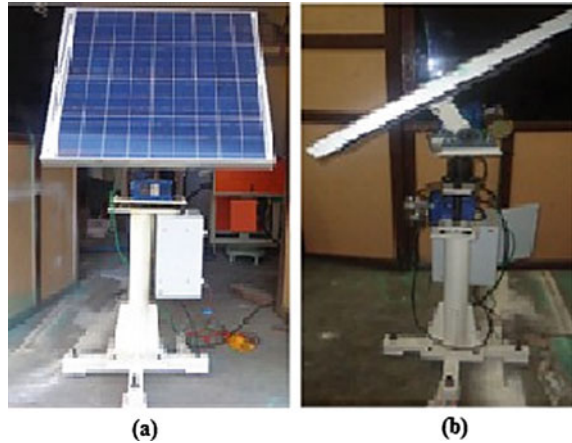
where delta is the declination phi is the latitude,

alpha is the elevation HRA is the Hour angle.

4 Construction of Tracker

The solar tracker is constructed for 50 Wp (watt peak) solar panel which is of dimension 655×600 mm. The four supporting legs, as shown in Fig. 3, are given to the tracker to withstand the weight of the system. The solar panel is bolted at 1.2 m height from the ground to ensure safe loading and unloading of the panel into the tracker. The mounting structure is fabricated using mild steel to withstand the PV panel weight (5.3 kg) as well as the admissible wind load. The two gear box (Moto-vario) of ratio 30:1 and 15: 1 each one is coupled with motor so that the speed of both the axis is reduced in the ratio of 450:1. The mounting structure is controlled in both the axis by 0.5 to 1 degree of accuracy. The permanent magnet Wiper motor is selected as DC motor drive since it is readily available and also easily suitable for solar tracking purposes. The time and date are set exactly and left unchanged

Fig. 3 Dual-axis solar tracker (a) front view, (b) side view



before initializing the tracker program. Microcontroller first gets time from RTC and computes sun angle at that time when it is daytime. It then checks the tilt and yaw angle of the panel from IMU. Microcontroller then activates both the motors until they tilt and yaw angle is equal to altitude and azimuth angle, respectively.

5 Result and Discussion

Altitude and azimuth angle from the astronomical calculation is verified for Chennai (13.08° N, 80.27° E), India by obtaining the result for every half an hour on the winter solstice (December 21) and comparing it with the sun chart for the same location obtained from the University of Oregon website [15]. The observation proves that the obtained result from the algorithm is the same as the sun chart diagram. The verification is shown in Fig. 4 for 8.00 am as obtained from microcontroller output with graph. In addition, the astronomical calculation is also verified manually using a magnetic compass. The power consumed by the altitude motor is 10 watts and azimuth motor is 8 W. Thus the maximum energy consumed by both the motor per day is 0.26 W hr (watt hour).

6 Conclusion

In this paper, a newly developed astronomical algorithm-based dual-axis solar tracking system is reported. Angle sensor is used for necessary feedback to the astronomical algorithm, which is a MEMS sensor. Atmel microcontroller is programmed to provide sun angles by getting time from RTC. It is seen from the results that the programmed output for the Chennai location is true with original sun angle. The

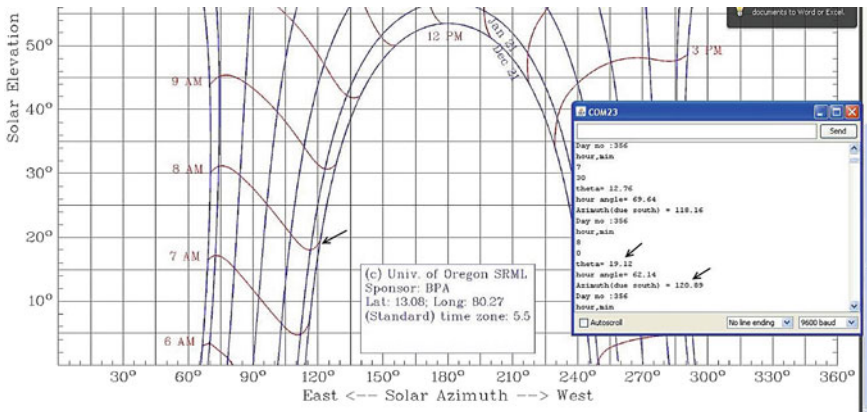


Fig. 4 Microcontroller result

total energy consumed by the two motors in a day is 0.26 W hour only, which is comparatively very low and negligible for a 50 W solar PV panel.

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Estimation of Magnetic Flux Linkage in SRM Using Various Defuzzification Techniques



D. Susitra, B. Hema Malini, and V. Meenakshi

Abstract Switched reluctance machine (SRM) has become the subject of interest among researchers in the field of electrical machines over the past few decades. This is due to the fact that SRM has proved to be a valid alternative and replaced conventional electrical machines in almost all industrial sectors. The performance and control accuracy of SRM extensively relies on the precision of its machine modeling. In this research paper, the estimation of magnetic flux linkage for SRM is presented using various defuzzification methods available in Fuzzy Inference System (FIS) is presented. There are different methods available for performing defuzzification process in FIS. Centroid, bisector, middle of maximum (MoM), largest of maximum (LoM) and smallest of maximum (SoM) methods are implemented in this work for estimation of flux linkage for SRM. The estimated flux linkage profile obtained using different defuzzification methods are evaluated and the results are analyzed. It is observed that the results from the centroid method of defuzzification are in good agreement with the original values.

Keywords Fuzzy Inference System · Non-linear flux linkage · Defuzzification methods · Switched reluctance machine (SRM)

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1 Introduction

Accurate flux linkage ($\Psi(I,\theta)$) estimation of SRM is the major requirement for its real-time control [1]. Many publications have reported various modeling methods for the same. Estimation of $\Psi(I,\theta)$ based on the complicated analytical method is reported in [2, 3]. The magnetic theory is used in [4], which is a time-consuming process. Finite Element Analysis (FEA) that provide accurate results is implemented in [5], whereas FEA involves heavy computational effort and complex mathematical concepts. Neural Network (NN) that requires a large amount of training data is used in [6, 7]. ANFIS and multivariate regression are used in [8, 9]. In this research, $\Psi(I,\theta)$ in SRM is estimated using various defuzzification methods available in MATLAB FIS. Comparative analysis of estimated results from different methods is made and presented. The paper is organized as follows. The $\Psi(I,\theta)$ profile for the machine is presented in Sect. 2. Estimation of $\Psi(I,\theta)$ from different defuzzification methods are presented in Sect. 3. The $\Psi(I,\theta)$ profile based on the bisector function is presented in Sect. 3.1. The $\Psi(I,\theta)$ profile based on the middle of maximum function is presented in Sect. 3.2. The $\Psi(I,\theta)$ profile based on the largest of maximum function is presented in Sect. 3.3. The $\Psi(I,\theta)$ profile based on the smallest of maximum function is presented in Sect. 3.4. The $\Psi(I,\theta)$ profile based on the centroid function is presented in Sect. 3.5. In each of these sections, the flux profile obtained from the respective defuzzification method compared with the actual data from SRDaS. In Sect. 4, the comparative analysis of all the methods are discussed, and Sect. 5 presents the conclusive remarks on research findings.

2 Magnetization Characteristics of SRM

The highly non-linear magnetic profile of a 6/4 pole SRM obtained from Switched Reluctance Design and Simulation software (SRDaS) [10] is shown in Fig. 1. This magnetic profile depicts the flux linkage (Ψ) values for various currents and at different rotor positions. The relationship is near to linearity only at the initial stage of the profile, after which the Ψ Vs current becomes highly non-linear as rotor position θ moves from 0° (unaligned position) to 45° (aligned position). The current (I), rotor position (θ) and flux linkage (Ψ) parameter values are obtained from these curves and are considered as actual data. This data set is used in the fuzzy system for the estimation of Ψ using various defuzzification methods (Fig. 1).

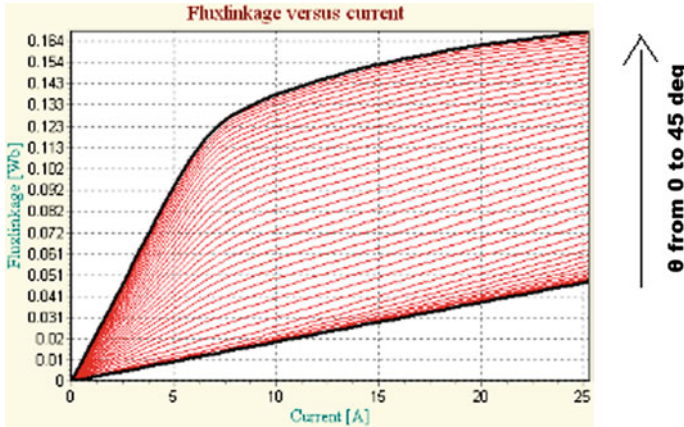


Fig. 1 Flux linkage profile of SRM from SRDaS

3 Fuzzy Logic Based Flux Linkage Modeling of SRM Using Various Defuzzification Techniques

The FIS based $\Psi(I,\theta)$ uses current and rotor position as two inputs and Ψ as its output. The SRM’s electromagnetic data for one electrical cycle is obtained from [10] with the ranges of $0 \leq I \leq 25$ A, $0 \leq \theta \leq 45^\circ$ and $0.0014 \leq \Psi \leq 0.02$ H. The results are compared using the statistical error measures such as Root Mean Square Error (RMSE), Mean Absolute Error (MAE), Maximum Absolute Value Error (MAVE) and Sum of Squared Error (SSE).

3.1 Flux Linkage Model of SRM Using Bisector Method

The comparison between the actual flux linkage values and the values predicted from the bisector-based FIS model is shown in Figs. 2 and 3.

Table 1 presents the error values, and on careful examination, it is observed that the flux linkage values from bisector function are not in good concurrence with the actual data, and hence it is inferred that this method is not suitable for estimation of Ψ values in SRM. The maximum absolute error obtained in this model is 0.08128.

Fig. 2 $\Psi(I, \theta)$ for actual versus bisector method

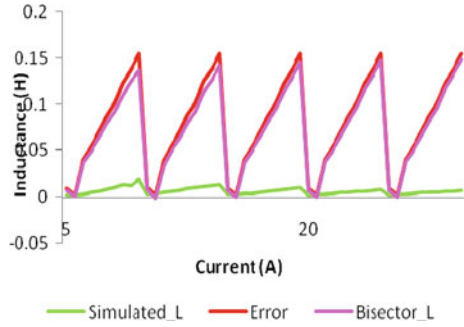


Fig. 3 Operating currents versus errors

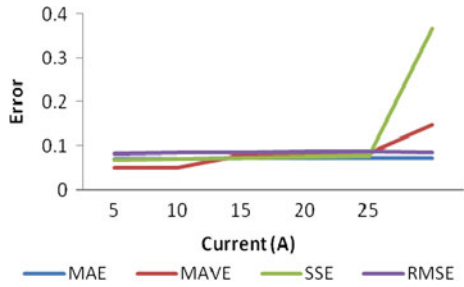


Table 1 Errors in $\Psi(I, \theta)$ using bisector model

Flux linkage errors (Error in henry)	RMSE	SSE	MAE	MAVE
5A	0.082874	0.068681358	0.069904	0.0494
10A	0.084159	0.07082813	0.07067	0.0497
15A	0.086066	0.074073031	0.072133	0.07987
20A	0.087383	0.076357148	0.073185	0.08105
25A	0.087914	0.077288482	0.073556	0.08128

Fig. 4 $\Psi(I, \theta)$ for actual versus MoM method

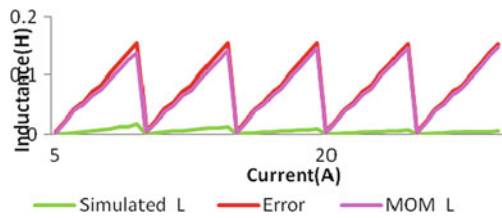


Fig. 5 Operating currents versus errors

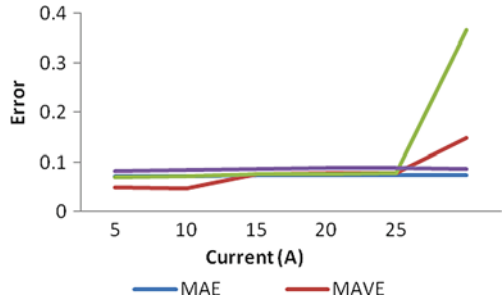


Table 2 Various errors in $\Psi (I, \theta)$ using MoM model

Flux linkage errors (Error in henry)	RMSE	SSE	MAE	MAVE
5A	0.082962	0.06882637	0.071344	0.0486
10 A	0.083811	0.07024241	0.07165	0.0473
15A	0.086152	0.07422143	0.073587	0.076667
20A	0.087169	0.07598429	0.074475	0.07785
25A	0.087566	0.07667889	0.07464	0.07808

3.2 Flux Linkage Model of SRM Using Middle of Maximum Method

Figure 4 depicts the actual and MoM based predicted flux linkage values and the errors are shown in Fig. 5.

Table 2 lists the error values, and on careful examination, it is observed that the flux linkage values from the MoM method is not in good agreement with the actual data, and hence it is inferred that this method is not suitable for estimation of Ψ values in SRM. The maximum absolute error obtained in this model is 0.07808.

3.3 Flux Linkage Model of SRM Using Largest of Maximum Method

Figure 6 depicts the actual and MoM based predicted flux linkage values, and the errors are shown in Fig. 7. Table 3 presents the error values, and on careful examination, it is observed that the flux linkage values from the LoM method is not in good agreement with the actual data, and hence it is inferred that this method is not suitable for estimation of Ψ values in SRM. The maximum absolute error obtained in this model is 0.08288.

Fig. 6 $\Psi(I, \theta)$ for actual versus LoM method

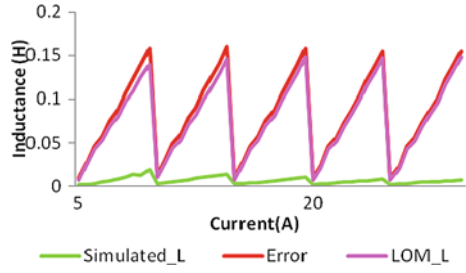


Fig.7 Operating currents versus errors

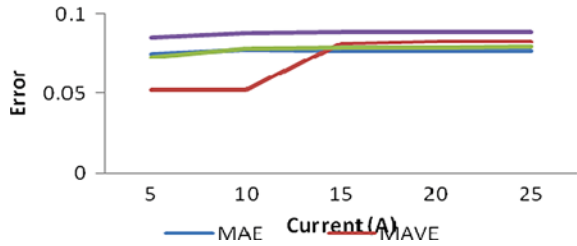


Table 3 Various errors in $\Psi(I, \theta)$ using LoM model

Flux linkage errors (Error in henry)	RMSE	SSE	MAE	MAVE
5A	0.085477	0.073062638	0.074884	0.0526
10A	0.088366	0.07808533	0.07753	0.0529
15A	0.088611	0.078519151	0.077047	0.081467
20A	0.088642	0.078573748	0.076795	0.08265
25A	0.088908	0.079046242	0.07678	0.08288

3.4 Flux Linkage Model of SRM Using Smallest of Maximum Method

Figure 8 depicts the actual and MoM based predicted flux linkage values, and the errors are shown in Fig. 9. Table 4 presents the error values, and on careful examination, it is observed that the flux linkage values from the LoM method are not in good agreement with the actual data, and hence it is inferred that this method is not suitable for estimation of Ψ values in SRM. The maximum absolute error obtained in this model is 0.07328.

Fig. 8 $\Psi(I, \theta)$ for actual versus SoM method

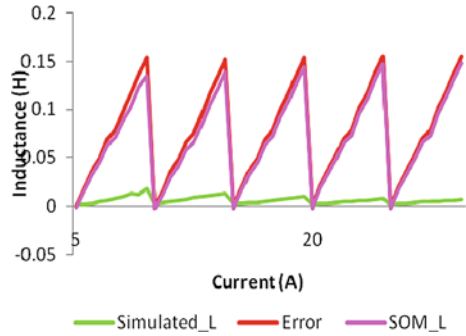


Fig. 9 Operating currents versus errors

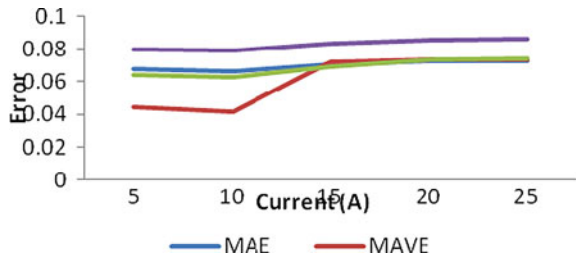


Table 4 Various errors in $\Psi(I, \theta)$ using SoM model

Flux linkage errors (Error in henry)	RMSE	SSE	MAE	MAVE
5A	0.080154	0.06424715	0.067896	0.0446
10A	0.079308	0.06289741	0.06615	0.0417
15A	0.083391	0.06954016	0.070327	0.071867
20A	0.085774	0.07357099	0.072605	0.07305
25A	0.086304	0.07448442	0.072948	0.07328

3.5 Flux Linkage Model of SRM Using Centroid Method

Figure 10 depicts the actual and centroid based predicted flux linkage values. From the depiction, it is observed that the predicted flux linkage values show fair concurrence with the actual values. Different errors are depicted in Fig. 11. By carefully examining the errors listed in Table. 5, it is observed that the predictions using centroid function has less errors for the entire set of the data range. It is in fair concurrence with the actual values and proves to be the potential method for SRM flux linkage estimation. The maximum absolute error obtained in this model is 0.00608.

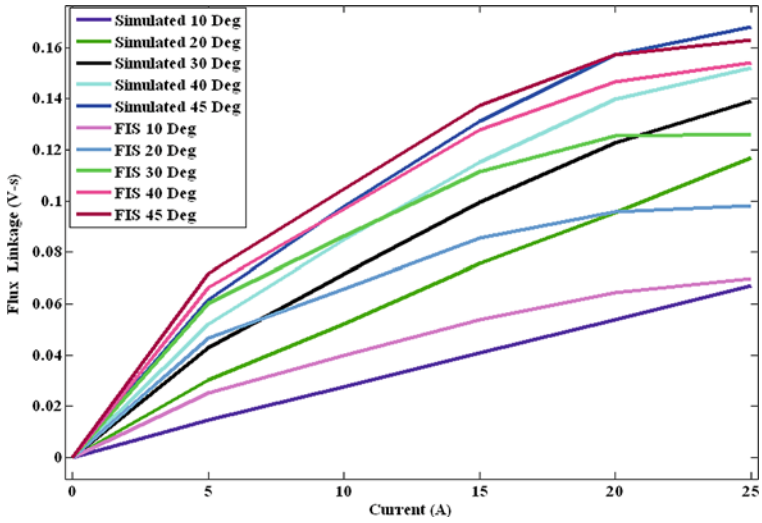


Fig. 10 $\Psi(I, \theta)$ for actual versus centroid method

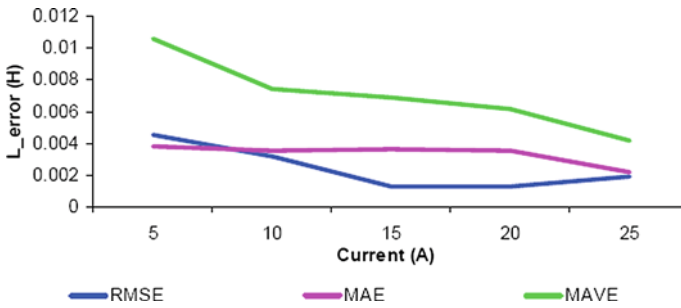


Fig. 11 Operating currents versus error

Table. 5 Various errors in $\Psi(I, \theta)$

Flux linkage errors (Error in henry)	RMSE	SSE	MAE	MAVE
5A	0.008373	0.000701127	0.006768	0.00364
10A	0.00816	0.00066579	0.0074477	0.00566
15A	0.006188	0.000382911	0.005667333	0.00608
20A	0.005056	0.000255585	0.004726	0.00507
25A	0.004665	0.000217612	0.0044512	0.00492

3.6 Comparison of SRM Flux Linkage Models Using Various Defuzzification Techniques

An overall comparative analysis of all the methods is presented in this section. Illustration of errors from different defuzzification functions is shown in Fig. 12. Figure 13 shows the non-linear mapping surface of $\Psi(I, \theta)$ obtained from centroid method.

From the comparison charts and listed errors from Table 6, it is observed that the obtained errors from LoM, MoM and bisector methods are very high. Error obtained in SoM method is comparatively is lesser, still not within the tolerance limits. From

Fig. 12 Operating currents versus errors

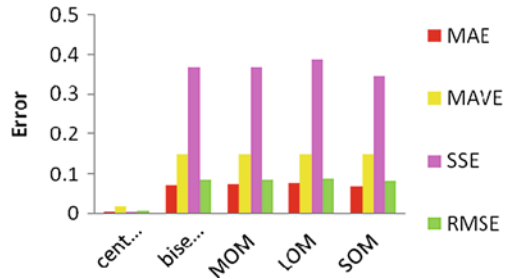


Fig. 13 Non-linear surface mapping view of $\Psi(I, \theta)$

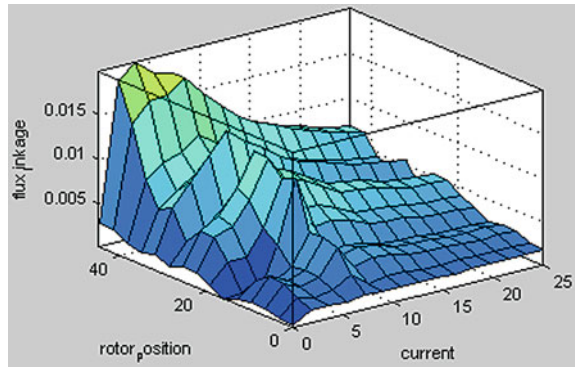


Table 6 Comparison of $\Psi(I, \theta)$ errors from various membership function

Types of errors	For θ varying from 0 to 45° at each phase current 1 to 25A				
	Bisector	MoM	LoM	SoM	Centroid
RMSE	0.0857	0.085552	0.08801	0.083035	0.006668
SSE	0.367228	0.365953	0.3872871	0.3447401	0.00222302
MAE	0.071889	0.073139	0.0766071	0.0699851	0.0058120
MAVE	0.14828	0.14828	0.14828	0.14828	0.01826