

Optimized Design of Three Phase Squirrel Cage Induction Motor based on Maximum Efficiency Operating under the Rated Voltage – based on Software Platform

Saini Raj Kumar^{1,2*}, Saini Devender Kumar¹, Gupta Rajeev¹ and Verma Piush³

¹University of Petroleum and Energy Study, Bidholi, Via Prem Nagar, Dehradun - 248007, Uttarakhand, India; rajsaini.acet@gmail.com, dksaini@ddn.upes.ac.in, rajeev@ddn.upes.ac.in

²Faculty of Shoolini University, Solan-Oachghat-Kumarhatti Highway, Bajol, Solan - 173229, Himachal Pradesh, India;

³Rayat-Bahra Group of Institutes, Patiala Campus, Village Bhedpura, Distt. Patiala, Punjab - 147001, India; pverma19@yahoo.co.uk

Abstract

The efficiency maximization of the three phase induction motor operating at rated voltage and under the rated voltage is carried out with the help of JMAG Express. A computer program based on the output equations of three phase squirrel cage induction motor has been developed to check the initial design and performance of the induction motor with the help of graphic user interface (GUI). The output of GUI program is feed in the input targeted values of JMAG Express for parameter calculations and efficiency optimization. To optimize the efficiency as an objective function multiple parameters will be optimized and dimensions of stator and rotor are calculated in terms of sensitivity analysis at efficiency optimization. Calculations of under rated voltages are based on the averages voltages of the three unbalanced phases. The performance of the motor is carried out by considering the copper and aluminum cage rotor respectively. Due to reactive power demand, generally the motors which are designed for the rated voltages, but are operating under the rated voltages away from the utility center. To reduce the energy crises the aim of this research article is to improve the design quality of such type of motors with the help of JMAG Express, which distinguish it from other optimum designed processes based on programming languages, as this software is friendly user.

Keywords: JMAG Express, Optimum Efficiency, Three Phase Induction Motor, Under Rated Voltage

1 Introduction

To reduce the energy consumption, Hooke Jeeves research technique is used in Ref.¹ to calculate the optimized parameters of three phase squirrel cage induction motor. However in Ref.² attempt was made to prove that the old Hooke Jeeves method is more useful as compared to recently used methods. In Ref.³ GA and PSO optimization techniques are used for the design of the spinning mill induction motor and the results are compared with the general purpose machine. The cost of active material is taken as an objective function in Ref.⁴ by using con-

strained optimization techniques called complex method. The authors applied three optimum techniques by taking 10 H.P motor as an example and compared the results with initial and industrial design motor for finding the better results in terms of low current and higher torque with better power factor⁵. Similarly in Ref.⁶ three optimum techniques are used for the design of the spinning mill induction motors and the obtained results are compared with the general purpose machine. To reduce the error between the estimated and manufacturing data, PSO technique is used on three different induction models with sensitivity analysis in Ref.⁷ More compressive

*Author for correspondence

study is carried out by using optimization techniques in Ref.⁸, which includes the relationship between efficiency, power factor and cost. The two optimizations methods, Powell and boundary search techniques have been discussed in Ref.⁹. An optimal efficiency method for vector controlled synchronous reluctance motor drive is used in Ref.¹⁰. The steady state characteristic of new design motors and material data required for a known geometry motors can be determined by using finite element method as discussed by the authors in Refs.¹¹⁻¹², While GA have been ranked as the best tool for optimization techniques, discussed in Refs.¹³⁻¹⁵. The advantages of GA over the standard nonlinear programming (NPL) are discussed in Ref.¹⁶ and further added that it does not require the use of derivatives of the functions. An optimized design was developed for a three phase induction motor by reducing the overall cost of the machine, but not ensuring about the overall performance of the machine¹⁷. While in Ref.¹⁸, the results are carried out by varying voltage and load and proofed that both variables are important for good results. The author presented a new algorithm which was a modified version of price method at low voltage in Ref.¹⁹. To get the desired torque speed characteristic an optimum design of rotor is develop with the help of initial reference design in Ref.²⁰. In literature²¹, the author develop a new geometry for slots design. In Refs.²²⁻²³, the authors describe that the unbalanced voltages increases the temperature of the machine which results in efficiency reduction and shorter life time of the machine. Study showed that even under unbalanced voltages the efficiency of machines can be improved. In another words a motor working on unbalanced voltage may have more efficiency than a motor working on balanced or rated voltages. In Ref.²⁴, the author find out some methods to improve the efficiency of squirrel cage induction motor operating under the rated voltages. Out of 25 elements there are 12 element which affects the efficiency of the motor. JMAG designer software²⁵⁻²⁶ is used to perform the electromagnetic analysis and to optimize the study model much easy. The authors in Ref.²⁷, find out the way to calculate the turn to turn fault that occur in the induction motor at no load conditions, while in Ref.²⁸ the authors find out a solution to calculate the stator resistance under balanced and unbalanced voltage conditions with the help of DC signal injected to AC voltage. The harmonic distortion have been reduced in induction motor by

using nine level inverter as compared to classical inverter simulated with the help of Simulink²⁹. In Refs.³⁰⁻³¹ support vector machine is used as a fault detector and embedded system is used to monitor the on line performance of the induction motor respectively.

1.1 Electric Motors Design and JMAG Express

The JMAG Express is a combination of inbuilt tools which have an aim to support the designer and researcher during the design process of induction motors. The software is friendly user. This innovative platform of software can be used not only for three phase induction motors, but it can be used for a set of electric rotating machines like DC motors, synchronous motors and single phase induction motor. Inbuilt tools have more flexibility for the variation of parameters with different combination of stator and rotor design to get its optimized design.

1.2 Different Definitions of Unbalanced Voltages

There are many definitions of unbalanced voltages which are given by different authors. For example the definition used in European standard, is the ratio of negative to the positive phase sequence voltage. For a voltage set of three phase circuit, let, V_{ab} , V_{bc} and V_{ca} be the positive phase voltages and negative phase sequence voltages V_{ab1} and V_{ab2} are related by the following relation.

$$V_{ab1} = \frac{V_{ab} + a \times V_{bc} + a^2 \times V_{ca}}{3}$$

$$V_{ab2} = \frac{V_{ab} + a^2 \times V_{bc} + a \times V_{ca}}{3}$$

Where,

$$a = -0.5 + j0.866 \text{ and}$$

$$a^2 = 0.5 - j0.866$$

And according to national electrical manufacturing association, the unbalance percentage of voltages are given by the following relation.

$$\%LVUR = \frac{\text{Maximum deviation from average line voltage}}{\text{magnitude of average Line Voltage}} \times 100$$

1.3 Motors Operating under the Rated Voltages

This is analyzed that the average voltage of the three phases are generally low due the presence of unbalanced voltages in the three phases, which increases the overall losses of the motor. The variable losses have more effects on the efficiency of the motor as compared to its constant losses. The wind age and friction losses are generally reported as 1 to 2 percentage of the output of the machine whereas the constant losses varies from 2 to 3 percentage.

1.4 Input Specifications

To optimize the performance of induction motor operating at rated voltage and under the rated voltage, a three phase squirrel cage induction motor have been proposed with the following input specifications as shown in Table 1.

Table 1. Input Specifications

Particulars	Values
Rating of the machine	7.5kw
Rated speed	1425 R.P.M
Maximum Speed	1500 R.P.M
No of poles	4
No of slots	36
Power supply in RMS	284 V
Maximum current	15Amp
Stator design	Parallel tooth opening round bottom
Rotor design	Rectangular type bar

In order to calculate the variation of voltages a study is done to judge the variation of voltages at the motor termi-

nals in electrical research laboratory and calculations are prepared for percentage unbalanced, average voltage and percentage below the rated voltage as shown in Table 2.

2. Simulation and Results

The proposed JMAG Express technique is used on 7.5 kW induction motor to calculate the sensitive parameters of stator and rotor at its rated voltage and under the variation of rated voltages. The module is built to give optimize efficiency as an objective function with multiple optimized parameters, discussed in Table 4. Variable parameters of stator and rotor are calculated in terms of sensitivity analysis. These are the parameters which have the most impact on the performance of the motor. To avoid the manufacturing error sensitivity analysis are important as discussed in Ref.³². Normal parameters calculation are being done by using copper cage and aluminum cage rotor and the results are presented in Table 3 and 4, while the process of optimization is completed with the help of JMAG Express, presented in Table 5.

In general cases the efficiency of the induction motor equipped with the copper cage is more as compared to the similar rating of machine using an aluminum cage at its rated speed, but by making the combination of rectangular type bar rotor with Parallel tooth opening round bottom as a stator, the efficiency at the initial stages of aluminum cage rotor is more as compared to copper cage motor for the same rating of the motor. The power developed by the aluminum cage motor is more as compared to copper cage motor at the initial stages. Losses are also more with high magnetizing current in case of aluminum cage motors as compared to copper cage motor with slightly low power factor, but having the advantage of better starting torque with aluminum cage rotor. The

Table 2. Calculation for percentage unbalanced, average voltage and rise in temperature.

S.No	V _{ab}	V _{bc}	V _{ca}	% (Unbalanced)	Ave (V)	% Below rated Voltage	% Rise in temperature
1	360	363	360	0.55	361	9.75	0.60
2	375	378	362	1.70	371.67	7.08	5.78
3	365	366	365	0.18	365.33	8.66	0.064
4	355	361	360	0.64	360	10	0.81
5	361	364	367	0.82	364	9.00	1.34
6	363	360	360	0.64	360.33	9.08	0.81
7	381	360	362	1.55	363.33	8.66	4.80
8	369	360	366	1.46	363.67	9.08	4.26

Table 3. Normal parameter Calculations for 7.5kw, 50Hz, 4 pole induction motor by selecting copper Cage.

Speed (R.P.M)	%age Efficiency	Power (w)	Copper Losses (w)	Iron losses (w)	Primary Current (RMS)	Torque (Nm)	First current loss(w)	Second current loss(w)	Magnetizing Current (Amp)
75	3.63	28.22	748.035	3.40	2.24	3.59	221.85	536.17	0.220
225	11.55	88.49	700.863	3.54	2.17	3.75	199.65	518.89	0.224
450	23.28	190.42	623.65	3.83	2.06	4.04	179.34	444.31	0.233
600	31.98	267.49	564.79	4.12	1.97	4.26	163.54	401.23	0.242
750	41.23	351.39	496.30	4.53	1.85	4.47	144.91	351.39	0.254
900	50.99	439.36	417.11	5.10	1.71	4.66	124.20	292.90	0.269
1050	61.49	515.49	318.009	5.94	1.51	4.68	97.08	220.92	0.290
1200	74.14	535.95	196.49	7.45	1.22	4.26	62.50	133.98	0.319
1425	87.67	236.87	23.93	9.36	0.52	1.58	11.47	12.46	0.365
1500	0	0	5.90	9.84	0.37	0	5.90	0	0.374

Table 4. Normal parameter Calculations for 7.5kw, 50Hz, 4 pole induction motor by selecting aluminum Cage.

Speed (R.P.M)	%age Efficiency	Power (w)	Copper Losses (w)	Iron losses (w)	Primary Current (RMS)	Torque (Nm)	First current loss (w)	Second current loss (w)	Magnetizing Current (Amp)
75	4.012	33.41	795.22	4.16	1.95	4.25	160.30	634.92	0.244
225	12.25	99.54	708.71	4.32	1.85	4.22	144.66	564.04	0.249
450	25.18	197.76	582.89	4.67	1.69	4.19	121.42	461.47	0.259
600	34.22	262.14	498.70	5.00	1.58	4.17	105.49	393.21	0.268
750	43.64	322.97	411.64	5.44	1.45	4.11	88.67	322.96	0.279
900	53.22	379.78	327.84	5.92	1.33	4.029	74.65	253.18	0.291
1050	63.21	419.17	237.40	6.59	1.17	3.81	57.76	179.64	0.307
1200	73.56	412.93	140.95	7.50	0.95	3.28	37.71	103.23	0.328
1425	86.56	176.98	18.36	9.13	0.46	1.18	9.040	9.31	0.362
1500	0	0	5.74	9.48	0.36	0	5.74	0	0.369

electrical grade copper is used in very large motors and in some small purposes motors as discussed in Ref.³³, the author also pointed that copper cage motors are not suitable for the production of millions of motors produced annually and also said that the copper cage rotor would be preferable but the process has not been economical due to high melting point of copper. For economically better manufacturing, in this research article aluminum cage rotor has been given the preference to calculate the optimization results that are presented in Table 5.

The dimensions of stator and rotor in terms of sensitivity analysis are calculated and are presented in Table 6.

Results show that the stator bore diameter, outside side diameter of rotor and width of stator tooth are highly sensitive which effects the efficiency of the motor.

Figure 1 shows that the temperature will rise due to the presence of unbalanced voltages in the three phases, which increases the overall losses of the motor and hence lower down the efficiency of the motor and also the life span of the motor is directly proportional to its working temperature.

Figure 2 presents the normal and optimized losses at rated speed by selecting aluminum cage rotor. Results shows that the losses are reduced which indicates the

Table 5. Optimized parameter Calculations for 7.5kw, 50Hz, 4 pole induction motor by selecting aluminum Cage, under the variation of voltage (400V - 363V).

Speed (R.P.M)	%age Efficiency	Power (w)	Copper Losses (w)	Iron losses (w)	Primary Current (RMS)	Torque (Nm)	First current loss (w)	Second current loss (w)	Magnetizing Current (Amp)
75	5.017	27.03	642.44	3.46	1.74	3.44	128.85	513.58	0.218
225	13.26	80.72	573.95	3.60	1.66	3.42	116.52	457.43	0.222
450	26.21	160.94	473.59	3.89	1.52	3.41	98.057	375.53	0.231
600	35.26	213.73	405.90	4.17	1.42	3.40	85.30	320.59	0.240
750	44.68	263.73	335.50	4.54	1.30	3.35	71.77	263.73	0.250
900	54.25	310.38	267.51	4.94	1.19	3.29	60.59	206.92	0.261
1050	64.22	343.10	194.09	5.49	1.06	3.12	47.04	147.04	0.275
1200	73.56	338.94	115.58	6.26	0.85	2.69	30.84	84.73	0.293
1425	87.58	146.37	15.056	7.63	0.417	0.98	7.35	7.70	0.324
1500	0	0	4.60	7.92	0.33	0	4.60	0	0.330

Table 6. Calculation of stator and rotor dimensions for 7.5kw, 50Hz, 4 pole induction motor with sensitivity analysis at efficiency optimization.

Variables	Values
DS2:Stator bore diameter	54.56 mm
RD1: Outside diameter	53.5 mm
WST:Width of stator tooth	2.29 mm
RW1:Slot opening width	0.576 mm
DSS:Depth of stator slot	17.5 mm
HSTT:Hight of stator tooth tang	1.94 mm
WSSO:With of stator slot opening	0.64 mm
RT2: Bar thickness	6.95 mm
DS1: Stator outside diameter	107 mm
RD2:Shaft diameter	16 mm
RT1:Tooth tang thickness	1.07 mm
ANGSTT:Angle of stator tooth tang	22.9 deg

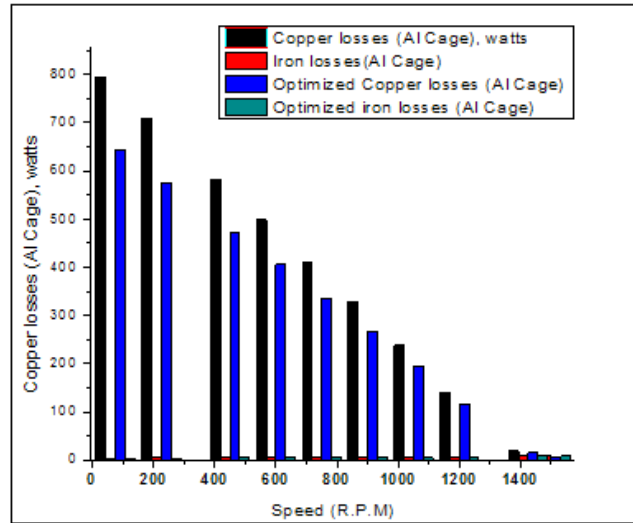


Figure 2. Speed Vs losses

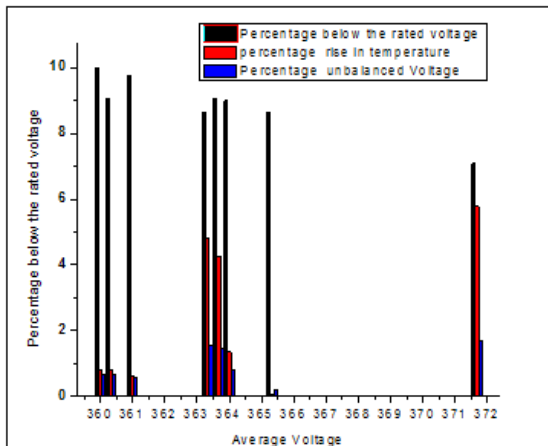


Figure 1. Average voltage Vs below rated voltage.

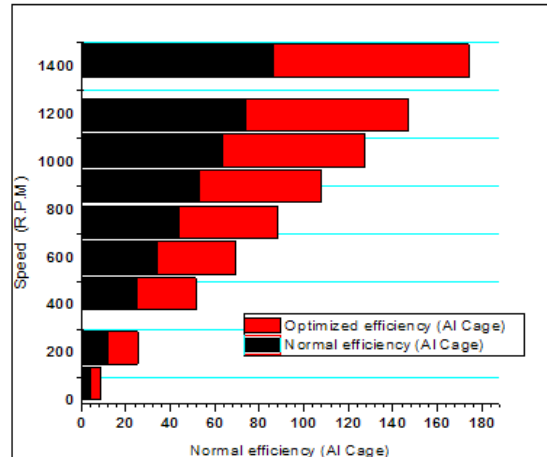


Figure 3. Speed Vs efficiencies

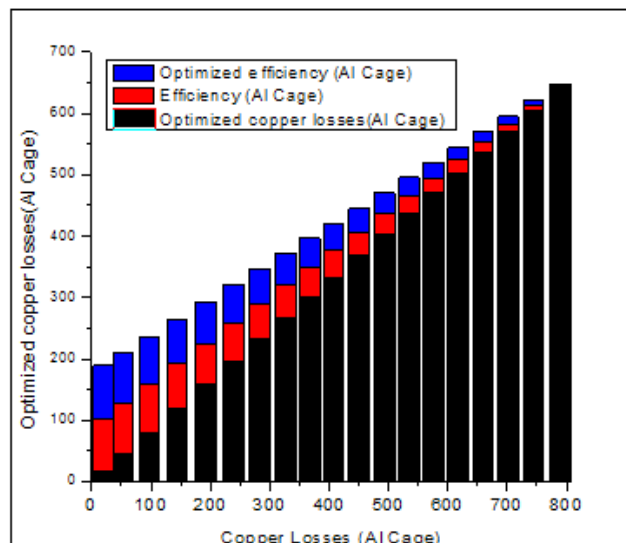


Figure 4. Copper losses Vs Optimized copper losses and efficiencies

improvement in the efficiency of the motor. Figure 3 indicates normal and optimized efficiency with aluminum cage, similarly Figure 4 also indicates the results of normal and optimized efficiency with normal and optimized copper losses.

In this software Genetic Algorithm (GA) is used as an inbuilt tool for optimization techniques and calculations of sensitivity analysis are completed by using correlation matrix.

3. Conclusion

Three phase induction motors are one of the most important functional group in industries as well as for the domestic purposes. The design of three phase induction motors needs more attention to improve the efficiency even when the motors are operating under the rated voltages far away from the utility center. To reduce the energy crises there is more need right from the early design stages of the motor in order to obtain its optimized design. This is the reason that this research article possess an automatic eco design software called JMAG Express, which has an aim to support the whole design of the rotating electric machines under different variable factors. In this article the main focus is given to optimize the parameters of three phase induction motors which are operating under the wide range of variation of voltages. The design process is very quick. Further experimental results on the

real design of this motor will allows us to give more suggestions regarding the performance of the motor.

4. Acknowledgment

The license key for JMAG Express provided by Engineering Technology Division JSOL Corporation Tokyo, 1040053-Japan to the corresponding author is highly appreciated.

5. References

1. Faiz Jawad. Optimum design of a three phase squirrel-cage induction motor based on efficiency maximization. Elsevier, Computers Elect. Engg. 1995; 21(5):367-73.
2. Li C and Rahman A. Three-phase induction motor design optimization using the modified Hook Jeeves method. Elect. Much. Power Systems 1990; 18:1-12.
3. Thangaraj Radha. Optimal Design of Induction Motor for a Spinning Machine Using Population Based Metaheuristics. IEE, International Conference on Computer Information Systems and Industrial Management Applications (CISIM). 2010; p. 341-46.
4. Nagrial MH. Computer-aided design optimization of poly-phone induction motors. Computer & Elect. Engng. 1984; II(4):191-99.
5. Faiz Jawad. Optimal design of three phase induction motors and their comparison with a typical industrial motor. Computers and Electrical Engineering. 2001; 27:133-44.
6. Thanga Raj C. Design optimization of induction motors with differential evolution algorithms with an application in textile spinning. Applied Artificial Intelligence. 2012; 26:809-31.
7. Sakhivel VP. Multi-objective parameter estimation of induction motor using particle swarm optimization. Engineering Applications of Artificial Intelligence. 2010; 23:302-12.
8. Appelbaum J. Optimization of three-phase induction motor design part 1: formulation of the optimization technique. IEEE Transactions on Energy Conversion. 1987 September; EC-2(3):404-14.
9. Fci R, Fuchs EF & Huaug H. Comparison of two optimization as applied to three-phase induction motor design. IEEE Transactions on Energy Conversion. 1989; 4(4):651-9
10. Kim GK. Control of induction motors for both high dynamic performance and high power efficiency. IEEE Transaction. Ind. Electron. 1992; 39:323-33.
11. Abido MA. Optimal power flow using particle swarm optimization. Electrical. Power Energy Syst. 2002; 24:563-71.
12. Huang C, Wang M. A particle swarm optimization to identifying the ARMAX model for short-term load

- forecasting. *IEEE Transactions on Power. Systems*, 2005; 2(20):1126–33.
13. Uler GF, Mohammed OA, Koh CS. Utilizing genetic algorithms for the optimal design of Electromagnetic devices. *IEEE Transition. On Magnetics*. 1994; 30(6):4296–98.
 14. Bianchi N, Bolognani S. Design optimization of electric motors by Genetic Algorithm. *IEE Proc. Electr. Power Appl.* 1998; 145: 475–83.
 15. Wicczorek JP. An evolutionary algorithm for the optimal design of induction motors. *IEEE Transition on Magnetics*. 1998; 34(6):3882–87.
 16. Pant Millie, Thangaraj Radha & Singh VP. Efficiency optimization of electric motors: a comparative study of stochastic algorithms. *UK World Journal of Modelling and Simulation*. 2008; 4(2):140–48.
 17. Erlicki MS and Appelbaum J. Optimized Parameter Analysis of an Induction Machines. *IEEE Transactions on Power Apparatus and Systems*. 2009; pas-842(11):1017–24.
 18. Giridhar Kini P. Effect of Voltage and Load Variations on Efficiencies of a Motor-Pump System. *IEEE Transactions on Energy Conversion*. 2010 June; 25(2):287–92.
 19. Daidone A. A new method for the Design optimization of Three-phase Induction Motors. *IEEE Transactions on magnetics*. 1998 September; 34(5):2932–35.
 20. Dianhai Zhang. A New Optimal Design Method of Rotor Slot of Three-Phase Squirrel Cage Induction Motor for NEMA Class D Speed-Torque Characteristic Using Multi-Objective Optimization Algorithm. *IEEE Transactions on magnetics*. 2012 February; 48(2):879–82.
 21. Zaixun Ling and Libing Zhou. Equivalent Circuit Parameters Calculation of Induction Motor by Finite Element Analysis. *IEEE Transactions on magnetics*. 2014 February; 50(2).
 22. Williams. Operation of three-phase induction motors on unbalanced voltages. *AIEE Trans, Pt-III-A, and Power Apparatus Syst.* 1954; 73(April):125–33.
 23. Faiz Jawad. Influence of unbalanced voltage supply on efficiency of three Phase squirrel cage induction motor and economic analysis. Elsevier, *Energy Conversion and Management*. 2006; 47:289–302.
 24. Hasuikie K. Efficiency improvement study of low voltage three phase squirrel cage induction motor for general purpose. *IEEE Trans on power apparatus system*. 1993 December; pas-102(12).
 25. Govindasamy K, Sathishkumar. Design and fabrication of high efficiency squirrel cage induction motor using finite element method. *ARPN Journal of Engineering and Applied Sciences*. 2015 March; 10(4).
 26. Motor models furthering model based Design—Introducing JMAG RT. Ed: JSOL Corp., Error! Hyperlink reference not valid. Date accessed: 30/08/2010.
 27. Abitha Memala W and Rajini V. Information Theoretic Criteria for Induction Motor Fault Identification. *Indian Journal of Science and Technology*. 2015 November; 8(30):1–6. Doi: 10.17485/ijst/2015/v8i30/70494.
 28. Sabaghi Masoud and Farahani Hassan Feshki. Monitoring of induction motor temperature under unbalanced supplying by stator resistance estimation. *Indian Journal of Science and Technology*. 2012 Mar; 5(3):2354–59.
 29. Pandian G and Rama Reddy S. Simulation and analysis of multilevel inverter fed induction motor drive. *Indian Journal of Science and Technology*. 2009 Feb; 2(2):67–69.
 30. Ghate VN and Dudu SV. SVM based fault classification of three phase induction motor. *Indian Journal of Science and Technology*. 2009 Mar; 2(4):32–35.
 31. Anbazhagu UV, Praveen JS and Soundarapandian R. A Proficient Approach for Monitoring Induction Motor by Integrating Embedded System with Wireless Sensor Network. *Indian Journal of Science and Technology*. 2014 November; 7(S7):174–79.
 32. Sakthivel VP, Bhuvaneswari R and Subramanian. Multi-objective parameter estimation of induction motor using particle swarm optimization. *Engineering Applications of Artificial Intelligence*. 2010; 23:302–12.
 33. Tiberiu Rusu. Script Controlled Modeling of Low Noise Permanent Magnet Synchronous Machines by using JMAG Designer. *Journal of Computer Science and Control Systems*. 2013 May; 6(1):91–94.