Reliability Indices Evaluation of SEIG Rotor Core Magnetization with Minimum Capacitive Excitation for WECs

Lokesh Varshney, R. K. Saket

***Abstract*—**This paper presents reliability indices evaluation of the rotor core magnetization of the induction motor operated as a self excited induction generator by using probability distribution approach and Monte Carlo simulation. Parallel capacitors with calculated minimum capacitive value across the terminals of the induction motor operated as a SEIG with unregulated shaft speed have been connected during the experimental study. A three phase, 4 poles, 50Hz, 5.5 hp, 12.3A, 230V induction motor coupled with DC Shunt Motor was tested in the electrical machine laboratory with variable reactive loads. Based on this experimental study, it is possible to choose a reliable induction machines operated as a SEIG for unregulated renewable energy application in remote area or where grid is not available. Failure density function, cumulative failure distribution function, survivor function, hazard model, probability of success and probability of failure for reliability evaluation of the three phase induction motor operating as a SEIG have been presented graphically in this paper.

***Keywords*—**Residual magnetism, magnetization curve, induction motor, self excited induction generator, probability distribution, Monte Carlo simulation.

I. Introduction

SELF Excited Induction Generator (SEIG) has many advantages over an alternator. But it faces some problems such as poor voltage regulation and reactive power consumption. The availability of designed SEIG is not very popular compare with the Induction Motor. However, SEIG is very popular in unregulated renewable energy source such as micro hydro, wind etc in hills or remote areas. SEIG is directly connected with turbine and turbine attached with renewable energy source. There is no need of dam, gear-pulley and other mechanical attachment. Use of the Induction motor as SEIG, the performance of this type of generator is undesirable. The reason for the poor performance is because the parameter values determined during the design stage were chosen, because they optimized the performance of the machine as a motor and not as a generator. In order to demonstrate this concept, it is important to understand that an induction machine is a magnetic circuit; and therefore, it will be influenced by hysteresis. Thus, an induction machine has two regions of operation based on this hysteresis. Specifically, an induction machine will operate in an unsaturated (linear) region or a saturated (nonlinear) region. In most instances, it is not desirable to operate an induction motor in saturation since this reduces the relative permeability of the iron and increases the MMF required to operate the motor. On the other hand, operating in the linear region does not fully utilize the capabilities of the iron; and therefore, this approach is not economical. As a result, the most desirable operating points for an induction motor are on the knee of the saturation curve. These points maximize the use of the iron while minimizing the saturation. However, the operation of a SEIG is stable when its magnetic circuit saturates. Thus, in order to use an induction motor as a generator, the terminal voltage of the induction motor is increased until the magnetic circuit is saturated [4], [6]. As a result, SEIG operates after the knee of the saturation curve; however induction motor operates on or before the knee of the saturation curve. Less hysteresis loss is considered in the design of rotor core of the induction motor; hysteresis loss depends upon the area of hysteresis loop. As this condition, soft magnetic material is used in the rotor core of the induction motor, whose hysteresis loop is narrower. On the other hand, hard magnetic materials are used in the rotor core of the designed SEIG, whose hysteresis loop is broad. Therefore, hysteresis effect in this machine’s rotor is more. Thus, rotor core have sufficient residual magnetism, which required for initial excitation in the SEIG. As this condition, the problem of loss of excitation may occur to use the induction motor as a SEIG. However, IM operate as SEIG compare the designed SEIG is more economical and available. Thus, using IM as a SEIG is very popular. Evaluation of reliability of the rotor of the machine is required, which will work as SEIG.

This paper is organized as follows: Loss and restoration of residual magnetism have been presented in Section II. This section briefly describes the three methods of restoration of residual magnetism. Section III describes the concept, causes and factor of failure operation of SEIG. Section IV evaluates the experimental minimum capacitive value for excitation on SEIG. Section V evaluates the reliability of the rotor core magnetization of SEIG with minimum value of capacitor and

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Lokesh Varshney is with the Department of Electrical Engineering, Indian Institute of Technology (Banaras Hindu University), Varanasi (Uttar Pradesh), India. (e-mail:lokesh_varshney@rediffmail.com).

Dr. R. K. Saket was with the Electrical and Electronics Engineering group, Birla Institute of Technology and Science, Pilani (Rajasthan), India and Rajiv Gandhi University of Technology, Bhopal (Madhya Pradesh), India. He is now with the Department of Electrical Engineering, Indian Institute of Technology (Banaras Hindu University), Varanasi (Uttar Pradesh), India (Corresponding author: phone: +91-0542-6702837, mobile: +91-9451067022. e-mail: rksaket.eee@itbhu.ac.in, drrksaket@gmail.com).

determines the failure density function, cumulative failure distribution, survivor function, hazard rate and the curve respectively. The probabilities of success and failure have been evaluated by using Monte Carlo simulation. Section VI presents conclusion of the work.

II. Loss and Restoration of Residual Magnetism

A. Loss of Residual Magnetism

The short circuit or too increase reactive load will cause the voltage dip suddenly and residual magnetism of the rotor is destroyed. Any method of the Section II *B* can give the temporary excitation to the iron core to restore the residual magnetism.

B. Restoration of Residual Magnetism

Generally three methods are useful for restoration of the residual magnetism in the machine rotor.

(1) By operation of the experimental machine as an induction motor for 10 to 15 minutes excited by the ac source.
(2) By switching of the experimental machine by charged terminal capacitors to restore residual magnetism. If the capacitors are charged up to a high voltage, say rated machine voltage, the discharge current is normally sufficient to cause self excitation even with a degaussed rotor.
(3) By increasing the machine speed above the rated value, causing the resonant speed at low magnetization to be exceeded, and thereby initiating self excitation (note that the machine's rotor and bearings must be rated for the higher speed).

When the machine is at rest then connect a 6 volt battery across two terminals of the machine for 10-15 minutes. Or by passing a DC current through the machine before it is run up to speed, sufficient residual magnetism may be guaranteed.

First method is better than the other approaches with the availability of the power grid. Third method is useful for unavailability of the grid [5].

III. Problem with Excitation Failure of SEIG

In this paper, induction machine is used as an SEIG with suitable value of capacitor for excitation. Generation based on SEIG depends on shaft speed, residual magnetism, reduced permeability at low magnetization, and value of the capacitor connected in the machine. The reliability of the self excitation must be very high, either by increasing the speed or increasing the capacitor value or both [1], [9]. SEIG generates active power only and the reactive power is supplied to the SEIG for excitation and to the reactive load (Q_L) by capacitors. SEIG is started on no load with suitable value of capacitor. Capacitor gives reactive power (Q_E) to SEIG for excitation and left reactive power (Q_S) is supplied to the reactive load. If the reactive load (Q_L) is little increased from the Q_S, just then the terminal voltage is dipped. Increase either capacitor value or shaft speed or both to prevent the terminal voltage. However, residual magnetism and permeability of the iron core of the rotor cannot be changed during working stage of the SEIG. If capacitor value and shaft speed has not been increased, terminal voltage is dipped and load disconnects. Many times, loss of residual magnetism is occurred. This problem of the experimental SEIG has been considered for reliability evaluations. It has been done at minimum value of capacitor (The minimum terminal capacitor is required for SEIG to the voltage build up). The comparison of the reliability of different SEIG's is suggested to evaluate at minimum value of capacitor.

IV. Experiments on SEIG with Minimum Capacitive Excitation

The rating of the induction machine operated as SEIG is 3-phase, 4-pole, 50Hz, 230V, 12.3 A, 5.5 hp. The per-phase equivalent parameters of the IM in per unit are $R_s = 0.0496$, $R_r = 0.0350$, $X_s = 0.1344$, $X_r = 0.1344$. The evaluated magnetization curve of the IM has described in the Fig. 2. The evaluated minimum value of capacitor is 24.48 µF [3], [10].

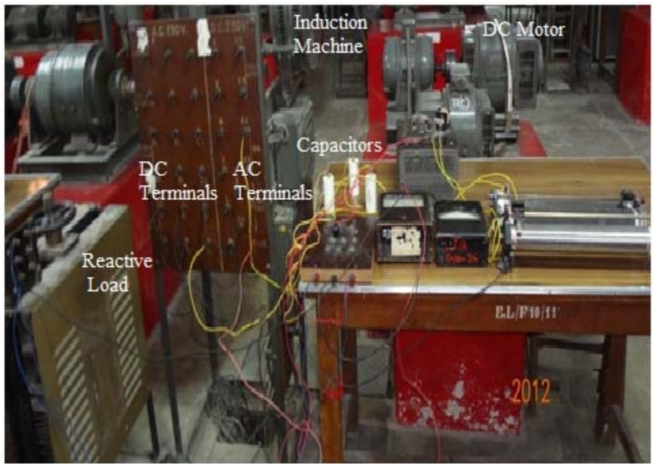

Fig. 1 Experimental setup with reactive load

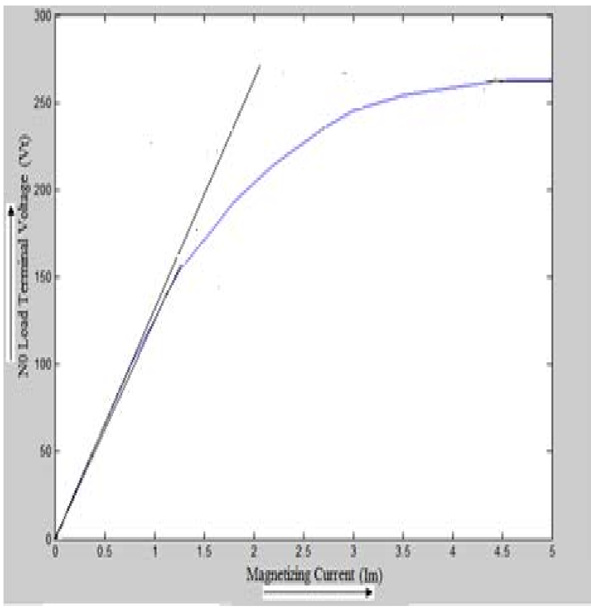

Fig. 2 No Load Magnetization Curve of induction machine

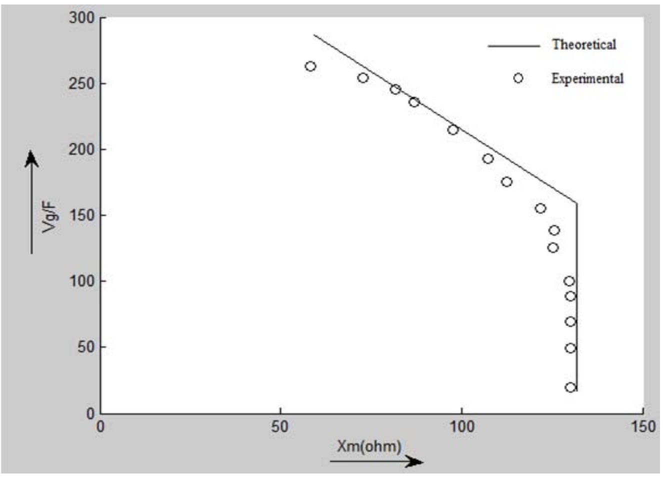

Fig. 3 Variation of Vg/F with Xm

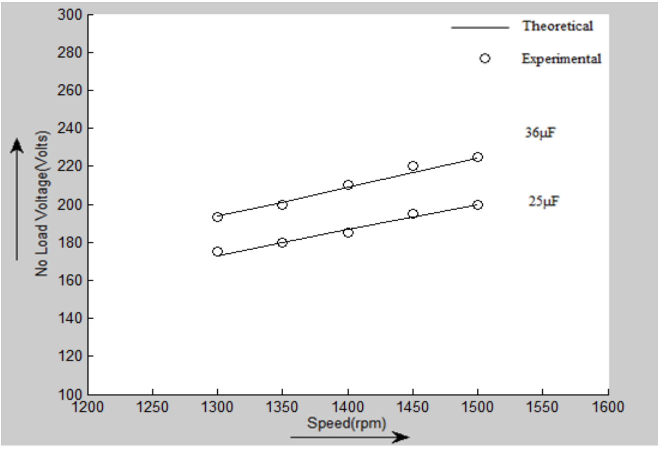

Fig. 4 Variation of terminal voltage with speed and capacitance for no load

Fig. 3 shows the function of Vg/F for the test machine. The operation of Induction machines as an SEIG is evaluated with measurement of terminal voltages with different speed of prime mover. Variation in generated delta connected no load terminal voltages with different speed of prime mover at 25 μF and 36 μF capacitors delta connected is shown in Fig. 4 [7]. As seen here, the agreement between measured and the computed values of the terminal voltage is sufficient which confirm the validity of the analysis.

V. Reliability of Rotor Core Magnetization of SEIG with Minimum Value of Capacitor

In this paper, loss of excitation has only considered for the generation failure of the SEIG. The loss of excitation is being considered as the main component for the failure of machine operation. Other components of the SEIG system failure, like generation failure due to construction / manufacturing defects and the operating conditions, are not being considered during experimental period. Evaluation of the reliability of SEIG excitation has been performed using minimum value of capacitor. Evaluated reliability indices are presented in Table I.

A. Evaluation of Reliability Functions

Here, reliability evaluation of SEIG excitation is being described by probability distribution functions. Initially almost 32 number of experiment has been done on SEIG in first day. It means that 32 times reactive load has increased. In next day, all the experiments minus all failure in the previous time interval have been considered as the total number of experiments. The number of failures is collected experimentally for seven intervals. The probability indices like: failure density function, cumulative failure distribution, survivor function and hazard function have been described in Table I [2], [8].

TABLE I
PRACTICAL FAILURE DATA AND EVALUATION OF RELIABILITY INDICES

Time interval	Failure in each interval	Cum. failures	N	f(t)	F(t)	S(t)	h(t)
0	15	0	32	0.469	0.000	1.000	0.638
1	8	15	17	0.250	0.469	0.531	0.615
2	4	23	9	0.125	0.718	0.281	0.571
3	2	27	5	0.062	0.844	0.156	0.500
4	1	29	3	0.031	0.906	0.094	0.400
5	0	30	2	0.000	0.938	0.062	0.000
6	1	30	2	0.031	0.938	0.062	0.660
7	1	31	1	0.031	0.969	0.031	2.000
		32		Sum = 1.000	1.000	0.00	

The procedure for evaluation of reliability indices are as follows:

1. Computation of total failures in each interval. Time interval is 1 day.
2. Evaluation of reliability indices like: failure density function, cumulative failure distribution, survivor function and hazard rate. All reliability indices have been described graphically in Figs. 5, 6, 7 and 8 respectively. Description of table is as follows:

a) Columns 1 and 2 represent the time interval (in days) and number of failures which have obtained experimentally.
b) Column 3 (cumulative failure) is obtained by cumulating all the failures in the previous time intervals.
c) Column 4 (number of experiment) is obtained by subtracting the cumulative number of failures. Initial number of experiment performed in first day is 32.
d) Column 5 (failure density function) the ratio between the number of failure during a time interval and initial number of experiment performed in first day.
e) Column 6 (cumulative failure distribution) is the ratio between the cumulative number of failures and initial number of experiment performed in first day.
f) Column 7 (survivor function or reliability) is the ratio between the cumulative number of survivor and initial number of experiment performed in first day.
g) Column 8 (hazard rate) is the ratio between the number of failure in an interval and the average number of survivor for that period [2].

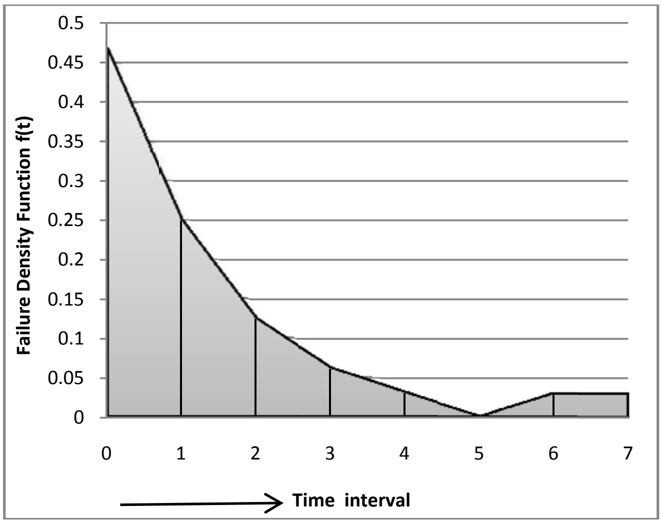

Fig. 5 Failure Density Function Curve

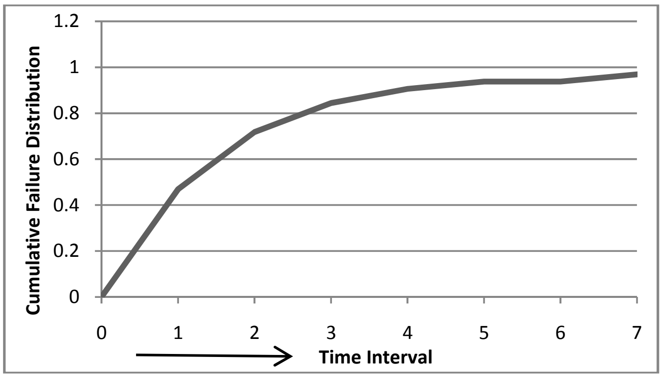

Fig. 6 Cumulative Failure Distribution Curve

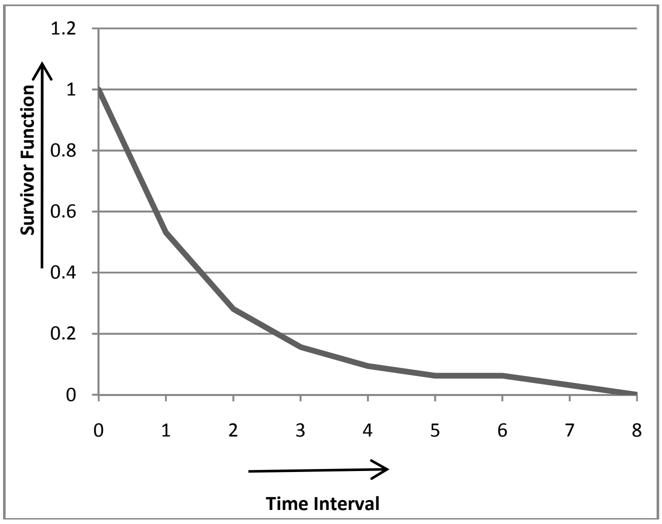

Fig. 7 Survivor Function Curve

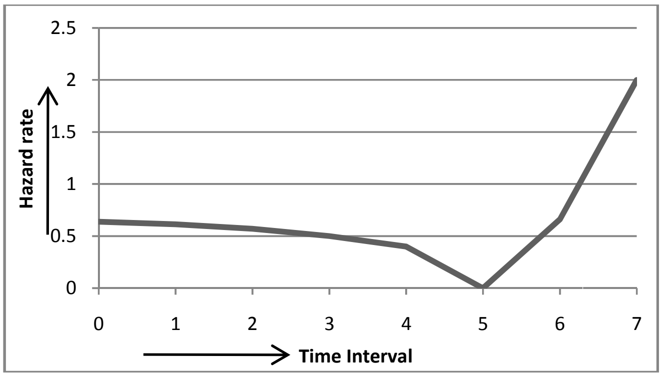

Fig. 8 Hazard Curve

B. Probability of Success and Failure

Probability of success and failure has been evaluated by using Monte Carlo Simulation (MCS) method in this paper. The difference between the analytical and simulation approaches is the way in which the reliability indices are evaluated. Analytical techniques represent by mathematical model, which is often simplified, and evaluate the reliability indices from this model using direct mathematical solutions. On the other hand, MCS estimate the reliability indices by simulating the actual process and random behavior of the system. The method therefore treats the problem as a series of real experiments conducted in simulated time. It estimates probability and other indices by counting the number of times an event occurs [2].

Laboratory experiments on setup started with minimum value of capacitance (25µF). Success and failure chances of excitation of induction machine working as SEIG has been checked practically using MCS. Total 71 tests have performed with in eight days. Various test results (success/failure excitation) has been obtained in experiment on the SEIG. These are shown in Table II.

TABLE II
OUTCOMES OF SUCCESS AND FAILURE GENERATION OF SEIG

No. of Experiment	Experiment Result outcome	Probability	
		Success	Failure
1	S	1	0
2	S	1	0
3	F	0.67	0.33
4	S	0.75	0.25
5	F	0.60	0.40
6	S	0.67	0.33
7	F	0.57	0.43
8	F	0.50	0.50
9	S	0.56	0.44
10	F	0.50	0.50
11	S	0.55	0.45
12	S	0.58	0.42
13	S	0.62	0.38
14	F	0.57	0.43
15	S	0.60	0.40
16	F	0.56	0.44
17	F	0.53	0.47
18	F	0.50	0.50
19	S	0.53	0.47

No. of Experiment	Experiment Result outcome	Probability	
		Success	Failure
20	S	0.55	0.45
21	F	0.52	0.48
22	F	0.50	0.50
23	S	0.52	0.48
24	F	0.50	0.50
25	F	0.48	0.52
26	S	0.50	0.50
27	F	0.49	0.51
28	S	0.50	0.5
29	S	0.52	0.48
30	S	0.53	0.47
31	F	0.52	0.48
32	S	0.53	0.47
33	S	0.55	0.45
34	F	0.53	0.47
35	F	0.51	0.49
36	S	0.53	0.47
37	S	0.54	0.46
38	F	0.53	0.47
39	S	0.54	0.46
40	S	0.55	0.45
41	F	0.54	0.46
42	F	0.52	0.48
43	S	0.53	0.47
44	S	0.55	0.45
45	F	0.53	0.47
46	S	0.54	0.46
47	F	0.53	0.47
48	S	0.54	0.46
49	F	0.53	0.47
50	S	0.54	0.46
51	F	0.53	0.47
52	S	0.54	0.46
53	S	0.55	0.45
54	F	0.54	0.46
55	F	0.53	0.47
56	S	0.54	0.46
57	F	0.53	0.47
58	S	0.53	0.47
59	S	0.54	0.46
60	F	0.53	0.47
61	S	0.54	0.46
62	S	0.55	0.45
63	F	0.54	0.46
64	S	0.55	0.45
65	F	0.54	0.46
66	S	0.55	0.45
67	S	0.55	0.45
68	S	0.56	0.44
69	F	0.55	0.45
70	S	0.56	0.44
71	F	0.55	0.45

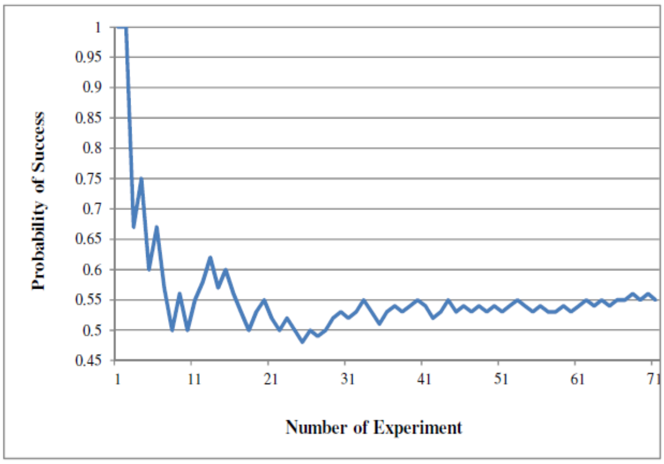

Fig. 9 Monte Carlo Simulation of the Probability of Success

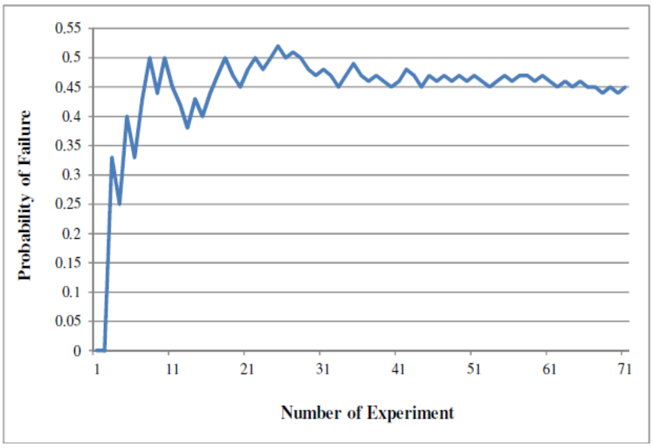

Fig 10 Monte Carlo Simulation of the Probability of Failure

C. Result and Discussion

The probability of success and failure of the SEIG with minimum value of capacitor has been evaluated using Monte Carlo simulation. Various simulation parameters are shown in Figs. 9 and 10. The simulation results conclude the following:

1. A large number of tests on SEIG give the better result of probability of failure and success.
2. The value of probability of success and failure oscillates on the true value after the sufficient tests. The mean value of the probability of success and failure is not good estimation of the true value.
3. The value of probability of success and failure has a tendency towards the true value as the number of test is increased.
4. The value of probability of success and failure has tended towards 0.55 and 0.45 respectively in the simulation results.

The probability of success (P_s)/failure (P_f) has evaluated by using analytical method. The value of probability of success (P_s)/failure (P_f) is the ratio between the number of success(s)/failure (f) tests and numbers of possible outcomes (T). These evaluations are given below.

$$Ps = \frac{s}{T} = \frac{39}{71} = 0.549$$

$$Pf = \frac{f}{T} = \frac{32}{71} = 0.451$$

VI. Conclusion

Evaluation of reliability of success operation of the SEIG is remarked with minimum capacitive excitation. The evaluation of the probabilities of success and failure of 3-phase, 4-pole, 50Hz, 230V, 12.3 A, 5.5 HP has been performed successfully in this paper with minimum value of capacitance 25 µF. The obtained analytical values are Ps = 0.549 and Pf = 0.452. These values based on Monte Carlo simulation tends toward Ps = 0.55 and Pf = 0.45. Both analytical and simulation results are near about equal. Failure density curve, survivor curve, cumulative curve and hazard model have been obtained experimentally. In failure density curve, area under the curve is one and generation failure decreases with decrease in number of tests.

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Lokesh Varshney received his B. E. Degree in electrical Engineering from Shri G. S. Institute of Technology and Science, Indore (Madhya Pradesh), India in 2004 and M. Tech. Degree with specialization in Electrical Machines and Drives from Indian Institute of Technology, Banaras Hindu University, Varanasi (Uttar Pradesh), India in 2009. Previously, he was a faculty member in the department of electrical engineering at Shri Vaishnav Institute of Technology and Science, Indore (Madhya Pradesh), India from 2004 to 2007.

Currently, he is a doctoral research scholar in the department of electrical engineering, Indian Institute of Technology (BHU), Varanasi (Uttar Pradesh) India. His research interest includes electrical machines and drives, self excited induction generator, MATLAB / Simulink, reliability engineering and renewable energy systems. He has published many papers in the national / international journals and conference proceedings.

Dr. R. K. Saket born in a small village Dhaurahara located in the Vindhya region near tehsil Amarpatan, District Satna of the Madhya Pradesh state of India on July 15, 1972. He is working as Associate Professor in the Department of Electrical Engineering, Indian Institute of Technology (Banaras Hindu University), Varanasi (Uttar Pradesh), India. Previously, he was a faculty member at Birla Institute of Technology and Science, Pilani (Rajasthan), India; Sam Higginbottom Institute of Agriculture, Technology and Sciences-Deemed University, Allahabad (Uttar Pradesh), India and University Institute of Technology, Rajiv Gandhi University of Technology, Bhopal (Madhya Pradesh), India.

He has contributed more than 60 scientific articles including prestigious book chapters and research papers in reputed books, handbooks, international journals and conference proceedings. His research interests include reliability engineering, electrical machines and drives, renewable energy systems, power system reliability and reliability issues in MANETs and wireless communication.

Dr. Saket is a life member of the *Indian Society of Technical Education, New Delhi (India).* He is an editorial board member of the *International Journal of Research and Reviews in Applied Sciences; International Journal of Management, Modern Science and Technology (UAE); and Engineering, Technology and Applied Science Research (Greece).* He is a Reviewer of the scientific article and research papers of the *IEEE Transactions on Industry Applications, IET Renewable Power Generation, International Journal of Modeling and Simulations, International Journal of Electric Power and Energy Systems and International Journal of Global Energy Issues.* “Nehru Encouragement Award” conferred him on January 26, 1989 and January 26, 1991 by Madhya Pradesh state Government of India for academic and research Excellencies towards his higher technical education.