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Reliability evaluation of SEIG rotor core magnetization with minimum capacitive excitation for unregulated renewable energy applications in remote areas

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Abstract This paper presents reliability evaluation of residual magnetism in rotor core of the induction motor operated as SEIG using probability distribution approach and Monte Carlo simulation for unregulated renewable energy applications in remote areas. Parallel capacitors with calculated minimum capacitive value across the terminals of the induction motor operated as SEIG with unregulated shaft speed are connected during the experimental study. A three phase, 4 poles, 50 Hz, 5.5 hp, 12.3 A, 230 V induction motor coupled with DC Shunt Motor is tested in the electrical machine laboratory with variable reactive loads. Using this experimental study, it is possible to choose a reliable induction machines operated as SEIG for unregulated renewable energy application. 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.

1. 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. SEIG is operated as either the designer attempted to build a SEIG or suitable value of capacitor connected in shunt across the terminals of the Induction Motor (IM). The availability of designed SEIG is not very popular compared with the induction motor. However, SEIG is very popular in unregulated renewable energy source such as micro hydro and wind in hills or remote areas. SEIG is directly connected with turbine and turbine attached with renewable energy source. There is no need of

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dam, gear-pulley and other mechanical attachment. The performance of an induction motor operating as SEIG with suitable value of capacitance 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 [1,2]. 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 2. This section briefly describes the three methods of restoration of residual magnetism. Section 3 describes the concept, causes and factor of failure operation of SEIG. Section 4 evaluates the experimental minimum capacitive value for excitation on SEIG. Section 5 evaluates the reliability of the rotor core magnetization of SEIG with minimum value of capacitor and 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 6 presents conclusion of the work.

2. Loss and restoration of residual magnetism in SEIG

2.1. Loss of residual magnetism

The loss of residual magnetism in SEIG is due to short circuit condition and connection of extra reactive load. These conditions cause the sudden terminal voltage drop and loss of residual magnetism in rotor core of the SEIG. The experimental setup with reactive load is shown in Fig. 1. Following (any one) method of Section 2.2 can give the temporary excitation to the iron core to restore the residual magnetism.

2.2. Restoration of residual magnetism

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

1. Running the machine as a motor from an exciting ac system for 10–15 min.
2. By switching in charged terminal capacitors. If the capacitors are charged to a high voltage, say rated machine voltage, the discharge current is normally sufficient to cause self excitation even with a degaussed rotor.

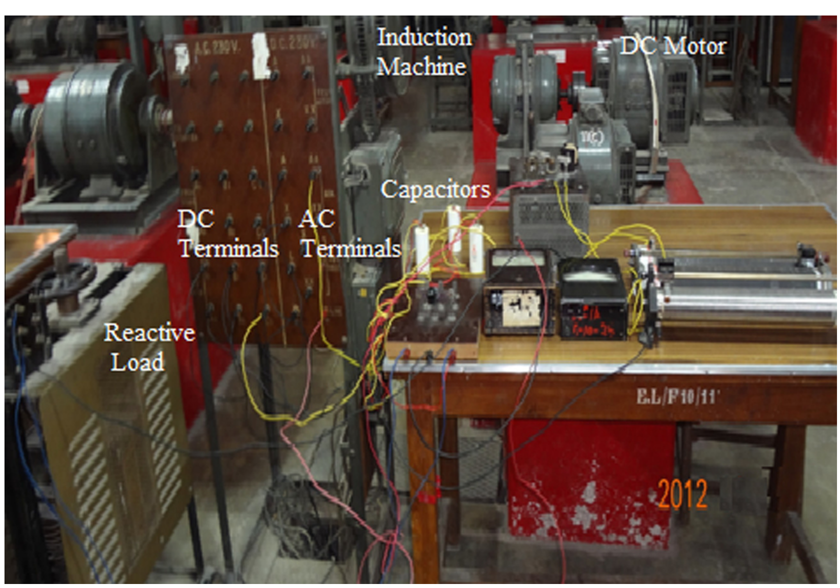

Figure 1 Experimental setup with reactive load.

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).
4. When the machine is at rest then connect a 6 volt battery across two terminals of the machine for 10–15 min. 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 [3].

3. SEIG excitation failure problems with renewable energy systems

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 [4,5]. 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. The shunt capacitance and shaft speed of the designed SEIG have been increased to prevent the terminal voltage during experiment. 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.

4. Experiments on SEIG with minimum capacitive excitation

The rating of the induction machine operated as SEIG is 3-phase, 4-pole, 50 Hz, 230 V, 12.3 A, 5.5 hp. The per-phase equivalent parameters of the IM in per unit are $Rs = 0.0496$, $Rr = 0.0350$, $Xs = 0.1344$, $Xr = 0.1344$. The evaluated magnetization curve of the IM has described in Fig. 2. The evaluated minimum value of capacitor is 24.48 μF [6,7].

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 [8]. As seen here, the agreement between measured and the computed values of the terminal voltage is sufficient which confirm the validity of the analysis.

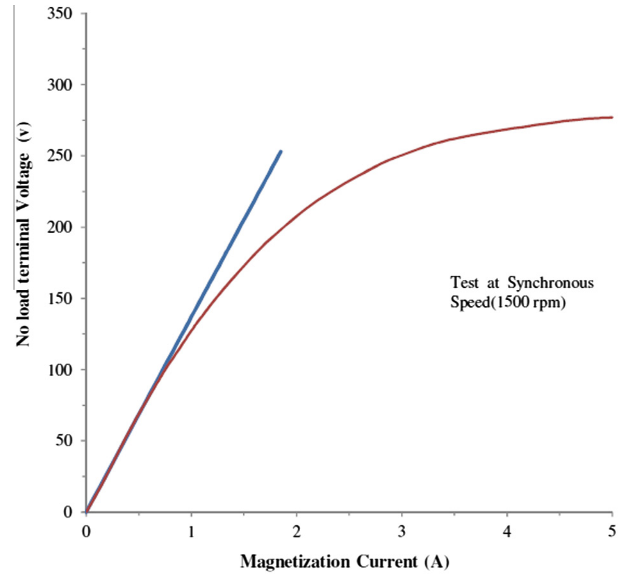

Figure 2 No load magnetization curve of induction machine.

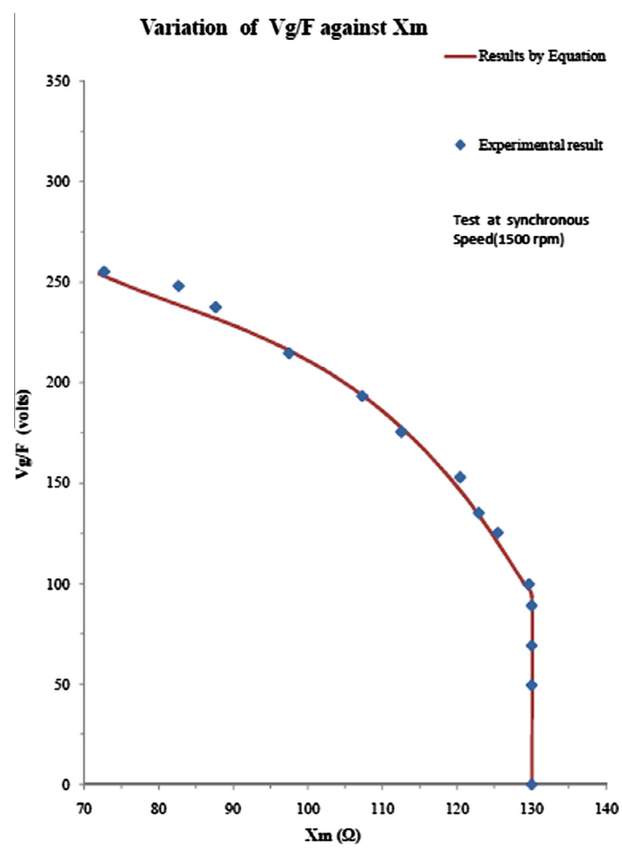

Figure 3 Variation of Vg/F with Xm.

5. Reliability evaluation 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

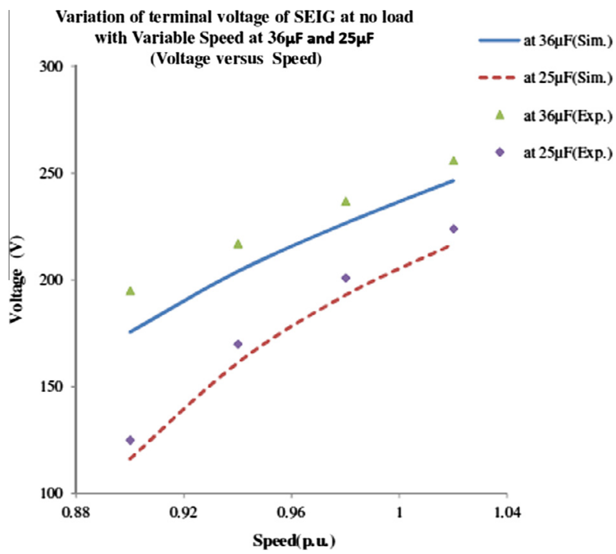

Figure 4 Variation of terminal voltage with speed and capacitance for no load.

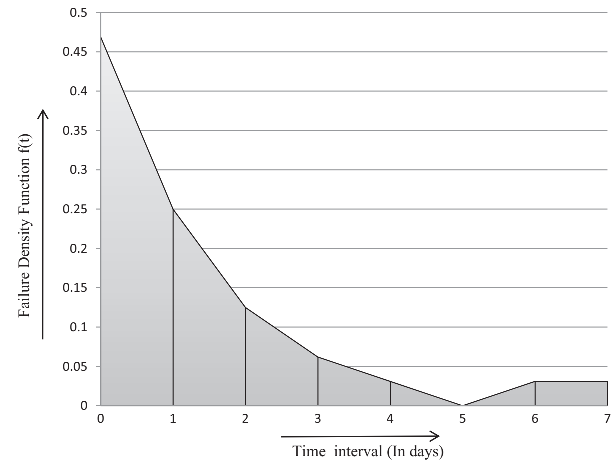

Figure 5 Failure density function curve.

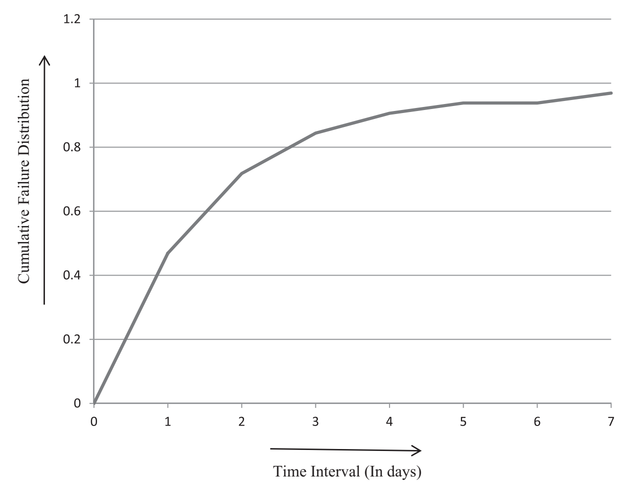

Figure 6 Cumulative failure distribution curve.

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 1.

5.1. 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 1 [9,10]. 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. 5–8 respectively. Description of table is as follows:

Table 1 Practical failure data and evaluation of reliability indices.

Time interval	Number of failure in each interval	Cumulative failures	Number of experiment	Failure density function	Cumulative failure distribution	Survivor function	Hazard rate
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	

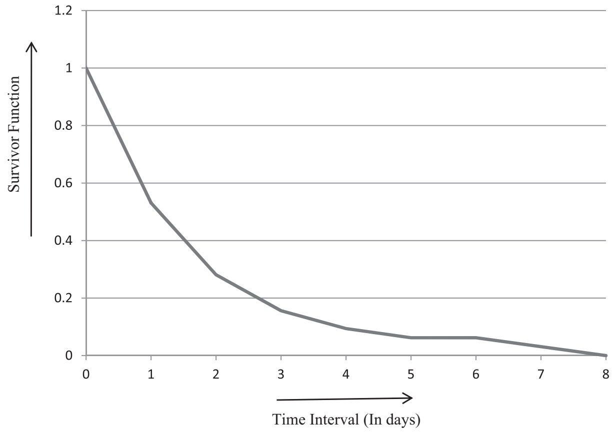

Figure 7 Survivor function curve.

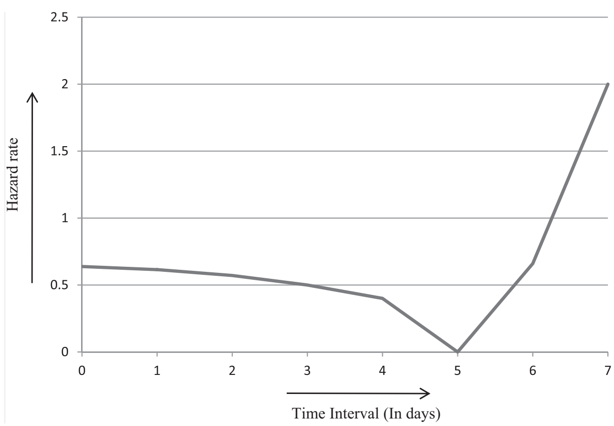

Figure 8 Hazard curve.

(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 [9].

5.2. Success and failure probabilities

Probability of success and failure has been evaluated by using Monte Carlo Simulation (MCS) method in this paper. The

Table 2 Outcomes of success and failure generation of the 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
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

Table 2 (*Continued*).

No. of experiment	Experiment result outcome	Probability	
		Success	Failure
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

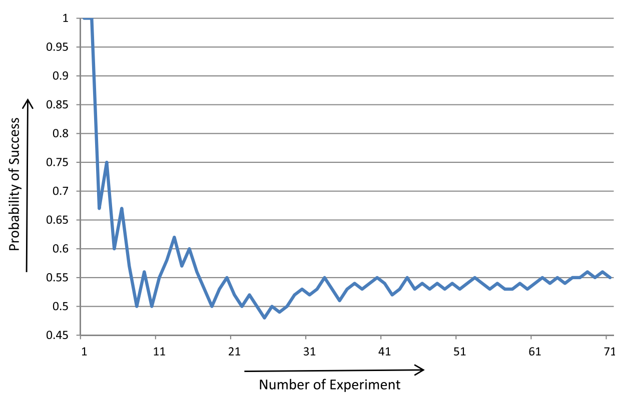

Figure 9 Monte Carlo simulation of the probability of success.

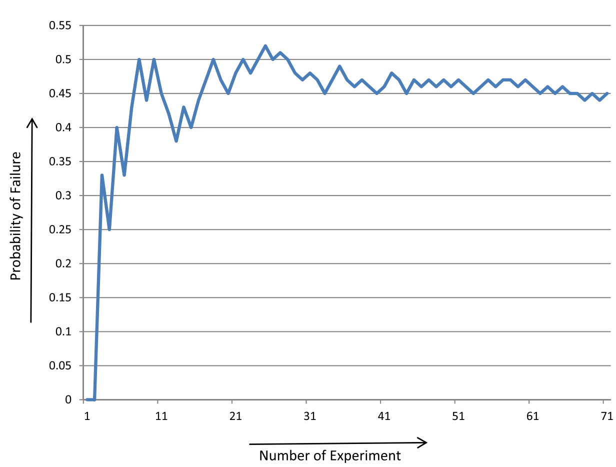

Figure 10 Monte Carlo simulation of the probability of failure.

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 estimates 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 [9].

Laboratory experiments on setup started with minimum value of capacitance (25 μF). 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 8 days. Various test results (success/failure excitation) have been obtained in experiment on the SEIG as shown in Table 2.

5.3. 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 toward the true value as the number of test is increased.
4. The value of probability of success and failure has tended toward 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.

Success probability $(P_s) = s/T$

$$P_s = 39/71 = 0.549$$

Similarly,

Failure probability $(P_f) = f/T$

$$P_f = 32/71 = 0.451$$

6. Conclusions

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, 50 Hz, 230 V, 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 $P_s = 0.549$ and $P_f = 0.452$. These values based on Monte Carlo simulation tends toward $P_s = 0.55$ and $P_f = 0.45$. 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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