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Reliability Evaluation of Renewable Energy Integrated Power System in Presence of Energy Storage System

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ABSTRACT: Power system reliability is important for design and planning of the modern power system. This paper focuses on evaluation of power system reliability with wind energy as intermittent energy source (renewable sources) and presence of Energy storage system (ESS), supplying the power to non-chronological load by Monte Carlo simulation (MCS) technique using software PSPICE. Earlier, reliability assessment was done using analytical techniques with certain assumptions and due to assumptions, some significance was being ignored in results. Here, this is overcome by simulation techniques which can estimate by actual process and random behavior of system in simulating software. Monte Carlo simulation is a computational algorithm which works on repetitive random number generation to estimate the performance of desired parameter by converting random number in to numerical values. ESS is used as the supporting unit of intermittent energy source integrated with power system, which stores the surplus energy due to renewable source and utilizes the stored energy at the time of increase in load demand or low generation or unit outage of any of the source. Power system Reliability has been evaluated in terms of Probability of system success from the probability of system failure. In this regard, failure probability of elements of the system has been estimated using the probability distribution histogram from MCS. By applying outage conditions on every component of the system, considering most general possible failure occurrence and Reliability in terms of probability has been estimated. For the system reliability studies, the results of simulated system from MCS approach has been obtained for reliability comparison of system without ESS and for system with ESS.

Keywords: Energy storage**,** intermittent energy, Power System, PSPICE, Monte Carlo, Reliability, Random number.

I. INTRODUCTION

Power system reliability evaluation is concerned with the determination of the adequacy of the combined generation and transmission system for providing a suitable supply at the load points, which helps to evaluate the performance of power system. Today, energy market has more competition due to the presence of private sector power companies, which try to provide better continuity of power supply, power quality, ancillary services etc. to attract the customers. Therefore, the reliability evaluation plays an important role in planning, designing and operation of installations of new power plant which has combined configuration of conventional source and renewable source due to economic benefits and environmental issues. It is also useful for installation of Energy Storage System (ESS) in existing power plant.

The usage of renewable energy resources like solar, wind, ocean etc. are growing worldwide due to the awareness about the global warming as well as limitations of the conventional resources and also to satisfy the increasing rate of the energy consumption. These resources are intermittent in nature like wind energy. Sometimes it has low potential of wind power, sometimes high potential of wind power and sometimes totally absent at time of most needed. So large wind plant can create fluctuations in power system and it has risk to provide continuous power in the system. Due to this the supply period of wind power is limited than the conventional energy.

The conventional power units are unable to respond quickly towards the fluctuations created by wind power and the output of wind power is not controllable at any time to make system stable and reliable. For that, there is a need of such system which controls the continuity of supply as well as gives quick switching response compared to conventional sources. This problem can be reduced by storing wind energy at high potential and use it at low wind or in no wind condition.

Energy storage system (ESS) is a technology to improve the adequacy of generating unit of power system integrated with intermittent energy source. The role of the ESS is to make power system stable and full fill the reduction in power supply caused by fluctuations of wind power. ESS is operated as, it will be in charging mode when wind source has surplus or sufficient, else it will supply the power to the system on behalf of wind source when wind source is in down state or outage. So, Reliability evaluation is important to know about the performance of power system containing wind energy and ESS.

For reliability assessment, there are two main approaches analytical and simulation. In analytical techniques, system is represented by mathematical model to evaluate reliability using numerical solutions. In today's world, electricity has more variations as well as electricity demand increases day by day. For that, integration of renewable sources and ancillary services with power system are needful to reach out the excess demand. Earlier most of studies were done for with or without renewable sources and ESS using analytical concepts which has drawback of more assumption and computational time, improper for complex system with more networks etc.

Simulation technique estimates reliability by actual process and random behavior of system. In simulation techniques Monte Carlo simulation (MCS) method is used to evaluate system reliability. Monte Carlo simulation is a computational algorithm related with repeated random sampling for obtaining numerical result. Generated samples are used to estimate system reliability in terms of probability. Mainly, failure probability (Unreliability) of system is estimated and from that success probability (Reliability) of system can be estimated. This method can estimate the behavior of unidentified component in terms of probability whose parameters as well as properties are unknown, which is not done by analytical methods because they need some input to perform mathematical operations.

Reliability results without ESS are given in [1] as well as methodology which is given in [1] has been used to estimate the reliability of power system with ESS. Results of Hemansu and Anuradha [1] which are received from using simulation method are compared with the results given in [17] standard reference which are received from analytical method. Which is proof of the trueness of presented method? In similar way reliability study has been done with effect of ESS on power system.

Hu *et al.*, [2] has presented simulation technique for wind farm and energy storage operating strategies to maintain stability from the wind penetration effect and system reliability. Use of Monte Carlo simulation for adequacy of generating capacity evaluation to satisfy chronological load demand of Roy Billinton Test System (RBTS) within hourly time intervals. Reliability indices, loss of load expectation (LOLE) and loss of energy expectation (LOEE) are evaluated by simulation of system reserve profile.

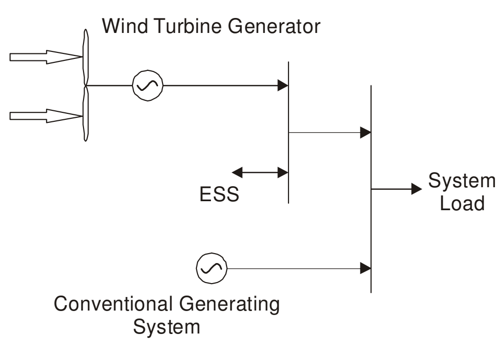

Fig. 1. Model of WTG, ESS and CGUs.

Wind speed model based on auto-regressive moving average (ARMA) time series is used to simulate hourly wind speed. From that expected surplus wind energy index (ESWE) is evaluated and surplus power is used for storage. Three scenarios have been presented for energy storage and wind farm operation. In first scenario, conventional power and wind power both are not sufficient for load then stored energy is used for system load. In second, only wind power is not enough for supply and storage with wind is operated for system load. In third, only conventional power is not enough for supply in which energy storage is used to support the conventional generating units (CGUs). In result analysis LOLE and LOEE indices are used and the effect of wind site location, effect of charging/discharging of energy storage, effect of energy storage capacity and effect of wind energy dispatch restriction are considered for above three scenarios. From results of simulation they conclude that facility of energy storage is used to reduce fluctuating nature of wind and improve continuity of power supply and for reliability benefits different operating strategies are analyzed in which third scenario is useful option for energy storage economically.

Parvini *et al.*, [3] has presented evaluation algorithm which can assess the effect of factors like penetration rate of wind, capacity of energy storage system, and operational strategies for wind and ESS as well as other generating units. By modification in PJM method, they model the short-term variability of wind farm generation in reliability studies and with help of algorithm examining the effect of ESS in reliability level of system. In which, general procedure for collecting data, model of CGUs, wind farm output modeling, load model, evaluation of reliability indices like Unit Commitment Risk (UCR) and Expected Energy Not Supplied (EENS) are considered. In ESS studies considered is ESS contribution and its operating strategy. From that they analyze operational reliability within ESS as well as without ESS and obtain results for normal case and reliability constrained operation. From that they conclude that operating strategy has more importance to maximize the benefit of ESS for improving operational reliability.

Wang *et al.*, [4] has proposed evaluation technique for operational reliability and energy utilization efficiency of power system containing high wind penetration level. They used IEEE-RTS (Reliability Test System) for application of proposed method with reliability indices EENU (Expected Energy Not used) and EENS (Expected Energy Not supplied). For system modeling wind speed model, WTG (wind turbine generation) output model, load model, energy storage model, generator reliability model etc. are considered. Reliability evaluation procedure has several steps in which determination of committed CGUs for operating period and state probability for system contingency state are evaluated from system modeling. From that reliability indices are assesses using the load and generation condition. Results of proposed system described with three cases which are power system with only CGUs, power system with CGUs and WTG, power system with CGUs, WTG and ESS. From results concluded that System without ESS has limited reliability improvement in system and with ESS wind power capacity improved significantly.

Shi and Luo [5] has proposed a method which calculates the capacity value of energy storage and its contribution to the generation adequacy for system reliability. Used EFC (Equivalent Firm Capacity) approach to assess the Capacity Value of Energy Storage (CVES) with probability method.

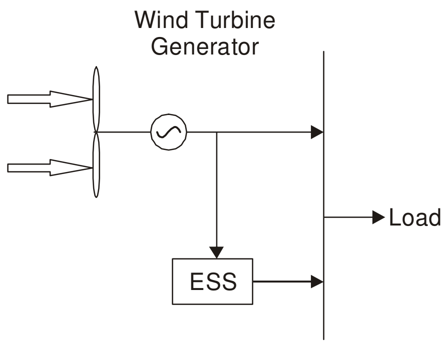

Fig. 2. Schematic diagram of Wind system and ESS.

In EFC method they used reliability index HLOLE (hourly loss of load expectation). In system modeling, considered models are Load modeling (IEEE-RTS), Wind power modeling, ESS modeling, charging and Discharging, Energy stored in system, Available power of ESS, Charging period of ESS. Simulation results are described in two parts System analysis and sensitivity analysis. In System analysis, CVES of energy storage examined by test systems IEEE-RTS and RBTS. In sensitivity analysis, analyses of the factors Impact of load, Impact of installed capacity of WT, Impact of wind speed, and Impact of maximum energy stored, Impact of Temperature, Impact of failure rate of ESS is done. From these analyses conclusion is that CVES has quantified the contribution of ESS to system. When ESS utilized sufficiently, CVES reaches its maximum and when ESS is not used, CVEs reaches at minimum. Impact of failure rate and temperature affects the CVES.

Rei and Schilling [6] have proposed some important aspects for two methods, contingency enumeration and non-sequential MonteCarlo simulation for probabilistic reliability assessment in Brazilian power system. Contingency enumeration is simple and fast for single outage. However, performance of MCS is better for the number of component outages. They presented main steps for bulk power system probabilistic reliability assessment which are System state selection, selected state assessment, and Reliability indices evaluation. For contingency enumeration, some criteria are given which is strict contingency level, Probability, Selected contingencies list. Which are implemented on computational programming and reliability indices are obtained. In MCS method system states are evaluated by sampling from probability distribution function and its results are estimates of the real system performance. MCS does not depend on size of system but it affects the required accuracy. From results of both methods, it is concluded that state enumeration is easier and has less computation only for single order contingences. When MCS has large computation efforts but it is easiest for higher order contingencies.

Hou *et al.*, [7] has proposed impact- increment based decoupled (IID) reliability evaluation approach for power system reliability. This approach is used for both method SE (state enumeration) and MCS method. Reliability indices are obtained by decoupling the power system into two parts: Generation adequacy and Transmission reliability. Then, impact-increment based state enumeration technique applied on generation adequacy and transmission reliability. In which, for higher order contingency, states reduction technique is used and so number of analyzed contingencies are reduced. This proposed approach is performed with reliability test system RTS-79, RTS-96 and provincial power system of china. There are three cases in which results are obtained. In first case, for RTS-79 composite power system considered computational speed and accuracy as well as the effect of preset parameter. Similarly, case second for RTS-96 and third case for practical system is performed whose results are compared with traditional method of reliability assessment. From the results, they conclude that IID's accuracy is near with MCS method and its computational speed was higher compared to SE and MCS for large scale system.

II. METHODOLOGY

For reliability assessment mainly two approaches are used:
(1) Analytical (probabilistic)
(2) Failure sequences in MCS method

Probabilistic method represents reliability of system in terms of probability. Which is evaluated from data of components availability and unavailability? MCS method estimate the failure probability of system component from failure sequences using simulated samples.

In this method random numbers are generated by the random number generators in digital computer with uniform random number found in interval of (0, 1). These numbers are tested for component random behavior and failure probability of particular component is obtained as output. Using different random seed number and different range of runs are performed in MCS simulation. For different seed value different failure probability are obtained and its cumulative values are plotted to get the failure sequences are generated from failure event of component as shown in Fig. 5-8. Cumulative values lead the sequences near true failure probability. From that failure probability of particular component is estimated.

From failure probability, success probability of system can be obtained which represents the system reliability. These methods are given in detailed in Eqn. [1] and with similar process of MCS method has been used to estimate power system reliability with ESS.

Expression of sequence given as,

$$S_{ij} = \frac{I_{ij}}{NMCSij} \quad (1)$$

where, S_i = sequence number at *j* trial
I_{ij} = number of cumulative overlapping failure
N_{MCSij} = simulation trials

Then the failure probability of power system is given as,

$$Q = \sum_j [P(Bj)P1j] \quad (2)$$

$Q = \sum_j Pj$ (3)

$R = 1 - Q$ (4)

Where,

Bj = an outage condition in power system

p(Bj) = failure probability of outage element

P1j=‘probability of load at generation bus exceeding the maximum load which can be supplied at that bus without failure’

R = reliability of power system

Q = failure probability of system

In which outage states with ESS also have been considered. So, it has total 23 Outage states *Bj* compared to 17 outage states of [1]. From that, results of both cases without ESS and with ESS have compared to show the effect of ESS on power system Reliability.

A. Power System Reliability with ESS

One of the main advantage of ESS is that it gives quick response compared to other supporting unit at switching when need of immediate supply is required. It has better flexibility and control in electrical usage. ESS has been used as the supporting unit only for wind source to improve the adequacy of wind unit in outage condition. In which, wind source has priority to serve the load in normal condition and ESS will be considered as in charging mode or remain in shut down.

In outage condition of wind source, ESS will be in discharging mode or available for power supply to the grid. There will be enough power supply within outage condition in system and it will act as normal operating condition. So, outage condition of wind source cannot affect the continuity of power supply of the system which shows that the ESS has improved the reliability of power system.

III. SYSTEM NETWORK AND SOFTWARE MODELING

A. Description of Power System

Single line diagram of Power system with Energy storage system shown in Fig. 3, consisting two generating plant G1 and G2. Plant G1 has four generating units each of 20 MW and Plant G2 considered as wind energy source which has two generating units each of 30MW as well as it’s connected with ESS of 50 MW.

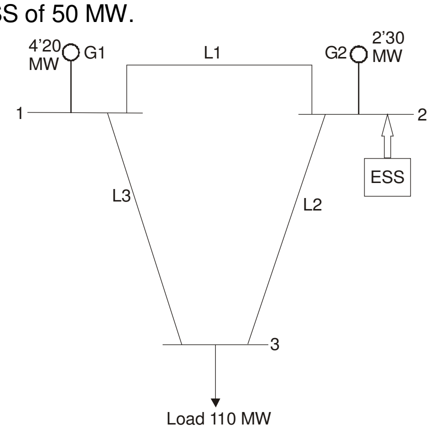

Fig. 3. Three bus network.

Peak load of the system is 110 MW and assuming that it’s remaining constant. All CGUs of plant G1 express G1 and unit of wind plant G2 express as G2 for their outage conditions. Similarly, here ESS is connected at generating plant G2, so E2 subscript has been used for it.

For proposed power system generation data is given in Table 1 and transmission line data is given in Table 2 with their unavailability [14].

Table 1: Generation Data.

Plant	No. of Units	Capacity (MW)	Unavailability
G1	4	20	0.01
G2	2	30	0.05

Table 2: Transmission Line Data.

Line	R	X	B/2	Unavailability
L1	0.0912	0.4800	0.0282	0.00363667
L2	0.0800	0.5000	0.0212	0.00454545
L3	0.0798	0.4200	0.0275	0.00341297

B. Software Modeling

Three phase Power system network of Fig. 3 is modeled in schematic of Orcade Pspice which is modeled in four parts (1) Generator model, (2) Transmission Line mode, (3) Load model and (4) ESS model.

C. Generator model

In this model, plant G1 has total generation capacity of 80 MW and wind plant G2 has 60 MW with 50MW reserve capacity of ESS. Total generation of system is 140 MW and system peak load is 110 MW. All generating units are connected in star connection.

D. Transmission Line model

In this model, π model is considered for three phase transmission lines and which have no capacity restriction and considered as fully reliable.

E. Load model

In this model, Load is presented as three phase RL load with star connection which is non-chronological and has peak load of 110MW.

F. ESS model

Energy Storage System of 50 MW is connected at bus 2 to support the generating unit of wind source at Generating plant G2 for only outages of generating plant 2 otherwise it will be in shut down or in charging mode. For MCS analysis, ESS will be considered as fully charged or reliable initially when outages are applied on G2. There are so many types of systems of energy storage technologies which can be used in power system like Batteries, Pumped hydro storage, Thermal energy storage, Compressed air energy, Flow batteries, Fuel cells, Chemical storage, Flywheel, Superconducting magnetic energy, Super capacitors etc. These all are having common function to supply stored energy to the system when renewable source is on outage or in down state.

IV. SIMULATION RESULTS AND DISCUSSION

The proposed system model analyses with MCS in PSPICE and failure sequences are obtained from MCS histogram for Outage elements. Samples generated from histogram for outage condition for one unit of generation plant G1 is shown in Fig. 5. For every state two sequences are considered and each sequence starts with new seed generated randomly. Number of failures is obtained from probability distribution of samples from histogram.

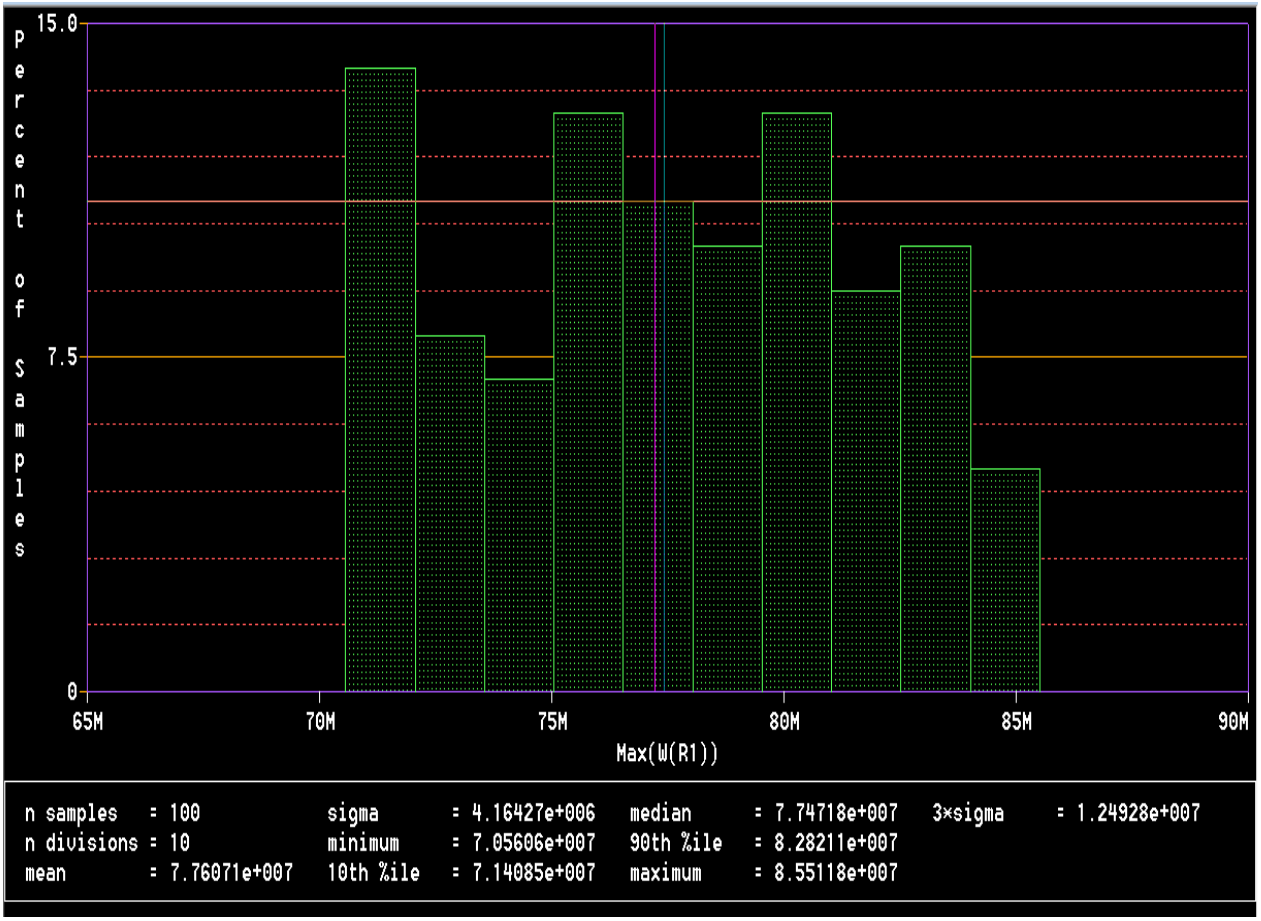

Fig. 4. MCS histogram in PSPICE.

In MCS histogram y-axis represents the percentage of samples and x-axis represents the value of selected output variable. Generated samples are displayed in the form of bar chart and have ten columns. Every column represents group of samples in percentage for particular values on x-axis.

These samples are generated using random seed values and for different trials of runs. From this samples failure event of particular component is decided using sample percentage and its cumulative probability graph lead the failure sequences near at true value of failure probability. This process is repeated for all the common outage combination of power system and their particular failure probability has been obtained.

Then, from these failure probabilities the overall system failure probability Q is obtained which is shown in Table 3. Its procedure as well as mathematical calculation has been provided in [1, 13, 14, 15].

For outage condition of G1, G2, E2 and L1 with presence of Energy Storage System, their failure sequences are shown in Figs. 5, 6, 7 and 8. These failure sequences are plotted as cumulative probability of component failure vs. number of trials of Monte Carlo simulation. Cumulative values of probability lead the sequences forward way towards and near the true value of probability.

Cumulative values are obtained from individual failure of outage component. From that cumulative probability of component failure is obtained using Eqn. (1) to generate the failure sequences. Sometimes, these failure sequences continue to oscillate even after a large number of trials. Sometimes oscillating above, sometimes below and sometimes around the true value. So, resultant probability of component failure is estimated probability and from that reliability of power system has been estimated in terms of success probability of system as shown in Table 3.

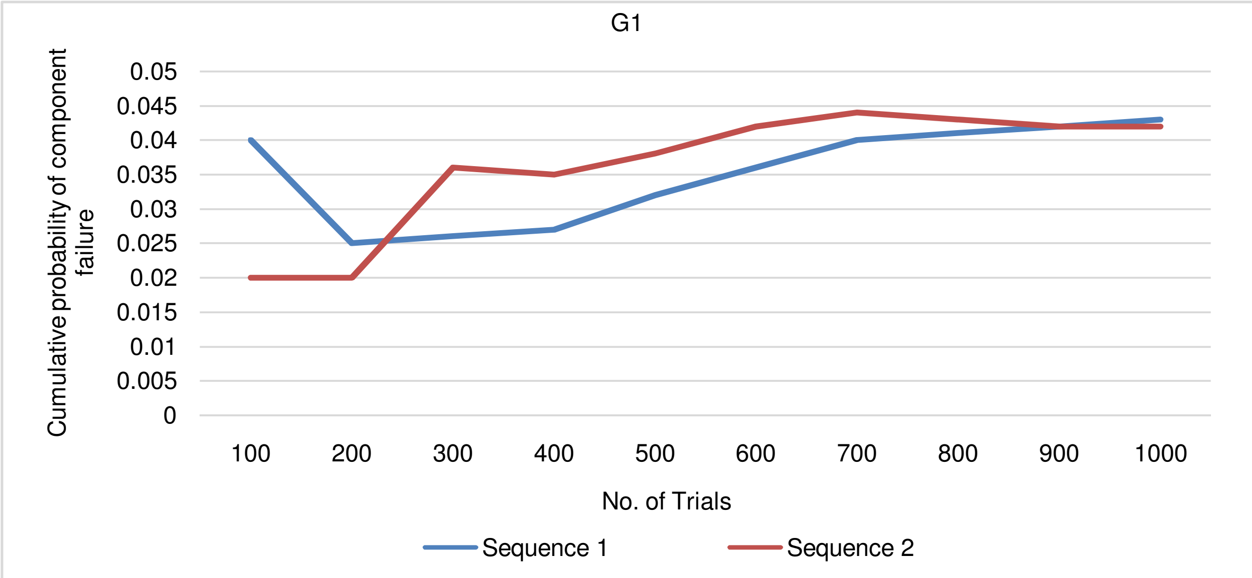

Fig. 5. Failure sequence of G1 with ESS.

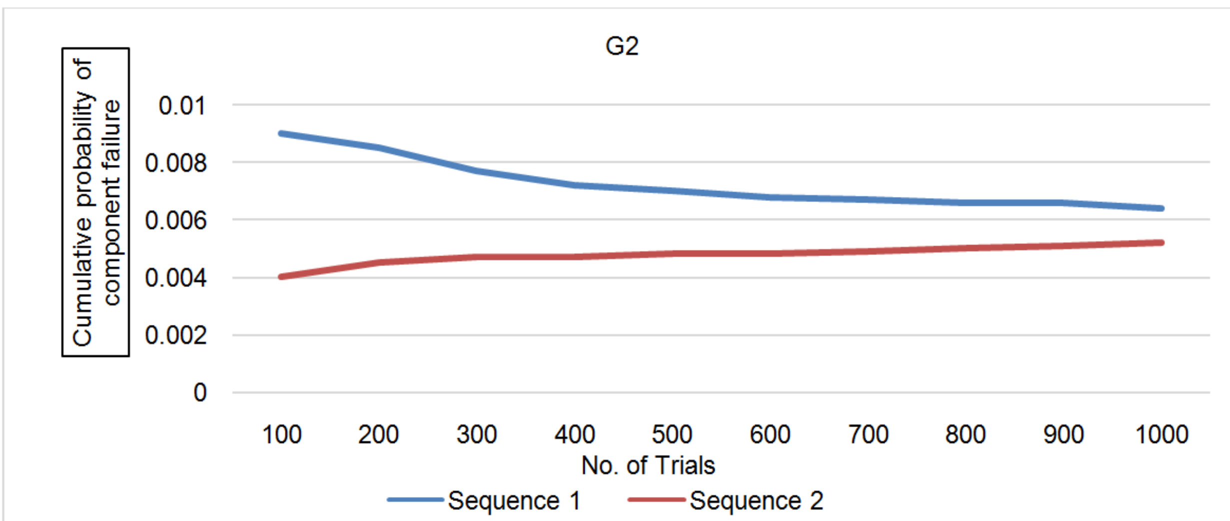

Fig. 6. Failure sequence of G2 with ESS.

Power system network has total 23 outage states. In Simulation 22 outage states are outage state. L2, L3 has very low probability near to zero for occurrence of outage which is negligible. Occurrence of this outage will totally disconnect system Load from remaining part of system which will definitely fail the system network. The failure sequences of outage state G1 is shown in Fig. 6 where only one unit of plant G1 is in outage and remaining components of system are considered as fully reliable for this outage condition. In similar way, outage state of G2 (one units in outage) and E2 (only ESS in outage) shown in Fig. 7 and 8 respectively. Similarly, sequences of remaining states are obtained and Comparison of simulation results without ESS and with ESS is given in Table 3.

Failure probability *Q* obtained using the Eqn. (2) and from that the reliability of system *R* was obtained using Equation (3), which shows increase of system reliability as well as decrease in failure probability with ESS.

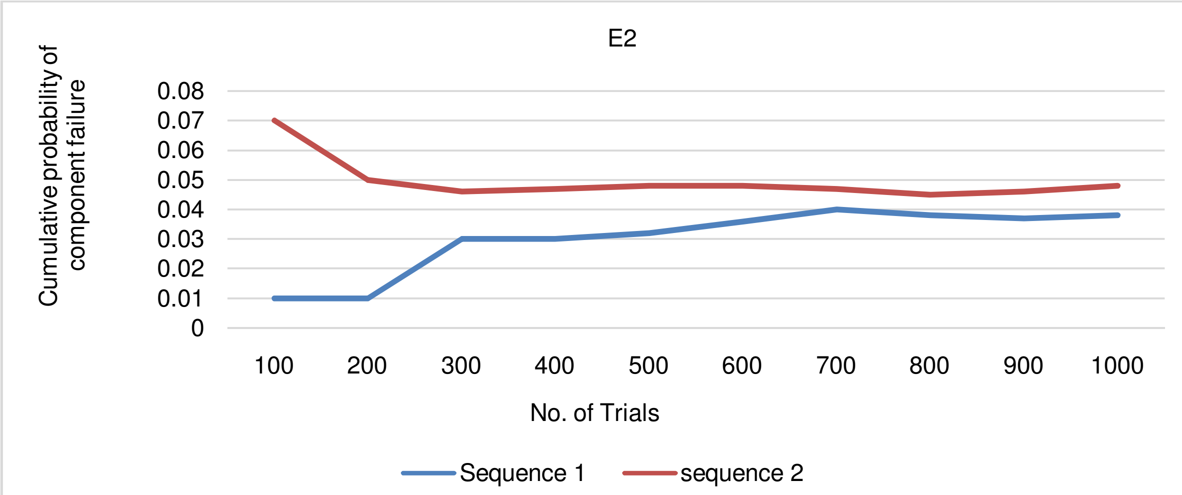

Fig. 7. Failure sequence of E2 (ESS).

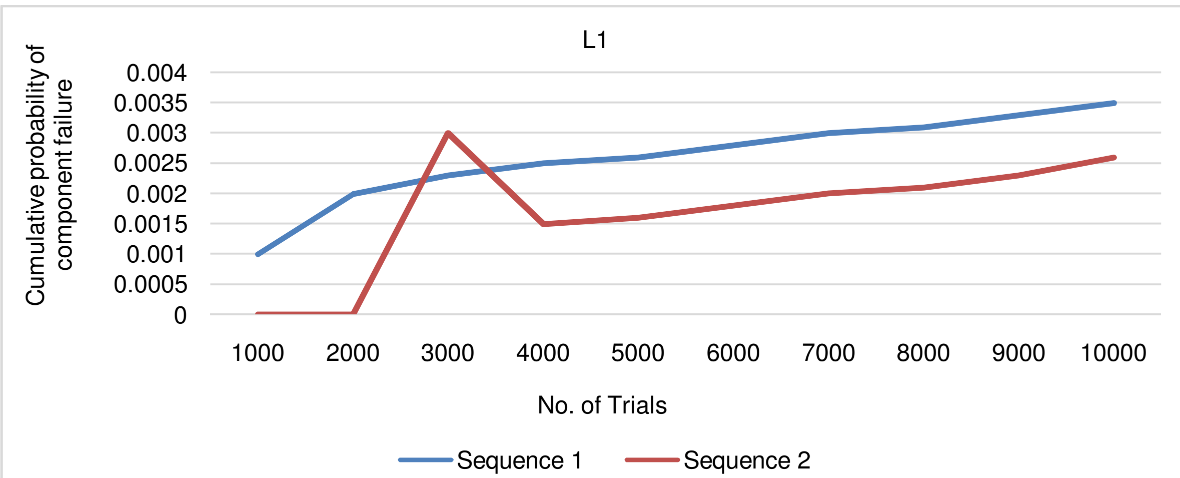

Fig. 8. Failure sequence of L1 with ESS

Table 3: Comparison of simulation results without ESS and with ESS.

State B_j	Element on Outage	Outage Probability of $P(B_j)$		P_{1j}	Failure probability P_j	
	—	Without ESS	With ESS	—	Without ESS	With ESS
1	G1	0.03100	0.0400	0	—	—
2	G1, G1	0.00062	0.0020	1	0.00062	0.0020
3	G1, G2	0.00350	0.0035	1	0.00350	0.0035
4	G1, E2	—	0.0030	0	—	—
5	G1, L1	0.00025	0.0006	0	—	—
6	G1, L2	0.00025	0.0006	0	—	—
7	G1, L3	0.00028	0.0007	0	—	—
8	G2	0.08400	0.0055	1	0.08400	0.0055
9	G2, G2	0.00260	0.0030	1	0.00260	0.0030
10	G2, E2	—	0.0050	1	—	0.0050
11	G2, L1	0.00043	0.0007	1	0.00043	0.0007
12	G2, L2	0.00042	0.0006	1	0.00042	0.0006
13	G2, L3	0.00042	0.0006	1	0.00042	0.0006
14	E2	—	0.0420	1	—	0.0420
15	E2, L1	—	0.0035	1	—	0.0035
16	E2, L2	—	0.0038	1	—	0.0038
17	E2, L3	—	0.0037	1	—	0.0037
18	L1	0.00370	0.0030	0	—	—
19	L1, L2	0.00012	0.0006	1	0.00012	0.0006
20	L1, L3	0.00011	0.0005	1	0.00011	0.0005
21	L2	0.00400	0.0026	0	—	—
22	L2, L3	0	0	1	0	0
23	L3	0.00260	0.0025	0	—	—
Q =					0.09222	0.0750
Reliability = 1 – Q =					0.9078	0.9250

V. CONCLUSION

This paper has presented approach of Monte Carlo analysis to estimate the reliability of power system which is integrated with renewable energy and energy storage system using PSPICE. By applying Outages on different components of power system modeled in Pspice and simulating the failure states to obtain failure probability for the component which is obtained from cumulative probability sequences generated using simulation samples in MCS process. For generating unit and transmission line outages considered whose occurrences are highly possible in the system.

The simulation results showed that the proposed simulation method significantly estimate the reliability of given system. Also, Monte Carlo simulation in Pspice confirms that and can estimate reliability of modeled system. Presence of ESS has significant effect on system reliability. From the result of Table 3, ESS Provides effective support in outages of plant G2 and improves the reliability of plant G2 as well as power system.

In this research work considered system has less number of elements compared to the practical power system, only for simulation of system containing single non-chronological load with intermittent energy and ESS. Also, to compare the simulation results without ESS and with ESS. So, for future work, this proposed approach can be used to estimate power system with higher number of components.

VI. FUTURE SCOPE

The software development using PSPICE can be used for various types of outages, contingencies analysis and big size of power system with IEEE configuration.

Conflicts of Interest. The authors declare no conflict of interest.

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