Impact of Energy Storage Integration On Composite System Reliability

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***Abstract*—This work deals with the impact of integration of energy storage and wind energy considering optimal placement on composite system reliability. Benefits of electrical energy include electric energy time shift, frequency regulation and transmission congestion relief. In case energy storage is integrated at non optimal places it will lead to increase in cost, system losses and larger capacity hence having opposite effect to the desired. Sequential Monte Carlo Simulation (MCS) technique is used which simulates chronological history of each component in system which refers to up and down cycles of generators, transmission equipment and fluctuations of load. The main contribution of this paper is to propose a reliability evaluation framework based on MCS and DC Optimal Power Flow (DCOPF) to accurately quantify the reliability impact brought out by optimal placement of wind energy and energy storage. Analytical study on IEEE 24-bus Reliability test system (RTS) has provided valuable insights on power system reliability impact derived from energy storage integration.**

***Keywords*—Composite system reliability, Monte Carlo Simulation, DC Optimal power flow, Energy Storage Integration, Expected Energy Not Served.**

I. INTRODUCTION

Composite system reliability is concerned with problem of assessing the ability of generation and transmission system to supply adequate and suitable electrical energy to major load points. It is significant to assess the reliability of system, the effect of outages on system and its consumer and cost alternative expansion plans its relative merits and operation scenarios. A reliability cost/worth evaluation method which incorporates the impact of wind energy and energy storage integration in electrical power systems is presented in [1]. In [2] author has evaluated system reliability by considering wind and hydro power coordination, the hydro facilities with energy storage capability are utilized to alleviate the impact of wind power fluctuations and also improve the system adequacy. In [3] methodology for operation of a hybrid plant with wind power and hydrogen storage to maximize economic benefits in a market environment is presented. In [4] − [6] investigation on operation strategies of energy storage on the bulk power system level and evaluation of reliability impact is done.

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There are five scenarios while utilizing wind energy for electric power generation. They are: (a) Wind energy without energy storage based systems, (b) Wind energy without energy storage combined with conventional generation based systems, (c) Wind energy with energy storage based systems, (d) Wind energy with energy storage combined with conventional generation based systems, and (e) Wind energy based systems connected to relatively large electric power grid. Benefits aroused by utilizing wind energy and energy storage can be assessed by conducting relevant reliability studies. Previous reported work has been on reliability impact of energy storage operation strategies within the distribution system and coordination by bulk power system operator on bulk power system [7]. In [8] − [11] work has been done on efficient planning including distribution automation devices to enhance the reliability and efficiency of the power distribution system and assessment of contingency-load-loss index (CLLI) as evaluation of reliability measure.

This paper's main contribution is on improvement in reliability by integrating the energy storage and wind energy at optimal location. Optimal integration of energy storage system and renewable energy generation is done using DCOPF. It would be located so that the transmission lines are least stressed, there is higher reduction in losses, without any violation to the voltage profile. Optimal placement would help to maximize the benefits of integration of wind energy and energy storage.

In this paper, A reliability evaluation framework based on MCS and DCOPF is proposed in order to accurately quantify the reliability impact brought out by optimal placement of wind energy and energy storage. To quantify the reliability impact composite system reliability index i.e. Expected Energy Not Served (EENS) is evaluated and comparison is drawn to show the improvement in reliability of composite system upon optimal integration of energy storage and renewable energy generation. MCS is a commonly used method to implement composite system adequacy assessment.

Simulation methods estimate the reliability indices by simulating the actual process and random behaviour of the system. The Monte Carlo methods mimic the failure and the repair history of components and the system using the probability distributions of component states [12]. The states of the system are generated in a sequential manner by transition from one state to the next using probability distributions of component state duration and random numbers from 0 to 1 [12]. Status of the equipment stays fixed until next transition happens and load for each node is updated to current hours during that time. For determining the loss of load conditions for each hour during that period Optimal Power Flow is used. These steps are repeated while simultaneously updating reliability indices each time until convergence condition is reached. Hence the system state is defined by the component (generator, transmission line) status and load pattern obtained from annual load curve. All available generation will be re-dispatched using centralized Optimal Power Flow (OPF) evaluating the state.

The rest of the paper is organized as follows: Section II presents the composite system reliability evaluation methodology using sequential MCS considering integration of energy storage and renewable energy generation. In Section III analytical study on IEEE 24-bus RTS and its findings have been reported. Finally, the overall contributions in brief have been concluded in section IV.

II. Composite System Reliability Evaluation Methodology

To quantitatively evaluate and study the reliability impact on system brought by wind energy and energy storage integration at optimal location, a composite reliability evaluation methodology is proposed. The proposed methodology is based on Sequential MCS. For reliability assessment, power system is either considered in success state or failure state. When loss of load occurs, the system is in failure state. The energy not served during the loss of load is the reliability index. The assumptions are: (a) Only the active power is considered, (b) The power loss is not considered, (c) Voltage levels are assumed to be properly regulated. For reliability analysis these assumptions are normally acceptable.

Taking the consideration of component failures and congestion in power system, the distribution system with renewable energy generation and energy storage can be operated in four modes [7]: (a) Grid Connected Mode, (b) Coordination Mode, (c) Islanding Mode, and (d) Failure Mode.

Grid Connected Mode: Here the distribution system with renewable energy generation and energy storage are connected to external grid. Power flow analysis is conducted for bulk power system to find whether entire load is covered by generation and energy storage. In case generation is not sufficient or leads to line congestion or loss of load, then the system is said to be in failure state.

Coordination Mode: Here the bulk power system requires extra energy from distribution system with renewable energy generation and energy storage to avoid loss of load event due to line or generator outages. If energy storage devices could cover loss of load in external grid then the system is in success state else if there is no sufficient energy from energy storage devices due to limited stored energy or line congestion it will be in failure state.

Islanding Mode: Due to failures in external grid, a condition arises such that it can not deliver power to distribution system at some load points. In this case energy storage devices and renewable energy generation should support the distribution system and for external grid the power flow analysis must confirm that load in external grid is covered. Then on a whole bulk system is said to be in success state otherwise it is in failure state.

Failure Mode: Here there is failure in distribution side and power can neither be supplied from external grid nor from energy storage devices. In case there is fault in distribution system side where there is no energy storage device it will lead to loss of load event.

The bulk power system state has to be determined, to know whether the energy storage is charging or discharging. In case bulk power system is in grid connected mode and sufficient generation is there in external grid to provide power to load and there is no peak load condition then the energy storage devices are considered to be charging (considered as load) either from external grid or renewable energy generation or both, in case it is peak load condition energy storage is considered to be discharging (considered as generation). In case there is loss of load event, the energy storage can reduce the unserved energy or can even avoid the loss of load event. By charging the energy storage devices in non-peaks and discharging in peaks distribution system side load is adjusted to lower level when loss of load events are more likely to occur, hence mitigating the total systems peak load. During peak load periods chances of inadequate generation is reduced which improves the bulk power system reliability.

Sequential Simulation: It is based on sampling the probability distribution of the component state duration. Chronological component state transition processes for all components are first simulated by sampling. The chronological system state transition process is then created by combination of chronological component state transition process. This approach uses component state duration distribution function. In two-state component representation, these are the operating and repair state duration distribution functions and are usually assumed to be exponential. The sequential simulation can be summed up in following steps:

Step by step algorithm for sequential simulation

[Step 1] Initial state of each component is specified. Generally, it is assumed that all components are initially in the success or up state.

[Step 2] The duration of each component residing in its present state is sampled from its probability distribution. Example, an exponentially distributed random variate has the probability density function [13],

$$F_T(t) = \lambda e^-(\lambda t) \tag{1}$$

Where λ is the mean value of the distribution.

Its cumulative probability distribution function is

$$F(t) = 1 - e^-(\lambda t) \tag{2}$$

Using inverse transform method the random variate T is given by:

$$T = -\frac{1}{\lambda} ln(1-U) \tag{3}$$

Where U is a uniformly distributed random number.
Since *1-U* distributes uniformly in the same way as U in the interval [0,1]

$$T = -\frac{1}{\lambda} ln(U) \tag{4}$$

If the present state is up state, λ is failure rate of the component. If present state is down state, λ is the repair rate of the component.
[Step 3] Step 2 is repeated in given time span, i.e., usually a year and sampling values of each state duration for all components are recorded. The chronological system state transition process can be obtained by combining the chronological component state transition processes of all components.
[Step 4] System analysis is conducted for each different system state to obtain the reliability index function $\phi(S)$. Let P(s) be the probability of the system sate. For index or test function of all system sates the mathematical expression is given by:

$$E(\phi) = \sum_{S \varepsilon G} \phi(S) P(S) \tag{5}$$

where G is set of system states.
Upon substituting the sampling frequency of state S for its probability *P(S)* gives

$$E(\phi) = \sum_{S \varepsilon G} \phi(S) \frac{n(S)}{N} \tag{6}$$

Where N is total number of samples and *n(S)* is number of occurrences of state S. $\phi(S)$ can be obtained by appropriate system analysis.

A. Convergence Criteria

If Q denotes unavailability of a system and X_i is a one-zero indicator variable or index function which states that.
$X_i = 0$, if the system is in up state.
$X_i = 1$, if the system is in down state.
Then,the estimate or the expectation of system unavailability is given by.

$$V(\bar{Q}) = \frac{\sum_{i=1}^{N} (X_i)}{N} \tag{7}$$

where N is the number of system sample states.
The sample variance is

$$V(X) = \frac{\sum_{i=1}^{N} (X_i - \bar{Q})^2}{N-1} \tag{8}$$

the uncertainty around the estimate can be measured by the variance of the expectation estimate

$$V(\bar{Q}) = \frac{V(X)}{N} \tag{9}$$

Coefficient of variation, β is used to represent the accuracy level of Monte Carlo simulation, which is defined as

$$\beta = \frac{\sqrt{(V(\bar{Q}))}}{\bar{Q}} \tag{10}$$

In Power system reliability evaluation, different reliability indices have different convergence criterion in order to guarantee reasonable accuracy in a multi-index study [14]. To quantify the effect of integrating the energy storage and renewable energy generation at optimal location on composite system reliability, system reliability index Expected Energy Not Served(EENS) [15] is found out.

$$EENS = \frac{\sum_{i=1}^{NS} \left(\sum_{j=1}^{n_i} SYSENS_{ji} \right)}{NS} \tag{11}$$

where,
n_i, number of system interruptions in year i,
$SYSENS_{ji}$, is the amount of system energy not served calculated in MWh for the interruption j in year i,
NS, number of simulation years.

First the optimal location for integration of energy storage and renewable energy to the bulk power system is found, then after fixing the location EENS is found out. For finding the optimal location, DC Optimal Power Flow should be run by considering the energy storage devices and renewable energy integrated at Bus 1 and finding out the total cost of generation and transmission line flows. This should be repeated by changing the location of energy storage devices and renewable energy integration by placing it at all buses and finding total cost of generation and transmission line. The bus where integration of energy storage devices and wind energy leads to minimum total cost of generation and the transmission lines are less stressed is considered as optimal location for its placement.
Objective function for DC OPF is

$$\textit{Obj Fun} = min(\sum_{i=1}^{N_G} (a_i P_{Gi,t}^2 + b_i P_{Gi,t} + c_i)) \tag{12}$$

Subject to the following constraints :
a) Power output limit of thermal generating units:

$$P_i^{min} \leq P_{i,t} \leq P_i^{max} \tag{13}$$

b) Maximum line flow limit of transmission lines:

$$PL_{ij,t} \leq PL_{ij,t}^{max} \tag{14}$$

c) Power balance equation

$$P_{gen,t} + R_t = L_{j,t} + \eta_c C_t - \eta_d D_t \tag{15}$$

where,
$P_{gen,t}$, Power from external grid for current period t,
$L_{j,t}$, Total load for current period t,
R_t, Power from renewable energy generation for current period t,
C_t, Charging power for energy storage for current period t,
D_t, Discharging power by energy storage for current period t,

η_c and η_d charging and discharging efficiencies of energy storage.
η_c will be considered when the battery storage is being charged then $\eta_d = 0$. If the ess is discharging η_d will be considered then $\eta_c = 0$.

Algorithm for Composite System Reliability Assessment Using Sequential Monte Carlo Simulation

Initially consider the system is able to serve the load i.e. success state and set all the components (generators and transmission lines) to Up state $U(i) = 1$, $D(i) = 0$, $U1_n(i) = 1$, $D1_n(i) = 0$, $\lambda(i)$ be failure rate and $\mu(i)$ be repair rate. Let us assume that the n^{th} transition has just taken place at time t_n and time to next transition of components $T_{n+1}(i)$ is found using,

$$T_{n+1}(i) = -\frac{1}{\lambda(i)} ln(x(i)) \tag{16}$$

where *x(i)* is a random variable drawn between 0 to 1.
Consider failure rate $\lambda(i)$ in case $U1_n(i) = 1$ or repair rate $\mu(i)$ in case $D1_n(i) = 1$.
[Step 1] The next transition time $T = min(T_{n+1}(i))$ change the corresponding state of components whose transition time matches with T to $U1_{n+1}(i) = 0$ if $U1_n(i) = 1$ and $D1_{n+1}(i) = 1$ if $D1_n(i) = 0$, $D(i) = D(i) + 1$ else $U1_n + 1(i) = 1$ if $U1_n(i) = 0$, $U(i) = U(i) + 1$ and $D1_{n+1}(i) = 0$ if $D1_n(i) = 1$ and for remaining components there states remain same accordingly either U(i) or D(i) are updated.
[Step 2] The simulation time is now advanced by, $t_{n+1} = t_n + T$
[Step 3] The residual times to remaining component state transitions are calculated by $T^r_{n+1} = T_n(i) - T$
[Step 4] The residual time for component p causing transition becomes zero and time to its next transition $T_{n+1}(p)$ is determined by drawing a random number and considering failure rate ($\lambda(p)$) if $U1_n(p) = 0$ or $D1_n(p) = 1$ else considering repair rate ($\mu(p)$) if $U1_n(p) = 1$ or$D1_n(p) = 0$.
[Step 5] From t_n to $t_{n+1}$the status of generators and transmission lines are fixed and following steps are performed,
a) Load at each node is updated to the current hour
b) Now run DC OPF for current hour (i.e. perform generator scheduling and run DC Power Flow)
c) Check for line overflows.
[Step 6] In case there is no line overloading go for next hour and repeat the steps in Step 5 till $t = t_{n+1}$ and if $t = t_{n+1}$ go to Step 8.
[Step 7] In case there is overloading
a) Reduce loading at each bus by 5% and rerun DC OPF if there is no overloading of lines go for next hour and repeat the steps in Step 5 till $t = t_{n+1}$.
b) In case the line overloading persist then go for load reduction of 10%, 20%, 30% so on.
c) In case the line overloads still persists then go for combinations of load reduction i.e. two loads, three loads so on.
d) The unserved energy for t_n to t_{n+1} will be the load not met during this period.
[Step 8] Repeat the steps from Step 1 for a span of one year (i.e. till t=8760 hours).
[Step 9] This one year horizon is repeated for 100 times. For all simulations total unserved load is calculated.
[Step 10] Compute EENS,

$$EENS = \frac{Total\ Unserved\ Load}{100} \tag{17}$$

III. ANALYTICAL STUDY

A. Test System

In order to provide a basis for comparison of reliability index obtained by integrating energy storage and wind energy at optimal location and at heavily loaded bus, it is desirable to have a reference or "test" system which incorporates the basic data needed in reliability evaluation. The IEEE 24-bus RTS which provides such "reliability test system"[16] has been utilized for testing.

B. Load Data

The load model gives hourly loads for a span of a year on a per unit basis; it is expressed in chronological fashion so that daily, weekly, and seasonal patterns can be modelled. The generating system contains a total of 32 units, ranging from 12 to 400 MW. Data is given on both reliability and operating costs of generating units [16]. In the transmission system 24 load/generation buses are connected by 38 lines or autotransformers at voltage levels of 138 and 220 kV. The line length, impedance, ratings, and reliability data is included in transmission system data. The Load variation is calculated from IEEE 24-bus RTS. The annual peak load of the test system is 2850 MW.

C. Wind Data

The Wind data from January 2014 to January 2015 has been taken from Iowa Environmental Mesonet [17]. The energy storage devices are assumed to be perfectly reliable. Original annual peak load of the system is 2850 MW.

The optimal location for integration of energy storage and renewable energy generation is at Bus 6, whereas the heavily loaded bus is Bus 18.

Considering the original system is relatively reliable and upon annually increasing load makes the system less reliable, the bulk power systems load is scaled so that the annual peak load is 2992.5 MW (1.05 x 2850 MW) and 3243 MW (1.15 X 2850 MW) respectively in the analytical study. Here the energy storage power ratings range from 0 MW to 80 MW. First base cases without energy storage or wind turbine are first studied. The results of base case are given in Table I.

Different sizes of energy storage and wind turbine capacities are integrated in distribution system. The reliability results for bulk power system with peak load at 2992.5 MW (i.e. 105% of peak load) considering the integration of energy storage and wind energy at heavily loaded bus is shown in

TABLE I
RELIABILITY INDICES BASE CASE

Load(MW)	Energy Storage Power(MW)	EENS 10^3MWh/yr	
		Energy Storage at Bus 18	Energy Storage at Bus 6
1.05*RTS load	00.00	3.4632	3.4632
1.05*RTS load	20.00	3.2832	2.8471
1.15*RTS load	00.00	15.634	15.634
1.15*RTS load	20.00	14.497	13.720

TABLE II
EENS (10^3MWH/YR) WITH 105% LOAD SCALE CONSIDERING WIND ENERGY AND ENERGY STORAGE INTEGRATION AT HEAVILY LOADED BUS 18

Energy Storage Power(MW)	Wind Turbine Generation (MW)					
	2	10	20	30	40	50
20.00	3.183	3.177	3.099	3.088	3.085	3.048
40.00	3.179	3.138	2.989	2.971	2.970	2.932
60.00	2.997	2.957	2.951	2.931	2.930	2.908
80.00	2.989	2.923	2.835	2.722	2.720	2.504

TABLE III
EENS (10^3MWH/YR) WITH 105% LOAD SCALE CONSIDERING WIND ENERGY AND ENERGY STORAGE INTEGRATION AT OPTIMAL LOCATION BUS 6

Energy Storage Power(MW)	Wind Turbine Generation (MW)					
	2	10	20	30	40	50
20.00	2.825	2.821	2.809	2.795	2.756	2.717
40.00	2.799	2.749	2.649	2.605	2.596	2.594
60.00	2.752	2.689	2.582	2.589	2.579	2.540
80.00	2.697	2.532	2.423	2.259	2.202	2.109

TABLE IV
EENS (10^3MWH/YR) WITH 115% LOAD SCALE CONSIDERING WIND ENERGY AND ENERGY STORAGE INTEGRATION AT HEAVILY LOADED BUS 18

Energy Storage Power(MW)	Wind Turbine Generation (MW)					
	2	10	20	30	40	50
20.00	14.29	14.04	13.97	13.74	13.69	13.49
40.00	14.09	14.00	13.89	13.70	13.65	13.28
60.00	14.02	13.99	13.98	13.59	13.50	13.42
80.00	14.00	13.99	13.79	13.39	13.38	13.19

Table II. Whereas considering the integration of energy storage and wind energy at optimal location is shown in Table III.

Table IV and table V shows the results for the bulk power system with peak load at 3243 MW (i.e. 115% of peak load) considering the integration of energy storage and wind energy at heavily loaded bus and integration of the energy storage and the wind energy at optimal location.

The analytical study results demonstrate the improvement in reliability brought by integration of energy storage and wind energy and by incorporating the proposed methodology for integrating the energy storage and wind energy at optimal location has further increased reliability.

Table I for system with peak load 2992.5 MW (i.e. 105% of peak load), integrating an energy storage device alone of 20 MW power rating (i.e. merely 0.67% of 2992.5 MW peak load), could reduce bulk power systems EENS by 5.2% ((3.463-3.2832)/3.463) by considering heavily loaded Bus 18 for integration, whereas upon considering optimal location the reduction in EENS is 17.8% ((3.463-2.847)/3.463). Upon optimally integrating both energy storage and renewable energy generation the reliability improvement of system is even more significant compared to integrating them at heavily loaded bus.

In Table IV and Table V results for the system with annual peak load of 3243 MW (i.e. 115% the annual peak load) is given. For the same expansion of energy storage and wind energy it has effective impact on reliability improvement for 115% load scale system , compared to 105% load scale system. Hence improving reliability for a less reliable system.

IV. CONCLUSION

This paper presents an improvement in reliability of the system brought by integration of energy storage and renewable energy generation at optimal location. Evaluation of reliability index, EENS was done and compared using sequential MCS in combination with DC OPF considering curtailment of load in case there were any line limit violations on the IEEE 24-bus RTS. Taking into consideration the potentially large scale integration of energy storage systems and renewable energy generation, the study of reliability impact on power system is important to determine the value of energy storage to be integrated and the bus at which it need to be integrated. This study can be further extended for planning and expansion of energy storage and renewable energy integration, its cost worthy analysis, economic feasibility analysis.

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TABLE V
EENS (10^3MWH/YR) WITH 115% LOAD SCALE CONSIDERING WIND ENERGY AND ENERGY STORAGE INTEGRATION AT OPTIMAL LOCATION BUS 6

Energy Storage Power(MW)	Wind Turbine Generation (MW)					
	2	10	20	30	40	50
20.00	13.42	13.38	13.11	12.71	12.71	12.48
40.00	13.26	13.16	13.11	12.31	12.30	12.20
60.00	13.22	13.11	13.10	12.20	12.11	12.01
80.00	13.12	13.03	13.00	12.10	11.85	11.18

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