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Quantifying energy storage augmented capacity value of wind generation in electricity market

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Abstract

Wind generation has been regarded as the most promising source of renewable energy. Many utilities and electricity markets around the world are, however, finding the task of integrating wind generation into the system very challenging due to its uncertainty and intermittency. Hence, confidence shown by majority of utilities and electricity markets in wind generation as a capacity source is extremely low. These challenges have spurred a wide range of research activities in this area, and many perceive energy storage technology has a potential solution to mitigate the adverse impacts of these uncertainties and intermittencies. This paper presents a methodology to model energy storage in conjunction with wind generation to quantify their contribution to system adequacy, and to assess the ability of energy storage to augment capacity value of wind resources in meeting acceptable reliability criteria. A study has been conducted in a test system with large wind penetration operated with energy storage. A range of studies are presented considering various market operating scenarios to illustrate the contribution to augmenting capacity value to the intermittent sources in energy system planning. Furthermore, the contribution of energy storage towards capacity deferral and reliability enhancement has been assessed for different electricity market scenarios.

Keywords: renewable energy, wind power, energy storage, capacity value, electricity market

1. Introduction

Power system operators and planners across the world are striving for economic energy generation with minimum carbon emission while maintaining acceptable system reliability. Quest for this goal has expedited the installation of renewables; mainly wind generation. Wind generation facilitates environmental compliance while compromising the economics and reliability of the system. These challenges have invigorated many researchers to investigate possible solutions. Many papers are published using various approaches in quantifying the capacity credit of wind generation. Energy storage technology is perceived as a potential solution. Reference [1] presents the dependency of different characteristics of energy storage system (ESS) on its capacity credit (CC) based upon expected energy not served (EENS) as the reliability index, employing sequential Monte Carlo simulation approach. Various methodologies for capacity value assessment of wind and solar generation along with their suitable applications, their strengths and weaknesses are discussed in [2]. Among various approaches to evaluate the CC of wind generation, the methods based on the probabilistic reliability indices, the loss of load expectation (LOLE) and the loss of energy expectation (LOEE), appear to be the most widely accepted methods by researchers. Many utilities, however, use different forms of deterministic approaches to assess the CC of wind generation. The capacity value evaluation of energy storage technology hasn't yet been explored as exhaustively as the wind generation and other renewable sources. Reference [3] presents a comparative CC evaluation based on the existing practices of different utilities, time period analysis and probabilistic analysis. Power system planning is mainly guided by an established system adequacy criterion to meet the demand. Adequacy studies for generation planning considers the overall generation

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capacity and system load ignoring transmission line constraints. Almost all utilities view wind generation as an energy source rather than a capacity source due to its non-dispatch-able nature. Most of the electricity markets only allow the wind generation to operate as a price taker in their systems [4]. Apart from that an independently owned ESS is operated with the objective of energy arbitrage in an energy market, which apparently adds to the system demand. A coordinated operation of wind generation and ESS can complement their individual capacity values. However, this added capacity value has no quantifiable tangible return in an energy market where the monetary values are determined by the net energy supplied and the associated energy prices that vary with the system supply and demand characteristics. But, rising affinity towards renewables have opened up new opportunities like capacity markets, for the generators, where electricity markets are willing to pay for the assurance of a generator being available to meet the system load, payment being proportional to the demand of the system at the time of generator's availability [5]. ESS can support wind generation sources to participate in the capacity market as well and add economic value to renewable technology from an electricity market perspective. This paper mainly discusses the ESS augmented capacity value of wind generation and its evaluation based on an analytical approach of the effective load carrying capability (ELCC). Operating scenarios are presented in which wind generation operates, in coordination with ESS in energy and capacity markets, to meet certain share of the system demand. Studies to quantify the capacity value and the benefits of such operation to the wind farm and ESS operator and to the overall system in terms of reliability and economics is also presented using a test system for illustration.

2. Methodology for Capacity Value Evaluation

The methodologies available for the capacity value assessment of wind generation can be broadly classified into capacity factor based approximate methods and probabilistic reliability indices based methods.

2.1. Capacity factor based approximate methods

These methods require limited data and enable faster computation, but do not recognize the stochastic system characteristics. These methods merely consider the capacity factor of wind resources over a subset of high-risk hours with high loads or LOLPs. An inherent assumption in this methodology is that loss of load mainly occurs during the high load periods and such events can be ignored during the off peak periods. Top load or LOLP and top LOLP-weighted method, are the preferred approach for this methodology [2]. These methods completely discount the wind generation's contribution to the system reliability during the off peak hours.

2.2. Probabilistic reliability indices based methods

These methods recognize the stochastic system characteristics and yield results with consistent risks. However, the evaluation process requires comprehensive data of generation facilities and load of the system, and computation is burdensome. Unlike the capacity factor based methods, these methods can incorporate detailed system scenarios. Most electric utilities, however, use the approximate methods, as they are primarily concerned about the availability of wind generation during the peak load periods. While considering the renewable generation operated in coordination with ESS, the neglected contribution of renewables and ESS during the off-peak hours in the capacity factor method becomes even more significant. Hence, probabilistic reliability indices based methodologies are better suited to take into account the contribution of renewables as well as ESS to the system reliability and thereby the capacity value of such system. The LOLE and LOEE are the two extensively used reliability indices for the reliability-based methods of capacity value assessment. The ELCC, equivalent firm capacity (EFC) and equivalent conventional capacity (ECC) are the commonly used approaches. A description of the ELCC approach was first presented in [6]. The ELCC metric is computed based on the additional peak load the system can carry with the addition of a generating unit without changing the overall system reliability. The additional load that the system is able to carry is quantified as the capacity value of the added generation. The work presented on this paper is also based on this metric and the reliability level of the system is measured in terms of the LOLE.

3. Wind Generation and Energy Storage Operation

This study considers a power system integrated with wind generation and ESS facility where the integrated facilities are operated in coordination to meet a specified share of the system load. Wind penetration has been growing rapidly in the power systems across the world, driven mainly by financial incentives, favorable market opportunities or commitment towards the Renewable Portfolio Standards (RPS) [7]. However, the intermittency and uncertainty in wind power generation creates challenges in continuously balancing the supply and demand, and therefore, requires fast responding generation technologies like hydraulic units and gas turbines to mitigate the problems. Feasible wind penetration in any power system network is dependent upon the composition of generation technologies along with the ancillary services at disposal for that system. Wind generation due its nominal operating cost can considerably lower the overall system operating costs. But its unpredictable nature necessitates increased operating reserves with high ramping capabilities. Thus, wind generation's capacity value is pessimistically evaluated in most jurisdictions. Keeping in mind, this limitation of wind generation, it has been assumed in this study that wind generation operates in coordinated manner with the energy storage which will solely operate to firm up the wind capacity, without creating additional demand to the system. The role of ESS in a system is guided by the prevalent operating conditions/electricity market and the policies set by the system-operator [8]. Considering this scenario, it has been assumed in this study that the operation of the wind and energy storage systems is restricted by an operating limit. The operating limit set by the operator is assumed to be set in terms of percentage of the system peak load. The operation of this system is represented by power transfer and the ESS charging and discharging process. The power transfer 'P_i' from the wind farm to the ESS in the 'i_{th}' hour is given by (1) while the state of charge (SOC) 'SOC_i' of the ESS is given by (2)

$$P_i = \begin{cases} \min[(W_i - c.L_i), \rho], \text{if } P_i \geq 0 \\ \max[(W_i - c.L_i), \sigma], \text{if } P_i \leq 0 \end{cases} \tag{1}$$

$$SOC_i = \begin{cases} SOC_{i-1} + \eta . P_i, if\ SOC_{min} \leq SOC_{i-1} \leq SOC_{max}\ and\ P_i \geq 0 \\ SOC_{i-1} + \dfrac{P_i}{\beta}, if\ SOC_{min} \leq SOC_{i-1} \leq SOC_{max}\ and\ P_i \leq 0 \\ \qquad and \\ SOC_{i-1}, \begin{cases} if\ SOC_{i-1} = SOC_{max}\ and\ P_i \geq 0 \\ if\ SOC_{i-1} = SOC_{min}\ and\ P_i \leq 0 \end{cases} \end{cases} \tag{2}$$

where, $P_i \geq 0$ represents charging and $P_i \leq 0$ represents discharging, 'W_i' is the wind generation, 'L_i' is the system load, 'ρ' and 'σ' are the charging and discharging rates and 'η' and 'β' are the charging and discharging efficiencies of the ESS respectively. The operating constraints 'c' is the percent share of the system demand allocated to wind and ESS.

4. System Model

The studies in this work requires analyses of three types of power systems; a system with only conventional generating units, with wind generators added, and with wind generators and ESS added to the system. The conventional generators are commonly modeled by two- state Markov models, and combined to obtain the overall generation model in the form of a capacity outage probability table (COPT) [9].

Hourly wind generation is evaluated based on the hourly wind speeds and the wind power curve which is expressed in (3).

$$W_i = \begin{cases} WP_r X(a + b.s_i + c.s_i^2)\ , if\ s_{ci} < s_i < s_r \\ WP_r\ , \qquad\qquad\qquad\quad if\ s_r < s_i < s_{co} \\ 0\ , \qquad\qquad\qquad\qquad\quad if\ s_i > s_{co} \end{cases} \tag{3}$$

where 'WP_r' is the rated power of the wind turbine generator, 's_i' is the wind velocity for hour 'i', 's_{ci}', 's_{co}' and 's_r' are the cut-in, cut-out and rated wind velocity respectively. 'a', 'b' and 'c' are wind turbine generator parameters.

There are two approaches in integrating wind generation models in the power system: (1) modeling wind as generation and combining with the system generation model, or (2) modelling wind as negative load and using it to modify the system load model [2]. Although many studies model wind generation as a reduction in load, this approach is not suitable for large wind penetration as it assumes all the wind power generated is always consumed by the system.

Since ESS operates in both the generation and load modes at different times, there is added difficulty in obtaining a suitable ESS model. This work, therefore, collectively develops the wind generation and ESS model and embeds the combined model into the system generation model. This approach is more appropriate for the coordinated operating strategy of wind generation and energy storage without grid support. This approach is extended in this paper to obtain the combined capacity of wind power and energy storage as shown in (4).

$$WPES_i = \begin{cases} W_i + \beta.SOC_i, if \beta.SOC_i < \sigma \\ W_i + \sigma, if \beta.SOC_i \geq \sigma \end{cases} \tag{4}$$

where, '$WPES_i$' is the combined capacity of wind and ESS in the 'i_{th}' hour of the time series data.

The challenge of system modelling for reliability evaluation process with wind generation and ESS is to retain the correlation and dependencies between different variables; i.e. wind generation, system load, state of charge and state of health of ESS. One of the main reason of using sequential simulation approach for reliability evaluation of systems with wind generation and ESS is its ability to easily incorporate these correlations, dependencies and chronology involved. Sequential simulation however, requires significant computational time. This paper utilizes an analytical approach using hourly clustering method to reduce the computation time. The wind generation, state of charge of ESS and the system load each retains a specific characteristic value in a particular hour of the day. An hourly clustering method, corresponding to the hours of the day, is used to preserve the dependencies and correlation as well as the chronology of these variables, and therefore, model the characteristics of the overall system operation. For each hour of the day the corresponding wind power generation and combined capacity of wind generation and ESS data is converted into its generation model of multi state capacity table. The number of states is determined based on the Sturge's rule. The generation models thus obtained, can be convolved with the conventional generation model to obtain the resultant generation model. This is convolved with the hourly load model using a period analysis to obtain the system LOLE as shown in (5).

$$LOLE_{resultant} = \sum_{hr=1}^{24} LOLE_{hr} \tag{5}$$

where, 'hr' represents the hour of the day. The LOLE is evaluated for various peak loads which is compared with the LOLE criterion for quantifying the additional reliability provided by the added wind generation first and then by the combined effect of wind and ESS. The overall evaluation process of the ESS augmented capacity value of wind generation is shown in Fig.1.

The capacity value of the added wind generation is first evaluated by calculating the incremental ELCC value (ELCC1) over the ELCC of the original RTS. The incremental ELCC value (ELCC2) of added wind generation and ESS is then evaluated over the ELCC of the original RTS. The augmented capacity value of wind generation (ACVW) due to ESS can be calculated using (5).

$$ACVW = ELCC2 - ELCC1 \quad (5)$$

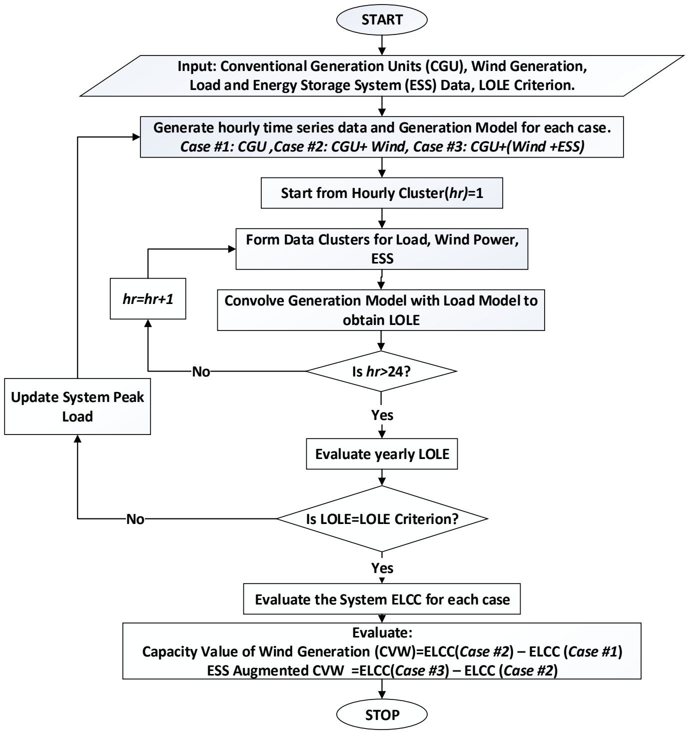

Fig.1. ESS augmented capacity value evaluation flow-chart

5. Capacity Value Evaluation

A study was first carried on the IEEE RTS [10] to assess the capacity value of wind generation. A 600 MW wind farm with Swift Current, Canada wind speed data was considered in the study. It is assumed that wind generation in excess of 150 MW is spilled due to ramping constraints of reserve generation. Fig. 2 shows the system LOLE as a function of the peak load with and without considering wind generation. The RTS system LOLE without wind power was found to be 1.6 hrs/yr. Using this LOLE criterion , the ELCC or the capacity value of wind is 125 MW, which is 20.8% of its installed capacity.

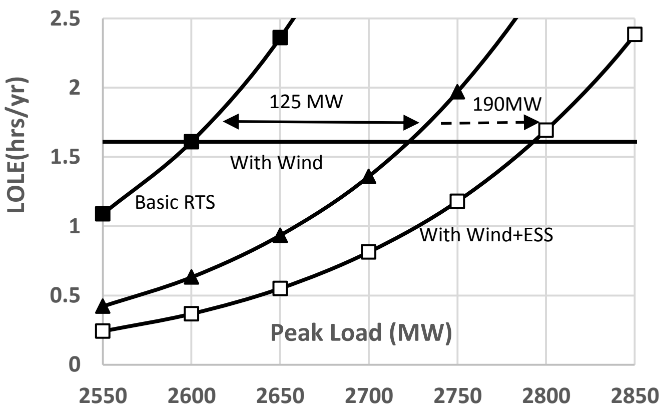

Fig.2. Capacity value for different system configurations

If a 1600 MWh ESS is added to the above system and continuously operated in coordination with wind generation to provide 150 MW commitment to the system, the combined capacity value of wind is increased to 190 MW as shown in Fig. 3. The ACVW is therefore 65 MW. This improvement in capacity value is insignificant, from the perspectives of the wind farm owner, ESS owner or the system operator. However, if the ESS is operated with wind to provide a commitment of 150 MW only during the peak hours between 5-9 PM daily, the ACVW is increased from 65 MW to 200 MW. This is a noticeable improvement. The results clearly show that the operation duration as well as service hours considerably determines the magnitude of capacity value contribution provided by ESS.

6. Factors Affecting Augmented Capacity Value

The augmented capacity value of wind power due to ESS (ACVW) is contingent upon different factors. The level of wind penetration, ESS storage capacity, ESS charging and discharging rates, operational hours and the demand limit allocated by the system operator determines the magnitude of augmented capacity value. Apart from impacting the capacity value, these factors bear conflicting interests for the system operator and the owners of wind farm and ESS system. Since augmented capacity value is a complex resultant of all these factors, sensitivity study was done to investigate the impact of the previously mentioned factors on ACVW. The results are summarized in Fig.3 shows that increment in ESS storage capacity from 600 MWh (keeping wind farm capacity constant at 600 MW) by 200% (to 1800 MWh) and 400%(to 3000 MWh) results in improvement of ACVW from 95MW by 84% (to 175MW) and 126% (to 215 MW) respectively. Similarly, the increment in wind farm capacity (keeping ESS storage capacity constant at 1800 MWh) from 600 MWh by 100% (to 1200 MWh) and 200% (to 1800 MWh) results in improvement of ACVW) from 175 MW by 46% (to 255 MW) and 68% (to 295 MW) respectively. Percentage improvement in ACVW for both cases are not proportional to the percentage increment in ESS storage capacity and wind farm capacity. This necessitates a coordinated increment of ESS storage capacity and wind generation capacity. On the other hand, ACVW tends to decline along with the rise in the percentage of system demand served and the service hours of the wind generation and ESS system. Thus, optimization between all these factors needs to be maintained to obtain an optimal capacity value.

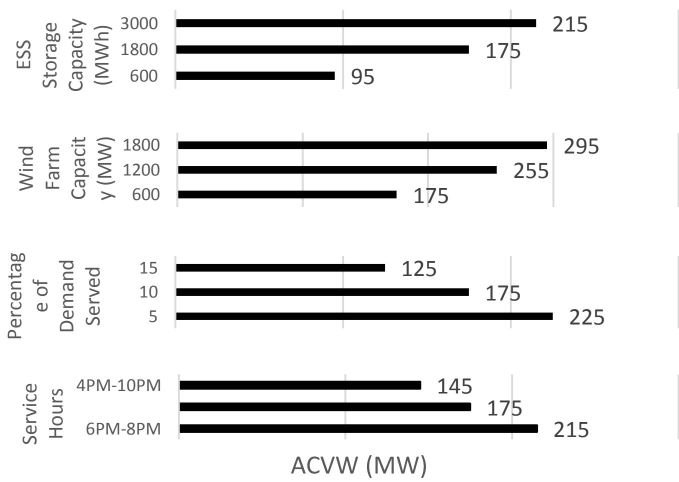

Fig.3. Augmented Capacity Value of Wind Generation (ACVW) Vs installed wind generation/ESS storage capacity/% of demand served/ service hours

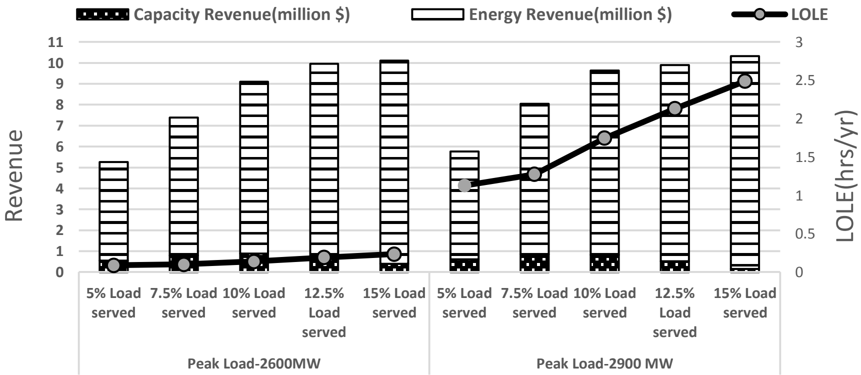

Fig.4. Revenue/LOLE for different scenarios

7. Capacity Market Scenario

A study was conducted considering two different load levels, i.e. 2600 MW and 2900 MW, in the RTS for capacity market scenarios where wind generation and ESS operate in coordination to meet 5-15 % of system load during the peak hours daily.

Fig. 4 illustrates the benefits from the wind generation and ESS operation to its owner quantified in terms of the revenue generated for different load levels while serving different shares of the system load. Capacity value of wind resources are virtually ignored and are mostly dependent upon energy revenue, however with ESS operated in coordination, capacity from wind generation and ESS can extract capacity value from the capacity market. Hence, co-ordinated operation of wind farm and ESS can obtain additional revenue from the capacity market in the form of capacity payments. Additional revenues obtained for scenarios of wind generation and ESS system serving 5%, 7.5%, 10%, 12.5% and 15% of the system load for peak demands of 2600 MW and 2900 MW are shown in Fig 4. It can be seen that unlike energy revenue, capacity revenue starts declining after reaching certain percentage of load to be served. This can be attributed to the fact that as the wind generation and ESS target for higher share of the system load, the ability of such system to adequately fulfill the committed demand diminishes due to the limitation in the energy storage. Apart from that, expected SOC level of energy storage gets reduced thereby exposing the system to higher LOLE. Consequently, the capacity value of the combined system is degraded and thereby causing the decline in the capacity revenue. Deterioration of LOLE along with higher percentage of load commitment thus, limits the maximum percentage of load to be served by a particular combination of wind generation and ESS.

Fig 5 presents the achievable capacity value (capacity deferrals for system operator) for three representative cases when the wind generation and ESS system serves 5%, 10% and 15% of the system load during peak hours, which is equivalent to 347.5 MW, 289 MW and 240 MW of conventional capacity, which is in line with the previous discussion. In an energy only market, wind generation and ESS would pursue to serve higher % of load in order to gain higher revenue which effectively reduces the capacity value of such system, which is a loss for the system operator from the achievable capacity deferral perspective. Thus, in order to maximize the achievable benefit of capacity value from wind generation and ESS for both wind generation and ESS owner and the system operator, system operator should allocate appropriate credit to the capacity value of such system along with justifiable share of system load to be served.

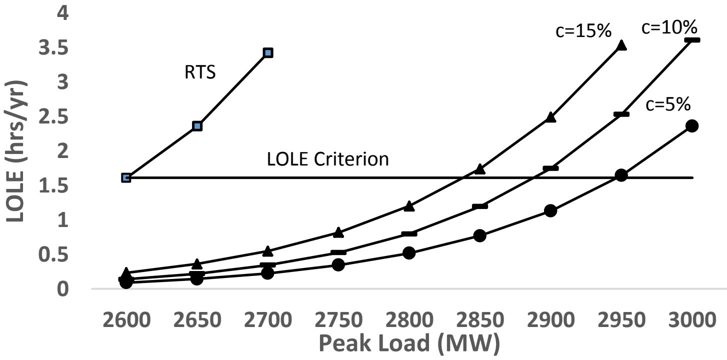

Fig.5. Capacity deferral for different percentages of system demand served by Wind Generator and ESS system

8. Conclusions

This paper presents a method to incorporate the ESS model into an analytical reliability evaluation framework to quantify the contribution of ESS in augmenting the capacity value of wind generation in terms of the economic benefits, additional revenue for the wind generation and ESS owner and capacity deferral benefits to the system operator. Operation of ESS in coordination with wind generation provides a steady and reliable power which can be counted upon by the system operators, if the capacity market policies permit the co-ordinated operation of wind farm and ESS to achieve maximum ACVW and pays for it as well. The achievable capacity value along with the benefits, however starts declining if the combination commits to serve the system load beyond a certain limit resulting in a loss of capacity payment to the combined wind and ESS owner and loss of opportunity of capacity deferral for the system operator. Hence, a suitable policy to recognize the ACVW achievable from co-ordinated operation of wind farms and ESS to assist system adequacy becomes necessary so that such operations can be viable.

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