Application of Battery-based Energy Storage in Grid-connected Wind Farms in Order to Improve Economical Utilization

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Abstract—In presence of wind farms in a power system, operators will encounter more complexity in system utilization than before, because of the stochastic and fluctuating nature of the wind farm output. The presence of some constraints in power systems utilization may cause some restrictions in wind energy injection to the power system. Therefore, wind farm utilization may become non-cost effective in presence of these constraints. Using energy storage systems (ESS) in wind farms will have positive effects on power system utilization, which depend on regional wind regime and hourly energy prices. In this research, a new method is proposed to change the direction of wind farms’ capacity allocation studies towards increasing wind farms’ capacity. In fact, in this study, the capacity of ESS and the wind farm hourly output power are determined in a way that wind farm total income in one year and its capacity factor are increased as much as possible. So, power system users’ tendency towards increasing wind power penetration in power system will be raised as total income and wind farm capacity factor increase. In this paper, particle swarm optimization (PSO) is applied to find optimal ESS capacity and hourly energy management. Results demonstrate that despite high cost of energy storage systems, by using the proposed method in energy management optimization, the total income from wind energy sales will increase. Also, these results acknowledge all justifications proposed towards increasing the wind farm capacity in primary planning studies.

Keywords- wind energy; wind farm energy management; energy storage system (ESS); economic utilization

I. INTRODUCTION

Recently, wind energy penetration in power grids has increased in comparison with other renewable energy resources. The stochastic and variable nature of wind speed causes the output power and terminal voltages of wind farms to become fluctuating. It also decreases the power quality in wind farms [1]. In [1] and [2], the effects of wind farm on grid power quality have been investigated. Because of power quality’s importance in wind farms, the IEC-61900-21 standard is introduced for wind farm power quality investigation [3]. In [4], the effects of different parameters on grid voltage variation in presence of wind farms have been investigated. These fluctuations not only decrease the network power quality, but also cause some problems in wind farm output power planning. In presence of wind farms in a power system, operators will encounter more complexity in system utilization than before [5]. This complexity will be increased as the penetration of wind energy in power systems rises. Furthermore, adding the wind generation to a power system affects the operations of other power units in the power system and this may cause utilizing the power systems to become non-cost effective, no matter how accurate our planning is. So, a complete understanding of the value of wind power on an integrated power system is an important, but not simple, matter [6]. Because of the presence of some constraints in power systems utilization, the wind power penetration in power systems will be limited which depend on grid characteristic and regional wind speed. In addition to aforementioned problems, low accordance between load curve (or price curve) and wind speed curve may reduce economic aspects of wind farm utilization. In fact in most sites, wind energy is unavailable when we need it. So, cost effective utilization of wind farm directly depends on various factors in power system utilization and regional wind regimes which are out of wind farm owners’ control. Therefore, an economic analysis is needed to find the optimal grid-connected wind farm capacity.

Despite these problems in wind farm utilization, energy storage system (ESS) application is an effective policy for increasing penetration of variable energy resources like wind generation in power systems. By using ESS in a wind farm, the output of the wind farm can be controlled for improving the power quality and having more economic utilization. In [7], ESS has been applied for increasing wind farm output prediction accuracy. In other studies, ESS has been used for energy management and wind farm output smoothing in long periods [8].

Energy storage systems can store extra energy generated by wind farm when it is not necessary (off-peak) and release it when needed (peak load). This controllability will be proportional to the ESS capacity. However, the ESS capacity and ESS output power management must be determined according to ESS application goals such as power quality, system stability and economic utilization. In this paper, a new method has been proposed in which the ESS capacity

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84
and the hourly ESS output power management are determined proportional with hourly energy price and hourly wind speed in a way that further income from wind energy sale can be acquired in a year and systems’ voltage and stability is guaranteed. This paper targets the application of a heuristic optimization technique, Particle Swarm Optimization (PSO) [9], for ESS sizing and energy management in a grid-connected wind farm. In this research, a real wind distribution, which has been recorded in Perley Station, ND, has been used [10]. The hourly energy price data has been extracted from IESO website [11]. In this study, Newton-Raphson-based power flow has been used and system modeling has been carried out in MATLAB/mfile environment.

II. FORMULATION OF OPTIMIZATION PROBLEM

The objective function developed for grid-connected wind farm energy management presented here is the total income from energy sales in a one year period with taking into account the ESS cost, as well as the technical constraints of the optimization procedure. In this section, the cost function of ESS and Point of Common Coupling (PCC) voltage constraint has been investigated.

A. Energy Storage System Cost

Some recent researches have been reported regarding the presence of energy storage in wind farms. In [12] flywheels have been used in wind farms to improve the power quality and stability. In [13] and [14] supercapacitors and superconductors are utilized to smooth the wind farm output power, but their high cost and low capacity have limited their applications in wind farms. In [15] some investigations have been done regarding battery application in wind farms to improve the power quality and stability. Because of suitable cost and capacity scaling of batteries, more attention has been paid to them than other storage systems in power systems.

The total investment cost of ESS consists of two separate costs: energy capacity cost and power capacity cost [16-17]. The ESS energy cost is related to storage part which is proportional to energy capacity and is represented by $/KWh. The ESS power cost is related to inverters, converters and electronic devices. It is proportional to power capacity of ESS and is represented by $/KW. The storage system cost is calculated by the following equations:

\[ PCS = PCSU \times P_{\text{rated}} \]  
\[ SUC = SUCU \times J_{\text{rated}} \div \eta \]  
\[ BOP = BOPU \times J_{\text{rated}} \div \eta \]

All abbreviations are summarized in the Appendix. The TCC, which is the sum of the total cost for the power electronics, storage units and balance of plant, is:

\[ TCC = PCS + SUC + BOP \]  

The annual total investment cost is represented by:

\[ ACC = TCC \times CRF \]  

Where:

\[ CRF = \frac{i_{e}(1+i_{e})^{2}}{(1+i_{e})^{2} - 1} \]

When batteries are used as the energy storage system, they may have to be replaced one or more times during the life of the plant. This cost is annualized (US$ per kilowatt-hour) as:

\[ A = F \times [1/(1+i_{e})^{r} + (1+i_{e})^{-2r} + \ldots] \times CRF \]

In energy storage system replacement cost calculation, the life length of storage system is determined by the number of charge/discharge cycles:

\[ r = \frac{C}{n \times D} \]

The annual replacement and maintenance costs are calculated as:

\[ ARC = A \times J_{\text{rated}} \div \eta \]

\[ OMC = OM \times P_{\text{rated}} \]

At the end, the total storage system annualized cost is expressed as:

\[ TAC = ACC + OMC + ARC \]

B. Voltage analysis for PCC:

Injecting more wind power in the system may cause undesirable voltage drop in PCC. If wind farm utilizers do not damp additional wind energy with different control technologies, it may reduce power quality or result in voltage instability. Thus, system voltage fluctuation is an important issue, which should be considered in wind farm energy management.

In Fixed-Speed Wind Turbine (FSWT), which has been installed widely around the world, the induction generators consume some reactive power during operation, which is
proportional to the active power generated. The active and reactive power consumed or generated at the wind farm is calculable based on its produced mechanical power and PCC voltage [18]. Since this kind of wind generator cannot control the PCC voltage, buses with FSWT are modeled as P-Q buses in the load flow study. In this paper, only the influence of FSWT is studied.

Equation (12) and (13) are used for calculating generated active power \( P_e \) and consumed reactive power \( Q_e \) by FSWT respectively [18]. By having mechanical power output of generator \( P_m \), terminal voltage \( V \) and all other parameters of the induction machine, the electrical active power \( P_e \) and consumed reactive power \( Q_e \) of that machine can be computed:

\[
P_e = P_m + \frac{V^2}{R_e} + \frac{2R_e P_m}{V^2} \quad (12)
\]

\[
Q_e = \frac{V^2}{X_m} + \frac{2X_m P_m}{V^2} - \frac{2X_m P_m}{V^2} \quad (13)
\]

Like other P-Q buses, the bus voltage, active and reactive power in (12) and (13) may be unknown and iterative power flow algorithms can be used to find them.

So, voltage magnitude at PCC is determined with power flow accomplishment. Since the active and reactive power output of a wind farm depend on wind speed, the voltage deviation may vary with wind speed fluctuation. To ensure reliable operation of the power system, it is necessary to maintain voltage fluctuations in an acceptable range. Therefore, in this paper voltage fluctuations range is defined as a constraint in wind farm energy management. This range has been determined in some standards. These standards are introduced in [19]. Usually, the maximum voltage fluctuations range is considered 0.1 [20]:

\[
\left| \frac{\Delta V}{V} \right| < 0.1
\]

III. PROPOSED WIND FARM ENERGY MANAGEMENT

By connecting the wind farm to the grid, the generated power by wind farm will be injected to the grid, if there is no technical limitations. But, sometimes there are some technical constraints which restrict the wind power injection to the grid. Furthermore, wind energy may be unavailable when energy price is high (peak load). Owing to these problems, being capable of controlling wind farm output is an effective policy for improving wind farm economic utilization. This will become possible by using ESS in wind farms. So, by presence of ESS in wind farms, utilizors will have easier and more cost effective utilization from wind farms than before. In fact, by doing so, wind farm owners have more control on generated wind energy sales. A grid-connected wind farm along with ESS is shown in Figure 2. As shown in Figure 2, wind power injection to the grid can be managed by controlling the ESS output (PES).

While improving economical aspect in wind farm utilization is an important goal in this study, accurate ESS output management and choosing a suitable ESS capacity is necessary too.

Wind energy injection to the grid can be shifted from off peak hours (when the energy price is low) to peak load hours (when the energy price is high) by an effective management on ESS output. On the other hand, high cost of ESS limits their use in different applications. Therefore, ESS output management and its capacity selection must be done in a way that there would be a consistency between ESS costs and its benefits. Otherwise, wind power utilization may be non-cost effective.

Since the energy price changes in different hours, wind farm hourly energy management must be based on hourly energy price. Energy price changes can be represented in four periods [21]. Figure 3 represents the average annual value of electricity energy price which has been extracted from IESO website [11]. As shown in Figure 3, there are two peaks (period B and D) and two off-peak periods (periods A and C). B and D are peak periods (high energy price and high demand), A and C are off-peak periods (low energy price and low demand). During period A and C, the energy generated by wind farm must be stored in storage system. However, if this energy is higher than the nominal ESS energy capacity, the exceeding energy will be injected to the grid. During periods B and D, in addition to wind farm generated power, the stored energy in ESS will be injected to the grid.

![Figure 3. Average annual value of electricity energy price](image)

In [21], the length of periods is constant for all days during a year and the charging/discharging operation will be started from the first hour of each period without any attention to subsequent hours.
For example, in period B at the first hour the stored energy will be injected to the grid up to ESS nominal power capacity. However, in the subsequent hours energy price may be higher than the first. Therefore, wind farm output power management may not be optimal by using this method for different wind regimes and market's energy price. In this paper, a new method has been proposed in which the length of periods is not constant for all of the days and the length of periods is variable for different days during a year. Furthermore, the ESS output power for each hour in a period is determined based on energy price and wind speed in respective hour.

In [22], a method has been used for ESS output determination in which the ESS output has been determined with respect to wind farm generated power. As previously discussed, the wind farm generated power will be calculated by using power flow algorithm. Whereas the ESS output can be included as a load connected to PCC, it can be effective on PCC voltage and also wind farm generation. So, ESS output must be considered in power flow studies for wind farm generated power calculations. In the proposed method in this paper, the ESS output power is determined independently from the wind farm's generated power and it is considered in power flow accomplishment to determine wind farm generated power. Next, the application of the proposed method for ESS output power determination in different periods has been explained.

A. Periods A and C
In A and C periods, the average energy cost is lower than other periods (B and D). Therefore, generated wind energy must be stored in the ESS and be injected to the grid when energy price is high (periods B and D). In period A or C, storing energy by ESS must be higher during the hours which energy price is low. In fact, these hours have higher priority in power storing. In these periods (A and C), the free space of ESS can be distributed between different hours proportional to energy price in respective hour. By doing so, the hours with lower energy price will have a bigger share from free space of ESS more than other hours. However, in these hours, the generated wind power may also be low. As previously mentioned, at such conditions because of low energy price in these hours, more percents of ESS free capacity will be reserved for this hours. Whereas wind power generation in these hours is low, an amount of reserved capacity of ESS may be unused. On the other hand, at the other hours which wind power generation is high, the ESS reserved capacity is low. So, under this condition optimal utilization from ESS capacity will not be achieved. In order to avoid such conditions, the free capacity of ESS is distributed between different hours proportional to energy price and wind speed in respective hour. In fact, the stored energy in each hour has an inverse relation with energy price and a direct relation with wind speed.

\[ PES, = \frac{1}{ep} \ & \ V, \]

(15)
The appropriation of free space of ESS capacity for each hour can be obtained by the following equations:

\[ Per = [h_1, h_2, ..., h_n] \]

(16)
Where, \( P_{er} \) represents a period which consists of \( n \) hours \( (h_1, ..., h_n) \).

\[ NEP = \left[ \sum_{i=1}^{n} ep_i \right] \]

(17)
\[ VN = \left[ \sum_{i=1}^{n} v_i \right] \]

(18)
In equations (17) and (18), the energy price and wind speed at each hour during the period have been normalized based on sum of the energy price and wind speed at all hours. The amount of energy that must be stored in ESS at each hour can be determined by a coefficient. This coefficient represents a portion of ESS free capacity. This coefficient will be obtained as follows:

\[ E_P = \left[ (1 - NEP) (1 - NEP) ... (1 - NEP) \right] \]

(19)
\[ \alpha = \left[ \frac{EP_i \cdot NV_i \cdot EP_{i+1} \cdot NV_{i+1} \cdot EP_{i+2} \cdot NV_{i+2} \cdot ... \cdot EP_n \cdot NV_n}{EP_1 \cdot NV_1} \right] \]

(20)
\[ \beta = \left[ \frac{1 - \alpha}{1 - \sum_{i=1}^{n} \alpha_i} \right] \]

(21)
In equation (20), \( \alpha_n \) is the coefficient which determines the portion of ESS free space capacity for each hour based on ESS free space capacity at the beginning of the period. \( \beta_n \) is the coefficient which determines the portion of ESS free space capacity for each hour based on ESS free space capacity at the beginning of the hour \( n \). The amount of power that must be stored at each hour is represented by (22):

\[ PES_i = \begin{cases} -P_{s}\frac{\beta_n (1 - SOC) \cdot J_{soc} \cdot \frac{\eta_{soc}}{J_{rated}}} {\beta \cdot (1 - SOC) \cdot J_{soc} \geq P_{s}} \\ -P_{s}\frac{\beta_n (1 - SOC) \cdot J_{soc} < P_{s}} \end{cases} \]

(22)
The state of charge of ESS for hour \( t \) is updated as follows:

\[ SOC_i = SOC_{i-1} - \frac{PES_i}{\eta_{soc}} \]

(23)
At the end, the total injected power to the grid is calculated as:

\[ P_{out} = P_{w(t)} + PES_i \]

(24)
B. Periods B and D
In B and D periods, the average energy cost is higher than other periods (C and A). Therefore, the stored energy in ESS must be injected to the grid. In periods B or D, delivering energy by ESS must be higher at hours which energy price is higher than other hours. In fact, these hours have higher priority in injecting power to the grid. In these periods (B and D), the stored energy in the ESS can be
distributed between different hours proportional to energy price at respective hour. By doing so, the hours with higher energy price will have a bigger share from stored energy in ESS than other hours. However, in these hours, the generated wind power may also be high. As previously mentioned, under such conditions because of high energy price in these hours, more percent of stored energy in ESS will be appropriated for these hours. Whereas wind power generation in these hours is high, an amount of generated power may be damped because of existence of some constraint as mentioned previously. So, under these conditions the optimal utilization from stored energy will not be achieved. So, in order to avoid such conditions, the stored energy is distributed between different hours proportional to energy price and wind speed at respective hour. In fact, the stored energy in each hour has a direct relationship with energy price and an inverse relationship with wind speed.

\[ \text{PES}_{\text{t}} = \text{ep} \cdot \eta \frac{1}{V_{\text{t}}} \]  

(25)

The appropriation of stored energy in the ESS for each hour can be obtained by the following equations:

\[ V^* = 0 \sum_{i=1}^{n} (1-NV_{i}) \]  

(26)

\[ \alpha = \left[ \sum_{i=1}^{n} (NPE_{i}: V_{i}), \sum_{i=1}^{n} NPE_{i} : V_{i} \right] \]  

(27)

\[ \beta = \left[ \alpha, \alpha, \ldots, 1-\sum_{i=1}^{n} \alpha, 1-\sum_{i=1}^{n} \alpha \right] \]  

(28)

In equation (27), \( \alpha \) is the coefficient which determines the portion of stored energy for each hour for injecting to grid based on stored energy in the ESS at the beginning of the period. \( \beta \) is the coefficient which determines the portion of stored energy for injecting to grid at hour \( n \) based on stored energy in the ESS at the beginning of the hour \( n \). The power that must be injected to grid from ESS at each hour is obtained by equation (29):

\[ \text{PES}_{\text{t}} = \left\{ \begin{array}{ll}
\text{Pout} & \text{if } \beta \cdot \text{SOC}_{\text{t}} \geq \text{Pout} \\
\text{SOC}_{\text{t}} & \text{if } \beta \cdot \text{SOC}_{\text{t}} < \text{Pout}
\end{array} \right. \]  

(29)

The charging state of ESS for hour \( t \) is updated as follows:

\[ \text{SOC}_{\text{t+1}} = \text{SOC}_{\text{t}} - \frac{\text{Pout} \cdot \text{PES}_{\text{t+1}}}{\text{rated}} \]  

(30)

The total injected power to the grid is calculated as previous section.

**IV. PARTICLE SWARM OPTIMIZATION**

**A. A Brief Overview of PSO**

Particle swarm optimization (PSO) was developed by Kennedy and Eberhart in 1995, based on swarm behavior such as fish and bird schooling in nature [8]. Particle swarm optimization may have some similarities with genetic algorithms and ant algorithms, but it is much simpler because it does not use mutation/crossover operators or pheromone. Instead, it uses the real-number randomness and the global communication among the swarm particles.

This algorithm searches the space of an objective function by adjusting the trajectories of individual agents, called particles, as these trajectories form piecewise paths in a quasi-stochastic manner. The movement of a swarming particle consists of two major components: a stochastic component and a deterministic component. Each particle is attracted toward the position of the current global best \( p^g \) and its own best location \( p^i \) in history, while at the same time it has a tendency to move randomly. When a particle finds a location that is better than any previously found locations, then it updates it as the new current best for particle \( i \). There is a current best for all \( n \) particles at any time \( t \) during iterations. The performance of each particle is measured according to a predefined fitness function, which is related to the problem to be solved. The aim is to find the global best among all the current best solutions until the objective no longer improves or after a certain number of iterations. Reference [23] gives a comprehensive overview of PSO and its application in power systems, and discusses its fast convergence speed and advantage over other stochastic methods. The movement of particles is schematically represented in Figure 4 where \( p^i \) is the current best for particle \( i \), and \( p^g \approx \min \{ f(x^j) \} \) for \( i = 1,2, \ldots, n \) is the current global best.

![Figure 4. Schematic representation of the motion of a particle in PSO](image)

The new velocity vector is determined by the following formula [8] and [25].

\[ v^i_{k+1} = \alpha_k v^i_k + c_1 r_1 \left( p^i_k - x^i_k \right) + c_2 r_2 \left( p^g_k - x^i_k \right) \]  

(31)

Equation (31) is used to determine each particle’s new velocity \( v^i_{k+1} \) based on its previous velocity and the distance of its current position \( x^i_k \) from its own best experience and the best experienced position of its own informants \( p^i_k \). \( K \) and \( l \) indicate a pseudo time increment and number of particles, respectively. \( c_1 \) and \( c_2 \) are two positive constants which are chosen as \( c_1 = c_2 = 2 \) in this study. \( r_1 \) and \( r_2 \) represent uniform random numbers between 0 and 1, which will be regenerated at each iteration [8],[24]. The inertia weight \( \omega_k \) in (31) must be neither too large, which may result in premature convergence, nor too small which may slow down the convergence excessively [24]. The new position can then be updated by Eq.(32):

\[ x^i_{k+1} = x^i_k + v^i_{k+1} \]  

(32)
Each particle is associated with a pseudo velocity $v_{k+1}^i$ ($-v_{\text{max}}^i \leq v_{k+1}^i \leq v_{\text{max}}^i$), which represents the rate of the position change for the particle [8], [24].

B. PSO- Based Energy Management

According to previous explanations, in this optimization, the length of each period and the ESS energy capacity and ESS power capacity are selected as decision variables to be optimized by PSO. So, the system is initialized with a population, which consists of variables with different nature. The variables which are related to periods are positive integer numbers and the other which are related to ESS power and energy capacity are positive numbers. Since the initial population is generated randomly, the portion of variables which is related to daily periods and is generated at first population, may not be an integer. Therefore, they must be rounded at first. Figure 5, shows variables which are related to periods in a particle of generated population. In this figure $T_{ij}$ indicates period $j$ at day $i$.

\[
\sum_{j=1}^{4} T_{ij} = 24 \quad \text{for } i = 1, 2, 3, \ldots, n \quad (33)
\]

In Eq. (33), $T_{ij}$ indicates the period $j$ from day $i$ and $n$ represents the number of total days being studied. So, the initial population revision is done by equations (34) and (35):

\[
\begin{align*}
\text{if } \sum_{j=1}^{4} T_{ij} &< 24 \quad T_{ij} = 24 - \sum_{j=4}^{n} T_{ij} \quad (34) \\
\text{if } \sum_{j=1}^{4} T_{ij} &> 24 \quad \begin{cases} 
T_{ij} = 22 - \sum_{j=1}^{4} T_{ij} & \text{if } \sum_{j=1}^{4} T_{ij} > 23 \\
T_{ij} = 23 - \sum_{j=1}^{4} T_{ij} & \text{if } \sum_{j=1}^{4} T_{ij} = 24
\end{cases} \quad (35)
\end{align*}
\]

After modifying the initial population by equations (33) and (34), the periods must be arranged (A, B, C, D) as explained in section III – A and B. By determining the ESS output at each hour and also injected power to the grid by applying power flow algorithm, the fitness value of each particle will be determined. Then the new population will be generated as explained in last section. The subsequent populations must be modified by using equations (33) and (34).

In this paper, the objective function is defined as annual ESS cost subtracted from total wind energy sales which is formulated by the following equation:

\[
\text{fitness} = \sum_{i=1}^{n} P_{G(i)} * e_{p_i} - TAC \quad (36)
\]

The flowchart of the proposed method for solving the optimization problem is shown in Figure 6:

V. SIMULATION RESULTS

A specific wind farm investigated in this research consists of fixed speed induction generators with 2 MW rated power and their characteristics have been mentioned in [25]. The wind farm has been connected to an infinite bus by a transmission line, the details of which are given in [26]. The wind farm's annualized investment cost is given in [27]. In this paper, zinc–bromine flow battery [28] has been used in the wind farm. This kind of battery is very suitable for high capacity requirements because of its high energy and power capacity, suitable capacity scaling, easy operation and maintenance, fast response to changes and long life [29]. By applying the proposed method in [21] for this specific wind regime and hourly cost data, the maximum annual income has been achieved at different capacity of wind farm when no ESS has...
been applied for different lengths of periods. It is shown that by using this method the output power of the wind farm cannot be managed perfectly. The proposed method in this paper has been applied for different wind farm capacities. (26, 28 and 30MW). Table I shows the annual injected energy to the grid and annual wind farm income for different capacities at presence and absence of ESS. According to the results, in presence of ESS in the wind farm, the annual injected power to the grid and annual wind farm income from energy sales have been increased. As demonstrated in this table, the slope of annual income increment has been decreased by wind farm capacity rising. In fact, in high wind farm capacities, voltage constraint limits ESS in shifting electrical energy between different hours. Therefore, energy shifting from off-peak hours (low energy price) to peak hours (high energy price) will be reduced. In such conditions, the effect of ESS in shifting generated power from A and C periods to B and D periods will be decreased. Thereupon, the percent of increasing in wind farm annual income in presence of ESS will be reduced by wind farm capacity increasing.

TABLE I. Annual injected energy and annual wind farm income for different wind farm capacities

<table>
<thead>
<tr>
<th>Wind farm capacity (MW)</th>
<th>Presence of ESS</th>
<th>Absence of ESS</th>
<th>Total income from energy sold in one year ($)</th>
<th>Increasing percentage %</th>
</tr>
</thead>
<tbody>
<tr>
<td>26</td>
<td>134683.21</td>
<td>134542.47</td>
<td>42238357.16</td>
<td>41656061.17</td>
</tr>
<tr>
<td>28</td>
<td>139657.47</td>
<td>139348.72</td>
<td>43685863.31</td>
<td>43247204.48</td>
</tr>
<tr>
<td>30</td>
<td>143229.53</td>
<td>142953.50</td>
<td>44485973.53</td>
<td>44439906.72</td>
</tr>
</tbody>
</table>

Table II demonstrates the net wind farm annual income in presence and absence of ESS, for different wind farm capacities. As illustrated in this table, the highest annual income has been achieved when ESS has been used in wind farm which is related to 30MW wind farm capacity. While total annual income for 28MW wind farm capacity is too closed to total annual income for 30MW wind farm capacity. Therefore, power system planners must select one of the 28MW or 30MW capacities for the wind farm which is equipped with ESS, subject to other problems in planning (voice emission, etc.).

TABLE II. Net wind farm annual income in presence and absence of ESS

<table>
<thead>
<tr>
<th>Wind farm capacity (MW)</th>
<th>Net wind farm annual income in presence of ESS ($)</th>
<th>Net wind farm annual income in absence of ESS ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>26</td>
<td>31838357.16</td>
<td>31256061.17</td>
</tr>
<tr>
<td>28</td>
<td>32485863.31</td>
<td>32047204.48</td>
</tr>
<tr>
<td>30</td>
<td>32485973.53</td>
<td>32439906.72</td>
</tr>
</tbody>
</table>

Figure 4 shows the produced power distribution for different ranges of hourly energy cost in one year for 26MW wind farm capacity. As it is seen in this figure, using ESS in the wind farm has increased the injected power to the grid in peak load, when the energy cost is high. Also, the injected power is reduced during off-peak, when the energy price is low.

VI. CONCLUSION

In this paper, a new method for wind farm output management and optimum ESS capacity determination has been proposed. In this study, shifting energy from off-peak hour to peak hour and also reducing damped power in wind farm is the aim of ESS application in wind farm. As results show, by using optimal capacity of ESS in wind farms and accomplishing a perfect management on its output, a cost effective utilization of wind farm will be achieved while voltage margin constraint is satisfied. This proposed method can be useful in power system primary planning studies to determine wind farm capacity which will have the highest cost effective utilization. However, this method can be used in assigning optimum capacity of ESS in existing wind farms and managing output power.
REFERENCES


APPENDIX

NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{\text{ES}}$</td>
<td>Energy storage power.</td>
</tr>
<tr>
<td>$P_{\text{err}}$</td>
<td>Difference between Scheduled power and wind farm output.</td>
</tr>
<tr>
<td>$J_{\text{rated}}$</td>
<td>Rated power output capacity of energy storage system (kW).</td>
</tr>
<tr>
<td>$P_{\text{rated}}$</td>
<td>Energy storage system rated energy capacity.</td>
</tr>
<tr>
<td>$z$</td>
<td>Planning horizon (year).</td>
</tr>
<tr>
<td>$P_e$</td>
<td>Electrical active power.</td>
</tr>
<tr>
<td>$Q_e$</td>
<td>Electrical reactive power.</td>
</tr>
<tr>
<td>$P_m$</td>
<td>Mechanical power.</td>
</tr>
<tr>
<td>$\epsilon_t$</td>
<td>Energy price at hour t.</td>
</tr>
<tr>
<td>$V_t$</td>
<td>Wind speed during hour t.</td>
</tr>
<tr>
<td>$P_{\text{ES}}$</td>
<td>Energy storage system output during hour t.</td>
</tr>
<tr>
<td>$SOC_t$</td>
<td>Energy storage system state of charge during hour t.</td>
</tr>
<tr>
<td>$PG_t$</td>
<td>Injected power to the grid during hour t.</td>
</tr>
<tr>
<td>$PW(t)$</td>
<td>Wind farm generated power during hour t.</td>
</tr>
</tbody>
</table>