Abstract—High integration of renewable sources in power systems requires additional assets that can sustain reduced controllability and increased variability of these sources. Energy storage has emerged as a flexible asset that increases flexibility and ensures a more economic and secure power system operation. This paper integrates large-scale battery energy storage in power system under different levels of wind power penetration. As opposed to many models already available, we use the full AC model approach that accurately represents power system operation, but at a cost of high computational burden. The proposed model is applied to the IEEE 24-bus test case modeled in GAMS environment and solved with. The power system operation is simulated with and without battery energy storage to show its contribution to the reduction of power system operating costs.

Keywords: unit commitment, active and reactive optimal power flow, energy storage

I. INTRODUCTION

Unit commitment is a short-term decision-making problem, usually solved for the 24-hour time horizon [1]. It determines the generator commitment decisions and estimates their production levels at each hour while meeting the generator, system, network, and environmental constraints [2]. With the integration of renewable power sources into power systems, the operation of battery energy storage (BES) units is becoming more and more common [3]. Although there are different BES ownership models (see [4]), effects of BES on power system operation is best understood in typical unit commitment models, e.g. [5] and [6].

In this paper, we also assume a typical unit commitment problem, where the system operator is in charge of delivering electricity to its customers, as well as setting the operating points of generators and BES in the most cost-effective way. The objective function is the minimization of total system operating costs. Power system operation is represented using a rectangular representation of optimal power flow constraints, which is related to the full AC model [7].

Most research papers accommodate models that use the DC representation of power flows, which considers only active power flows and disregard network losses, to obtain convex solutions and shorter computation times. For instance, the authors in [5] propose a method for siting and sizing of energy storage in the highly renewable power system. The proposed approach consists of a three-stage planning procedure, where the optimal operation of new storage units is determined to alleviate congestion in the network and, consequently, reduce power system operating costs. It is concluded that the location and capacity of storage units is dependent on the distribution of wind resources and their level of penetration. Another use of DC power flow is demonstrated in [9], where a significant reduction of wind curtailment is obtained by introducing energy storage system in both the unit commitment and market clearing environment. Deterministic unit commitment model proposed in [10], also uses the DC representation of power flows and co-optimizes controllable conventional generators and energy storage units. The decrease in operating costs is obtained without distortion of the system reliability.

In general, in a renewable-dominant environment is considered, many models use a stochastic unit commitment model. The impact of significant uncertainties in both wind production and load are researched in [11]. Authors show that, by comparing the operating costs with the planned operation and the performance of the provided schedules, the stochastic optimization results in lower system operating costs. Also, they conclude that with a high value of wind production, the need for reserve is decreased. An important conclusion is that the peaking units’ operation and power flows on interconnections are significantly modified. A parallel implementation of the Lagrangian relaxation is presented in [12] to solve the stochastic unit commitment under a set of scenarios using two different approaches: i) narrowing the duality gap of the Lagrangian, and ii) increasing the number of scenarios in order to obtain a more efficient power system operation schedule. It is shown that the first tested approach yields comparable benefits to the one with an increased scenario set, in the case of a reliable scenario selection algorithm.

As opposed to [4]-[12], which use DC power flow representation, AC network models that consider both the active and reactive power flows are used in [13]-[18]. Full AC models cannot be easily applied to large networks. The
Authors in [15] examine the DC and the AC model with Benders decomposition. They conclude that switching from the DC representation to the AC should be accompanied with additional auxiliary constraints. The importance of balancing economic and security issues in restructured markets is discussed in [16]. The proposed model is a security-constrained unit commitment model with additional system constraints: time-limited emergency controls for a given contingency and fuel and emission limits. Moreover, to solve a non-convex mixed-integer nonlinear program, authors in [17] propose a solution technique that co-optimizes both active and reactive power scheduling and dispatch under the AC optimal power flow and unit commitment constraints. The proposed model can be extended to use security constraints.

II. METHODOLOGY

The following assumptions are considered: i) we assume an economic dispatch problem, where binary variables modeling the generator commitments are neglected; ii) as common in the literature, energy scheduling of energy storage and wind power units is made considering that they only provide active power. The proposed model is tested with and without energy storage units and its formulation includes active and reactive power flow constraints using real complex equations.

Unlike the DC formulation, the full AC formulation includes the voltage magnitudes, reactive power flows, and network losses. The proposed model uses a rectangular representation of the optimal power flow constraints and is based on model from [14]. For convenience, the notation used in this formulation is listed in appendix at the end of the paper.

\[
\begin{align*}
\text{Minimize} & \quad \sum_{t} \sum_{i} P_{g,t,i} \cdot o_{i,t} \cdot Z \\
\text{subject to:} & \quad \sum_{w \in M^n} P_{w,t,w} + \sum_{i \in M^n} P_{g,t,i} - \sum_{o(t) \in M^n} P_{t,o} + \sum_{d(t) \in M^n} P_{t,d} = PD_{t,n} \forall n \in \Omega^N, \forall t \in \Omega^T \\
& \quad \sum_{i \in M^n} Q_{g,t,i} - \sum_{o(t) \in M^n} Q_{t,o} + \sum_{d(t) \in M^n} Q_{t,d} = 0 \\
0 & \leq P_{g,t,i} \leq P_{g}^{\text{max}} \forall i \in \Omega^I, \forall t \in \Omega^T \\
Q_{g,t,i} - \kappa_{t,i} \cdot Q_{g,t,i}^\text{min} & \leq Q_{g,t,i} \leq Q_{g,t,i}^{\text{max}} + \kappa_{t,i} \cdot Q_{g,t,i}^{\text{max}} \forall i \in \Omega^I, \forall t \in \Omega^T \\
P_{t,o} = Y_i \left[ V_{t,n}^2 \cdot \cos \theta_{t,n} - V_{t,n} \cdot V_{t,m} \cdot \cos \theta_{t,m} - \theta_{t,m} - \theta_{t,n} \right] & \forall \{n,m\} \in \Omega^L, \forall t \in \Omega^T \\
Q_{t,o} = -Y_i \left[ V_{t,n}^2 \cdot \sin \theta_{t,n} - V_{t,n} \cdot V_{t,m} \cdot \sin \theta_{t,m} - \theta_{t,m} - \theta_{t,n} \right] & \forall \{n,m\} \in \Omega^L, \forall t \in \Omega^T \\
P_{t,l}^2 + Q_{t,l}^2 & \leq \left( S_{l}^{\text{max}} \right)^2 \forall l \in \Omega^L, \forall t \in \Omega^T \\
V_{t,n}^{\text{min}} - \kappa_{t,n} \cdot V_{t,n}^{\text{min}} & \leq V_{t,n} \leq V_{t,n}^{\text{max}} + \kappa_{t,n} \cdot V_{t,n}^{\text{max}} \forall n \in \Omega^N, \forall t \in \Omega^T \\
P_{g,t,i} - P_{g,t-1,i} & \leq RU_{t,i} \forall i \in \Omega^I, \forall t \in \Omega^T \\
P_{g,t,i} - P_{g,t-1,i} & \geq -RD_{t,i} \forall i \in \Omega^I, \forall t \in \Omega^T \\
\text{soc}_{t,I} = \text{soc}_{t-1,I} + p_{t,I}^{\text{ch}} \cdot \eta_{ch} - p_{t,I}^{\text{dis}} \cdot \eta_{dis} \forall s \in \Omega^S, t \in \Omega^T \end{align*}
\]

Equation (13) calculates the state of charge for the remaining time periods. The state of charge in the last hour should not be lower than the initial one, which is set by (14). Minimum and maximum limits on storage state of charge are imposed by constraint (15). Power charging and discharging limits are enforced by (16) and (17). Upper and lower limits on voltage angles are imposed by (18). Used wind power and wind power spillage are equal to the available wind power production in (19).

III. CASE STUDY

The proposed models are tested on a case study based on the IEEE 24-bus system test case [18]. The original system has been modified including 7 wind farms in the upper part of the power system, and two battery energy storage units at buses 15 and 19, as shown in Figure 1. Data for this case study are taken from [19]. All simulations are performed under GAMS 24.9.1 on a Linux-based server with 11 2.9-GHz processors and 250 GB of RAM. CONOPT solver is used for solving the full AC formulation without BES units and DICOPT for solving the full AC formulation with BES units. Load data (active and reactive power) used in this model are represented in the upper graph in Figure 2. Peak active load is 2,513 MW and it appears during the late afternoon in hours 18-19. Overall daily active energy consumption is 50 GWh, and reactive is 5 GVArh.
The lower graph in Figure 2 shows the wind production available in the considered day by each wind farm. This case is considered as wind factor $f = 1.0$. Total wind production is 49 GWh and is denoted as $P_{w_{\text{det},ini}}^t$. Wind speed data are available in [19]. Wind production is very high throughout the day, but varies across location. For example, wind farm $w_4$ produces at its maximum until hour 14, and then in the second part of day its production drops almost to 30% of its installed capacity. Wind farm $w_6$ produces almost 100% the first two hours and during hours 4-10 does not produce at all. After hour 10, the available wind output is around 50% of the installed capacity and at hours 23-24 it reaches the maximum production level. These two wind farm output examples show how much variability wind power can introduce in a power system.

In case when there is more available wind power than needed in the power system, a part of the wind power production is curtailed. In these cases the battery storage systems take their major role, as they store excess electricity and inject it back into the network when needed. This article analyzes how different wind factor levels (lower and higher than the power outputs in the lower graph of Figure 2) affect the total generation costs. Each BES unit has maximum state of charge 120 MWh and maximum charging/discharging power 40 MW. It is assumed that the energy efficiencies of both charging and discharging processes are 0.9.

### IV. RESULTS

Table I shows the total operating costs (TOC) under different wind penetration levels pertaining to factor $f$. In this manner, the available wind power production is computed as $P_{w_{\text{det},ini}}^t = f \cdot P_{w_{\text{det},ini}}^t$. With no wind in the system, TOC obtained using the full AC power flow formulation are the highest and amount to €713,741. Observe that the differences between TOC obtained in proposed model decreases as the wind power penetration increases. It should be noted that introducing BES decreases TOC in all cases. In case when there is no wind in the system, TOC are only slightly decreased, by 0.06%. For wind penetration factor $f$ of 0.5, TOC are reduced by 0.65%. TOC savings for wind penetration factor 1 are significantly higher, 4.33%. When increasing wind factor to 1.5, the proposed model has very low TOC, only €13,869 without BES with additional 19.11% savings with BES operation.

Figure 3 shows the overall wind curtailment for different wind power penetration factors. For factor 0.5, there is no wind spillage. However, for wind energy penetration factor 1.0 wind curtailment increases raises to 3,375 MWh without the BES devices and 3,155 MWh with BES in operation. The highest wind curtailment (23,221 MWh) is achieved for 1.5

### Table I

| Model  | Wind factor $f$ | TOC without BES (€) | TOC with BES (€) | TOC savings with BES (%)
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Full AC</td>
<td>0</td>
<td>713,741</td>
<td>713,294</td>
<td>0.06</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>275,003</td>
<td>273,230</td>
<td>0.65</td>
</tr>
<tr>
<td></td>
<td>1.5</td>
<td>48,135</td>
<td>46,049</td>
<td>4.33</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>13,869</td>
<td>11,218</td>
<td>19.11</td>
</tr>
</tbody>
</table>
wind penetration factor when there is no BES. Introduction of BES devices reduces slightly wind spillage by 2.89%.

Active power losses are shown in Table II. With increased wind generation, active power losses in the full AC model increase as well. The most noticeable difference in active power losses under different factors is the one between the state where there is no wind and under wind power factor of 0.5, where the active power losses are increased by 692 MWh. Introducing BES in the power system with no wind power results in 2 MWh reduced active power losses. For all the other wind factors, the active power losses are slightly increased after the introduction of BES.

![Fig. 3. Wind curtailment for different wind penetration factors](image)

**Fig. 3.** Wind curtailment for different wind penetration factors

<table>
<thead>
<tr>
<th>Time (h)</th>
<th>SOC (MWh)</th>
<th>Power ch/dis (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>336</td>
<td>1,030</td>
</tr>
<tr>
<td>1</td>
<td>1,766</td>
<td>1,774</td>
</tr>
<tr>
<td>1.5</td>
<td>1,804</td>
<td>1,809</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Wind factor</th>
<th>Active power losses without BES (MWh)</th>
<th>Active power losses with BES (MWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>338</td>
<td>336</td>
</tr>
<tr>
<td>1</td>
<td>1,030</td>
<td>1,041</td>
</tr>
<tr>
<td>1.5</td>
<td>1,766</td>
<td>1,774</td>
</tr>
<tr>
<td>2</td>
<td>1,804</td>
<td>1,809</td>
</tr>
</tbody>
</table>

**TABLE II**

**Total active power losses in the full AC model with and without BES for different levels of wind penetration**

To better understand the resulting total operation costs of the proposed model with BES operation and for wind penetration level equal to 1, generator committed statuses are shown in Figure 5. The most used generators are 22 and 23 at buses 18 and 21, respectively. These generators are nuclear and operate at the lowest cost. All generating units are started at hour 8. Referring to these results, it can be seen that high level of renewable power in the system results in few generating units in operation. The full AC model without BES has higher generation cost due to committed unit 12 in hours 9-10 with cost of 17.19 €/MWh, and unit 9 in hour 23 with cost of 17.59 €/MWh. BES unit replaces these generators units and decreases overall system operating costs.

Figure 6 shows voltage magnitudes at buses 15 and 19 and the differences in voltage levels with and without the BES in operation. The different voltage levels appear only during BES operation - compare to Figure 4. During the charging process of the BES unit in hours 1 and 2, voltage magnitude at bus 15 is slightly decreased, and while the BES is discharged in hours 3-4, voltage magnitude is higher. Again, the voltage is decreased due to charging of the BES in hours 5-7. In hours 9-10, the voltage magnitudes are closer to their nominal value (1 p.u.). There are no voltage magnitude differences in the second part of the day due to the BES inactivity in this period. Similar results are obtained for bus 19, where the other BES is installed. In general, voltage magnitudes at buses 15 and 19 are very close to their nominal value (1 p.u.).

**Execution times of the proposed model are listed in Table III. Generally, the formulation that includes BES operation**
requires more time due to additional binary variables that impose simultaneous charging and discharging. Execution time of the full AC model without the BES is 57.8 s and the number of variables is 8,789. This high number of variables is a result of additional constraints that calculate network losses across transmission lines and voltage levels. Introducing the BES units in the full AC model yields a mixed-integer nonlinear problem (MINLP) and execution time for DICOPT solver is much higher (252 s), while the number of variables is increased to 9,555.

V. CONCLUSION

This paper proposes and analyzes a formulation for the unit commitment problem considering battery energy storage under the full AC model. We compare its performance with and without the BES and for different factors of wind power penetration levels: 0, 0.5, 1, 1.5. The results show the following main conclusions:

1) By increasing the wind penetration level, TOC of the full AC model is decreased in comparison when there is no wind in the power system: from 61.47% under wind penetration factor 0.5, 93.25% under initial wind penetration factor, and 98.06% under wind penetration factor 1.5.

2) By introducing BES units into the power system, total wind curtailment is generally decreased. The voltage magnitudes are less variable and less dependent on the wind generation since energy storage evens out the copious and scarce wind generation. Also, the number of committed generators is decreased.

3) The full AC formulation requires lower execution time without BES units than the full AC formulation with BES units due to addition of binary variables in the model.

Finally, the formulated AC models contribute with more realistic solutions and provide better insight in the operation of a power system since they capture losses, voltage magnitudes and reactive power flows.

APPENDIX (NOMENCLATURE)

Sets and Indices

\[ i \in \Omega^I \] Index of thermal generator \( i \), belonging to set of thermal generators \( \Omega^I \).

\[ l \in \Omega^L \] Index of transmission line \( l \), belonging to set of transmission lines \( \Omega^L \).

\[ n \in \Omega^N \] Index of bus \( n \), belonging to set of network buses \( \Omega^N \).

\[ s \in \Omega^S \] Index of BES unit \( s \), belonging to set of BES units \( \Omega^S \).

\[ t \in \Omega^T \] Index of time period \( t \), belonging to set of periods \( \Omega^T \).

\[ w \in \Omega^W \] Index of wind farm \( w \), belonging to set of wind farms \( \Omega^W \).

Parameters:

\[ b_l \] Series susceptance of transmission line \( l \) (S).

\[ c_{\text{ch}}^{\text{max}} \] Maximum charging power of BES unit \( s \) (MW).

\[ d_{\text{dis}}^{\text{max}} \] Maximum discharging power of BES unit \( s \) (MW).

\[ o_i \] Generating cost of thermal generator \( i \) (€/MWh).

\[ P_{D,n}^t \] Active power demand at bus \( n \) in period \( t \) (MW).

\[ P_{g_i}^{\text{max}} \] Maximum active power output of thermal generator \( i \) (MW).

\[ P_{w_{\text{det}}^t}^w \] Maximum power output of wind farm \( w \) under wind factor \( f \) (MW).

\[ P_{w_{\text{det},i}^{\text{ini}}}^w \] Maximum power output of wind farm \( w \) under the initial factor 1 (MW).

\[ Q_{D,n}^t \] Reactive power demand at bus \( n \) in period \( t \) (MVAr).

\[ Q_{g_i}^{\text{max}} \] Maximum reactive power output of thermal generator \( i \) (MVAr).

\[ Q_{D,i}^{\text{ini}} \] Minimum reactive power output of thermal generator \( i \) (MVAr).

\[ R_{D,i} \] Maximum ramp down of thermal generator \( i \) (MW/h).

\[ R_{U,i}^{\text{max}} \] Maximum ramp up of thermal generator \( i \) (MW/h).

\[ S_{\text{max}}^l \] Maximum power rating of transmission line \( l \) (MVA).

\[ \text{soc}^{\text{ini}}_{i,s} \] Initial value of state of charge of BES unit \( u \) (MWh).

\[ \text{soc}^{\text{max}}_{i,s} \] Maximum state of charge of BES unit \( u \) (MWh).

\[ V_{\text{max}}^n \] Maximum voltage magnitude at bus \( n \) (p.u.).

\[ V_{\text{min}}^n \] Minimum voltage magnitude at bus \( n \) (p.u.).

\[ Y_l \] Admittance of transmission line \( l \) (S).

\[ \theta_l \] Nominal value that converts from p.u.

\[ \theta_{\text{dis}}^{\text{max}} \] Maximum allowed voltage angle (rad).

\( \eta_{\text{ch}} \) Efficiency of charging BES unit \( s \) (-).

\( \eta_{\text{dis}} \) Efficiency of discharging BES unit \( s \) (-).

<table>
<thead>
<tr>
<th>Model</th>
<th>Time (s)</th>
<th>Number of continuous and binary variables</th>
<th>Time (s)</th>
<th>Number of continuous and binary variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full AC</td>
<td>57.8</td>
<td>8,789</td>
<td>252.01</td>
<td>9,555</td>
</tr>
</tbody>
</table>
variables:

\[ P_{t,l} \] Active power through transmission line \( l \) in period \( t \) (MW).

\[ p_{t,s}^{ch} \] Charging power of BES unit \( s \) in period \( t \) (MW).

\[ p_{t,s}^{dis} \] Discharging power of BES unit \( s \) in period \( t \) (MW).

\[ P_{g,t,i} \] Active power output of thermal generator \( i \) in period \( t \) (MW).

\[ P_{w,t,w} \] Power output of wind farm \( w \) in period \( t \) (MW).

\[ Q_{t,t} \] Reactive power through transmission line \( l \) in period \( t \) (MVAr).

\[ Q_{g,t,i} \] Reactive power output of thermal generator \( i \) in period \( t \) (MVAr).

\[ s_{Q,t,s} \] State of charge of BES unit \( s \) in period \( t \) (MWh).

\[ V_{t,n} \] Voltage magnitude at bus \( n \) in period \( t \) (rad).

\[ w_{t,w} \] Wind spillage of wind farm \( w \) in period \( t \) (MWh).

\[ Q_{t,max} \] Slack variable ensuring feasibility of constraint on maximum reactive power output of thermal generator \( i \) in period \( t \) (MVAr).

\[ Q_{t,min} \] Slack variable ensuring feasibility of constraint on minimum reactive power output of thermal generator \( i \) in period \( t \) (MVAr).

\[ V_{t,max} \] Slack variable helping in ensuring feasibility of constraint on maximum voltage magnitude at bus \( n \) in period \( t \) (rad).

\[ V_{t,min} \] Slack variable helping in ensuring feasibility of constraint on minimum voltage magnitude at bus \( n \) in period \( t \) (rad).

\[ \theta_{t,n} \] Voltage angle at bus \( n \) in period \( t \) (rad).

Binary variable:

\[ x_{t,s}^{ch} \] Binary variable equal to 1 when BES unit \( s \) is being charged during time period \( t \), and 0 otherwise.

References:


