Scheduling of Energy Storage Transportation in Power System Using Benders Decomposition Approach

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Abstract—Two most important challenges for Independent System Operator (ISO) are system security and reliability in deregulated power system. Grid integrated Battery-Based Energy Storage Transportation (BEST) can be utilized by ISO to compensate these issues. BEST can act as load as well as source and needs to be modeled adequately in Security Constrained Unit Commitment (SCUC) formulation with adequate reserve constraint to gain the reliable performance. In this regard this paper proposes a SCUC scheduling with BEST considering N-1 contingency is performed in DC network security assessment. Due to consideration of network security constraints the proposed model is computational demanding and necessitates computational fast approach to optimize generation and vehicle routing problem (VRP) schedule. Therefore, proposed model is solved by Benders Decomposition (BD) method which reduces computational time. Modified IEEE 30-bus system is considered as numerical case study. In addition comparative analysis explores the impact of overall operational costs; transportation costs; and locational marginal price.

IndeTerms—Security-constrained unit commitment, benders decomposition, battery based energy storage transportation, vehicle routing problem.

I. INTRODUCTION

Power system industry is facing enormous challenges due to predominant change in the energy sources from fossil fuel to renewables in a sustainable manner. Additionally, wind farm locations in the remote geographical areas with limited network capability often cause transmission congestion during high wind and low demand hours [1]. To alleviate such conditions, energy storages are being used to absorb surplus wind power, which is further necessitated to be transmitted to deficit zones. Energy Storages Technology primarily consists of mechanical storages worldwide which suffer from locational constraints making them unfit them for power grid integrations [2]. Battery Based Energy Storage (BESS) offers a pollution free, overload discharge time, high efficiency, and fulfill growing energy demand in a sustainable manner [3-4]. They can be suitably used in the power grid as major source of electricity transmission in the form of battery source of Electric Vehicle (EV), Battery Energy Storage Transport (BEST), and ships etc. Optimal and coordinated scheduling of charging and discharging of their battery can alleviate network congestion thus rendering grid stability under economical renewable energy sources flexibility [5]. They also assist in load shifting and peak shaving [6]. These BESS, due to their operation as a source and a load, must be considered by ISO in Security Constrained Unit Commitment (SCUC) formulation for their economic scheduling along with committed generators with an aim to minimize overall costs while subjected to network constraints considering security and reliability. Fast SCUC model with BESS offers considerably recognized approach and alleviate network congestion to a certain extent in [7-8]. BESS approach in vehicles to grid (V2G) and the effect of its mobile applications with electric grid economics are deliberated comprehensively in [9-11]. [9], [10] study the effect of EV on thermal generating units in SCUC model using MIP method. SCUC model with EV in [11] shows that the BESS mobility can decrease congestion and lower operation cost. However, the fast charging and discharging may deteriorate the battery life early and needs further research in this direction. Also, the large density battery technology of BEST is economically beneficial as compared to other BESS [12]. The route plan and battery capacity of BEST is fixed and known to the ISO beforehand. Hence, its usage to assist renewable energy integration is suitable. BEST solution for transmission of electricity via rail in the form of storage is sensible and quite economical to alleviate transmission congestion and decrease of operational costs.

In this work, the integration of BEST technology provides hourly charging/discharging and locational schedule in the SCUC model. The proposed model would also present the vehicle routing problem (VRP) as an optimization problem [13] with time window (VRPTW) [14-15]. Additionally hourly SCUC solution must satisfy network transportation constraints. Although the SCUC model with BEST is profitable, reduction in computational burden considering network constraints is necessary. The approximation of DC-OPF is used as a simplification considering a linear programming (LP) single sprint problem [16]. In several literatures, DC-OPF model excluding network security constraints has been used to evaluate LMPs for practical power systems, due to its speed and simplicity [17]. The SCUC considering large wind integration and BEST is solved without considering network contingency [18]. The proposed work models N-1 contingency criteria to ensure system security as in [19]. On N-1 contingency criterion, ISO states successive cost of three components with a maximum time
period of variation. A ranking of generation cost based on N-1 contingency analysis with DC power flow solution is presented in [20]. However, the complexity of SCUC problem increases manifold with the inclusion of BEST and N-1 contingency criteria for large-scale systems. Thus, Bender decomposition (BD) approach [21] has been used to solve DC-SCUC scheduling considering Time space network (TSN) based BEST model [22]. The key contributions of proposed work are summarized as follows:

a) Propose a novel and computationally fast SCUC model with integrated TSN based BEST formulation considering transportation and DC network security constraints.

b) Incorporating N-1 contingency criteria based network constraints in DCOPF framework. Moreover, proposed model investigates the impact of SCUC on operational cost, LMP, commitment and dispatch of the generator.

The organization of the remaining paper is as follows: mathematical modeling of SCUC with BEST which is describes in Section II; Section III illustrates the methodology of SCUC framework; Case studies are discussed in Section IV; Finally Section V discussed the appropriate conclusions.

II. PROBLEM FORMULATION OF SCUC WITH BEST

The SCUC model considering BEST synchronized through DC network security to determine LMP at each hour, hourly charging and discharging schedule of BEST. Novel SCUC model has been amended to include transmission and network security constraints.

A. Objective function

Objective function (1) is formulated to minimize SCUC and BEST costs subject to generator, emission, transmission line and storage constraints. It consists of two expressions in objective function; first expression includes grid operational cost of fuel, start-up and shutdown costs. While second expression minimize loss of load and transportation costs [18]

$$
\text{min} \sum_{g \in G} \sum_{t \in T} \left[ FSC_{g} \left( P_{g,t} \right) U_{g,t} + STC_{g,t} + SDT_{g,t} \right] + \sum_{b \in B} VOLL \times LS_{b} + \sum_{k \in K} \sum_{s \in S} C_{ij,k} U_{ij,s,k} \tag{1}
$$

In Eqs. (1), $P_{g,t}$ specify real power generation of unit $g$ at time $t$, $G$ indicates set of generator units, where $g$ is index of units, $T$ indicates set of time period, where $t$ is index of time similarly $B$ indicates set of bus, where $b$ is index of bus, $U_{g,t}$ is the on/off status of unit $g$ at time $t$ and $Z_{ij,k,s}$ is the arc $ij$ status of BEST $k$ for time span $s$. First expression states that fuel cost $FSC_{g} \left( P_{g,t} \right)$, shut-down costs $STC_{g,t}$, start-up costs $SDT_{g,t}$, of units. While second expression states that loss of load cost VOLL with load shedding $LS_{b}$ at bus $b$ incorporated and $C_{ij,k}$ specifies transportation cost of arc $ij$ on BEST $k$. Analysis of the above Eqs.(1), the power grid constraints are incorporated as:

System Power Grid Constraints

$$
\sum_{g \in G} P_{g,t} - \sum_{k \in K} \sum_{b \in B} P_{b,k,t} = PD_{t}, \quad \forall t \tag{2}
$$

$$
\sum_{g \in G} SR_{g,t} + \sum_{k \in K} \sum_{b \in B} SR_{b,k,t} \geq RS_{t}, \quad \forall t \tag{3}
$$

Where, $PD_{t}$ and $RS_{t}$ indicates hourly demand and spinning reserve at time $t$. Whereas, $P_{b,k,t}$ and $SR_{b,k,t}$ denote injected power and spinning reserve of BEST $k$ at bus $b$ for time $t$. Eqs. (2) and (3) signifies that power balance and reserve constraints. Here some additional constraints are included in SCUC model as follows:

Limits of Generating Units

$$
P_{g,t} U_{g,t} \leq \bar{P}_{g,t}, \quad \forall g, \forall t \tag{4}
$$

Minimum up and down times

$$
\sum_{t \in U_{t}} \left( 1 - U_{g,t} \right) = 0, \quad \forall g, \forall t \tag{5a}
$$

$$
\sum_{t \in U_{t} + \text{MUT}^{on}_{t} - 1} U_{g,t} \geq \text{MUT}^{on}_{g} \chi_{g,t}, \quad \forall t \tag{5b}
$$

$$
\sum_{t \in D_{t}} \left( U_{g,t} - \chi_{g,t} \right) \geq 0, \quad \forall t = T - \text{MUT}^{on}_{g} + 1
$$

$$
\sum_{t \in U_{t}} U_{g,t} = 0, \quad \forall g, \forall t \tag{6a}
$$

$$
\sum_{t \in U_{t} + \text{MUT}^{off}_{t} - 1} \left( 1 - U_{g,t} \right) \geq \text{MUT}^{off}_{g} \chi_{g,t}, \quad \forall t \tag{6b}
$$

$$
\sum_{t \in U_{t}} \left( 1 - U_{g,t} - \gamma_{g,t} \right) \geq 0, \quad \forall t = T - \text{MUT}^{off}_{g} + 1
$$

Ramp up and down constraint

$$
P_{g,t} - P_{g,t-1} \leq UR_{g} \left( 1 - \chi_{g,t} \right) + P_{g,t} \chi_{g,t}, \quad \forall g, \forall t \tag{7}
$$

$$
P_{g,t-1} - P_{g,t} \leq DR_{g} \left( 1 - \gamma_{g,t} \right) + P_{g,t} \gamma_{g,t}, \quad \forall g, \forall t \tag{8}
$$

Fuel and Emission constraints

$$
F_{FT} \leq \sum_{t \in T} \sum_{g \in G} \left[ FSC_{g}^{f} \left( P_{g,t} \right) U_{g,t} + \text{STC}^{f}_{g,t} + \text{SDT}^{f}_{g,t} \right] \leq F_{FT} \tag{9}
$$

$$
\sum_{t \in T} \sum_{g \in G} \left[ FSC_{g}^{e} \left( P_{g,t} \right) U_{g,t} + \text{STC}^{e}_{g,t} + \text{SDT}^{e}_{g,t} \right] \leq E_{e} \tag{10}
$$

Where $UR_{g}$, $DR_{g}$, $\bar{P}_{g}$, $\text{MUT}^{on}_{g}$, $\text{MUT}^{off}_{g}$ illustrates ramp up and down limit, maximum and minimum real power generating units $g$, minimum up and down time generating units $g$. Likewise, $FSC_{g}^{f} \left( P_{g,t} \right)$ and $FSC_{g}^{e} \left( P_{g,t} \right)$ illustrates fuel emission and consumption function of unit $g$.

B. Network Constraints

The determination of the SCUC model is to regulate the value of bus voltage, and line contingency at each node. However, optimal capacity at each bus necessities to
recognized the earlier examined matters are alleviated. Network constraints are mentioned as follows:

Security constraints
\[-F_{\text{L}_{i,j}}^{\text{max}} \leq F_{\text{L}_{i,j}} \leq F_{\text{L}_{i,j}}^{\text{max}}\] (11)

DC power flow constraints
\[F_{\text{L}_{i,j}} = \delta_{j,t} - \delta_{i,t} X_{i,j}\] (12)

Constraints (11) and (12), \(F_{\text{L}_{i,j}}\) represent line flow at bus \(j\) and \(i\) at time \(t\). Where, \(X_{i,j}\) represent inductance of line connecting bus \(i\) and \(j\). Moreover, \(\delta\) and \(F_{\text{L}_{i,j}}^{\text{max}}\) are representing bus angle, maximum line flow at bus \(i\) and \(j\) correspondingly.

C. BEST Model

Integrated SCUC considering BEST model regulate the location and determine schedule of BEST charging and discharging. Due to limit of storage resources, the additional constraints are essential for BEST model which provide hourly SCUC solution [14]. A TSN-based proposed model is used to solve VRPTW subproblem subject to network transportation system [15]. However, proposed optimizations modeled are represented in Equation (13-20).

\[\sum_{i,j \in N_{s}} U_{i,j,k,s} = 1, \forall k, \forall s \] (13)

\[\sum_{i,j \in N_{s}} U_{i,j,k,s+1} = \sum_{i,j \in N_{s}} U_{i,j,k,s}, \forall s = 1,\ldots,S-1, \forall k, \forall i\] (14)

\[\sum_{i,j \in N_{s}} U_{i,j,k,1} = U_{i,k,0}, \forall k, \forall i\] (15)

\[\sum_{i,j \in N_{s}} U_{i,j,k,MS} = U_{i,k,MS}, \forall k, \forall i\] (16)

\[U_{k,ij,s} P_{b,k} \leq U_{k,ij,s} T_{b,k}, \forall s, \forall k, \forall i\] (17)

\[E_{k} \leq E_{k,t} \leq E_{k}, \forall t, \forall k\] (18)

\[E_{k,t} = E_{k,t-1} + \sum_{b \in B} P_{b,k,t}, \forall k, \forall t\] (19)

\[E_{k,t} = E_{k,MS} - t = MS, \forall k\] (20)

Here, \(ij\) indicates arcs index in TSN form station \(j\) to \(i\), \(N_{s}\) is the sets of arc in TSN on single time span, \(N_{s}', N_{s}''\) represent sets of arc in TSN were start and end at station \(i\). In Equation (13) signifies BEST constraint in which individual BEST \(k\) contains single arcs in time span \(s\). Connection BEST model specify in Equation (14-16). In (14), all BEST \(k\) in station \(i\) in the TSN at the ending of span time \(s\) in bus \((s,i)\) must be equal to next time span \(s+1\), which start from bus \((s,i)\). In (15), for single time span 1, the initial state of BEST \(k\) equal to outflow of each station, whereas (16), indicates final time span MS, in which terminal station of BEST \(k\) equal to inflow of each station. In (17) represent BEST discharging/charging grid constraints. Finally Equation (18-20) represents BEST energy capacity, balance and terminal capacity constraints. Where \(U_{ij,k,0}, U_{ij,k,MS}, P_{b,k}, P_{b}, E_{k}, E_{k}\) indicates initial and terminal state, minimum/maximum power exchange rate and energy capacity of BEST \(k\). Similarly \(E_{k,t}\) and \(E_{k,MS}\) represent initial/terminal energy stored of BEST \(k\).

III. PROPOSED ALGORITHM

In this case, the proposed algorithm has been explained and deliberated for optimal SCUC including integrating BEST model considering integrated transportation and DC network constraints. The explanation of proposed mathematical model which is elaborated in Section II; benders decomposition is the appropriate way to check this model. BD concert be relevant to decrupt such SCUC model into master problem resolve UC and ED. Figure 1 shows the transportation and network security check problem. Comprehensive conversation schedule is obtained using BD [21]. After the solution of master problem (SCUC), ISO verifies the node locations where the battery charging/discharging for each hour. However the solution becomes infeasible when considering network and transportation constraints in the subproblem.

If there any transmission violation emerge on several subproblem results, benders cuts would be formed and added to the (SCUC) master problem in subsequent maximum iterations of SCUC. However, the iteration among the SCUC and BEST model with network security subproblem can be decoupled and solved separately till no more violation produce in VRP.

IV. SIMULATION RESULTS

The proposed method used a modified IEEE 30-bus system for simulation is used to implement BEST model in the form of railway track which are connected at node locations as shown in Fig.2. There are nine thermal units, five railway station (at nodes 1, 26, 30, 15, 17) and forty one transmission lines. Generator, bus and transmission line data are provided in [23]. Optimization of SCUC model in GAMS 24.2.3 [24],
and solved by CPLEX 12.6.0, MIP solver an Intel core i5 on a PC, 4 GB RAM and 3.20 GHz CPU. Assuming travel time trip connecting two railway stations will capture 3 hour, so that the span time is set as a 3 hour. Fig.3 shows that the forecasted load profile data, where BEST signify eight cars and one locomotive with a total power and energy in this case are 50 MW and 140 MWh respectively. Different test cases, are considered to illustrate SCUC model on modified IEEE 30-bus system as follows: I) SCUC without BEST II) Hourly SCUC including BEST and network constraints. III) Effect of SCUC on line contingency.

Case 1: SCUC without BEST (base case)
In case 1, SCUC is explained with MIP method for base case. The proposed model solved only the (SCUC) master problem. Correspondingly the SCUC problem considering all thermal units from Eqs.(1-12), is satisfied. However without BEST and security operating constraints, the SCUC problem confirm the commitment and dispatch of units states, and the total power and energy in this case.

Case 2: Hourly SCUC with BEST
In this case, extra differences are experimental in commitment results and power line flows are discussed in this section. VOLL is set to be 1000 $/MWh. For every trip linking 2 stations the transportation cost is $320. In this case two situations are evaluated:

1) Situation 1: BEST system with starting station for node 1
2) Situation 2: BEST system with starting station for node 1 and 30.

| Table I: SCUC status of IEEE-30 bus system without BEST |
|---------------------------------|-----------------|
| Total costs = $86421.87         |                 |

<table>
<thead>
<tr>
<th>Region Bus</th>
<th>Hours (1-24)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td></td>
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<tr>
<td>30</td>
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<td>11</td>
<td>1 1 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0</td>
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<td>20</td>
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<td>19</td>
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<td>1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0</td>
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</tbody>
</table>

In Case 2 for situation 1 the total costs including BEST and network security is $83214.98 which is $3206.89 less than Case 1, whereas computational time ~189.76(s) is more than the previous case. Charging/discharging outline of BEST gives for scenario 1 in Fig. 4. BEST status shows in Table II. Two time span (0-6) h, the BEST schedule from station 1 during station 26 to station 30. Then after charging for next two span (6-12) h by travelling to station 15 at time span 5 (12-15) h. After discharging time span (15-18) h, BEST returns back in the last two time span (18-24) h by travelling to station 15-7-1. For situation 2 represent two starting station BEST 1 at node 1 and BEST 2 at node 30 respectively. The total costs in this case $83201.52 which is $3220.35 less than the Case 1 and computational requirement 223.41(s) more than the previous case. Charging/discharging outline of BEST 1 and BEST 2 are shown in Fig. 5 and Fig.6. Table III shows the status of BEST route. The status of BEST 1 is similar to the scenario 1 status but the power exchange is somewhat dissimilar. Moreover considering DC network constraints, the additional cheap units of BEST 1 would not offer the demand at peak hour (6-9) time span and transportation costs are costly unit in this case. BEST 2 travels first two span (0-6) h from station 30-26-1, however there are different number of time which power exchange from the grid: 1) charging from (6-9) h; 2) transporting from (9-12) h; 3) discharging from (12-15) h; 4) again charging from (18-21) h. This is because due to low demand in this system. BEST 2 travels continue from station 15 where it is charged at (18-21) h, and lastly back to the starting station at the end time span (21-24) h.

Case 3: Effect of hourly SCUC including line contingency
In Table IV shows that the ranking select on line outages 23-24, which is highly critical contingency to illustrate the unique significance on the production values, and transportation cost to obtain the railway network. Region B, units G13 was obliged to take the absent line of phase because adding line residual at point particular resources at G15 is incapable to deliver the area excluding violations. Moreover at 1 to 16 h, all units are committed. However, DCOPF framework is used to simulate the transmission flow limits and transportation network (VRPTW) which are satisfied. Contingency which proves to be incredibly costly and the total cost including DC network security with VRPTW out to be $89671.36.
TABLE II SCUC status of IEEE-30 bus system with BEST in Case 2 (Scenario 1)

<table>
<thead>
<tr>
<th>Time span (0-24)</th>
<th>0-3</th>
<th>3-6</th>
<th>6-9</th>
<th>9-12</th>
<th>12-15</th>
<th>15-18</th>
<th>18-21</th>
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<tr>
<td>Location of BEST</td>
<td>1-26</td>
<td>26-30</td>
<td>30-30</td>
<td>30-30</td>
<td>30-15</td>
<td>15-15</td>
<td>15-7</td>
<td>7-1</td>
</tr>
<tr>
<td>Status of BEST</td>
<td>Tr</td>
<td>Tr</td>
<td>Ch</td>
<td>Ch</td>
<td>Tr</td>
<td>Dch</td>
<td>Tr</td>
<td>Tr</td>
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</tbody>
</table>

*Tr= Transporting; *Ch= Charging; *Dch= Discharging

TABLE III SCUC status of IEEE-30 bus system with BEST in Case 2 (Scenario 2)

<table>
<thead>
<tr>
<th>Time span (0-24)</th>
<th>0-3</th>
<th>3-6</th>
<th>6-9</th>
<th>9-12</th>
<th>12-15</th>
<th>15-18</th>
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<tr>
<td>Location of BEST 1</td>
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<td>26-30</td>
<td>30-30</td>
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<td>15-15</td>
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<td>7-1</td>
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<tr>
<td>Status of BEST</td>
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<td>Tr</td>
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<td>Ch</td>
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<td>Dch</td>
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<tr>
<td>Location of BEST 2</td>
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<td>1-1</td>
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</table>

Integration of the loss of line 23-24 outage happens to be expensive $3249.49 that is ~ 3.76% larger than above Case 1. The computational time in this Case 289.65 (s) is more as compared to other cases.

Impact of hourly LMP on SCUC with BEST

Fig.7, indicates that the LMPs at each hour for five railway station. In this case, LMPs is used to integrate the summation of cost of losses and marginal cost, and transmission congestion cost. When congestion occurs on transmission line at branch 6-28 and 1-2 have low LMP at node 1 and 26 during peak hour 12. However, node 1 has the lowest LMPs value is equivalent to 43.32 $/MWh as compared to all 4 nodes.

The transportation (VRPTW) is economical units and may be additionally scheduled and dispatched in experience to persuade the demand at each bus. The additional schedule would be essential in this case while effortless generating
units did not be completely utilized, due to congestion occurs at node 7 has highest LMPs value 74.46 $/MWh during peak hour 12, and require transportation network constraints of expensive units, to satisfy the load. However, node 15 and 7 LMP changes more significantly when BEST located near load. The decrease in LMP will affect the costs of supply demand at consequent nodes. It has been observed that including transportation (VRPTW) and network constraints increases congestion cost as well as LMP at 24 hour extensively.

V. CONCLUSIONS AND FUTURE WORK

This paper proposes a computationally efficient SCUC framework with integrated BEST model considering DC network constraints and solved using BD approach. Proposed model is simulated on modified IEEE-30 bus system. The evaluation of the proposed approach has been done on the basis of system operating cost, transportation cost, commitment and dispatch of the thermal units and load leveling. BEST incorporatated power system charging/discharging scheduling manages load leveling by avoiding the charging on peak hours. The proposed model also lowers operational costs for both the cases of with and without network security constraints. Further, the proposed model can be possibly extended to explore the effect of BEST with renewable integration.

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