Energy Storage Planning for Resiliency enhancement against Renewable Energy Curtailment

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Abstract

The optimal allocation and sizing of energy storage systems in transmission networks is investigated in this paper. The objective function is defined as total operation and investment costs which should be minimized subject to technical constraints. The proposed model is tested on IEEE RTS 24 bus to justify its applicability and strength.

1 Introduction

The penetration level of solar/wind energy resources has been increasing in the last decade. Enhancing the grid flexibility to host these technologies would be essential. The traditional solution to this problem is making new transmission lines. However, obtaining the public acceptance for building new transmission lines as well as the environmental concerns have made non-wire solutions more appealing. The candid solution should be able to answer the needs of transmission network in normal and contingency situations. In other words, the transmission network should be resilient against variability of renewable energy resources in normal and contingency cases.

The energy storage systems can be very effective in resiliency enhancement against the energy curtailment. These curtailment can be because of several issues such as network constraints, generation constraints, uncertainty of renewable energies and etc. This paper investigates the role of Energy storage systems (ESS) in reducing the renewable energy curtailment at transmission level. The proposed approach is implemented on the IEEE 24-bus system to demonstrate its applicability. The conclusions drawn from this work are listed as follows:

- The proposed MILP formulation finds the optimal location and size of energy storage units to reduce the total operating costs and renewable energy curtailments.
- The proposed framework is a MILP model and can be used in large scale transmission networks.
- The uncertainty of wind/solar power generation will be investigated to make the proposed model closer to reality.

- The proposed framework determines the on/off states of generating units while the unit commitment constraints are taken into account.

2 Problem formulation

The optimal ESS allocation and sizing for solar/wind energy curtailment is formulated as follows:

\[-\bar{P}_{ij}^{\text{max}} \leq P_{ij,t} = \frac{\Delta t - \sum_{t}^{\text{SOC}}}{\Delta t} \leq \bar{P}_{ij}^{\text{max}} \]  (1)

This equation calculates the flow of power on line connecting the bus i to bus j at time t.

\[\bar{P}_{g}^{\text{dch}} + \bar{P}_{g}^{\text{dch}} - \bar{P}_{g}^{\text{dch}} + \bar{P}_{g}^{\text{dch}} = \sum_{t}^{\text{SOC}} P_{f,i,t} + P_{f,j,t} - \bar{P}_{f,i,j,t} \]  (2)

This will ensure the nodal generation-demand balance in bus i at time t.

\[\text{SOC}_{i,t} = \text{SOC}_{i,t-1} - \left(\frac{\bar{P}_{\text{dch}}^{\text{g}}}{\bar{P}_{\text{dch}}^{\text{g}}} - \eta_{\text{dch}} P_{g}^{\text{ch}}\right) \Delta t \]  (4)

Equation (3) states the relation between state of charge and charging/discharging power in ESS.

\[\text{SOC}_{i,t} \leq U_{t} \text{Cap} \]  (7)

\[\bar{P}_{\text{dch}}^{\text{g}} \leq \text{SOC}_{i,t} \]  (8)

\[\bar{P}_{\text{dch}}^{\text{g}} \leq \text{SOC}_{i,t} \]  (9)

\[\bar{P}_{\text{dch}}^{\text{g}} \leq L_{t} M \times \text{Cap} \]  (10)

\[\sum_{i}^{1} U_{i} \leq N_{\text{ESS}} \]  (12)

The integer variable \(U_{i}\) in equation (7) indicates that how many blocks of ESS should be installed in bus i. Equation (10) and (11) indicate that at any time step the ESS can be in charging or discharging mode (not both simultaneously).

The availability of wind and solar resources as well as the curtailments are modelled as follows:

\[0 \leq P_{w,t} \leq \bar{P}_{w,t} \]  (13)

\[P_{w,t} \leq P_{w,t}^{\text{max}} \]  (14)

\[0 \leq P_{w,t} \leq \bar{P}_{w,t}^{\text{min}} \]  (15)

\[P_{w,t} \geq \bar{P}_{w,t}^{\text{min}} - P_{w,t}^{\text{max}} \]  (16)

\[OF = \gamma \left[\sum_{t}^{T} \alpha(P_{w,t}^{\text{max}} + P_{w,t}^{\text{min}}) + \sum_{t}^{T} b_{t} P_{g,t}^{\text{dch}}\right] + \sum_{t}^{T} \theta_{t} U_{i} \text{Cap} \]  (17)

The objective function is minimized using a set of decision variables (DV):

\[DV = \{P_{w,t}^{\text{dch}}, P_{w,t}^{\text{dch}}, P_{w,t}^{\text{dch}}, \text{SOC}_{i,t}, P_{i,t}^{\text{dch/dch}}, P_{g,t}^{\text{dch}}, \theta_{t}, U_{i} \text{, } i \text{, } t \} \]
3 Simulation results

The proposed model is applied to IEEE RTS 24 bus system [1]. It is shown in Figure 1. The proposed model is coded in GAMS environment and solved using CPLEX solver [2]. It is assumed that the investment cost ($\theta$) for ESS is $0.5\text{Million/MWh}$. The interest rate ($r$) is assumed to be 5% and the investment costs are capitalized over the life time of the asset (which is assumed to be 30 years) using the following formula: $r(1+r)^n \over (1+r)^n+1$. The curtailment penalty is assumed to be $50/\text{MWh}$.

![IEEE network under study and the connection buses of solar and wind power](image)

**Figure 1** IEEE network under study and the connection buses of solar and wind power

The wind – solar and demand variation pattern are given in Figure 2

![Demand, wind and solar power variation vs time](image)

**Figure 2** Demand, wind and solar power variation vs time

The connection nodes as well as the capacities of wind and solar power plants are indicated in Table 1.

| Bus | Wind capacity (MW) | Bus | Solar capacity (MW) |
|-----|-------------------|-----|---------------------|
| 1   | 200               | 6   | 400                 |
| 3   | 200               | 18  | 200                 |
| 9   | 200               | 13  | 400                 |
| 24  | 200               |     |                     |

**Table 1** RES capacities and connection points

For sake of comparison, two studies have been performed. The first one is solving the problem without considering the ESS option and the second one is taking into account the ESS flexibility.

![Characteristics of thermal generating units](image)

| Unit | Bus | $b_i$ | $p_{g,min}$ | $p_{g,max}$ | $RD_{g}$ | $RU_{g}$ |
|------|-----|-------|-------------|-------------|----------|----------|
| Gen1 | 1   | 130   | 16          | 20          | 15       | 15       |
| Gen2 | 1   | 130   | 16          | 20          | 15       | 15       |
| Gen3 | 1   | 16.0811 | 15.2       | 76          | 15       | 15       |
| Gen4 | 1   | 16.0811 | 15.2       | 76          | 150      | 150      |
| Gen5 | 2   | 130   | 16          | 20          | 150      | 150      |
| Gen6 | 2   | 130   | 16          | 20          | 15       | 15       |
| Gen7 | 2   | 16.0811 | 15.2       | 76          | 50       | 50       |
| Gen8 | 2   | 16.0811 | 15.2       | 76          | 15       | 15       |
| Gen9 | 7   | 43.6615 | 25         | 100         | 15       | 15       |
| Gen10| 7   | 43.6615 | 25         | 100         | 150      | 150      |
| Gen11| 7   | 43.6615 | 25         | 100         | 175      | 175      |
| Gen12| 13  | 48.5804 | 69         | 197         | 15       | 15       |
| Gen13| 13  | 48.5804 | 69         | 197         | 15       | 15       |
| Gen14| 13  | 48.5804 | 69         | 197         | 50       | 50       |
| Gen15| 14  | 0     | 0           | 0           | 15       | 15       |
| Gen16| 15  | 56.564 | 2.4         | 12          | 50       | 50       |
| Gen17| 15  | 56.564 | 2.4         | 12          | 15       | 15       |
| Gen18| 15  | 56.564 | 2.4         | 12          | 15       | 15       |
| Gen19| 15  | 56.564 | 2.4         | 12          | 50       | 50       |
| Gen20| 15  | 56.564 | 2.4         | 12          | 125      | 125      |
| Gen21| 15  | 12.3883 | 54.3      | 155         | 125      | 125      |
| Gen22| 16  | 12.3883 | 54.3      | 155         | 50       | 50       |
| Gen23| 18  | 4.4231 | 100         | 400         | 50       | 50       |
| Gen24| 21  | 4.4231 | 100         | 400         | 100      | 100      |
| Gen25| 22  | 0.001 | 10          | 50          | 100      | 100      |
| Gen26| 22  | 0.001 | 10          | 50          | 50       | 50       |
| Gen27| 22  | 0.001 | 10          | 50          | 210      | 210      |
| Gen28| 22  | 0.001 | 10          | 50          | 210      | 210      |
| Gen29| 22  | 0.001 | 10          | 50          | 150      | 150      |
| Gen30| 22  | 0.001 | 10          | 50          | 40       | 40       |
| Gen31| 23  | 12.3883 | 54.3      | 155         | 15       | 15       |
| Gen32| 23  | 12.3883 | 54.3      | 155         | 15       | 15       |
| Gen33| 23  | 11.8495 | 140        | 350         | 10       | 10       |

**Table 2** Characteristics of thermal generating units
3.1 Base case (no ESS)
In this section, the problem defined in equation (1) to (17) is solved without considering the ESS option. The OF is obtained as $4.0575E+5$. The variation of wind and solar power curtailment vs time is shown in [Figure 3].

![Figure 3](image1.png)

Figure 3 Wind and solar power curtailment in base case

The variation of thermal unit power generation is shown in [Figure 4]. This figure shows that the thermal units are less used in the middle of the day since the solar power availability is high during those periods.

![Figure 4](image2.png)

Figure 4 Total thermal power generation vs time (pu)

3.2 ESS allocation and sizing case
In this case, the full optimisation model is solved and the optimal location and sizes of ESS are found. The optimal buses for hosting the ESS are 6, 11 and 14. The ESS capacity is going to be 50 MWh for all these locations. The state of charge, charging and discharging pattern are shown in [Figure 5]. The OF is obtained as $3.9659E+5$.

![Figure 5](image3.png)

Figure 5 Charging and discharging pattern of ESS in different buses (pu)

3.3 ESS operation in maintenance period of transmission lines
Now suppose that the optimal locations and capacities of ESS units are obtained as in section 3.2. In this section, the applicability of ESS units will be analysed in reducing the operating costs in maintenance period/contingencies of
transmission lines. Since the outage of line connecting bus i to bus j may increase the flow of other lines and causing the congestion in those lines then the TSO should be equipped with some strategy in these periods. The various line contingencies considered in this work are shown in Figure 7.

The proposed model is solved for each contingency case, knowing the values of ESS connection and the total costs are calculated as follows:

Contingency $S_1$: If there is no ESS in the network then the total costs would be $4.3787E+5$. However if ESS is used the total cost reduce to $4.2315E+5$. The wind and solar curtailments are shown in Figure 8.

Contingency $S_2$: If there is no ESS in the network then the total costs would be $4.6528E+7$. However if ESS is used the total cost reduce to $4.6521E+7$. The wind and solar curtailments are shown in Figure 9.

Contingency $S_3$: If there is no ESS in the network then the total costs would be $4.2277E+5$. However if ESS is used the total cost reduce to $4.1114E+5$. The wind and solar curtailments are shown in Figure 10.

The proposed framework can still be improved by analysing the impacts of uncertainties influencing the decision making process [3].
Nomenclature

| Symbol   | Description                                                                 |
|----------|------------------------------------------------------------------------------|
| $P_{ij}^{\text{max}}$ | Line rating of line connecting bus $i$ to $j$                               |
| $\delta_{j,t}$       | Voltage angle of bus $j$ at time $t$                                         |
| $P_{i,t}^{\theta}$   | Generated power of thermal unit connected to bus $i$ at time $t$             |
| $P_{d,i,t}$          | Power demand in bus $i$ at time $t$                                          |
| $P_{s,i,t}$          | Generated power of solar power connected to bus $i$ at time $t$              |
| $P_{w,i,t}$          | Generated power of wind turbine connected to bus $i$ at time $t$             |
| $P_{c/i,c/dc,i,t}$   | Charged/discharged power of ESS connected to bus $i$ at time $t$            |
| $SO_{C,i,t}$         | State of charge in ESS connected to bus $i$ at time $t$                      |
| $RD_{i}$             | Ramp down limit of thermal unit in bus $i$                                  |
| $RU_{i}$             | Ramp up limit of thermal unit in bus $i$                                    |
| $\eta_{ch}$          | Charging efficiency of ESS                                                  |
| $\eta_{dch}$         | Discharging efficiency of ESS                                               |
| $\text{Cap}$         | Capacity of each ESS block                                                  |
| $N_{\text{ESS}}$     | Total number of ESS in the system                                            |
| $\vartheta$          | Investment costs of ESS                                                    |
| $\alpha$             | Curtailment penalty                                                         |
| $\Delta_t$           | Duration of period $t$                                                      |

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Conclusion

The allocation and sizing problem of ESS for resiliency enhancement of transmission network against renewable energy curtailments are investigated in this works. The simulation results showed that the ESS can reduce the total wind and solar curtailment in normal and contingency conditions.

References

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