Using Energy Storage to Relief Transformer Overloading after Coal-Fire Generator Retirement

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Abstract. Energy storage system (ESS) is believed to be a significant source of power system operational flexibility given renewable generation with high penetration. This work reports a unique scenario of relieving the overloading of a 500kV transformer after the retirement of a coal-fire generator. ESS is proven to be an ideal solution in terms of technical feasibility and economic performance. A look-ahead operation strategy is to utilize ESS to mitigate the identified transformer overloading bottleneck. A case study using a synthetic version of Zhejiang power grid confirms the effectiveness of the proposed ESS based approach.

1. Introduction

Energy storage systems (ESS) are widely recognized to be an effective approach to offer significant flexibility in modern power system planning, operation and control [1]. The decreasing cost in energy-oriented batteries observed in recent years has dramatically boost the grid-scale application of ESS [2]. Especially in the integration of renewable energy generation [3], energy storage technology is believed to be a both feasible and economic approach to overcome various challenges including variability, intermittency, and low system inertia.

Existing literature have reported a number of scenarios where ESS is able to enhance system-level, site-level and component-level flexibility. A system-level congestion bottleneck identification was proposed by [4] and the identified bottlenecks were proven to be eliminated by installing more ESS into the system. In this particular scenario, ESS is able to provide additional flexibility in operation stage, especially ramping rate capability. A site-level ESS planning and control scheme is proposed in [5], ESS is utilized to filter out unacceptable fluctuations caused by wind generation. Therefore, a robust ramp control of ESS assisted wind farm is achieved. A component-level of ESS application can be found in [6], where an ESS is installed on the DC bus of a permanent magnet synchronous machine (PMSM) based wind turbine, so that advanced control such as emergency frequency support can be accomplished.

Given extensive investigation of ESS application scenarios reported in the literature, this work looks at a particular scenario of using ESS to relief transformer overloading after coal-fire generator retirement, which is currently observed in practical operation conditions in Zhejiang power grid, China. Such scenario is expected to be not limited in Zhejiang power grid, it may be seen in other regional grid in both developed and developing countries where the major power source is experiencing an upgrade from 220kV connected old generators (e.g., possibly less-efficient coal-fire ones) to 500kV connected more-efficient generators or high voltage direct current (HVDC). It will be revealed in this
work that such operational bottleneck can be easily relieved by designing a proper charging/discharging schedule strategy for ESS. Compared with other solution candidates, energy storage is with a promising technical and economic performance.

A similar approach of using ESS to relief transformer overloading can be found in [7] where ESS is employed in the scale of a building distribution network. Due to the reducing cost of ESS installation and various ESS deployment plans in Zhejiang power grid by either grid operator or generation company in the near future, ESS is believed to an effective solution to the studied problem.

In this work, a brief description is provided to showcase the aforementioned transformer overloading scenario during the transition of generator upgrade. Then, a preventive operation strategy to modulate charge/discharge output of ESS to relief such overloading bottleneck is presented. A case study based on a synthetic version of Zhejiang power grid is demonstrated to validate the effectiveness of the proposed approach.

2. Scenario Description and Analysis

2.1. Scenario Description

Zhejiang power grid, with the peak load in 2019 of 82 GW, is a major receiving-end power grid in East China. It has been experiencing a significant generator upgrade since 2010, due to more strict emission restriction by Chinese government to relief air quality. This upgrade process especially speeds up since China signed Paris Agreement in 2016 [8]. In the scope of Zhejiang Province, the government further limited the usage of coal-fire generation by initiating a campaign to reduce six million standard coal equivalent (SCE) consumption by 2020 [9]. A number of coal-fire generators, originally built in 1990s or early 2000s with their capacity of 150-300 MW and connected to 220kV meshed transmission network, have been forced to be retired. Their generation capacity is mostly replaced by the newly built ultra-high-voltage (UHV) AC transmission network ring connecting East China region and several UHV DC lines delivering energy from renewable-dominated southwest of China. Meanwhile, as for the transmission network topology in Zhejiang power grid, 500kV based backbone transmission network has been established, therefore existing 220kV network shifts its role from integrate supply to serving demand [10]. In the transition described above, 500kV transformers, which deliver power from 500kV backbone network to 220kV demand-serving network, have been observed to suffer significant overload at peak period. This is because: the loads connected on 220kV network was originally supplied locally by the generators which are to be retired. Hence, such loads have to be supplied by the power delivered from 500kV transformer after the coal-fire generator retirement. An illustrative demonstration is provided in Fig. 1 to show this particular overloading scenario.

![Figure 1](image.png)  
*Figure 1. An illustrative example showing the impact of generator retirement.*
2.2. Scenario Analysis

To further explain the principle of this scenario, an illustrative example is provided in Fig. 1. The 500kV backbone network is abbreviated as a power source G1, supplying energy to 220kV network using a transformer connecting B1 and B2. Meshed 220kV network is then abbreviated as a ring with three buses B2-B4, where a coal-fire generator G4 is to be retired. It can be observed that, according the power flow illustration, the generator is able to provide power supply to local load and therefore reduce the loading condition of the transformer T1. However, once it is retired, all the loads in 220kV network have to be supplied by the transformer T1, causing a significant increase in power flow from B1 to B2 and the overloading of T1.

To relief such transformer overloading, distributed generation [11] and demand response [12] can be effective candidate approaches. However, such schemes may not be directly accessible by system operators due to their distributed nature or privacy concern. Hence, ESS is then believed to an ideal technology to solve this problem. In the next section, we will develop an operation strategy to dispatch ESS installed in 220kV in order to mitigate the overloading condition of the studied transformer.

3. ESS Operation Strategy

3.1. Principle

The role of ESS to relief transformer overloading is twofold: First, it has to provide sufficient generation, i.e., discharging capacity, at the time of overloading. Second, it is required to be with adequate reserve in order to accommodate possible forecast error of the peak load.

Based on this basic idea, a multiple time period based optimal power flow (OPF) formulation is proposed to offer the operation strategy for ESS. Load and wind/solar generation forecasting data is used to establish the look-ahead form of optimization. The capacity constraint of the target transformer (i.e., T1 in Fig. 1) is explicitly included in the formulation.

Note that the ESS aforementioned above can be either centralized grid-side ESS managed by vertical utility company or aggregated customer-side ESS located in commercial or industrial facilities.

3.2. Model Formulation

Consider a set of look-ahead time intervals $T_\Sigma$, a DC power flow can be established for each time interval $t$.

$$A_G P_G + A_{ESS} P_{ESS} - P_L - B' \theta' = 0$$  \hspace{1cm} (1)

where $A_G$ and $A_{ESS}$ are the connecting matrix of generators and ESSs, respectively. $P_G$, $P_{ESS}$ and $P_L$ denote to the power of generators, ESSs and loads at time interval $t$. and $\theta'$ represent the imaginary part of admittance matrix and bus voltage angle at time interval $t$.

Ramping constraints are considered for generators but not for ESSs, since they are generally with full charge/discharge adjustment rate given operational time interval in minutes.

$$R_G \leq P_G^t - P_G^{t-1} \leq R_G$$  \hspace{1cm} (2)

State of Charge (SOC) of ESSs are tracked using a set of variables $E^t$. It is linked with charge/discharge power as (3).

$$P_{ESS}^t = E^t - E^{t-1}$$  \hspace{1cm} (3)

Box constraints for both generators and ESSs have to be considered. ESSs have a negative lower bound to represent charging condition like a load. Note that the upper/lower bounds have to be set to zeros if a generator/ESS is scheduled to offline for corresponding time interval.

$$P_G \leq P_G^t \leq P_G$$  \hspace{1cm} (4)
\[ P_{\text{ESS}} \leq P'_{\text{ESS}} \leq \overline{P}_{\text{ESS}} \]  \hfill (5)

Similar box constraints are also considered for SOC.

\[ E \leq E' \leq \overline{E} \]  \hfill (6)

Transmission line and transformer capacity constraints share the same form of power flowing from one bus to another.

\[ P_t \leq T' \theta' \leq \overline{P}_t \]  \hfill (7)

where \( T' \) is the line admittance matrix. Note that both \( T' \) and \( B' \) can be time variant caused by line switching action observed in the considered time span.

Objective function of the established model is to minimize total operation cost over the considered time intervals, including both generators and ESSs. The cost functions can be formulated in either linear or nonlinear form. The later may be linearized using piecewise linear formulation. Also, the cost function of ESS can be time-variant so as to reflect energy cost difference in different time interval in a day.

\[ \phi(P'_{G}, P'_{\text{ESS}}) = \sum C_{G,i}(P'_{G,i}) + \sum C_{\text{ESS},j}(P'_{\text{ESS},j}) \]  \hfill (8)

Therefore, the overall multiple time-interval OPF model can be established as follows.

\[
\begin{align*}
\min_{\phi(P'_{G}, P'_{\text{ESS}}), t} & \quad \phi(P'_{G}, P'_{\text{ESS}}) \\
\text{s.t.} & \quad (1)-(7), t \in \mathbb{S}_T
\end{align*}
\]  \hfill (9)

The established model (9) is solved every time interval, when load (as well as renewable) forecast data is available. Hence, the ESSs are dispatched along with generators to achieve optimal cost saving while satisfying various constraints including transformer loading condition aforementioned above.

4. Case Study

4.1. Test Case

Due to the data confidential regulation, this work is only able to demonstrate the result using a synthetic Zhejiang power grid for analysis. Such test case inherits the basic topology of real-world 500kV and 220kV substations in Zhejiang power grid, but the generation/load data is fictional. Despite the censorship, it is still able to emulate the identified transformer overloading situation. Detailed test case analysis can be found in the next subsection.

4.2. Power Flow Snapshot Analysis

PowerWorld software [13] is employed to illustrate the snapshot of power flow in peak period, when the transformer overloading situation is observed.

As it is shown in Fig. 2, the test case includes basically two parts: one is a meshed 500kV backbone network of the whole Zhejiang power grid, the other is the local 220kV network serving the city of Jinhua area, including three substations: Shuanglong, Zhiyan and Xinan, which are shown in the bottom-left of the figure.
The studied 220kV network has two power sources: one is a coal-fire thermal generator of 200MW capacity connected to Xinan 220kV substation, the other is the transmission line connecting Danxi 500kV substation and Shuanglong 220kV substation. Once the 200MW generator is retired, all loads of the three 220kV substations have to be supplied by the 500kV/220kV transformer installed in Shuanglong substation, causing the undesired overloading issue.

Figure 2 demonstrates the power flow snapshot before the generator retirement, from which we are able to observe the transformer is with low loading level and most of the load of Jinhua area is locally supplied.

Figure 3 illustrates the power flow distribution after the generator retirement, given the same load condition as Fig. 2. It can be observed the transformer at Shuanglong substation is heavily overloaded.

4.3. Validation of ESS Operation Strategy

In order to validate the effectiveness of using ESS to relieve the identified transformer overloading, an ESS with 100MW/100MWh is installed at the original site of the retired generator, connected to Xinan substation. This is a cost-efficient approach in practice, since the facility construction and service line can be directly re-used.
Figure 4 shows the transformer loading condition as well as energy storage charge/discharge operation in a typical summer peak day, with the time interval of 15 minutes. It can be observed that the ESS is able to mitigate the transformer overloading by properly charge before the load peak to release energy at the right time.

4.4. Discussion

The required ESS power capacity is no less than the loading power exceeding the transformer capacity, which results in a small and on-demand ESS usage.

Compared to other options like upgrading the transformer or building a new transmission line, an ESS with a rather small capacity is able to relief the transformer overloading concern in an economic way. Furthermore, an ESS may be operated with multiple roles, like renewable integration, frequency regulation or other auxiliary service. That means the ESS can follow other operation strategy for off-peak period when the transformer loading condition is not a concern. Therefore, ESS may bring more flexibility in system operation.

5. Conclusion

Among a number of investigations on the role of utility-level ESS, this work identifies a unique application scenario, in which ESS is able to relief transformer overloading after a local generator is retired. Such scenario has been observed in real-world planning and operation practice in Zhejiang power grid, China. In order to mitigate such overloading problem, this work presents a look-ahead operation strategy for ESS, based a multiple time period OPF model. It is able to determine proper SOC for the ESS and shave the peak load of the transformer so as to relief the undesired overloading congestion. This approach is validated using a case study with synthetic Zhejiang power grid data. ESS is proven to be an ideal solution for this particular scenario.

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