Coordination of Preventive Dispatch and Black-Start under Extreme Operational Conditions using Robust Optimization

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Abstract. Extreme operational conditions, e.g., wind storms and ice storms, have been posing great challenges for power grid operation. The extreme conditions are likely to cause widespread blackout, therefore a black-start procedure is needed to restore the non-blackstart generating units and transmission assets. To facilitate the black-start procedure, the coordination between post-event preventive dispatch and post-event black-start dispatch is established, considering the uncertainty of forced transmission line outage scenarios. A two-stage robust optimization model is built to coordinate the preventive dispatch and black-start procedure. An iterative decomposition algorithm is applied to solve the proposed model. A synthesized Chinese 372-bus system is used to illustrate the proposed method. It is shown that, in the worst-case blackout scenario, the coordinated black-start procedure can accelerate the entire process by 15% and reduce the black-start capacity requirements.

1. Introduction

1.1. Background and motivation

Power grid resilience against extreme operational conditions (e.g., extreme weather condition, cyber-attacks, and natural disasters) has been identified as a key feature of future power grids[1]. The power grid is expected to ride through the extreme events with appropriate operational strategies and to recover promptly to normal states after those undesirable events.

In particular, geographical or weather-related and extreme events are one-time events with a predictable start and end point. Moreover, the unfolding pattern of these events are also predictable and will not alter in response to mitigation efforts[2]. Therefore, the pre-event and post-event operational strategies can be coordinated to reduce the overall impact of these events within a predetermined timeframe.

On the other hand, extreme operational conditions may lead to a wide-spread blackout. It is critical to plan both the preventive dispatch and black-start procedure to facilitate a prompt recovery process of the power grid. In view of this challenge, this paper proposed to coordinate the aforementioned dispatch stages within an optimization model.

1.2. Literature survey

To motivate this work, the existing work is reviewed as below.

To reduce the loss during extreme operational conditions, preventive dispatch [3], emergency dispatch [4], and restorative dispatch [5] have been applied individually. Some work considered the
coordination among these dispatch stages to reduce the overall loss of the extreme event [6-8]. Robust optimization has been widely used in establishing coordinated dispatch plans. In particular, a heuristic method to coordinate the preventive dispatch and restorative dispatch was proposed in [9], where the preventive dispatch is optimized independent from restorative dispatch, and uncertainty of the outage scenario was not thoroughly addressed. To resolve this issue, this paper proposes to integrate preventive dispatch and black-start procedure under extreme operational condition into one optimization model.

1.3. Paper contributions and organization
For sake of clarification, the major contribution of this paper is summarized below.

- The coordination of preventive dispatch and black-start procedure is established using a robust optimization model, considering the uncertainty of the forced transmission line outage scenarios.
- A decomposition strategy is proposed to solve the proposed robust optimization model. This strategy comprises three building blocks, namely the optimal preventive dispatch, the optimal black-start procedure, and the combinatorial optimization to identify the worst-case blackout scenario. An iterative algorithm is developed with these three building blocks to achieve the coordination of preventive dispatch and black-start procedure.

The rest of this paper is organized as below. In Section 2, the coordination of preventive dispatch and black-start procedure is formulated as a robust optimization model. In Section 3, the iterative decompostion algorithm is applied to solve the proposed model. In particular, the worst-case blackout scenarios are identified. In Section 4, a synthesized Chinese 372-bus system is used to illustrate the effetivenss of the proposed method. The work is concluded in Section 5.

2. Model formulation
In this section, the coordination of preventive dispatch and black-start procedure is formulated as an robust optimization model. The compact formulation is described as below.

2.1. Preventive dispatch
The objective of preventive dispatch is to minimize the proactive load shedding on dispatchable load, so as to maintain a minimal secure operating point of the power grid prior to the advent of the extreme event. Line switching on a pre-selected set (estimated to be affected by the extreme event) of transmission lines are also considered. The model of preventive dispatch based on DC power flow model is given below.

\[
\begin{align*}
\min & \sum_i \Delta P_{D,j} \\
\text{s.t.} & P_{G,i} - (P_{D,j} - \Delta P_{D,j}) - P_{Dc,j} = \sum_{j \in C_i} P_j, \quad \forall i \\
& P_j = B_j (\theta_i - \theta_j), \quad \lambda_{ij}^P \leq \Delta P_{ij}^\text{min} \leq P_j \leq \lambda_{ij}^P \Delta P_{ij}^\text{max}, \quad P_{G,j}^\text{min} \leq P_{G,j} \leq P_{G,j}^\text{max}
\end{align*}
\]

In the above model, \(i\) is the bus index, \(P_{G,i}\) is the generator output on bus \(i\), \(P_{D,j}, \Delta P_{D,j}\) are the dispatchable load and load shedding on bus \(i\), respectively, \(P_{Dc,j}\) is the critical load on bus \(i\), \(P_j\) is the branch power flow between bus \(i\) and bus \(j\), \(\theta_i\) is the phase angle of bus \(i\), \(B_j\) is the branch admittance between bus \(i\) and bus \(j\), \(C_i\) is the set of buses connecting to bus \(i\), \(\lambda_{ij}^P\) is a binary variable indicating the on-off state of the corresponding linein preventive dispatch, \((\bullet)^\text{max}, (\bullet)^\text{min}\) are the upper and lower bound of the corresponding variables, respectively.
2.2. Uncertainty set of blackout scenarios
The uncertainty set of blackout scenarios are expressed by the combination of line and generator outages. Noted that the affected part of the power grid during the extreme event is predictable. As a result, the set of affected lines and generators can be pre-determined. To estimate the maximum adverse impact of the extreme event subject to a budget of total outage elements, a uncertainty set is formulated as below,

$$U = \left\{ \sum (1 - \lambda_y) + \sum (1 - \lambda_{G,j}) \leq \eta \right\},$$  \hspace{1cm} (2)

where $\lambda_y$ and $\lambda_{G,j}$ are the binary variables indicating the on-off state of the corresponding line and generator during the extreme event.

2.3. Black-start procedure
The objective of black-start procedure is to crank the off-line generators and establish transmission line from the survival generators to the off-line generators. Meanwhile, it is critical to pick up minimum dispatchable loads to maintain power balance for the on-line generators. The multiple-step black-start procedure is formulated as below.

$$\min \sum \sum \Delta P_{D,l,j}^{Bla} \hspace{1cm} (3a)$$

s.t. $P_{G,i,t}^{Bla} - \Delta P_{D,l,j}^{Bla} - P_{D,l,j} = \sum_{j \in G_i} P_{j,l}^{Bla}, \hspace{0.5cm} \forall i, \forall t$

$$P_{j,l}^{Bla} = B_j \left( \theta_{j,l}^{Bla} - \theta_{i,l}^{Bla} \right) \hspace{1cm} (3b)$$

$$\lambda_{y,i,t}^{Bla} P_{y,i,t}^{min} \leq P_{y,i,t}^{Bla} \leq \lambda_{y,i,t}^{Bla} P_{y,i,t}^{max}, \hspace{0.5cm} \lambda_{G,j,t}^{Bla} G_{j,t}^{min} \leq P_{G,j,t}^{Bla} \leq \lambda_{G,j,t}^{Bla} G_{j,t}^{max}$$

$$\lambda_{y,i,t}^{Bla} = \lambda_y^{Bla}, \lambda_{G,j,t}^{Bla} = \lambda_{G,j,t}^{Bla} \hspace{1cm} (3c)$$

In the above model, $t$ is the time index, $\Delta P_{D,l,j}^{Bla}$ is the dispatchable load on bus $i$ at time interval $t$ in the black-start stage, $P_{y,i,t}^{Bla}$ is the generator output on bus $i$ at time interval $t$, $\theta_{i,l}^{Bla}$ is the phase angle of bus $i$ at time interval $t$ in the black-start stage, $\lambda_{y,i,t}^{Bla}$, $\lambda_{G,j,t}^{Bla}$ are the on-off states of the corresponding lines and generators at time interval $t$. Equation (3c) enforces the state dependency between the uncertainty set, preventive dispatch and the initial state of the black-start process.

The robust optimization to coordinate preventive dispatch and black-start procedure is written in a compact form as below.

$$\min \sum \sum \Delta P_{D,l,j}^{Bla} + \max \min \sum \sum \Delta P_{D,l,j}^{Bla} \hspace{1cm} (4)$$

s.t. (1b), (3b-3c)

3. Solution method
It is noted that the proposed model is a robust optimization with binary variables in the inter minimization problem. Therefore, the dualization cannot be applied to solve the max-min problem. To facilitate the computation, an iterative decomposition algorithm is proposed to calculate equation (1), equation (2), and equation (3) independently. The steps of this algorithm are described as follows.

- Step 1: solve equation (1) to obtain a trivial preventive dispatch plan.
- Step 2: solve equation (2) to obtain a new worst-case blackout scenario.
Step 3: With the states obtained by Step 1 and Step 2, solve equation (3) to obtain a feasible black-start procedure.

Step 4: solve equation (1) with a fixed worst-case scenario to obtain an optimized preventive dispatch plan, compare the preventive dispatch with previous plans, if not significant change, stop; otherwise proceed.

Step 5: solve equation (2) to obtain a new worst-case blackout scenario, solve equation (3) is obtained a feasible black-start procedure. If the worst-case loss is not significantly changed, fix the worst-case scenarios. Otherwise, go to step 4.

When the strategy is obtained, the time durations between adjacent time intervals are calculated by the difference of generator outputs and the ramping rate.

By following the above steps, an optimized preventive dispatch and a black-start procedure under the worst-case blackout scenario are obtained.

4. Illustrative examples

To validate the proposed method, a synthesized Chinese 372-bus system is used as illustration. The modeling is implemented in MATLAB with YALMIP. The simulations are conducted on a personal computer with 16 GB RAM and i7 CPU. The system parameters are given below in Table 1.

| Electric Equipment        | Number |
|---------------------------|--------|
| Bus                       | 372    |
| Transmission Line         | 204    |
| Transformer               | 194    |
| Important load            | 0      |
| Dispatchable load         | 0      |
| Generator                 | 32     |

The system consists of 372 buses, 204 transmission lines and 194 transformers. There are 32 generators, including 8 black-start generators. Therefore, the restoration procedure can be divided into 24 stages. The test system was simulated based on two different restoration strategies, and Figure 1 depicts the restored generation output versus time.

The base restoration strategy is calculated as follows. First, black-start generators provide starting power to the tripped generators to restore their capacities. Second, transmission lines and transformers are restored to establish a stable transmission network skeleton. The base restoration strategy requires maximizing the load to be recovered at each time point under operating constraints such as frequency response, overvoltage, overload, and so on. In contrast to the base strategy, the coordinated restoration strategy introduces load, over-voltage and low-voltage constraints into the optimal power flow model.
in the preventive stage, to minimize the active load shedding of dispatchable loads. As a result, it helps to restart available non-black starting generators and critical loads promptly. Specifically, the coordinated restoration strategy can be used to find the minimum recovery time, including the restoration of all available generator sets and critical loads that meet the operational constraints. The detailed compassions are given below.

Basedon the base restoration strategy, the total restoration time of the system is 542.40 minus. Under the coordinated restoration strategy, due to the change of initial conditions before restoration, the system chose a different restoration path, and the total time was 462.94 minus, which was shortened by 15%. It is shown that, the coordinated restoration strategy can accelerate the entire restoration process.

The relationship between the restored AC lines and time intervals is shown in Figure 2. It can be seen that, the coordinated restoration strategy restored more lines after 50 minus. The relationship between the system restored capacity and the number of restoration stages is shown in Figure 3. The total restored capacity of the system under the coordinated restoration strategy is larger than that of the base restoration strategy, before step 6 and after step 13. It is shown that, the capacity requirements can be reduced under the coordinated restoration strategy.

5. Conclusion

The extreme operational conditions are likely to cause wide-spread power grid blackout. To facilitate a prompt black-start procedure, this paper proposes to coordinate the preventive dispatch and the black-start procedure considering the worst-case blackout scenarios. The major work done in this paper is summarized as follows. First, the coordination of preventive dispatch and black-start procedure is established using a robust optimization model. Second, a decomposition strategy is proposed to solve the proposed robust optimization model. To achieve the coordination of preventive dispatch and black-start procedure, an iterative algorithm is developed to solve the preventive dispatch subproblem, the black-start subproblem, and the worst-case blackout scenario subproblem.

From a case study using a synthesized Chinese 372-bus system, it is shown that the coordination between preventive dispatch and black-start procedure can efficiently reduce the black-start duration and lead to a prompt generation capacity recovery. As a result, the power grid resilience is greatly improved by the proposed method.
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