Load restoration strategy considering the recovery state of power plants in system restoration stage

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Abstract. Load restoration is important for reducing outage time and loss of smart grid after a blackout. Load recovery strategy of network reconfiguration is maximizing load amount during system restoration without considering the startup characteristic of thermal plants, which may result in the time-delay of hot-start generators and decrease the efficiency of power system restoration. In order to increase the restoration efficient of network reconfiguration stage, this paper proposes a load restoration strategy considering the recovery state of power plants based on logical preference description language (LPDL). Firstly, the load selection constraint determined by the recovery state of power plants in each time step is formulated by LPDL. Then, a non-linear optimization model for load restoration during network reconfiguration is established with the load selection constraint. Artificial Bee Colony algorithm (ABC) is employed to obtain the optimal load restoration scheme. Finally, the New England power system is employed to demonstrate the validation of the proposed method.

1. Introduction
Due to the advance control technology and widespread interconnection, the reliability is higher. But when the power system working on the limit states for the economic operation, it also has the risk of large area blackout which is caused by natural disasters or occasional faults [1, 2]. Several large area blackouts have happened in the past few years, such as India blackout in 30 July 2012, Japan blackout in 14 March 2011, Brazil and Paraguay blackout in 10 November 2010, which have caused millions of people out of electric service. After the blackout, it’s necessary to restore power supply quickly to decrease the loss caused by blackout. Therefore, the load restoration strategy is very important for power system restoration.

Power system restoration can be divided into three stages: preparation, system restoration (or network reconfiguration), and load restoration [3, 4, 5]. A large number of researches have been focused on load restoration strategy in load restoration stage. In this stage, major generators and backbone transmission lines have been restored and power supply is sufficient, optimal objective is to recover load as fully and rapidly as possible under the promise of constraints. With the ramp rate constrains of generators, the load restoration will last for several hours and be accomplished through step-by-step load pickup. For each small load pickup step, a mathematical model is formulated in [6] to determine the maximum restorable load of a substation while considers transient voltage constraint. A mixed-integer nonlinear load restoration model with AC power flow and reserve constraints during load restoration is formulated in [7]. A combinatorial optimization model taking the sequencing problem of load restoration into account is proposed in [8]. With the development of wide area monitoring system...
(WAMS) and synchrophasor technology, a mathematical model to estimate the maximum restorable load is presented in [9] which employs WAMS data. A two-stage hierarchical method is presented in [10] to recover maximum possible level of loads, which includes the optimization of amount and location and real-time executing and monitoring. Besides above researches of load restoration powered by backbone transmission system, load restoration in distribution system and the microgrid also has got a lot of attention. A load restoration algorithm based on distributed multi agent is adapted for microgrid in [11]. An optimization model for the load restoration incorporating DGs is proposed in [12, 13].

In the network reconfiguration stage, in order to stabilize generating units, balance reactive power and provide satisfactory voltage profiles, a reasonable amount of important load will also be recovered simultaneously at the stage of network reconfiguration [14]. The optimization of restorable load under security constraints can accelerate the restoration of power system. A load restoration strategy coordinating the unit restoration with load restoration is proposed and an extended black-start multi-objective optimization model is established in [15]. An optimization model of load restoration considering load restoration cost, load characteristics, load importance and the influence of the load restoration on the succeeding network reconstruction is formulated in [16]. Load restoration is employed as a control method for standing phase angle reduction in [17]. A two-stage optimization model of network reconfiguration and load recovery is proposed in [18] including a MILP model optimizing transmission line charging and load pick-up and a nonlinear model minimizing the restoration duration.

In above researches, all the loads in blackout system are employed for restoration during network reconfiguration, while extra lines will recover the loads, which are not in the restored path. Due to the startup characteristic of thermal plants, additional restoration time may result in time-delay of hot-start generators and decrease the efficiency of power system restoration, meanwhile, thermal plant is required to start within maximum hot-start time or beyond minimum cold-start time. In addition, there is a time interval between maximum hot-start time and minimum cold-start time, and it is necessary to recovery as many loads as possible during the interval. That is, the loads, which can be recovered, are different from the recovery state of power plants.

To improve the efficiency of power system restoration, a new strategy for load restoration considering recovery state of power plants is proposed in this paper. Firstly, logical preference description language (LPDL) is employed to formulate the load selection constraint that can determine the load to be recovered in each time step. Then, a nonlinear optimization model for load restoration during network reconfiguration is established to maximize the weighted capacity of load restoration. The maximum power constraint of each load, power flow constraint and other constraints are taken into account. The artificial bee colony (ABC) algorithm obtains the optimal load restoration scheme. Finally, the load recovery strategy is applied in fixed and optimized system restoration path of different power systems to validate the performance.

2. Load selection constraint based on logical preference description language

Logical preference description (LPD) is a new research field of artificial intelligence [19], which can be employed to make decisions according to different preferences where users may have preferences on different goals under different circumstances. In this paper, the loads to be recovered at each time step is determined by the recovery state, and LPDL is employed to select the loads satisfying the requirement of different recovery state.

According to current researches, many qualitative preference problems can be solved on the premise of the following conditions:

- A set V of Boolean variables is given.
- A set B of propositional formulas which means background knowledge is given.
- A set F of propositional formulas which means the preferences among goals is given.
- A set S of preference strategies is given.

2.1. Logical preference description language
LPD is developed by Gerhard Brewka in order to represent complex qualitative preferences among problem solutions [20]. LPDL consists of ranked knowledge bases (RKBs) and preference strategies. RKBs are adapted to represent the relative importance of different goals, while preference strategies are defined to express complex preferences among models, which represent problem solutions.

2.1.1. Ranked knowledge bases.
RKB is a set of propositional formulas together with a total preorder. It can be expressed as a set of \((f, r)\), where \(f\) is a propositional formula and \(r\) is the rank of \(f\). \(r\) is a non-negative integer, if \(f\) \(\geq \) \(f\_2\), if \(r\) \(\geq \) \(r\_2\).

2.1.2. Preference strategies.
Preference strategies consist of basic strategy identifiers \(\{T, \kappa, \leq, \#\}\) and standard propositional connectives \(\{\land, \lor, >, \sim\}\). Basic strategy identifier \(T\) is used in this paper to express the preference among loads. The strategy \(T\) can be described that \(T\) prefers \(m_1\) over \(m_2\) whenever the most important goal satisfied by \(m_1\) is more important than the most important goal satisfied by \(m_2\).

Based on the above knowledge, a basic preference description can be expressed as \(K^s\), where \(s\) is a basic strategy identifier, \(K\) is a RKB.

In order to illustrate LPDL, assuming that RKBs are defined as follows: \(K=\{(a, 3), (b, 2), (c, 1)\}\). Different models are defined according to RKBs, for example, \(ab\) means that in this model \(a, b\) are true, while \(c\) is false: \(M_1=abc; M_2=ac; M_3=bc; M_4=ab; M_5=a\).

If the basic strategy identifier \(T\) is adapted to express the preference among models, the LPD is \(K_T\). Based on this LPD, \(M_1 \succ \_\succ M_3\), because the rank of the most important goal satisfied by \(M_1\) is 3, while \(M_3\) is 2; while \(M_1 \succ T M_2\), because the rank of \(M_1\) and \(M_2\) are both 3. Similarly, \(M_2 \succ T M_1\), \(M_4 \succ T M_2\), \(M_2 \succ T M_3\), \(M_1 \succ T M_4\), \(M_1 \succ T M_5\) ... The non-dominated models are \(M_1\), \(M_2\), \(M_4\) and \(M_5\), the preference structure among models can be illustrated in figure 1 (arrows point to strictly preferred models):

![Figure 1. Strict preferences among models.](image-url)

2.2. Selecting Loads to Be Recovered Based on Logical Preference Description Language
During network reconfiguration, the preferences among loads are determined by recovery state of power plants at each time step. If there are any power plants can be recovered in hot-start time interval, only the loads on optimal path can be restored, because the restoration of loads out of the optimal path will expand system restoration time. Otherwise, hot-start time may be missed and generator can be started until cold-start time due to the start-up character of generator. In contrast, if there are not any power plants can be recovered in hot-start time interval, the loads neighbouring the optimal path way can be restored to maximize the restorable load.

As to the analysis above, the distance from load to optimal restoration path determines the priorities of load. The loads in the blackout system can be divided into three categories according to their positions: the load on optimal restoration path, the load on neighbouring paths and the load far from the optimal restoration path. In order to avoid the recovery of extra lines outside optimal path which may affect the efficiency of network reconfiguration, the preference rank of the load on optimal restoration path is the highest. If generator can start in hot-start time interval, the preference ranks of other loads are lower. If recovery state of generators is in the time interval between maximum hot-start time and minimum cold-start time, the preference rank of load on neighbouring path is also the highest. The load which is far from the optimal restoration path has lower preference rank.

We can represent this information using the following RKBs:

\[
\begin{align*}
K_1 &= \{(A.2),(B.1),(C.1)\} \\
K_2 &= \{(A.2),(B.2),(C.1)\}
\end{align*}
\]
where $K_1$ is a set of preferences if generator can start in hot-start time interval, $K_2$ is another set of preferences if generator is not ready to start until the critical minimum time. A, B, C are the positions of loads relative to the optimal restoration path. A means that load is on optimal restoration path, B means that load is neighboring optimal path, C means that load is far from optimal restoration path.

The loads selecting constraint can be represented as the LPD expression:

$$
\begin{cases}
K_1^T & \text{if } t_i \leq T_{ic_{max}} \text{ or } t_i \geq T_{ic_{min}} \\
K_2^T & \text{if } T_{ic_{max}} < t_i < T_{ic_{min}}
\end{cases}
$$

where $t_i$ is the time that cranking power has delivered to generator $i$, $T_{ic_{max}}$ is the critical maximum time interval of generator $j$ and $T_{ic_{min}}$ is the critical minimum time interval.

3. Problem formulation

3.1. Objective function

Load restoration during network reconfiguration can be divided into several time steps. The maximum restorable load of each time step is determined by the cranking power of generators at this time step. This paper establishes an optimization model for load restoration, where the optimization target is to maximize the weighted capacity of load restoration:

$$
\max f = \sum_{i=1}^{n} \sum_{j=1}^{m_i} \omega_{ij} x_{ij} P_{Lij}
$$

where $f$ is the weighted recovery capacity, $n$ is the load bus to be recovered at each time step. In this paper, we divide a load bus into several components, $m_i$ is the number of components of bus $i$. $\omega_{ij}$ is the weight of $jth$ load of bus $i$. $x_{ij}$ is the status of load bus, 1 means $jth$ load of bus $i$ has recovered, otherwise value is 0. $P_{Lij}$ is capacity of $jth$ load at bus $i$ which is waiting for recovering.

3.2. Constraints

During system restoration, several constraints are required to be comprehensively taken into account, in order to ensure system security during restoration. The constraints can be listed as follows:

3.2.1. The maximum capacity of load restoration constraint.

$$
\sum_{i=1}^{n} \sum_{j=1}^{m_i} x_{ij} P_{Lij} < \Delta P_L
$$

where the load restoration at a time step is shown on the left of inequality, $\Delta P_L$ indicates the increment of power output, which can be calculated from the power output curve. $P_{L}(t)$ is the power output of generator $i$, which can be obtained from [21].

3.2.2. The maximum capacity of load restoration considering transient frequency at each time step.

The maximum capacity of load restoration considering transient frequency at each time step is to ensure transient frequency within allowable ranges.

$$
P_{L_{max}} = \Delta f_{max} \sum_{i=1}^{n} \frac{P_{Ni}}{df_i}
$$

where $\Delta f_{max}$ is 0.5Hz in this paper, $df_i$ is transient frequency response of unit $i$, its value is mentioned in reference [16].

3.2.3. Steady state power flow constraints.
\[
\begin{align*}
    P_i &= V \sum_{j=1}^{N} V_j (G_{ij} \cos \delta_{ij} + B_{ij} \sin \delta_{ij}) = 0 \\
    Q_i &= V \sum_{j=1}^{N} V_j (G_{ij} \sin \delta_{ij} - B_{ij} \cos \delta_{ij}) = 0
\end{align*}
\]

where \( P_i \) and \( Q_i \) are injection active and reactive power to bus \( i \), \( V_i \) is voltage of bus \( i \), \( G_{ij} \) and \( B_{ij} \) are conductance and susceptance between bus \( i \) and bus \( j \) respectively, \( \delta_{ij} \) is the phase angle between \( V_i \) and \( V_j \), \( N \) is number of buses.

3.2.4. Loads selecting constraint.

\[
\begin{align*}
    K_1^T & \quad \text{if} \quad t_i \leq T_{i,\text{max}} \quad \text{or} \quad t_i \geq T_{i,\text{min}} \\
    K_2^T & \quad \text{if} \quad T_{i,\text{max}} < t_i < T_{i,\text{min}}
\end{align*}
\]

If the time that cranking power has delivered to generator \( i \) is within the maximum hot-start time \( T_{i,\text{max}} \) or beyond the minimum cold-start time \( T_{i,\text{min}} \), the loads to be recovered will be selected according to the preference strategy \( K_1^T \). If generator \( i \) is not ready to receive cranking power until the minimum cold-start time, the preference strategy \( K_2^T \) will be adapted to select loads to be recovered.

3.3. Model solving

The optimization model for load restoration proposed in this paper can be described as a 0-1 knapsack problem, which has been proved to be a nondeterministic polynomial complete (NPC) problem. Intelligent optimization algorithm is widely employed to solve this kind of problem. Compared with other swarm intelligence, such as genetic algorithm (GA) and particle swarm algorithm (PSO), ABC algorithm is of strong robustness, high searching accuracy and efficiency [22,23]. With its rapid convergence rate, less control parameters, high quality of solutions, strong robustness and global search capability, ABC algorithm has successfully applied in many areas, such as artificial neural network, power system optimization, engineering design, combinatorial optimization and so on. Therefore, ABC algorithm is applied to solve the optimization problem in this paper.

4. Case study

4.1. Example system and parameters

In order to verify the efficiency of the proposed strategy for load restoration, the 10-unit 39-bus system is employed for case studies. Suppose that generator in node 30 is a black start unit, which is a pumped storage power plant. Other units are all thermal power units, whose primary parameters are shown in table 1. The components of each load bus and their load capacity are shown in appendix. Start-up time of each line is 4min. In order to ensure that spinning reserve capacity is enough, assuming that unit 30 is a balancing machine whose maximum power output is 80% of its rated power.

4.2. Simulation Environment and Case Study

The generator start-up sequence is assumed to be obtained by dispatchers. The start-up sequence is 37-33-35-34-32-31-38-39-36. The optimal restoration scheme based on the proposed load restoration strategy at each time step is shown in table 2.

In the first four time steps, generators can start in maximum hot start time interval, according to the loads selecting constraint, loads on the optimal restoration path and in the recovered system are selected to be recovered. The restoration scheme at each time step is optimized based on ABC algorithm. In the fifth time step, generator 32 cannot start within maximum hot-start time. And loads neighboring the optimal path can also be recovered during the time interval between maximum hot-start time and minimum cold-start time, which will not affect the start-up time of other generators. In the last four time steps, start-up time of generators is beyond the minimum cold-start time, the increment of power output will be distributed to the loads on the optimal restoration path and in the recovered system.
Table 1. Parameters of generators.

| Node Num. | P_G (MW) | P_cr (MW) | K_i (Pe%/min) | T_cmax (min) | T_cmin (min) | T_PR (min) |
|-----------|----------|-----------|---------------|--------------|--------------|------------|
| 30        | 350      | -         | 2.0           | -            | -            | -          |
| 31        | 1145     | 68.7      | 1.0           | 45           | 180          | 10         |
| 32        | 750      | 52.5      | 1.0           | 45           | 180          | 10         |
| 33        | 750      | 67.5      | 1.0           | 60           | 180          | 10         |
| 34        | 660      | 46.2      | 0.8           | 60           | 180          | 10         |
| 35        | 750      | 75        | 1.0           | 60           | 180          | 10         |
| 36        | 660      | 52.8      | 1.0           | 60           | 180          | 10         |
| 37        | 640      | 38.4      | 0.8           | 40           | 180          | 10         |
| 38        | 930      | 46.5      | 1.0           | 40           | 180          | 10         |
| 39        | 1100     | 88        | 0.8           | 45           | 180          | 10         |

Table 2. Load restoration scheme at each time step obtained by proposed strategy.

| Generator start-up sequence | Recovered load | Fitness value | Start-up time of generators /min |
|-----------------------------|----------------|---------------|----------------------------------|
| 37                          | 25(1)(3)       | 16.6          | 12                               |
| 33                          | 3(1)(3)(4), 18(1)(3)(4), 16(1)(2)(3) | 72.46         | 36                               |
| 35                          | 21(1)(4)       | 18.32         | 48                               |
| 34                          | 21(6)          | 36.5          | 56                               |
|                             | 3(2)(5)(6)(7)(8)(9), 25(2)(5)(6), 18(2)(5), 16(4)(5)(6)(7)(8), 21(2)(3)(5)(7), 20(1)(2)(3)(4)(5)(6)(7)(8)(9)(10)(11), 4(1)(3)(4)(6)(7)(8)(9)(10)(11)(12)(1), 15(1)(2)(3)(5)(6), 27(1)(2)(3)(4)(7), 24(3)(4)(5)(6)(7), 26(1)(2)(3)(5)(6)(7)(8)(9) | 1060.3        | 180                              |
| 31                          | /              | 0             | 192                              |
| 38                          | 31(1), 29(1)   | 9.31          | 200                              |
| 39                          | 24(2), 26(4), 39(1)(4) | 28.03         | 208                              |
| 36                          | 4(2), 24(1), 23(3), 39(2)(3)(13) | 107.16        | 216                              |

Table 3. Load restoration scheme at each time step obtained by old strategy.

| Generator start-up sequence | Recovered load | Fitness value | Start-up time of generators /min |
|------------------------------|----------------|---------------|----------------------------------|
| 37                           | 3(4), 25(1), 26(3) | 24.52         | 12                               |
|                              | 3(3), 26(2)(5), 4(1)(2), 18(1), 28(1), 27(1), 16(3), 24(2), 20(1)(2) | 91.11         | 40                               |
| 33                           | 3(2)(8), 25(3)(5), 26(4)(7)(9)(10), 4(7)(8)(9)(10), 18(2)(6), 28(2)(4)(6), 27(2)(3)(4), 16(1)(4), 15(1)(6), 21(3)(6)(7), 24(3)(5), 20(3)(4)(7)(8)(9), 29(2)(6), 23(3) | 554.065       | 180                              |
| 35                           | 26(1)          | 2             | 199                              |
| 34                           | 25(2), 23(5), 12(1) | 70.74         | 215                              |
| 32                           | 20(11)         | 82            | 231                              |
| 38                           | 7(4)           | 23.04         | 235                              |
| 39                           | 8(2)(6), 21(1) | 60.1          | 247                              |
|                              | 39(13)         | 80            | 251                              |

4.3. Comparison and Analysis

According to the old restoration strategy, all the loads can be recovered at each time step without considering the recovery state of power plants, the optimal restoration scheme at each time step is
shown in Table 3. As we can see from the two tables, all the generators have regenerated at 216 min according to the strategy proposed in this paper. While in Table 3, all the generators have regenerated at 251 min because of the recovery of extra lines outside the optimal path, which results in the time delay of hot-start generators. It obviously illustrates that the improved strategy is much better in restoration time. What’s more, Figure 2 shows the comparison of the load restoration capacity based on two strategies, the capacity of load restoration based on the strategy proposed in this paper is much larger. Therefore, the results demonstrate that the proposed strategy is highly efficient.

![Figure 2](image)

**Figure 2.** The comparison of load restoration capacity based on two strategies.

5. Conclusion
In order to improve the efficiency of power system restoration, a new strategy for load restoration considering critical minimum and maximum time intervals of generators, which will not lead to the additional restoration time of extra lines, is proposed in this paper. Logical preference description language is adapted to describe the selection of loads. An optimization model with consideration of weighted capacity of load restoration is established and the Artificial Bee Colony Algorithm is adapted to solve it. The simulation results validate the effectiveness of the proposed strategy, which can increase the capacity of load restoration and improve the efficiency of network reconfiguration.

6. References
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