Study on Power Loss Reduction Considering Load Variation with Large Penetration of Distributed Generation in Smart Grid

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Abstract. With the increasing of penetration of distributed in the smart grid, the problems that the power loss increasing and short circuit capacity beyond the rated capacity of circuit breaker will become more serious. In this paper, a methodology (Modified BPSO) is presented for network reconfiguration which is based on hybrid approach of Tabu Search and BPSO algorithms to prevent the local convergence and to decrease the calculation time using double fitnesses to consider the constraints. Moreover, an average load simulated method (ALS method) load variation considered is proposed that the average load value is used to instead of the actual load to calculation. Finally, from a case study, the results of simulation certify the approaches will decrease drastically the losses and improve the voltage profiles obviously, at the same time, the short circuit capacity is also decreased into less the shut-off capacity of circuit breaker. The power losses won’t be increased too much even if the short circuit capacity constraint is considered; voltage profiles are better with the constraint of short circuit capacity considering. The ALS method is simple and calculated time is speed.

1. Introduction
With a large number of penetrations of DGs in smart grid, the reverse power may occur and the quantity of reverse power flow will be also different with the load variation. It will make the power losses changed more, whereas it is necessary to consider the load variation during the losses optimization calculation. It has been also discussed that network reconfiguration method described in the previous paper[1,2] are effective on power loss reduction in distribution systems. About network reconfiguration for loss minimization, one of the early papers published in this field was presented by Merlin and Back [3], who developed a heuristic approach. This solution scheme starts with a total meshed system in which all the switching elements are closed. They are then opened one by one until all the closed circuits are eliminated, and a radial system is obtained. Taking into account load variation, Bouhouras [4] presented network reconfiguration methodology implemented utilizing heuristics techniques and load variations were simulated by stochastic procedures. An optimal DG output power for minimal losses is applied by Saksornchai [5], this paper presents a method helping planning engineers to determine the suitable DG power output to be fed into their systems in a short period of time. Tzeng [6] presented an algorithm for minimal loss reconfiguration based on the dynamic programming approach considering the load variation.

One conclusion in common of these previous works is that they focus on the improvement of
network reconfiguration algorithm, not the load model characteristics during network reconfiguration. For loss minimization calculation for a time based on network reconfiguration, if the method of network configuration changed at unit time is used, it may make the switches changed frequently though the results of losses minimization is best, for example, for daily load, it will perform 24 operation modes in one day. To avoid this case, in the paper, the method to divide the fluctuant load into several stages is presented. The network configuration is the same at any time in the same stage, and the configuration is built based on the sum of losses minimization in each stage and short circuit capacity reduction by network reconfiguration.

Average load simulated method (ALS method) is proposed for calculation during network reconfiguration considering load variation. It will be illuminated in the next sections in detail.

2. Approach for Loss Minimization and Short Circuit Capacity Reduction

2.1. Problem Formulation

Mathematically, the problem can be formulated as follows:

[Objective]

Minimize

\[ f(X) = P_{loss} = \sum_{k=1}^{N_k} \sum_{j=1}^{N_b} \sum_{i=1}^{F} k_{ij} I_{ij}^2 r_{ij} \]  

(2.1)

Where

- \( I_{ij} \): current of branch \( j \) at \( i \) o’clock;
- \( r_{ij} \): resistance of branch \( j \);
- \( N_b \): number of branches in the system;
- \( N_k \): number of divided stages;
- \( X \): switch status array;
- \( T_{sk}, T_{ek} \): start and end time point in stage \( k \);
- \( k_{ij} \): switch status of branch \( j \) at \( i \) o’clock; if branch \( j \) is energized, \( k_{ij}=1 \), else \( k_{ij}=0 \);

[Constraints]

(Power flow equations)

\[ P_{Gi} - P_{Li} - V_i \sum_{k=1}^{N_k} v_k \{ G_{ik} \cos(\theta_i - \theta_k) + B_{ik} \sin(\theta_i - \theta_k) \} = 0 \]  

(2.2)

\[ Q_{Gi} - Q_{Li} - V_i \sum_{k=1}^{N_k} v_k \{ G_{ik} \sin(\theta_i - \theta_k) - B_{ik} \cos(\theta_i - \theta_k) \} = 0 \]  

(2.3)

(Voltage limit)

\[ V_{ij_{\text{min}}} \leq V_{ij} \leq V_{ij_{\text{max}}} \]  

(2.4)

(Switch status)

\[ SW_i = \begin{cases} 
0 & \text{(if switch i is open)} \\
1 & \text{(if switch i is closed)} 
\end{cases} \]  

(2.5)

(Branches capacity limit)

\[ I_{ij} < I_{b_{\text{max}}} \]  

(2.6)

(Short circuit capacity limit)

\[ SCC_{ij} < SCC_{\text{max}} \]  

(2.7)

(Radial distribution system)

\[ Neb = N-1 \]  

(2.8)

\[ \text{Rank} \ (A) = N-1 \]  

(2.9)

Where
2.2. Reconfiguration Algorithm for Power Loss for Minimum and SCC Reduction Based on MBPSO

In the paper, Modified Binary Particle Swarm Optimization (MBPSO) is used for switches optimal combination. BPSO is an optimization method of discrete problem based on PSO and be proposed by Kennedy and Eberhart in 1997[7]. BPSO has fewer parameters and can be converged fast, moreover the result isn’t affected by the initial state value. The demerit of BPSO is easy to lead to local convergence. Tabu Search algorithm is able to prevent the fitness from local convergence[8]. To avoid local convergence, Tabu Search algorithm and BPSO are hybrid to be used to find the gbest in this paper. In detail, if the value of gbest is invariable and the number of times for this gbest is over the setting threshold value, this gbest will be considered as the initial state, at the same time, Tabu search algorithm will begin. Furthermore, during searching process, once the fitness of gbest is better than the initial value(gbest), the tabu search process will be terminated. The above measures are performed and the proposed method is called the modified BPSO (MBPSO).

The constraints must be treated especially because the initial BPSO does not take into account them. The equation constraints will be statisfied while the network configured and power flow calculated. In this paper, to dispose the inequation constraints, the double fitnesses will be formed, namely, one is the loss minimized fitness, the other is the constraint fitness which is defined according to reference[9]. Furthermore, the constraint fitness will be priority. It can be sure to converge quickly into the solution zone.

2.3. Average Load Simulated Method

Average load simulated method (ALS method) is that the average load value is used to instead of the actual load to calculation. In detail, the daily load is divided into several stages according to different load (such as light, normal and heavy load stage), then calculating the average load ratio of every stage, afterward, network reconfiguration is done, the optimal switches combination is got by MBPSO algorithm. However, the fitness of switch status used to update pbest and gbest of particle is the losses, which is calculated by the average value of all loads in a stage. Therefore, the calculation time of network reconfiguration in a stage can be decreased. Finally, the hourly loss under optimal network configuration is calculated once more by using the actual load.

2.4. Algorithm of Proposed Method

The Algorithm of ALS method for loss minimization considering SCC reduction and load variation can be described in detail as follows:

1. Input the data and initial parameters. For example, the impedances of branches, active and reactive power of loads, initial status of switches, the number (Ns) of divided stages, number of particles, the value of criterion for stages divided.
2. Confirm the divided stages number ($N_s$) of each particle, stage $i=1$.
3. Get the optimal network in stage $i$ using the average load as described above and the flowchart is shown in Figure 2.
4. $i=i+1$, then go to step 3.
5. Continue until termination criterion ($i>N_s$) is satisfied.
6. Obtain the optimal network in each stage, and then calculate the hourly loss using the actual load.
7. Put out the $gbest$, which includes the loss minimum in a day, the optimal switch combination in each time stage and the optimal divided time mode in a day.

The flowchart of finding the optimal network by network reconfiguration is based on MBPSO in a stage. Figure 2 is the flowchart of finding the optimal network by network reconfiguration based on modified BPSO and average load in a stage. The whole flowchart of ALS method is shown in Figure 1.

3. Case Study
Based on the configuration of reference [10], the data of test system is modified. The test system is a 6.6kV distribution system with 33 nodes, 37 branches (including 5 tie branches). The peak load includes 6.17MW active power and 3.96MVar reactive power. The initial network configuration is shown in Fig. 1. In the figure, solid lines represent the branches in service and with closed switches; Dotted lines represent the cut-off branches with open switches. The numbers 0~32 represent the nodes 0~32 and the number with ‘s’ represents line switch, respectively. In the test system, the maximum of short circuit current through CB is the one through CB1 as CB1 is near to the upper system and all of the fault currents from generators flow through it. Hence the 3-phase short circuit is supposed to occur at the outlet of CB1 (lines side) in location A (Figure 3). The maximum of interrupting capacity of

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**Figure 1.** Flowchart of average load simulated method

**Figure 2.** Flowchart of network reconfiguration based on average load
CB1 is also considered as the constraint of SCC during simulation.

Figure 3. Initial network configuration of test system

The data of system constants is given in Table 1.

Table 1. System constants

|          | $S_b$ | $V_b$ | $V_{min}$ | $V_{max}$ | SCC$_{max}$ |
|----------|-------|-------|-----------|-----------|-------------|
|          | 1MVA  | 6.6kV | 0.95 p.u. | 1.05 p.u. | 143 p.u.    |

|          | $\omega_{max}$ | $\omega_{min}$ | $T_{kmax}$ | $C1$, $C2$ | Number of particles |
|----------|-----------------|-----------------|------------|------------|---------------------|
|          | 0.9             | 0.4             | 50         | 2          | 100                 |

DG units are rotary generators and in this case study, the DG is the decentralized type and data is given in Table 2.

Table 2. Data of DG

| DG          | Installed Node | P(p.u.) | Q(p.u.) | $x'_d$(p.u.) |
|-------------|----------------|---------|---------|---------------|
| Decentralized type | 2–17, 22–24 | 0.3     | 0.185   | 0.161         |

* $x'_d$: The sub-transient reactance of DG relative to its capacity

In the following simulations, the load variation will be considered when loss and SCC are calculated. The daily load curve in summer used for simulation and data is from reference [9].

For the decentralized type of DG, to compare with the results of ALS method the following three cases are considered; Case I is that the daily load is divided into three stages; Case II is that two stages are divided; and Case III is that there is only one stage in a day. The images of three cases are shown in Figure 4.

Figure 4. Simulated load curves of three cases

3.1. Comparision with Different Optimal Methods

In this section, to confirm the effects of modified BPSO method on convergence and precision of calculated results, the BPSO and Tabu Search methods are also done for test system with decentralized DGs. The losses minimum of each method during iteration is shown in Figure 5.
3.2. Results of Simulation

Table 3 shows the values of divided criterion (DR), average load (AL) and divided time (DT) in each stage for 3 cases.

|        | Case I     | Case II      | Case III |
|--------|------------|--------------|----------|
|        | Light      | Normal       | Heavy    | Low     | High   |
| DR     | <0.75      | [0.75,0.9]   | >0.9     | <=0.65  | >0.65  |
| AL     | 0.64       | 0.79         | 0.94     | 0.57    | 0.87   | 0.74    |
| DT     | 8, 17, 23 o’clock | 7, 23 o’clock | ---      |

This time, the network reconfiguration of ALS method is performed for each stage in the 3 cases by using load data shown in Figure 4. The optimal combination of switches is shown in Table 4. The loss and SCC1 in any time are calculated using optimal networks and the results are shown in Table 5. From the two tables, the conclusions of losses reduced and short circuit capacity decreased can be understood. The calculation time is about 1 hour and decreased by a wide margin.

However, in Case III, the results couldn’t be obtained. Voltages are over the limitation at some nodes for the actual load in the conditions of the optimal network obtained by average load. The reason is considered as follows: the optimal network is obtained based on average load, during reconfiguration, in order to minimize the losses; the margin of constraint variable to the limitation is few. If the value of actual load in a stage is bigger or smaller too much than the value of average load, calculation results using actual load may be over the constraint limitation. The differential of loads in the same stage for ALS method is small as far as possible.

|        | Case I      | Case II     | Case III |
|--------|-------------|-------------|----------|
|        | stage 1     | stage 2     | stage 1  |
|        | S9, S13, S23, S28, S33 | S5, S10, S14, S33, S34 | S7, S10, S13, S22, S34 |
|        | stage 2     | stage 2     | stage 2  |
|        | S4, S10, S13, S33, S34 | S5, S10, S14, S33, S34 | ---      |
| Open switches in normal | | | |

|        | Case I     | Case II     | Case III |
|--------|------------|-------------|----------|
| TCTOS  | 20         | 12          | ---      |
| SCC1(MVA)| 140.7~142.3| 138.6~142.3 | ---      |
| loss(kWh)| 1319.3 | 1324.2 | ---      |
| LRR    | 70.9%      | 70.8%       | ---      |

*: TCTOS is the number of total changing times of switch; LRR is power loss reduced ratio to the loss of initial network with DGs

Table 4. Open switches in each stage for 3 cases

4. Conclusion

As we know, when large penetration of DGs are connected to the distribution system, the power losses
may be increased and it happens probably that the short circuit current through some circuit breakers is over the interrupting capacity of CB in fault. From the discussion above, the characteristics of average load simulated method (ALS method) proposed can be summarized as follows:

In the paper, network reconfiguration based on MBPSO algorithm is used for power losses minimization and short circuit capacity. An approaches for losses minimization and short circuit capacity reduction are proposed considering load variation. MBPSO algorithm uses double fitnesses to consider the constraints, it can decrease the calculation time.

The power losses won’t be increased too much even if the short circuit capacity constraint is considered; voltage profiles are better with the constraint of short circuit capacity considering.

Considering the impacts of load variation on the losses, on account of the model of load used for the network reconfiguration, average load simulated method (ALS method) are approved. approach is to divide the loads into stages and network reconfiguration in each stage is done to minimize the losses and reduce the short circuit capacity, finally got the minimum of losses in the whole interval time. The results of simulation certify the approaches will decrease drastically the losses and improve the voltage profiles obviously, at the same time, the short circuit capacity is also decreased into less the shut-off capacity of circuit breaker.

The ALS method is simple and calculated time is speed, however, it is strict with the loads in the same stage.

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