Intelligent power supply restoration in power distribution networks with distributed generation

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Abstract—Currently the penetration of various forms of distributed generations (DGs) has significantly increased. Such active distribution network with bidirectional power flows brings direct challenges to network control and operation, e.g. increased fault levels and protection degradation. In this paper, an intelligent sequential power supply restoration solution is presented which can be carried out by either reconfiguring network topology or utilization of the embedded DGs for load supply in an island mode, to restore loads as much and quickly as possible. The proposed restoration model mainly considered three kinds of indicators: load recover rate and the current allowance of influenced branches when opening or closing a switcher, and time cost of changing the status of switchers in the sequential restoration process. What’s more, the priority of critical loads were satisfied as far as possible. The performance assessment of two test scenarios is carried out in the 53-bus distributed network and the numerical result verifies the effectiveness of the proposed solution.

Index Terms—Active distribution network; Power supply restoration; Topology reconfiguration

I. INTRODUCTION

The massive penetration of distributed generations in current medium/low voltage distribution networks bring direct challenges in terms of increasing fault level and protection degradation, and hence the security of power supply. The ultimate goal of power supply restoration is to restore as much supply to demand (critical loads with priority) as possible and as fast as possible upon the power supply interruptions [1]. The state-of-art approaches in the literature mainly coping with the power supply restoration issue have not been designed with explicit consideration of the restoration scope. The available power supply restoration solutions either deal with the partial failure through operation of connection switch gears (i.e. topology reconfiguration) (e.g. [2]-[4]) or utilize the embedded DGs to restore the power supply service once the power from the utility are not possible in a large scope (e.g. blackout [5, 6]).

However, with the increasing penetration level of DGs in existing power distribution network, the potential impacts of DGs in network restoration were studied in recent years. The work in [7] focused on service restoration in distribution systems with integrated DG units. The fault can be detected and located and the optimal reconfiguration of the system can be obtained by multi-agent control system. The author takes full account of post-fault response modes of DG units, and unintentional islanding operation of DG units can be avoided. In [8], the author dealt with the service restoration problem in renewable-powered micro-grids that are driven islanded by an unscheduled breakdown from the main grid. The light spot of this paper is that the intermittency nature of the renewable power and uncertainty of the duration of breakdown were taken into account in the paper. A two-scenario splitting, in which a Lagrangian technique and
dynamic programming method was utilized to solved the problem. In [9], a probabilistic based analytical method was developed to assess the distribution network reliability by using the performance metrics of average interruption duration and average interruption frequency in the presence of both dispatchable and nondispatchable renewable DGs.

Among all these relevant literature, some of them propose remarkable optimization algorithms, e.g. multi-agent system based solution [10], fuzzy multi-objective model [11] and genetic algorithmic solution [12]. A detailed analysis of stability during restoration using WAMS was proposed in [13]. In [14], the authors proposed a methodology, based on CPM/PERT graph theory, that allows power system restoration plans to be graphically visualized. By this way, the operating staff comprehension about the restoration plan were enhanced.

In the current literature, to the author’s best knowledge that there is no solution available to combine these two power restoration paradigms (topology reconfiguration and DG-based restoration) into a unified framework. This paper focus on power supply restoration problem in the context of active distribution networks with DGs, and present an intelligent sequential restoration model considering about the security and stability of the system and the priority of loads. The main technical contributions made in this paper can be summarized as follows:

1. The restoration solution can automatically select appropriate supply restoration strategy (i.e. topology reconfiguration or DG-based restoration) with the condition of satisfying the basic network demand, in accordance with the scale of the area affected by the faults and the network topology.

2. In the restoration optimization model, the impacts on security and stability of the system owing to the power flow variation were considered. The allowance of branches on which the power flow was influenced owing to the restoration process were utilized as an index to find the optimal sequential recovery path.

The rest of this paper is organized as follows. In section 2, the intelligent power supply restoration approach was introduced; section 3 presents two scenarios a set of numerical experiments are carried out to verify the effectiveness of the proposed power supply restoration approach; finally, the conclusive remarks are given in section 4.

II. PROPOSED RESOTRATION APPROACH

A. Power Supply Restoration Scheme

As most of the faults in the distribution system are transient, the increasing DG in the distributed system can be utilized to restore most part of the loads in some cases instead of changing the system topology like the traditional way. Obviously, the costs of DG-based restoration is far less than that of topology restoration, but in DG-based restoration, some non-critical but non-fault loads may remain unsupplied, which is acceptable in transient fault cases. Fig.1 illustrates the power supply restoration of the proposed solution two fault cases (case 1 and case 2): restoration process with and without changing the network.

In this paper, the system can automatically choose its restoration method to maximize the recovery loads, especially the critical loads, while minimize the costs of operating switchers. Recovery rate is regarded as the indicator to distinguish these two methods. The key component of the power supply restoration process can be summarized as follows:

1. Confirm the fault bus, and open the related switchers.
2. Firstly, DG-based restoration method is applied to recover as much as possible load;
3. Calculate the recovery rate of DG-based restoration method, and check if the requirements of recovery rate (recover all the critical loads and 70% of non-critical loads) are met;
4. If the restoration path obtained by DG-based restoration method can satisfy all the requirements, then stop;
5. If not, topology restoration method were chosen to restore the system, then stop.

B. Objective Functions

The power supply restoration problem in active distributed system with DG can be formulated as a multi-objective integer optimization problem [15]. The objective function of these two methods are approximate the same, but the difference is whether to change the status of the inter-switchers to change system topology.

\[
\min F = \sum_{n=1}^{N_{\text{swi}}} \left[ \beta_1 f_{1n} + \beta_2 f_{2n} + \beta_3 f_{3n} \right] 
\]

\[
f_{1n} = \sum_{i=1}^{N_{\text{swi}}} \sum_{q=1}^{N_{\text{t}}} \alpha_i x_{iq} 
\]

\[
f_{2n} = \sum_{i=1}^{N_{\text{swi}}} \sum_{j=1}^{N_{\text{t}}} \rho_{ij} y_{ij} / \text{dis}_{ij} 
\]

\[
f_{3n} = \sum_{i=1}^{N_{\text{swi}}} \sum_{k=1}^{N_{\text{t}}} \pi_{ik} I_{k} - I_{\text{limit},k} / I_{\text{limit},k} 
\]

In the sequential restoration process, one switcher was chosen to be closed at every turn. The objective function consists of the costs of all the switchers need to close in the restoration process. In (1), the objective function consists of three parts, time costs of switchers, penalty of not recovering all the non-fault loads and penalty of increased load rate of non-fault branches.

In (2), \(\alpha_i\) represents time costs of different types of switchers. The cost of local switcher is lowest, with \(\alpha_i = 0.1\).
and the cost of inter-switchers are higher relatively. What’s more, we suppose that all of the buses belong to different zones according to which bus line it connects to. And inter-switchers connecting the same zones ($\alpha_s = 0.2$) are lower than inter-switchers connecting two different zones ($\alpha_s = 0.3$). In (3), $\rho_{ij}$ present the priority of different loads. In order to recover the critical loads at first place, we suppose the priority of critical and non-critical loads is 100 and 1.

In (2), (3) and (4), $x_i, y_i$ and $z_i$ are the variables of function $f_{in}, f_{2n}$ and $f_{3n}$ respectively. However, in the process of optimization, $x_i$ is selected as the direct variable of $F^i$, while $y_i$ and $z_i$ are the indirect variables, which is changing with $x_i$.

It should be noted that, the importance of these three indicators is not the same. In general, the most important indicator is to recover highest possible loads, with $\beta_1 = 5$. The significance level of time cost ($\beta_2 = 3$) is higher than that of penalty of power flow variation ($\beta_3 = 2$). A hierarchical penalty mathematical function was introduced to fit the different importance of the indicators and normalized the indicators. In [2], $\phi(x)(i=1,2,3)$ is hierarchical function, which can be defined as follows [16], we had

$$\phi = \phi\left(f_i(x_n), x_n \in X\right)$$

where for all $x_i \in X$, $\phi(0) = 0$ and

$$d(\phi(f_i(x_n))) = \begin{cases} 
1, & 0 \leq f_i(x_n) < a_1 \\
3, & a_1 \leq f_i(x_n) < a_2 \\
10, & a_2 \leq f_i(x_n) < a_3 \\
70, & a_3 \leq f_i(x_n) < a_4 
\end{cases}$$

(5)

(6)

C. Constrains

Constraints were divided into three categories. In the restoration process, the constraints would be checked at every turn. If all the constraints were satisfied at one turn, then we can search for the next switches to close. Otherwise, the optimization would work until a feasible switcher was found.

1) Operation constrains

$$\sum_{i=1}^{N} P_i x_{\text{nom}, i} - \sum_{i=1}^{N} P_i x_{\text{nom}, i} = P_{i0} y_i$$

$$\sum_{i=1}^{N} Q_{i0} x_{\text{nom}, i} - \sum_{i=1}^{N} Q_{i0} x_{\text{nom}, i} = Q_{i0} y_i$$

$$I_j Z_{ij} = \frac{P_{ij} R_{ij} + Q_{ij} X_{ij}}{U_{ij}^2} x_{\text{nom}, i}$$

(7)

(8)

(9)

These constrains are the basic power flow constrains which should be satisfied during the period of operation. In (7) and (8), active power and reactive power balance equations were presented. While the constraint given in (9) represents the compliance to Kirchhoff’s second law for each branch of the system.

2) Safety constrains

$$y_i V_j \leq V_i \leq y_i V_j$$

$$I_j^2 \leq y_i I_j^2$$

(10)

(11)

The constraint given in (10) and (11) represent the operation limits of voltage and current, respectively.

3) Variable constrains

$$\sum_{i=1}^{N} x_i = 1$$

$$y_i + y_i \geq x_{\text{nom}, i}$$

$$x_i \in \{0, 1\}$$

$$y_i \in \{0, 1\}$$

(12)

(13)

(14)

(15)

The constraint (12) confirms one switcher can be operated at a time. In (13), it shows the relationship between $x_i$ and $y_i$. If the branch between bus $i^o$ and bus $j^o$ is closed, the status of $y_i$ and $y_j$ is 1. Otherwise, it is 0. In (14) and (15), the data ranges of $x_i$ and $y_i$ are given.

III. NUMERICAL RESULTS

In this section, a set of numerical experiments were carried out to verify the effectiveness of the proposed power supply restoration solution using the 53-bus distribution network, as adopted in previous work [2], [17]. The topology and configuration of the test network is shown in Fig. 3, and the parameters of buses and branches are adopted from [2]. There are in total 3 substations and 50 buses with the nominal voltage and total demand of 13.8 kV and 45.67+22.1 MVA, respectively. It is supposed that the substation bus voltage is 1.05p.u and the upper and lower voltage limits of buses are 1.05p.u and 0.95p.u. respectively.

The proposed power supply restoration approach is implemented in Matlab and the mixed integer programming optimization problem is solved using CPLEX version 12.5.

Fig. 3 The topology and configuration of 53-bus test network

A. Scenario 1

The proposed supply restoration method is assessed through a comparative study of two different supply restoration approaches: (1) no critical loads priority and no partition in the system (2) with critical loads priority and partition in the system. In the first method, all loads are in the same priority, and the costs of closing an inter-switcher connecting different or identical zones are the same. While in the second method, some of the loads are critical loads, which should be recovered firstly and quickly. What’s more, the inter-switcher connecting different or the identical zones...
shows different costs. All the single-point faults in the network were considered in the study.

The curve of recovering rate of critical loads and all loads with closing switcher times are shown in Fig. 4. From the Fig.4 (d), the recovery rate curve of critical loads changing rapidly in first three times and the recovery rate reached 70% after changing 3 switchers by using the second method. However, the uptrend of recovery rate of critical loads by using the first method, in Fig.4 (d) is slower than second method as a whole, and it almost need closing 5 switchers to recover 70% of critical loads. As for the condition of all loads, the curve of two methods are alike. Whereas, the difference is that the recovering rate in second method is a little lower than the first tests in that the recovering line is sparser in upper half of Fig.4 (c) than that in Fig.4 (a). As for the numbers of switchers to close to recover 70% all loads, the number are similar by these two methods, both about 6 times. In short, the recovering speed of critical loads is much faster in second method while the recovering trend of all loads is near the recovering trend of first method.

(a) Recover rate of all loads in first method; (b) Recover rate of critical loads in first method; (c) Recover rate of all loads in second method; (d) Recover rate of critical loads in second method

Fig. 4 The recovery rate for critical loads and all power load

In Fig. 5, the performance results in terms of the safety indicators of the power supply restoration process, which includes over-voltage rate and line capacity, is presented. The voltage limit in the restoration process is [0.95,1.05], but the anti-interference ability of the system is relatively stronger if buses voltage are in [0.98,1.02]. The excessive part over [0.98, 1.02] of all the buses were summed up, and the data are shown in Fig.5 (a). It’s not difficult to find that the total over voltage condition in second method is higher than that in first method owing to the priority of recovering critical loads. As for the capacity allowance, the load rates of some non-fault branches would be influenced accordingly if the system topology changes. And we hope the distances between the upper limit and actual value of current of each influenced branches are higher the better. The distances between the upper limit and actual value of current of each influenced branches in the restoration process were summed up in every single-point faults. In Fig.5 (b), the capacity allowance is mostly the same, but the capacity of second method is lower than that of first method in some cases. However, with the distinction of inter-switcher connecting different zones and the identical zones, the inter-switchers in the same zones would be chosen to recover loads, which can reduce the over limit of line in recovery process.

Over voltage rate

(a) Over voltage rate

(b) Capacity allowance

Fig. 5 The safety indicators of the restoration process

The system restoration always pay close attention to the time costs and the stability of the system. We consider the time costs and the safety allowance, which are the second and third indicators of $F$ relatively, as the total costs in the restoration process. The costs of first method were regarded as a benchmark, and the ratios between first and second method of every single-point faults were shown in Fig.6. In Fig.6, the costs of these two method is same in most cases, but the cost of second method is much lower than that of first method in some cases on account of the partition of the system. However, there are also some cases, where the costs of second method are a little higher than the first method, by the reason of the need of recovering critical loads.

Fig. 6 The cost ratios between tests with and without critical loads and partition

B. Scenario 2

In this scenario, a sets of experiments were carried out to verify the effectiveness of the intelligent selective method. In the first sets of experiments, the restoration method without selection but only topology restoration was utilized. While in the second sets of experiments, we can choose DG-based recovery or system configuration in the restoration process. All the cases of single-point faults were carried out likewise.

The curve of recovery rate of critical loads and all loads in both method are shown in Fig. 7. In (b) and (d), the curve
of recovery rate are almost same, except for two cases, where the supplied faster in second loads are same in both loads, the uptrend of two g. 7 (a) and (c), and the to recover 60% loads in method.

Fig. 7 The recovery rate of critical loads and all power loads

The results of safety indicators in two methods were presented in Fig.8. In (a), it’s not difficult to find that the total over voltage in second method is higher than that in first method, especially in right half of the figure. It’s because of lacking DG and inter-switchers in node 46-50, and when fault happens, the loads need to be recover is much higher than the supply. Thus buses are in unstable statuses. So the over voltage is higher. In Fig.8, the capacity allowance is mostly the same, except for some difference, and the capacity of second method is lower than that of first method owing to the intelligent selection of inter-switchers in the identical zones, which can ease the load rates of branches.

Fig. 8 The safety indicators of the restoration process

IV. CONCLUSION AND REMARKS

In this paper, an intelligent restoration scheme in distribution system with DG was proposed. A mathematical restoration model was presented to recover all the critical loads as soon as possible and as much as possible loads. And the mix integer model was solved efficiently by the commercial solvers, CPLEX. The numerical result obtained from the experiments clearly demonstrated the excellent performance of the intelligence restoration method with considering of the critical loads. In respect to the future work, two research directions are considered worth further efforts: The restoration algorithmic solution can be further validated and assessed through the application in trial studies in realistic networks. Also, the outcome of this study can be incorporated into the planning of active distribution works to optimally allocate the resources (e.g. DGs and storage units) to enhance the network robustness and reliability.

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REFERENCES


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