Service restoration to critical loads using microgrids considering dynamic performance of DGs

Lingyun Tao¹, Jinghan He¹, Ying Wang¹, Yin Xu¹,², Xiaojun Wang¹
¹School of Electrical Engineering, Beijing Jiaotong University, Beijing, People's Republic of China
²E-mail: xuyin@bjtu.edu.cn

Abstract: When an extreme weather event strikes a distribution system, it is helpful to use microgrids to restore the interrupted critical loads. Due to the relatively small capacity and low inertia of distributed generators (DGs), the switching operations during the restoration process may cause severe fluctuations in voltage, current, and frequency, leading to prime-mover stalling or triggering protection relays. It is essential to investigate the dynamic characteristics of DGs during the restoration procedure. The dynamic models of different types of DGs are developed to analyse the dynamic characteristics. Analytical constraints on the dynamic performance of DGs are obtained from the simulation results, which can be incorporated into the optimisation models of critical load restoration problems. The modified IEEE 32-bus test feeder is simulated to validate the effectiveness of the proposed method.

1 Introduction

Extreme weather events, such as hurricanes, floods, and thunderstorms, have become more intense in recent decades as a result of climate change and global warming. Electrical power systems may suffer severe attacks from extreme weather events, which can cause extended outages and significant economic losses. For instance, in 2008, a snow storm attacked Southern China and caused a power outage to over 14.66 million customers, leading to an economical loss of over 10.45 billion Chinese Yuan [1]. In such condition, restoring service to critical loads as fast as possible is of considerable importance.

A microgrid can operate either in the grid-connected or islanded mode. This feature makes microgrids a viable resource for service restoration in smart distribution networks. The interconnection of distributed generators (DGs) and microgrids enables distribution system self-healing and accelerates the restoration process by providing additional restoration capacity. After a major disaster, the utility power may be unavailable. In such cases, DGs and microgrids can be used to restore critical loads on neighbouring distribution feeders [2, 3]. In [4], integration schemes of DGs in network reconfiguration for service restoration are introduced. A decentralised multi-agent system approach using controlled DGs for service restoration is proposed in [5]. In [6, 7], the un-faulted outage region is sectionalised into temporary microgrids with DGs to provide power supply to local loads.

By modelling microgrids as virtual feeders, a spanning tree search algorithm is proposed in [8] to develop restoration strategies. Considering the limited capacity of DGs and the uncertainties of intermittent energy, a critical-load restoration method using microgrids is proposed in [9].

It is shown that microgrids can improve the restoration capability of a distribution system [10]. A major issue of using microgrids for service restoration is that DGs within a microgrid have relatively small generation capacity. Therefore, their ability to withstand disturbances and maintain system stability is not as good as that of large generators in transmission systems [11]. Restoration actions, such as load pick-up and transformers energisation can cause significant transients, which can cause a prime mover to stall or trigger relevant protection relays to trip the DGs [12]. Such undesirable events can result in failure in the implementation of a restoration plan. Therefore, it is essential to consider the dynamic performance of DGs when determining a restoration plan.

In this paper, the feasibility of service restoration plans is evaluated, considering the dynamic performance of DGs. The dynamic models of three types of DGs are developed. Simulations are conducted to investigate the dynamic performance of the DGs and assess the availability of using individual microgrid for service restoration. In addition, the dynamic constraints are extracted from simulation results, which can be incorporated into the restoration optimisation model. The contributions of this paper include:

(i) The dynamic performance of different types of DGs is analysed and used to assess the availability of a microgrid for service restoration. The availability assessment is more practical and can be used to determine the proper restoration scheme.

(ii) The dynamic constraints that can be incorporated into the restoration optimisation model are obtained by dynamic performance analysis. There is no need to run transient simulations in the optimisation process, which significantly reduces the computation time.

The remaining of this paper is organised as follows. Section 2 investigates the dynamic performance of DGs. Section 3 analyses the feasibility of using a microgrid for service restoration. In Section 4, numerical simulation results for a 32-bus test system are presented. The conclusion is given in Section 5.

2 Dynamic performance analysis of DGs

2.1 Operational considerations of service restoration

During the restoration procedure, the associated switching operations will result in an inrush current which depends on the amount of load energised and the capacity of transformer energised. Without a strong generation resource in island mode, the inrush current will cause large frequency and voltage transients. Moreover, in order to avoid the damage to connected devices, there are several standards and requirements for interconnection of DGs with electrical power systems [13–15]. These standards provide requirements relevant to the performance, operation, safety considerations, and maintenance of the interconnection. In addition, the connected DGs should respond to abnormal conditions arising on the grid. Tables 1 and 2 show the DGs’ response to abnormal voltage and frequency in different standards, respectively. According to those standards, the switching transients associated with service restoration operations may cause the connected DGs to trip off-line during the transients. The loss of DGs may increase the magnitude of the transient or cause the microgrid to become unstable and collapse. Therefore, the dynamic
performance of the DGs in a microgrid should be considered in the design of restoration schemes when using microgrids for service restoration.

2.2 Dynamic performance analysis of different types of DGs

The DGs in a microgrid can be categorised into two major types by the interface to the utility grid, i.e. synchronous-generator-based DGs and inverter-based DGs. Moreover, inverter-based DGs can be further categorised into rotating-machine-driven DGs and DC-source-driven DGs. There are differences in dynamic characteristics among different types of DGs. The dynamic features of the three types of DGs are studied in this paper, including the synchronous-generator-interfaced DG, inverter-interfaced rotating-machine-driven DG and DC-source-based battery energy storage system. Renewable energy generation systems with variable output, such as photovoltaic energy conversion systems, are not adopted for restoration because of the output uncertainties.

2.2.1 Synchronous-generator-interfaced DG: Microgrids with natural gas engine driven DGs are more likely to be favoured by both industries and utilities in the near future as a result of their low costs. The dynamic model of synchronous-generator-interfaced natural gas engine driven DG is presented to investigate the dynamic performance in islanded mode. The model has a series of subsystems to represent its physical behaviour. Typically, it contains a natural gas engine coupled to the synchronous generator through a mechanical shaft. The rotor speed is controlled automatically by a speed governor. A digital voltage regulator is used to control the excitation system which in turn regulates the terminal voltage. In the dynamic analysis, the maximum limit on the mechanical power given by the power curve of the prime mover is considered. Moreover, there is an inherent delay between the fuel flow and the actual torque production in natural gas engines. This time delay should also be considered [16].

A synchronous-generator-interfaced DG of a 208-kW rating power is developed to analyse the dynamic performance. Figs. 1 and 2 illustrate the output power and frequency of the synchronous generator-interfaced DG when a step change in the electrical load of 0–160 and 0–200 kW are applied, respectively. When a 160-kW load is applied, there is a drop in frequency as the mechanical torque cannot increase instantaneously to compensate the electromagnetic torque. The rotor speed is restored by the governor. However, it is observed in Fig. 2 that a 0–200 kW load change results in stalling of DG's prime mover and frequency collapse. The root cause of stalling lies in the slow response of the primary governor and a mechanical power limit of the reciprocating engine [17]. When a large load change occurs, the prime-mover speed is slowed down due to the delay in governor response. Because of the mechanical power limit, there is a mismatch between electromagnetic power and mechanical power. During a long-time power mismatch, the stored kinetic energy of the generator is depleted, resulting in prime mover stalling. For this reason, the load step change limit on individual synchronous-generator-interfaced DG should be considered when making a restoration plan.

2.2.2 Rotating-machine-driven inverter-interfaced DG: Microturbine generation systems are gaining popularity in distributed power generation because of their smaller size and higher efficiency compared with the conventional gas turbines. The studied microturbine generation system (MTGS) is composed of a permanent magnet synchronous generator (PMSG) and a gas turbine whose rotational speed is up to 80,000 rpm. The output power is developed to analyse the dynamic performance. Figs. 1 and 2 illustrate the output power and frequency of the synchronous generator-interfaced DG when a step change in the electrical load of 0–160 and 0–200 kW are applied, respectively. When a 160-kW load is applied, there is a drop in frequency as the mechanical torque cannot increase instantaneously to compensate the electromagnetic torque. The rotor speed is restored by the governor. However, it is observed in Fig. 2 that a 0–200 kW load change results in stalling of DG's prime mover and frequency collapse. The root cause of stalling lies in the slow response of the primary governor and a mechanical power limit of the reciprocating engine [17]. When a large load change occurs, the prime-mover speed is slowed down due to the delay in governor response. Because of the mechanical power limit, there is a mismatch between electromagnetic power and mechanical power. During a long-time power mismatch, the stored kinetic energy of the generator is depleted, resulting in prime mover stalling. For this reason, the load step change limit on individual synchronous-generator-interfaced DG should be considered when making a restoration plan.

Table 1 Interconnection system response to abnormal voltages

| Standard   | Voltage range (% of base voltage) | Clearing time, s |
|------------|-----------------------------------|------------------|
| IEEE 1547  | V<50                              | 0.16             |
|            | 50 ≤ V <88                        | 2.0              |
|            | 110 ≤ V <120                      | 1.0              |
|            | V≥120                             | 0.16             |
| IEC 61727  | V<50                              | 0.1              |
|            | 50 ≤ V <85                        | 2.0              |
|            | 110 ≤ V <135                      | 2.0              |
|            | V≥135                             | 0.05             |
| VDE-AR-N 4105 | V<80                      | 0.2              |
|            | V>110                             | 0.2              |

Table 2 Interconnection system response to abnormal frequencies

| Standard   | DG size     | Frequency range, Hz | Clearing time, s |
|------------|-------------|---------------------|------------------|
| IEEE 1547  | P ≤ 30 kW   | f > 60.5            | 0.16             |
|            |             | f < 59.3            | 0.16             |
|            | P > 30 kW   | f > 60.5            | 0.16             |
|            |             | f < 57.0            | 0.16             |
| IEC 61727  | S ≤ 10 kVA  | f > 51              | 0.2              |
|            |             | f < 49              | 0.2              |
| VDE-AR-N 4105 | S ≤ 30 kVA  | f > 51.5           | 0.2              |
|            |             | f < 47.5            | 0.2              |

Fig. 1 DG performance under a 0–160 kW step change in electrical load (a) Power output, (b) Frequency

Fig. 2 DG performance under a 0–200 kW step change in electrical load (a) Power output, (b) Frequency
Electromagnetic power of the PMSG is at high frequency. For this reason, a power conversion system between the microturbine and the utility load is required. Fig. 3 shows the typical configuration of an MTGS connected to the grid through a back-to-back pulse-width modulator converter. The generator-side converter is controlled to maintain the DC-link voltage and a unit power factor of the PMSG. The grid-side converter is controlled to maintain the AC side voltage and frequency. Similar to the synchronous-generator-interfaced DGs, the MTGSs with rotating machines as prime movers are also expected to stall when suffering large load changes. A 0–85 kW step change in load is applied to the terminal of an MTGS with a 90-kW rating power. As shown in Fig. 4, the power conversion system controls cannot prevent the output voltage collapse when prime-mover stalling occurs.

When an outage occurs, a microgrid can supply power to the interrupted area in the medium-voltage feeder through a step-up transformer. The inrush current occurs during transformer energisation due to flux saturation in the core. The saturation results in the high amplitude of magnetising inrush current which can exceed the nominal magnetising current more than hundreds of times and is comparable to short-circuit currents. The inrush current can cause malfunction of fuses or protective relays. Compared with the synchronous-generator-interfaced DGs, the inverter-interfaced DGs have relatively poor ability to withstand an overcurrent. Due to the poor overload capability of power semiconductor devices such as insulated-gate bipolar transistors (IGBTs), the over-current detection circuit and protection are used to protect semiconductor devices in the converters. A typical setting of an overcurrent relay of the IGBT in the converters is 150% of the rated current. Fig. 5 shows the inrush current when an MTGS of a 136.7 A rated current energises a step-up transformer. The maximum value of three-phase inrush currents is 238.6 A, which exceeds 150% of the rated current of IGBTs. It will trigger the overcurrent protection to trip the MTGS and may lead to instability of the microgrid. To avoid these issues, the feasibility of using MTGSs for service restoration should be assessed by considering its dynamic performance when developing a restoration scheme.

2.2.3 Inverter-interfaced battery energy storage system: Energy storage devices are another type of DGs that are one of the essential components in a microgrid. The energy storage plays an important role in stabilising the voltage and frequency under extreme load transients. The typical configuration of a battery energy storage system (BESS) is shown in Fig. 6. The battery is modelled by a controlled voltage source in series with a constant resistance [18]. The power conversion system includes a DC-to-DC converter and a DC-to-AC inverter, connecting the battery to the power grid. Fig. 7 shows the inrush current when a BESS of a 68-A rated current is used to energise a step-up transformer. The maximum instantaneous value of the inrush current is 119 A, which exceeds 150% of the rated current of IGBTs. Similar to the inverter-interfaced MTGS, availability of the BESS for service restoration should also be evaluated by considering its dynamic performance.
3 Feasibility evaluation of individual microgrid for service restoration

3.1 Microgrid availability assessment

A microgrid is an electrical network for integration and coordination of DGs and loads that can operate either in grid connected mode or in islanded mode. A simplified microgrid model is used in this paper, as shown in Fig. 8. Three DGs and an aggregated load representing critical loads are connected at the bus. The microgrid is connected to the distribution system through a transformer at the point of common coupling (PCC). For a microgrid with multiple DGs, droop control strategy is used to achieve active and reactive power sharing among the DGs.

As mentioned in Section 2, for a microgrid containing inverter-interfaced DGs, the energisation inrush of a transformer may exceed the threshold of the overcurrent protection of the inverters, which may trip the inverter-interfaced DGs. The undesired event can lead to power imbalance and instability of the microgrid. Therefore, the availability of individual microgrids, i.e. whether it can be used to restore the external loads, should be assessed before determining restoration strategies. In this paper, transient simulations are conducted to assess the availability of individual microgrids. Based on the simulation results, a microgrid whose DGs can withstand overcurrent caused by energising a transformer at PCC without being tripped off-line is defined as an available microgrid for service restoration to external loads.

3.2 Critical load restoration considering dynamic constraints

To design a restoration scheme using microgrids considering the dynamic performance of DGs for a specific distribution system, the procedure can be conducted as follows.

3.2.1 Microgrid availability assessment and dynamic constraints extraction: When an outage occurs, system status information, including the availability of DGs and lines and the amount of load at the moment of the outage, is obtained. According to the obtained information of microgrids, transient simulations are conducted to assess the availability of individual microgrids for service restoration.

For an available microgrid, the upper limit on the amount of load that can be picked up in one step is obtained and extracted as the dynamic constraint. To prevent the prime mover from stalling and causing voltage and frequency collapse, the dynamic constraint is then incorporated into the optimisation model. The dynamic constraint of an available microgrid is defined by (1), where \( P_{\text{lim}}^{H} \) denotes the upper limit on the amount of external load that can be picked up by microgrid \( i \).

\[
P_{\text{lim}}^{H} \leq P_{\text{lim}}^{H,i}
\]

(1)

3.2.2 Critical load restoration procedure: For service restoration after a major disaster, the target is to restore critical load as much as possible until the utility power is available while satisfying the operational and topological constraints. Therefore, the objective can be expressed as follows:

\[
\max \sum_{i \in I} w_{i} \left( P_{\text{gen},i} - \sum_{i \in G} P_{\text{load},i} \right)
\]

(2)

The objective is maximising the loads on the distribution feeders weighted by their priority \( (w_{i}) \) and minimising the power losses. The main objective is the first term so \( w_{0} \) can be adjusted to balance the importance of the two objectives. The detailed descriptions of the operational constraints and topological constraints considered in this paper are represented in [19, 20].

3.2.3 Restoration scheme validation: Transient simulations using PSCAD are performed on the corresponding portion of the distribution system to evaluate the feasibility of restoration schemes.

As mentioned in [11], most of the computation time is spent on performing transient simulations to evaluate the feasibility of restoration paths and restorative actions. In this paper, transient simulations are conducted to evaluate the availability of individual microgrids before determining the restoration strategy. There is no need to run transient simulations during the optimisation process, which significantly reduces the computation time.

4 Case study

4.1 System information

A modified 32-node network [21] is used for the case study, in which lines 6-18 and line 25-31 are added to the original network and line 4-5 together with line 25-26 are changed into tie lines. The network is a 12.66-kV system with 32 buses and 7 tie lines. The total amount of load is 3715 kW + 2240 kVar. The detailed information of the network can be obtained in [21]. The one-line diagram of the test system is shown in Fig. 9.

Assume that the test system contains four microgrids, which locate at buses 2, 13, 19, and 24, respectively. The generation and load data of the microgrids are described in Table 3. The loads in the distribution network are divided into three levels by their priorities. The weighting factors of first-level loads, second-level loads, and regular loads are 100, 10, and 1, respectively. In the network, the first-level critical loads are located at buses 3, 16, and 31, respectively, marked with solid arrows. The second-level critical loads are located at buses 7, 21, and 29, respectively, marked with hollow arrows.

4.2 Restoration strategy

It is assumed that after an extreme event, an outage happens, and the utility power is unavailable. Besides, two faults occurred in the distribution system, and the corresponding faults are at the line 6-18 and line 25-31, as indicated in Fig. 9.

Before determining a restoration strategy, transient simulations are conducted to obtain the availability and the dynamic constraints of each individual microgrid. There are three inverter-interfaced DGs with the same capacity in microgrid 4. The rated current of each inverter is 45.5 A. The set value of overcurrent protection of the inverter is 68 A. As shown in Fig. 10, the peak value of the inrush current flowing through the BESS when energising the transformer with a capacity of 150 kVA is 119 A that exceeds the set value of overcurrent protection. Since the restoration action may trigger the protection of the inverter and result in instability of microgrid 4, the microgrid is defined as an unavailable microgrid. The transient simulations demonstrate that transformer energisation will not trigger the overcurrent protections in the other three microgrids. Therefore, the other three microgrids are defined as available microgrids.

For the other three available microgrids, the dynamic constraints of individual microgrid are obtained by transient simulations. The power output upper limit of microgrids 1, 2, and 3 are 720, 640, and 560 kW, respectively.
Restoration results are shown in Fig. 11. Seven lines are determined to be opened: lines 1-2, 1-18, 2-22, 7-20, 8-9, 8-14, 15-16, 22-23, 23-24, and 26-27. The network is divided into three electrical islands, and each island is energised by one microgrid. The loads at hollow nodes in Fig. 11 are the loads remain unrestored and other loads are determined to be restored.

The electromagnetic transient simulations are carried out using PSCAD to verify the restorative actions. For each island, the lines are energised one by one and restore critical loads as soon as possible. Taking the island with microgrid 1 for example, the restoration actions are microgrid 1-transformer-load 2-load 3-load 4-load 5-node 6-load 7-load 25-load 26. The time interval between two consecutive actions is 20 s. The frequency and terminal voltage variations of the microgrid 1 during the restoration are shown in Figs. 12 and 13, respectively. The frequency and voltage variations are in the allowable range that will not cause instability or collapse of the microgrid.

5 Conclusion

This paper presents a method to evaluate the feasibility of service restoration plans that use microgrids to serve critical loads after a major disaster. Dynamic performance of DGs is considered. Different types of DGs are modelled to analyse the dynamic performance. Dynamic performance of DGs is incorporated as analytical constraints into the critical load restoration optimisation model, which reduces the time for decision making. The simulation results indicate that the analytical constraints proposed in this paper can guarantee the feasibility of the restoration schemes.

In this paper, loads are modelled as static loads. The motor starting transient and cold load pickup issues should be considered in the future work.

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Fig. 11  Restoration results by using the proposed method

Fig. 12  Frequency variations of microgrid 1

Fig. 13  Voltage variations of microgrid 1

7 References
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