Anti-Islanding Protection in Distribution Grids

JIANAN ZHANG
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Abstract

The growing number of distributed generation in the electrical system increases the risk of unintentional islanding. Power system islanding is the event that a part of the grid is continuously powered by the distributed generation, while it is already electrically separated from the power grid[1]. Several consequences can be caused by unintentional islanding, such as endangerment of personnel, uncontrolled voltage and frequency operation and equipment damage due to unsynchronised reclosing. Therefore, it’s important to detect islanding events quickly and reliably.

The main objective of this thesis was to investigate the performance of three passive islanding detection methods for Ellevio’s 50kV distribution network. These detection methods were under/over voltage, under/over frequency and rate of change of frequency (ROCOF). Aiming at the objective, a dynamic model was built in MATLAB/Simulink for Ellevio’s distribution network, where the three methods were implemented and applied to the DGs. Moreover, the performance of the methods was evaluated by the non detection zone (NDZ) and detection time, and it was studied under several simulations.

Firstly, a NDZ of each method was found for a Single Machine Infinite Bus (SMIB) system and compared with the results obtained in Ellevio’s network. Besides, the detection time was measured under various islanding conditions to evaluate the response speed of the detection methods. Apart from the sensitivity and response speed, the reliability of the detection methods was also investigated because the detection methods should not mistakenly operate in the case of non-islanding events. Thus, the load switchings and short-circuit faults were simulated as the disturbance events to test the reliability of detection methods. In the end, all three methods were compared, and their advantages and disadvantages were summarized.
Sammanfattning

Det växande antalet av distribuerad generering i elsystemet ökar risken för oavsiktlig ö-drift. Ö-drift innebär att en del av elnätet kontinuerligt drivs av den distribuerade genereringen, medan den redan är elektriskt separerad från elnätet [1]. Flera konsekvenser kan orsakas av oavsiktlig ö-drift, till exempel utsätta personal för fara, okontrollerad spänning och frekvens och skador på utrustning på grund av osynkroniserad återinkoppling. Därför är det viktigt att upptäcka ö-drift snabbt och tillförlitligt.

Huvudsyftet med denna avhandling var att undersöka prestanda av tre passiva metoder för att upptäcka ö-drift för Ellevios 50kV distributionsnät. dessa detektionsmetoder var under-/överspänning, under-/överfrekvens och frekvensförändring (ROCOF). I syfte att uppnå målet byggdes en dynamisk modell i MATLAB / Simulink för Ellevios distributionsnät, där de tre metoderna implementerades och tillämpades på den distribuerade genereringen. Dessutom utvärderades metodens prestanda av icke-detekteringszonen (NDZ) och detekteringstiden, och det studerades under flera simuleringar.

Acknowledgements

I would like to thank the Tin Rabuzin for being my thesis supervisor for the last five months, who gave me the biggest support during the darkest time. I would like to thank the professor Lars Nordström for being my examiner, to enable this master thesis. I would like to thank the Ellevio AB company for providing much technical support regarding the distribution grid model. I would like to thank my parents for supporting my abroad study and their forever encouragement. I would like to thank the KTH for providing such a good two years’ master program.
Abbreviations

AC  Alternating current
DG  Distributed Generation
NDZ  Non Detection Zone
PCC  Point of Common Coupling
PLL  Phase Locked Loop
ROCOF  Rate Of Change Of Frequency
SMIB  Single Machine Infinite Bus

Nomenclature

$\Delta P$  Active power difference
$\Delta Q$  Reactive power difference
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Chapter 1

Introduction

The presence of distributed generation (DG) in power systems has grown rapidly in recent years. Traditionally, energy is produced in large power plants and transmitted to remote customers. In contrast to that approach, distributed energy is a decentralized energy source, and it usually locates at the consumer side or the network’s distribution side[2]. A large number of DG units use renewable energy sources, such as wind power, solar power, hydropower and geothermal power[2]. It’s one of the potential solutions to the environmental issues caused by traditional coal and oil energy power plants. Furthermore, the EU government set the renewable energy target to achieve 20% consumed energy comes from renewable power by the year 2020[3]. Recently, this renewable energy target was updated to 30% by the year 2030. It can be predicted that the distributed generation will be much popular in the future grid.

However, as much distributed generation is connected to the main grid, several issues arise. Islanding is one of the typical problems which may occur when DG is present. It is the event when a part of the grid is continuously powered by the distributed generation while it is already separated from the rest of the network[1]. In other words, islanding creates a self-powered electrical island. The consequences of unintentional islanding are reduced power quality, endangerment of personnel, potentially unsafe and unstable voltage and frequency control, and equipment damage due to unsynchronised reclosing[4]. Thus, it’s important to take preventive actions after unintentional islanding events, and this process refers to anti-islanding. The IEEE 1547-2018 standard sets 2s as a maximum time for detection and disconnection of an islanded distributed generation source[5].

The report contains three parts. The first part is the study of three passive islanding detection methods for synchronous machine based DG. These
detection methods are under/over voltage, under/over frequency and rate of change of frequency (ROCOF). Firstly, a dynamic model of Ellevio’s network was built in MATLAB/Simulink. Secondly, the operation algorithm of three detection methods was implemented and applied to Ellevio’s network model.

In the second part, the performance of detection methods was evaluated by the non detection zone (NDZ) and detection time. Firstly, a NDZ of each detection method was found in the Single Machine Infinite Bus (SMIB) system and compared with the NDZ results obtained from the simulations in Ellevio’s network. Secondly, the detection time was measured in islanding cases where various power imbalances between generation and load were simulated. The detection time can be used to evaluate the response speed of the detection methods. Furthermore, several events, such as load switchings and short-circuit faults, were simulated to assess the reliability of the detection methods, because qualified detection methods should not mistakenly operate in the case of non-islanding events. Lastly, all three detection methods were compared, and their advantages and disadvantages were summarized.

To be mentioned, the DG units normally can be of two different types, inverter-interfaced or synchronously connected[6]. Since the generation in the considered Ellevio’s network is based on synchronous machines, this report only discusses relevant detection methods applicable to those type of units.

1.1 Objectives

This thesis aims to propose suitable islanding detection methods for Ellevio’s 50 kV distribution grid. The islanding detection methods should reliably operate when the system is islanded and other disturbance events, such as load switchings and short-circuit faults, should not trigger the operation of islanding detection methods. The thesis work was carried out in five stages:

1. Build a model of Ellevio’s distribution grid in MATLAB/Simulink. All components in the grid were modeled as accurately as possible. The elements of the model include synchronous machines, lines, loads and transformers.

2. All the three aforementioned islanding detection methods were implemented in MATLAB/Simulink.

3. The methods were applied to the modeled grid. For each of them, the performance of the method was evaluated and analyzed when the system was subjected to different conditions.
4. Thenon detection zone and detection time were found for the three passive islanding detection methods. Firstly obtain the NDZ in the Single Machine Infinite Bus system with only one DG, one load and one infinite bus. Secondly, repeat the same process to find the NDZ in Ellevio’s network. These two NDZs were compared. As for the detection time, it was studied under various islanding cases in Single Machine Infinite Bus system. Simulation results were analyzed, and the characteristics of detection methods were concluded.

1.2 Thesis Outline

The thesis report consists of 7 chapters. In Chapter 1, the general thesis background, objectives were introduced. Chapter 2 presents a literature review on islanding detection, the concept of NDZ, and associated challenges. Furthermore, the three detection methods were reviewed in more detail. Chapter 3 discusses the modeling of Ellevio’s network. Besides, the implementation of detection methods was discussed in more detail. Also, the methodology of finding non detection zone and detection time was introduced. Then chapter 4 presents the simulation results of NDZ, detection time and use cases. Based on the previous chapters, the overall conclusions to answer the research question were summarized in Chapter 5. And some future work was suggested in Chapter 6.
Chapter 2

Literature Review

2.1 Formation of an island

As mentioned in the introduction, an island is formed when a part of a local network is continuously powered by the distributed generation even though the utility grid is disconnected from the local network. As shown in Fig. 2.1, due to a fault event in the electrical system, the circuit breaker between distributed generation and utility tripped, which created an isolated power island.

Islanding is generally classified into intentional islanding and unintentional islanding. Intentional islanding is the islanding event initiated on purpose during, e.g., a system disturbance[4]. Intentional islanding can assure a reliable power supply for critical loads if well designed[7]. During a sudden power outage case, if several DG units are out of step from each other, it’s better to form intentional islanding in the place where the power mismatch between generation and load is the minimum[8]. In contrast, unintentional islanding is an islanding event which is not expected. Since it is not supposed to happen, the formation of unintentional islanding can cause unexpected personnel electric shock, because people are likely to touch the line which is supposed not to have electricity but can be powered due to islanding. Also, the severe consequences contain electrical device damage and the uncontrolled voltage and frequency operation.
2.2 Review of the islanding detection method

A lot of islanding detection methods have been developed, and they can be classified into local and remote detection methods.

Local methods can be further divided into passive, active and hybrid methods. The relation between methods are shown in Fig. 2.2. The principle of passive methods is to monitor system variables (e.g., voltage magnitude, frequency, phase shift, rate of change of frequency) at the point of common coupling (PCC) of a DG. If the system variable is out of predetermined range, then this would indicate islanding. Active methods base their operation on the introduction of small perturbations and observing the system’s output. It is expected that in the operation of grid-connected mode, the response to perturbations would be negligible. Conversely, in islanded mode, the perturbations would cause more significant changes in the system’s response[1]. Hybrid methods are the combination of passive and active methods. For instance, in the study led by W. Chang[9], a two steps based hybrid method was proposed to obtain higher effectiveness: the passive method was applied as the primary detection mechanism, while the active method was used subsequently to detect the islanding event again.

Remote detection methods are based on the communication of signals between a DG and utility. It usually uses a central processor to check the state of circuit breakers to determine the islanding event with the help of method algo-
Remote methods are usually more reliable than the local detection methods, but more expensive to implement[1].

Among all the islanding detection methods, passive detection method has the demerit of large NDZ, but it’s simple to implement in practice. Active detection method has smaller NDZ problem, but it introduces additional disturbance into the power system, and usually, it costs a lot to implement. Then, the hybrid detection method is discovered to combine passive and active detection methods. But it’s not simple enough. Thus, in one way, the current development of islanding detection methods gives people various options to choose from. In the other way, it’s hard to select one best detection method and make a balanced decision in terms of different consideration.

Since Ellevio is not able to modify the control systems of the DGs, this report didn’t consider the use of active nor hybrid detection methods. Moreover, due to cost considerations, studies of remote methods are also not included in this report. Therefore, what follows is the overview of applicable passive detection methods.

### 2.2.1 Local passive detection methods

The common system’s variables observed by passive detection methods are voltage, frequency or various derivatives of those. These parameters are expected to have a detectable change during islanding.
Under/over voltage

Under/over voltage based detection method is one of the common passive detection methods. It identifies the islanding event when voltage is out of the pre-specified range. For voltage threshold, the CIGRE report[10] provides some relay setting used in different countries. Norway and Finland used the 85% and 110% of base voltage as the under and over voltage thresholds respectively. Since the relay setting in Sweden was not mentioned in the report, the voltage thresholds in Norway will be referred to the islanding protection setting here. Thus, if voltage magnitude at the PCC is out of this range, islanding is identified. The relationship between voltage deviation and DG power imbalance is different in inverter-interfaced devices and synchronously rotating machines. A study in [11] shows that in the case of synchronous machines, the deviation of voltage magnitude at the terminals is related to the reactive power balance between the machine’s output and local load consumption. In the case of inverter-interfaced devices, the voltage variation depends on active power imbalance.

Therefore, for the synchronous generators, if there is no reactive power difference, the voltage magnitude will not change, which can lead to a failed detection. However, not only islanding will cause the voltage level change, but other events will make the voltage deviate. Short-circuit fault is an instance to cause a system voltage drop. Thus, it’s crucial to make use of the under/over voltage operation idea to detect islanding reliably.

Under/over frequency

Similar as in the case of under/over voltage detection method, islanding event can be detected if the frequency is not in the pre-specified range. In Sweden, the national normal frequency range is 49.9-50.1 Hz. But the specific frequency setting for islanding protection is vague. According to the Norwegian frequency setting in the CIGRE report[10], 48Hz and 51 Hz were selected as the under and over frequency thresholds in Ellevio’s network.

In synchronous machine based DG system, the frequency variation is mostly related to active power mismatch between DG and local load. The governing mechanism is described by a swing equation shown in Eq.2.1[12].

$$\frac{2H}{\omega_0} \frac{d\omega}{dt} = P_M - P_L = \Delta P \tag{2.1}$$

In Eq. (2.1), $H$ is the generator inertia constant; $\omega_0$ is the synchronous speed; $\omega$ is the rotor speed of generator; $t$ is the time; $P_M$ is the mechanical power; $P_L$ is the load electrical power; $\Delta P$ is the power difference[13].
Therefore, the system frequency increases when the DG output power exceeds the local load. Conversely, the frequency will decrease if the load is larger than the active power supplied by a DG. And during islanding, power mismatch is large, which leads to a much greater frequency deviation. As a result, the frequency can serve as the indicator of system islanding. However, if there is no active power imbalance, the system’s frequency will not change. The method is thus only effective if there is a certain active power mismatch.

Rate of change of frequency (ROCOF)

Rate of change of frequency detection method monitors the voltage waveform at the PCC and calculates the value of the rate of change of frequency $\frac{df}{dt}$.[13][14].

Under a given $\Delta P$ active power mismatch, ROCOF can be much larger during islanding situation. The reason is that when DG is grid-connected, the total inertia time constant is large. When a DG is islanded, the system inertia constant only consists of the DG inertia constant. The smaller inertia constant will cause an increase of ROCOF. So if the ROCOF exceeds the pre-defined threshold, it indicates the appearance of islanding. The threshold setting should be chosen properly to distinguish islanding from the rest of the system events. Typically the ROCOF threshold is between 0.1-1.2 Hz/s according to [14].

In the real ROCOF computation introduced in [15], the monitored voltage waveform is used to calculate the frequency by the three phase locked loop (PLL). Then, the calculated frequency is differentiated to obtain the value of ROCOF.

Compared with under/over frequency detection method, the ROCOF detection method has faster detection speed when the power mismatch is small[16]. However, it can be difficult to find a suitable ROCOF threshold. Moreover, if the active power mismatch between generation and load is zero, there will be no ROCOF value, which will lead to a failed detection.

2.2.2 Non detection zone

Non detection zone (NDZ) is an area where a detection method cannot detect the islanding event in a certain time[17]. It is a parameter to evaluate the performance of detection methods, in particular for the passive detection methods. Because the passive islanding detection methods have the disadvantage that they are not able to work when the DG generation matches local load perfectly, or the power difference between them is small.
Non detection zone can be either defined in the power mismatch space ($\Delta P$ and $\Delta Q$) or RLC load space according to [18]. In this report, the power mismatch space was considered to present the NDZ.

The power mismatch space is defined by establishing a coordinate system using an active power mismatch axis and a reactive power mismatch axis. The NDZ is plotted as a zone as shown in Fig. 2.3. The method with smaller NDZ will detect islanding event more effective under small power mismatch situation.

### 2.2.3 Challenges

As it was shown, each detection method comes with the inherent drawbacks arising from the operating principles. One issue is, as was mentioned, the existence of a NDZ under balanced power conditions, it reduces the effectiveness of a detection method. Another is the sensitivity of the detection methods to non-islanding disturbances in the grid. For example, a load switching or a short circuit fault can cause deviations of frequency and voltage, which can make a detection method operate mistakenly and reduce the reliability of a detection method.
Chapter 3
Methodology

In this thesis, islanding detection methods in Ellevio’s grid are the main analysis objects. Three islanding detection methods are applied to the DGs in Ellevio’s model. The NDZ, detection time and the trip signals for islanding events, are observed as the performance parameters. The NDZ was found firstly in the Single Machine Infinite Bus system and secondly in Ellevio’s network. The detection time was measured in the SMIB system under various islanding cases. Also, three places in Ellevio’s network were selected as the locations where islanding could occur. Moreover, events such as load switchings and short-circuit faults were applied to Ellevio’s model to test the reliability of detection methods.

In a nutshell, a qualified islanding detection method should only respond to islanding event and protect the grid promptly. Correct trip signals, short detection time and small NDZ are the three characteristics of a suitable islanding detection method.

The Ellevio’s network is a 50 kV distribution grid located in Dalarna, Sweden. As shown in Fig. 3.1, it contains 21 buses, three DGs, three transformers and nine loads. The base voltage of the black bus bars is 55kV, while the base voltage of the red bus bars is 135kV. All the network data is provided by Ellevio.

3.1 Power system modelling

A model of Ellevio’s network was built in MATLAB/Simulink. The two parts of the model, connected at bus 3751, are shown in Fig. 3.2 and Fig. 3.3. Different colors are used to distinguish the elements of the model as shown in Tab. 3.1. The three-phase constant voltage sources in color yellow, represent
Figure 3.1: Ellevio network
Table 3.1: Colors for different elements in the model

<table>
<thead>
<tr>
<th>Color</th>
<th>Element</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orange</td>
<td>Load flow buses</td>
</tr>
<tr>
<td>Blue</td>
<td>Power plants</td>
</tr>
<tr>
<td>Red</td>
<td>Circuit breakers to form islanding cases</td>
</tr>
<tr>
<td>Pink</td>
<td>Circuit breakers applied with detection methods</td>
</tr>
<tr>
<td>Green</td>
<td>Constant impedance loads</td>
</tr>
<tr>
<td>White</td>
<td>AC lines</td>
</tr>
<tr>
<td>Grey</td>
<td>Transformers</td>
</tr>
<tr>
<td>Yellow</td>
<td>Three-phase constant voltage sources</td>
</tr>
</tbody>
</table>

Table 3.2: Simulation Parameter

<table>
<thead>
<tr>
<th>Simulation type</th>
<th>Discrete</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample time</td>
<td>50µs</td>
</tr>
<tr>
<td>Solver type</td>
<td>Fixed-step</td>
</tr>
<tr>
<td>Solver</td>
<td>Runge-Kutta methods</td>
</tr>
</tbody>
</table>

the Thevenin equivalent circuits of the rest of Ellevio’s network.

The model was simulated with the parameters shown in Tab. 3.2. Before each simulation, system power load flow is calculated first to obtain the initial conditions for the dynamic simulation.

### 3.1.1 Component models

In the Simulink model, the generators were modeled by synchronous machines equipped with hydraulic turbine governors and excitation systems. Then, the generators were connected to the distribution grid via step-up transformers.

The synchronous generator is the electrical machine converting the mechanical power into electrical power and working under synchronous speed.

The hydraulic turbine is the machine that converts the hydropower into mechanical energy, which serves as the mechanical power provider for the synchronous generator. The hydraulic turbine works under the control of the governor, who plays a role in adjusting the water flow through the turbine to change the turbine’s speed or control the output power[19].

The excitation system supplies field current to the synchronous generator’s field winding and controls the power system operation by adjusting the field voltage and field current[12].
Figure 3.2: Part 1 of the Simulink Model
Figure 3.3: Part 2 of the Simulink Model
An example of generator model is shown in Fig. 3.4. The other two generator models have the same structure but with their respective parameters.

![Generator subsystem model](image)

**Figure 3.4: Generator subsystem model**

The PI line model was used as the model of AC lines, as shown in Fig. 3.5. The line resistance and inductance are represented as $R$ and $L$ respectively, and the line susceptance is distributed evenly at the two terminals of the line. Since the capacitance is in direct ratio with susceptance, the capacitance of each terminal is half of the total line capacitance. The line parameters were provided in the per-unit system, which should be expressed in absolute values.

There are six transformers in the Simulink model. Three of them are the step-up transformers given in the percentage of impedance; The other three transformers connect 50kV and 110kV networks and their equivalent resistances and reactances were given. In the Simulink model, the given impedance data had to be converted into two separate windings’ resistances and reactances.

![PI line model](image)

**Figure 3.5: PI line model**

For each of the step-up transformers connected with generators, the percentage of transformer impedance is equivalent to the per-unit impedance $Z_{pu}$.
Table 3.3: Transformer Impedance from IEC 60076

<table>
<thead>
<tr>
<th>MVA</th>
<th>Z%</th>
<th>X/R</th>
<th>Tolerance on Z%</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;0.630</td>
<td>4.00</td>
<td>1.5</td>
<td>±10</td>
</tr>
<tr>
<td>0.631-1.25</td>
<td>5.00</td>
<td>3.5</td>
<td>±10</td>
</tr>
<tr>
<td>1.251-3.15</td>
<td>6.25</td>
<td>6.0</td>
<td>±10</td>
</tr>
<tr>
<td>3.151-6.3</td>
<td>7.15</td>
<td>8.5</td>
<td>±10</td>
</tr>
<tr>
<td>6.301-12.5</td>
<td>8.35</td>
<td>13.0</td>
<td>±10</td>
</tr>
<tr>
<td>12.501-25.0</td>
<td>10.00</td>
<td>20.00</td>
<td>±7.5</td>
</tr>
<tr>
<td>25.001-200</td>
<td>12.5</td>
<td>45.0</td>
<td>±7.5</td>
</tr>
</tbody>
</table>

The IEC 60076 standard[20] gives some typical transformer impedance in Tab. 3.3. The value of the ratio between $X$ and $R$ refers to it.

The mathematical relation between impedance $Z_{pu}$, resistance $R_{pu}$ and reactance $X_{pu}$ is shown below

$$R_{pu}^2 + X_{pu}^2 = Z_{pu}^2$$  \hspace{1cm} (3.1)

An example of step-up transformer impedance calculation is shown for the transformer connected with generator 3758. The power capacity of the step-up transformer is 5 MVA. Referring to the Tab. 3.3, a transformer with the capacity between 3.151-6.3 MVA has the X/R value of 8.5. Thus, $X_{pu} = 8.5R_{pu}$. Since the value of $Z_{pu}$ is provided by Ellevio, then the values of $R_{pu}$ and $X_{pu}$ can be calculated respectively by solving the system of equations. However, no information is provided about the impedances of the primary and secondary windings. It was thus assumed that primary and secondary impedances have the same per unit values. Neglecting the magnetization impedance, the equivalent impedance of transformer $Z_{pu}$ can be expressed by the two windings as

$$Z_{pu} = 2 \cdot Z_{wpu} = (R_{pu} + jX_{pu})$$  \hspace{1cm} (3.2)

Then the primary winding and secondary winding both have half of the equivalent $R_{pu}$ and $X_{pu}$.

Lastly, all the loads in the distribution grid were assumed as the constant impedance loads. The impedance values were calculated from the initial powers supplied by Ellevio.
3.2 Implementation of the detection methods

The three passive islanding detection methods described in Chapter 2 were implemented in MATLAB/Simulink and applied to DGs in Ellevio’s model. The trip signals of the methods were sent directly to the circuit breakers located between DGs and the rest of the grid. The parameters and threshold settings for each method were found experimentally.

For under/over voltage detection method, the protection should trip when the generator output voltage is smaller than the lower boundary or bigger than the higher boundary for at least 0.2s. The base voltage is 55kV for the generators. As shown in Fig. 3.6, $V_{pu}$ is the per-unit three-phase voltage from the generator output. When the magnitude of $V_{pu}$ is less than 0.85 or larger than 1.1, it will give an activation signal to the timer. When the integration time of timer reaches the delay time 0.2s, it means the voltage magnitude has been out of 0.85-1.1 range for 0.2s. Then the timer will give a true value to S-R Flip-Flop, which will issue a trip command to open the circuit breaker.

![Figure 3.6: Under/over voltage detection method](image)

For under/over frequency detection method, the protection should trip when the system frequency is out of pre-specified operation range for at least 0.2s. The under and over frequency threshold settings for this method are 48Hz and 51Hz. As shown in Fig. 3.7, the system frequency is obtained from the generator output voltage after passing through the Phase Locked Loop (PLL). The delay time is set as 0.2s as well. The timer operation algorithm of this method and the following method are the same as what was introduced in the under/over voltage detection method.

For the rate of change of frequency detection method, the protection should trip when the measured $df/dt$ value exceeds 0.2Hz/s for at least 0.2s. As shown in Fig. 3.8, the rate of change of frequency is calculated by the derivative block.

There is some signal disturbance coming from the generator, because the synchronous machine starting brings some frequency deviation when the simulation starts. Even though the frequency deviation is very small, it can pro-
produce very large rate of change of frequency value after differentiation. According to simulations, the machine starting time is less than 0.2s in Ellevio’s network. Therefore, setting delay time to 0.2s can make sure that the operation of this method will not be affected by the machine starting. The rate of change of frequency threshold was set to 0.2 Hz/s, which is the experience choice after many test simulations.

3.3 Simulation cases

There are several cases simulated to analyze the performance of islanding detection methods.

3.3.1 Islanding cases

Each islanding event was simulated by opening the circuit breakers specified in Tab. 3.4. Ellevio’s islanding event history shows that an islanding event happened at bus 3751. So the part 1 of Ellevio’s network, as pictured in Fig. 3.2, can be the power island with high possibility. So this area should be studied in detail. There are three possible islanding location scenarios, named as islanding case 1 to islanding case 3, as shown in Tab. 3.4. In Fig. 3.2, the circuit
breakers used to form island are colored in red and the circuit breakers to be applied with detection methods are colored in pink.

### 3.3.2 Short-circuit fault cases

In the power system, the three-phase short-circuit fault is the most serious fault. The other faults, such as the single-phase line to ground faults, are more common to happen. But in Ellevio’s model, it is not able to simulate a single-phase line to ground fault because only positive sequence data was provided. Usually, a fault should be cleared by the respective protection relays. An ideal islanding detection method should be immune to fault disturbances. Therefore, three-phase short-circuit faults were simulated at the bus 3751 and bus 3758 respectively, which can investigate the stability of the detection methods.

There are some specified maximum fault clearing time for the transmission system in the high voltage level. For example, in the British grid protection code, at the voltage level lower than 132 kV, the national grid specifies the fault clearing time should be longer than 120ms[21]. However, the distribution system has longer fault clearing time than the transmission system at high voltage level. As introduced in the [22], the fault clearing time is usually between 50ms to 300ms in distance and differential protection system; while it becomes 200ms to 2000ms in over-current protection system with some delay time. Here it is assumed that the fault clearing time is 120ms. Under such fault events, the behavior of the detection methods was observed.

### 3.3.3 Load switching cases

To test the performance of detection methods under load switching disturbances, load 3752 was switched off from the Ellevio’s network and then switched back after a certain time. The reason why choosing load 3752 instead of other loads is that load 3752 is the maximum single load value in the initial load configuration. And this load value is even bigger than any of the generators’ nominal power. During the simulation, when a load switches in the network, the system variables (voltage and frequency) would change, which leads to the change of the islanding detection parameters. Therefore, if a detection method operates mistakenly, then this detection method is more sensitive to load switching disturbances.
3.4 Non Detection Zone application

This section presents the two NDZ study areas and how the NDZ can be found.

3.4.1 Non detection zone study area

Single Machine Infinite Bus system

A study of NDZs was performed in a SMIB system. This was done to check if a single model could be used to find NDZs of the detection methods with the hope that it could generalize well on the NDZs obtained using a more accurate model.

As shown in Fig. 3.9, a SMIB system consists of a generator with its local load. The generator here was modeled by the specific parameters of generator 3756 in Ellevio’s grid. The local load was modeled as a constant impedance load. And there is a power line between DG and an infinite bus. Furthermore, the opening of the circuit breaker at the generator terminals islands the generator. As will be mentioned, changing the power mismatch between the generator and the load can be utilized to find the NDZs of the methods.

![Figure 3.9: NDZ study area in Single Machine Infinite Bus system](image)

Ellevio’s network under Islanding case 3

When studying the NDZs in Ellevio’s network, islanding case 3 was used to simulate the islanding event. As it was discussed before, the opening of breaker 3 isolates the part 1 of Ellevio’s network from the rest of the grid. Assume that the line losses can be ignored, then the total power consumption on the island is the sum of the loads on the island, which is expressed by Eq. 3.3 and Eq. 3.4. The total power generation on the island is the production sum of generator 3758 and generator 3756, which is expressed by Eq. 3.5 and Eq. 3.6.
Thus, the power mismatch between total generation and total loads on the island can be calculated by Eq. 3.7 and Eq. 3.8. Keep the generator production constant and change the load value to obtain different power mismatch values. By running dynamic simulations of the model in these power mismatch cases, it is possible to find the NDZs for the three detection methods.

\[ P_L = P_{L3759} + P_{L3757} + P_{L3761} + P_{L3756} + P_{L3762} \]  
\[ Q_L = Q_{L3759} + Q_{L3757} + Q_{L3761} + Q_{L3756} + Q_{L3762} \]

\[ P_G = P_{G3758} + P_{G3756} \]  
\[ Q_G = Q_{G3758} + Q_{G3756} \]  
\[ \Delta P = P_G - P_L \]  
\[ \Delta Q = Q_G - Q_L \]

Figure 3.10: NDZ study area in Ellevio’s network under islanding case 3
3.4.2 Computation of NDZs

The algorithm of finding the NDZ can be described by three steps.

Firstly, create a point grid which contains some test points in the power mismatch space. Each test point represents one value of the power mismatch, as shown in Fig. 3.11.

Secondly, a new load flow was calculated for each load value, then the model was initialized, and the dynamic simulation was run. The trip signals of the breakers applied with detection methods were observed two seconds after the islanding event. If the islanding is not detected, then it implies this power mismatch case is a non detection zone case. The test point will be colored in red, which means it is a real NDZ point.

In the end, iterating the second step over all of the points in the defined grid. Then the NDZ can be found for the detection methods.

Since in the islanding case 3, both the generator 3758 and generator 3756 are islanded. So, for each detection method, two NDZs can be found based on the trip signal of breaker 3758 and the trip signal of breaker 3756.

![Non detection zone test grid](image)

Figure 3.11: Non detection zone test grid

3.5 Detection time in SMIB system

Detection time was measured under several islanding cases where the power difference between generation and local load varies. The detection time can be
used to assess the response speed of detection methods. In the SMIB system, a group of power difference was created from 0% to 100% of the generator’s apparent power. The power difference can be produced by keeping the DG output power constant and changing the local load value. For instance, a load with $150\% P_G + 150\% Q_G \cdot j$ value belongs to the 50% power difference case.

Assume $t_1$ is the time when the islanding occurs and $t_2$ is the time when the islanding is detected by a detection method. Then the detection time is the time difference between $t_1$ and $t_2$ as shown in Eq. 3.9. The simulation was run for each load value, and detection time was recorded.

$$\Delta t = t_2 - t_1 \quad (3.9)$$
Chapter 4

Result and Discussion

4.1 Non detection zone

The computation results of non detection zone are presented below. For each method, non detection zone was investigated both in the SMIB system and in Ellevio’s network. The power mismatches are expressed in percentages. The base power is the apparent power of the total generation on the island.

4.1.1 Single Machine Infinite Bus system

The non detection zone results for the three detection methods are shown in Fig. 4.1, Fig. 4.2 and Fig. 4.3 respectively. In each NDZ figure, an outline of NDZ was drawn manually according to the distribution of NDZ points.

![Graph](image)

Figure 4.1: Non detection zone of under/over voltage detection method in the SMIB system

As shown in Fig. 4.1, the NDZ of under/over voltage detection method is
between -80% to 80% of active power mismatch and between -35% to 95% of reactive power mismatch.

![Figure 4.2: Non detection zone of under/over frequency detection method in the SMIB system](image1)

As shown in Fig. 4.2, the NDZ of under/over frequency detection method is between -20% to 12% of active power mismatch and between -35% to 92% of reactive power mismatch.

![Figure 4.3: Non detection zone of rate of change of frequency method in the SMIB system](image2)

As shown in Fig. 4.3, the NDZ of the rate of change of frequency detection method is between -2% to 3% of active power mismatch and between -20% to 40% of reactive power mismatch.

If plotting the above three NDZs in one figure, as shown in Fig. 4.4, it can be found that the under/over voltage detection method has the largest NDZ, the under/over frequency detection method has the second largest NDZ and the ROCOF detection method has the smallest NDZ.
4.1.2 Ellevio network under islanding case 3

When finding the NDZ in Ellevio’s network under islanding case 3, two NDZs can be obtained for each method. The first NDZ was obtained by observing the trip signal of generator 3758’s protection breaker, and the second NDZ was found by using the trip signal of generator 3756’s protection breaker. And these two NDZs were plotted in one figure and distinguished by different colors.

The NDZs of under/over voltage detection method in Ellevio’s network are shown in Fig. 4.5. The NDZ obtained from the detection method applied to generator 3758 is a bit larger than the NDZ found by the detection method applied to generator 3756. The reason is that the generator 3758 produced more reactive power than generator 3756. When there was a load increase
after islanding event, the reactive power difference between generator 3758 and loads was less than the reactive power difference between generator 3756 and loads. Thus, less reactive power difference means less voltage drop during islanding. So the NDZ obtained from generator 3758 was larger than the NDZ computed from generator 3756.

![Figure 4.6: Non detection zone of under/over frequency detection method in Ellevio’s network](image)

The NDZs of the under/over frequency detection method are presented in Fig. 4.6 and the NDZs of the ROCOF detection method are shown in Fig. 4.7. In these two figures, the NDZs obtained from generator 3756 system were larger than the NDZs computed from generator 3758 system. Because both methods rely on the system frequency to indicate islanding, while the frequency is mostly related to active power imbalance of a synchronous machine. And the generator 3756 produced more active power than generator 3758 in
the simulation. So during the islanding event, the active power imbalance of
generator 3756 was less than the active power imbalance of generator 3758.
Less active power imbalance means less frequency deviation. So the NDZs
from generator 3756 was smaller than the NDZs from generator 3758.

Overall, on the power island containing multiple DGs, several NDZ results
can be found for different DGs. Since the generator 3756 model was also
used to model the DG in the SMIB system, here the NDZs obtained from
generator 3756 were compared with the NDZs in the SMIB system. Two small
conclusions can be made.

1. When studying the NDZs in Ellevio’s network, the under/over voltage
detection method has the largest NDZ. The under/over frequency detection
method has the second largest NDZ. The ROCOF detection method
has the smallest NDZ.

2. For each method, after comparing the NDZ obtained in Ellevio’s net-
work with the NDZ computed in the SMIB system, it can be found that
the two NDZs were approximately similar. They were not the same be-
cause the simulation environment was different. However, it is enough
to use the SMIB system to find the approximate NDZ results, especially
in the case of comparing the size of different NDZs.

4.2 Detection time in the SMIB system

The simulation results of detection time are shown in Fig. 4.8. The detection
time is related to the power difference between generation and loads, and the
relation is different for different detection methods.

For under/over frequency detection method, its detection time becomes
shorter as the power difference becomes larger. For under/over voltage detection
method, its detection time is at constant 0.2s since 20% power difference.
For the ROCOF detection method, the situation is a little different. When the
power difference is less than 40%, the detection time is around 0.3s. When the
power difference is more than 40%, the detection time is around 0.5s. The in-
creased detection time after 40% power difference can be explained by the osc-
cillation behavior of \( \frac{df}{dt} \) during islanding. Because the oscillation of \( \frac{df}{dt} \)
can activate and reset the timer without tripping the operation, but it increases
the detection time.
4.3 Islanding case

The simulation results in this section indicate the three detection methods can work properly and selectively under islanding cases. The initial load configuration provided by Ellevio was used to run the simulations.

4.3.1 Islanding case 1

When opening the breaker 1 to form an island, generator 3758 should be disconnected from the island. The final status of the breakers applied with detection methods is shown in Tab. 4.1. It implies the generator 3758 was disconnected by the detection methods successfully. And the other generators were not affected.

<table>
<thead>
<tr>
<th>Method</th>
<th>Circuit breaker</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Under/over voltage</td>
<td>Three-phase circuit breaker 3755</td>
<td>Closed</td>
</tr>
<tr>
<td></td>
<td>Three-phase circuit breaker 3756</td>
<td>Closed</td>
</tr>
<tr>
<td></td>
<td>Three-phase circuit breaker 3758</td>
<td>Open</td>
</tr>
<tr>
<td>Under/over frequency</td>
<td>Three-phase circuit breaker 3755</td>
<td>Closed</td>
</tr>
<tr>
<td></td>
<td>Three-phase circuit breaker 3756</td>
<td>Closed</td>
</tr>
<tr>
<td></td>
<td>Three-phase circuit breaker 3758</td>
<td>Open</td>
</tr>
<tr>
<td>Rate of change of frequency</td>
<td>Three-phase circuit breaker 3755</td>
<td>Closed</td>
</tr>
<tr>
<td></td>
<td>Three-phase circuit breaker 3756</td>
<td>Closed</td>
</tr>
<tr>
<td></td>
<td>Three-phase circuit breaker 3758</td>
<td>Open</td>
</tr>
</tbody>
</table>
4.3.2 Islanding case 2

When islanding event is simulated by opening the breaker 2, the generator 3756 should be cut off from the power island. The final status of the breakers is shown in Tab. 4.2. It implies that only generator 3756 was disconnected during islanding case 2 with the help of detection methods.

<table>
<thead>
<tr>
<th>Method</th>
<th>Circuit breaker</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Under/over voltage</td>
<td>Three-phase circuit breaker 3755</td>
<td>Closed</td>
</tr>
<tr>
<td></td>
<td>Three-phase circuit breaker 3756</td>
<td>Open</td>
</tr>
<tr>
<td></td>
<td>Three-phase circuit breaker 3758</td>
<td>Closed</td>
</tr>
<tr>
<td>Under/over frequency</td>
<td>Three-phase circuit breaker 3755</td>
<td>Closed</td>
</tr>
<tr>
<td></td>
<td>Three-phase circuit breaker 3756</td>
<td>Open</td>
</tr>
<tr>
<td></td>
<td>Three-phase circuit breaker 3758</td>
<td>Closed</td>
</tr>
<tr>
<td>Rate of change of frequency</td>
<td>Three-phase circuit breaker 3755</td>
<td>Closed</td>
</tr>
<tr>
<td></td>
<td>Three-phase circuit breaker 3756</td>
<td>Open</td>
</tr>
<tr>
<td></td>
<td>Three-phase circuit breaker 3758</td>
<td>Closed</td>
</tr>
</tbody>
</table>

4.3.3 Islanding case 3

The last islanding case was simulated by opening the breaker 3. Then a power island was formed which contained both generator 3758 and generator 3756. So both generators should be cut off from the island. The final status of breakers is shown in Tab. 4.3. It indicates the generator 3756 and generator 3758 were disconnected by opening breaker 3756 and breaker 3758 respectively. Besides, breaker 3755 was still closed because generator 3755 was not islanded.

Overall, in the above islanding cases, all three detection methods can detect islanding event successfully and disconnect the DGs selectively.

4.4 Detection variable during islanding

In this section, the detection variables, such as voltage, frequency and rate of change of frequency, were observed over time. Islanding case 3 is used to simulate the islanding event. In the simulation, islanding occurred at time t=0.5s, and the total simulation time was 3s.
Table 4.3: Circuit breaker status with different detection methods III

<table>
<thead>
<tr>
<th>Method</th>
<th>Circuit breaker</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Under/over voltage</td>
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<td>Closed</td>
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<tr>
<td></td>
<td>Three-phase circuit breaker 3756</td>
<td>Open</td>
</tr>
<tr>
<td></td>
<td>Three-phase circuit breaker 3758</td>
<td>Open</td>
</tr>
<tr>
<td>Under/over frequency</td>
<td>Three-phase circuit breaker 3755</td>
<td>Closed</td>
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<tr>
<td></td>
<td>Three-phase circuit breaker 3756</td>
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<td></td>
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<tr>
<td>Rate of change of frequency</td>
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<td>Open</td>
</tr>
<tr>
<td></td>
<td>Three-phase circuit breaker 3758</td>
<td>Open</td>
</tr>
</tbody>
</table>

### 4.4.1 Under/over voltage detection method

In under/over voltage detection method, the detection variables are the output voltages at the terminals of generators. As shown in Fig. 4.9, the output voltage at the terminal of generator 3755 increased a little bit after time $t=0.5\text{s}$, because the main grid suddenly stopped supplying power to the other two generators. During this time, the system generation was more than load consumption, which made the voltage increase. Conversely, for the generator 3756 and generator 3758, they lost the power supply from the main grid, so their output voltages decreased. The threshold boundaries are drawn as the red dashed lines at $V=0.85\text{pu}$ and $V=1.1\text{pu}$ respectively. During the whole simulation, the voltage at bus 3755 was always inside the boundaries, so no islanding signal was triggered for generator 3755. However, the voltages at bus 3756 and bus 3758 both decreased to the values that were lower than 0.85pu, which triggered the operation of the detection method.

### 4.4.2 Under/over frequency detection method

In under/over frequency detection method, frequency is the detection variable. The frequencies are shown in Fig. 4.10. At time $t=0.5\text{s}$, islanding caused a small frequency deviation in generator 3755 system, later the frequency went back to a new steady state. However, the frequencies in the generator 3756 and 3758 systems started to decrease after time $t=0.5\text{s}$. Because after islanding event, the load demand on the power island was more than the local generation. Thus, the decreasing frequencies triggered the detection method to disconnect
4.4.3 Rate of change of frequency detection method

In the ROCOF detection method, the detection variable is the frequency derivative (df/dt). The df/dt variation during islanding is shown in Fig. 4.11. From time t=0.5s, islanding caused some df/dt oscillation in the generator 3756 and 3758 system. After the oscillation, the df/dt began to decrease until triggering the operation of the detection method. For df/dt in generator 3755 system, even though it oscillated for a some time, it didn’t trigger the islanding protection due to the short activation time of the timer. It is obvious to observe the rate of change of frequency variation during islanding.
4.5 Fault case

This section presents the behavior of detection variables in the case of three-phase short-circuit faults. The faults were simulated at bus 3751 and bus 3758 respectively. In the simulation, fault happened at time \( t=1 \)s and ended at time \( t=1.12 \)s.

For under/over voltage detection method, it didn’t operate under fault disturbances. The voltage variation during faults was shown in Fig. 4.12. When fault happened at \( t=1 \)s, the voltage dropped suddenly. After the faults were cleared, the voltage went back to a normal level. It can be found that the time duration when the voltage was below the under voltage threshold was around the fault lasting time. Because the assumed fault lasting time (0.12s) is shorter than the setting time of timer (0.2s), so the method didn’t operate. It is also a limitation of this method. Because this method can only avoid the fault disturbances if the fault lasting time is less than the method’s delay time. Furthermore, when a fault was simulated at bus 3758, the voltage at bus 3758 dropped to around zero, while the voltage at bus 3755 and bus 3756 did not deviate a lot. Because generator 3758 was located closer to the fault location. It indicates the effect of faults is also determined by the location of faults.

For under/over frequency detection method, it can work reliably in fault cases. The frequency variation during fault is shown in Fig. 4.13. In both fault locations, the frequency oscillated without violating the under or over frequency threshold. So the fault events didn’t cause the operation of the detection method. Thus, the under/over frequency detection method was reliable under such fault disturbances.

For the rate of change of frequency detection method, it operated mistakenly. The DGs in Ellevio’s grid were disconnected from the network. The
Figure 4.12: Voltage variation during faults in under/over voltage detection method
Figure 4.13: Frequency variation during faults in under/over frequency detection method.
Figure 4.14: $\frac{df}{dt}$ variation during faults in ROCOF detection method
df/dt variation is shown in Fig. 4.14. During faults, the \( df/dt \) oscillation triggered the operation of the detection method. Thus, the ROCOF method was not reliable in such fault disturbances.

### 4.6 Load switching case

This section presents the behavior of the detection variables during load switching cases. In the simulation, the load 3752 switched off from grid at time \( t=1s \), and switched on back at time \( t=2s \).

![Graph showing voltage variation](image1)

Figure 4.15: Voltage variation during load 3752 switching case in under/over voltage detection method

![Graph showing frequency variation](image2)

Figure 4.16: Frequency variation during load 3752 switching case in under/over frequency detection method

The simulation results demonstrate that all three detection methods were still reliable under load 3752 switching disturbances. As shown in Fig. 4.15 and Fig. 4.16, the voltage and frequency deviated at time \( t=1s \) and \( t=2s \). However, the deviation ranges were too small to trigger the detection method. As
Figure 4.17: $df/dt$ variation during load 3752 switching case in the rate of change of frequency detection method

shown in Fig. 4.17, the $df/dt$ oscillation violated the thresholds for a certain time, but since the accumulated time of threshold violation was shorter than the delay time of the timer. The ROCOF detection method avoided false operation.

In a short, all three detection methods did not operate mistakenly, and they were reliable under load 3752 switching disturbances.
Chapter 5

Conclusions

Some conclusions were made based on the simulation results.

1. When studying the non detection zone either in the Single Machine Infinite Bus system or in Ellevio’s network, it was found that the under/over voltage detection method had the largest non detection zone, the under/over frequency detection method had the second largest non detection zone, and the rate of change of frequency detection method had the smallest non detection zone.

2. For each detection method, after comparing the non detection zone obtained in Ellevio’s network with the one computed in the Single Machine Infinite Bus system, it was found that the two non detection zones were approximately similar. It is enough to use the Single Machine Infinite Bus system to find the approximate non detection zone. It is useful to compare the non detection zone of several detection methods.

3. In Single Machine Infinite Bus system, the under/over voltage detection method had the shortest detection time, the rate of change of frequency detection method had the second shortest detection time, and the under/over frequency detection method had the longest detection time.

4. The detection time can vary under different power difference between generation and local loads. And the detection time of under/over frequency detection method was more sensitive to the change of power difference.

5. The three detection methods worked properly and selectively in the case of islanding. The basic function of the detection methods was achieved.
6. Under three-phase short-circuit fault disturbances, the under/over voltage and under/over frequency detection methods were reliable. While the rate of change of frequency detection method operated mistakenly, so it was not as reliable as the other two methods.

7. Under a load switching case, it was found that all three detection methods had the ability to tolerate load switching disturbance. The three detection methods were reliable under load 3752 switching disturbances.

Overall, all three islanding detection methods have their merits and disadvantages. The rate of change of frequency detection method has the smallest non-detection zone and very short detection time. It is more reliable in the case of load switching disturbances. However, it can operate mistakenly in the case of fault disturbance. The under/over voltage and under/over frequency detection methods are reliable in the case of load switching and fault disturbances. And the under/over voltage detection method can detect islanding event very quickly. However, both the under/over voltage and under/over frequency detection methods have the problem of large non-detection zone. Thus, the three detection methods should be considered respectively regarding the specific situation.
Chapter 6

Future work

This chapter lists some future work which can be done further based on the current results.

1. More islanding locations can be investigated in Ellevio’s network. For example, in the bottom part of Ellevio’s network, there are some locations where the islanding is likely to occur.

2. The behavior of detection methods can be studied under different load configuration. In the current work, only the initial load configuration provided by Ellevio was used to do the simulations.

3. The non-islanding disturbances can be applied at other locations in Ellevio’s network.
Bibliography


