IMPACT OF DISTRIBUTED GENERATION ON DISTRIBUTION NETWORK PROTECTION

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ABSTRACT

The 38kV distribution network in Ireland is primarily composed of radial feeders, designed for unidirectional power flow. Protection for the 38kV distribution network is mainly provided by plain Impedance Relays. The advent of widespread distributed generation has resulted in independent power producers supplying power to the radial distribution network. This has created a multidirectional power flow situation on parts of the distribution network which were originally designed for unidirectional power flow only. This fundamental change in operating principle can restrict the operation of the protection system causing false tripping of feeders (sympathetic tripping), blinding of protection and increased or decreased fault levels. This paper presents the potential problems distributed generation creates for a protection system. The authors use examples of case studies which have attempted to identify the impact on the utility protection performance following a proposed connection of distributed generation to specific areas of the Irish distribution network.

INTRODUCTION

The last decade has seen a dramatic increase in the amount of distributed generation being connected to the radial distribution network in Ireland. However, in rural areas the 38kV protection relays have been designed and configured to protect against faults, based on a unidirectional power flow situation. The increase in distributed generation has created a situation where fault currents are flowing in directions that were not expected when the protection system was designed. As a result, the additional fault current supplied by embedded generation can cause relays to under-reach or over-reach.

The ESB Networks Protection Policy specifies the protection requirements for feeders, transformers and busbars on the distribution network in Ireland. In some cases the addition of distributed generation can inhibit the protection system to the extent that the protection provided is no longer compliant with the requirements of the protection policy. Therefore, according to the AER (Alternative Energy Resource) technical policy, a protection review must be completed before any distributed generation, above 2MVA, is connected to the network. A protection review will access the impact of distributed generation on the local protection system and recommend protection upgrades if required.

38kV PROTECTION RELAYS

A protection relay is a device that continually monitors the power system using inputs from current and/or voltage transducers. The relay determines, based on a comparison between the relay settings and the system parameters, if a fault exists on the system. If the relay detects a fault it will issue a trip command to the circuit breaker to open and isolate the fault. The 38kV feeder protection in Ireland uses a combination of digital impedance relays, electromechanical impedance relays and electromechanical overcurrent relays.

Overcurrent Protection Relays

The overcurrent relay is designed to detect the increased current caused by a fault. The most common characteristic of 38kV overcurrent relays used on the ESB distribution network is a combined IDMT/Instantaneous characteristic as shown in Figure 1 (IDMT = Inverse Definite Minimum Time).

![Figure 1 IDMT/Instantaneous Characteristic](image)

The instantaneous part of the characteristic ensures fast clearance time for primary protection faults, for example fault A. Whilst the IDMT part of the characteristic provides the time delay required to coordinate with
Impedance Protection Relays

Impedance relays operate in a specific time for any faults occurring within a predefined zone of a distribution feeder. The relay compares the fault current seen by the relay against the voltage at the relay location and in doing so determines the impedance between the relay and the fault. As impedance is proportional to distance, this impedance represents the distance to the fault. Therefore if the fault impedance seen by the relay is less than the relay impedance settings, the relay will issue trip command for this fault.

There are two types of impedance relay used on the Irish 38kV distribution network: The Siemens R1kZ4A relay is an electromechanical impedance relay with a circular MHO characteristic and an overcurrent started fault detection element. The Siemens 7SA511 relay is a numerical impedance relay that has a quadrilateral operating characteristic and an impedance started fault detection element.

PROTECTION REQUIREMENTS

Distribution System Protection Policy:
The purpose of this Policy is to specify the minimum mandatory system protection requirements based on safety of people and plant and the minimum requirements to maintain acceptable operating standards.

According to the 1997 Distribution System Protection Policy:
1. Primary protection operation should clear 38kV line feeder phase faults in 0.5s or less. Backup protection operation should clear such faults in 2.0s or less.
2. Primary protection operation should clear 38kV busbars phase faults in 110/38kV substations in 0.5s or less. Backup protection operation should clear such faults in 2.0s or less.
3. Primary protection operation should clear 38kV busbars phase faults in 38/20kV and 38/10kV substations in 0.5s or less. Backup protection operation should clear such faults in 1.7s or less.
4. Coordinating margins of 0.4s are required to guarantee selective operation.

The impending 2005 revision of this policy requires faster fault clearance times and tighter co-ordinating margins.

Requirements for the connection of generators to ESB’s Distribution Network:
ESB Networks have a standard covering Parallel Operation of Private Generators. The purpose of these requirements is to protect the personal and plant of ESB and ESB’s customers from any adverse effects that could be caused by the connection of distributed generation. According to these requirements a customer, wishing to connect generator equipment to the distribution network, must ensure that the generator-system interface is adequately protected at all times. This includes ensuring that it is suitable for connection to a Distribution System where manual and automatic switching, including auto-reclosing, is a feature.

Distributed generator protection and control equipment should include some or all of:
- Over & under voltage protection
- Over & under frequency protection
- Loss of mains protection
- Directional overcurrent protection
- Earth fault protection
- Relay D.C Supply protection
- Trip Circuit Supervision protection

IMPACT OF DISTRIBUTED GENERATION

Each relay in a protection system has a set of relay settings that will determine the primary and backup protection that the relay will provide. The relay settings for each relay are calculated so that the relay fulfils the primary and backup protection requirements of the network it is protecting. Calculations are based on the maximum load current, the maximum and minimum fault currents and/or the impedance of feeders that the relay is protecting. Connecting distributed generation to the 38kV distribution network can affect the local protection system in the following ways:

Under-Reaching of Relays
Depending on its location, its capacity and the strength of the network to which it is connected, distributed generation may cause relay settings, which were previously adequate, to under-reach. To illustrate this consider the following example which is based on the model 38kV radial network shown in Figure 2, where:

Source Impedance + Impedance of Line from A to B:
$$Z_{Source} = 6.499 + 13.89j \Omega$$

Embedded Generation Impedance:
$$Z_{Gen} = 1.591 + 37.305j \Omega$$

Impedance of Line from B to C:
$$Z_{BC} = 4.347 + 4.42j \Omega$$

![Figure 2 Model 38kV Radial Network with Distributed Generation](image-url)
Before the distributed generation is connected to the 38kV feeder at busbar B, the fault current for a fault at busbar C, assuming a 1.07 p.u. pre-fault voltage, is:

\[ I_{\text{Fault}} = \frac{\text{SystemVoltage} \cdot 1.07}{\sqrt{3}(Z_{\text{Source}} + Z_{\text{Gen}})} \approx 1102 \angle 59^\circ \text{A/phase} \quad (1) \]

Therefore, the relay at busbar A can be set to provide backup protection for the relay at busbar B by setting the relay to trip for faults above 1102 Amps.

Adding the distributed generation to busbar B means the total fault current for a fault at busbar C is now:

\[ I_{\text{Fault}} = \frac{\text{SystemVoltage} \cdot 1.07}{\sqrt{3}(Z_{\text{Parallel}} + Z_{\text{AB}})} \approx 1393 \angle 62^\circ \text{A/phase} \quad (2) \]

Where, \( Z_{\text{parallel}} \) is the impedance of the parallel combination of \( Z_{\text{Source}} \) and \( Z_{\text{Gen}} \).

The total fault current is composed of the following contributions from both the source and the distributed generation:

\[ I_{\text{System}} \approx 1004 \angle 56^\circ \text{A/phase} \quad (3) \]
\[ I_{\text{Generation}} \approx 412 \angle 78^\circ \text{A/phase} \quad (4) \]

This calculation proves that, while the addition of the distributed generation has increased the total fault current, the current contribution from the source has decreased from 1102Amps to 1004Amps. As a result of the decrease in fault current, a fault at busbar C may not be tripped by the relay at busbar A in the required time. Therefore, in this example the connection of distributed generation causes a protection relay to under-reach and as such the required fault clearance time for backup protection is no longer provided.

**Over-Reaching of Relays**

The sample 38kV radial network in Figure 2 can also be used to demonstrate how the presence of distributed generation can cause a relay to over-reach. Before the connection of the distributed generation, the fault current for a fault at busbar C is 1102 \( \angle 59^\circ \)A/phase (1). The relay at busbar B can be set to provide primary protection for busbar C by setting the relay to trip for faults above 1102 Amps. When the distributed generation is connected to busbar B the fault current, for a fault at busbar C, increases to 1393 \( \angle 62^\circ \)A/phase (2). Therefore, if the protection relay at busbar B is an overcurrent relay or an overcurrent started impedance relay, the distributed generation could cause the relay to over-reach.

**PROTECTION REVIEW**

Before any distributed generation above 2MVA is connected to the 38kV network, a protection review is done to assess the impact of the distributed generation on the 38kV protection performance. The steps to undertake a protection review are as follows:

1. Model the proposed generator and connection arrangements, using the technical information provided by the customer.
2. Analyze the existing protection and determine the effects of the proposed generator connection.
3. Make recommendations to ensure that the protection system meets the requirements of the Distribution System Protection Policy.

The following is a protection review that was done in order to determine the impact on the local protection system following the connection of a 11.9MW wind farm to Tower Hill 38kV substation.

**Modelling of generation and connection arrangements**

A model of the proposed wind farm and the connection to the 38kV network is built using the existing network information and the technical information supplied by the wind farm developer. The proposed connection arrangement is shown in Figure 3.

![Figure 3 38kV Network and Proposed Wind farm](image)

The software used to complete the protection review is CAPE (Computer-Aided Protection Engineering). CAPE is used on conjunction with a database of the ESB Network which contains details of 110kV and 38kV: transformers, lines, cables, capacitors, reactors, relays, instrument transformers, relays etc. CAPE is used to simulate faults for determining short circuit levels and to simulate the reach of protection relays. The reach of a protection relays can be displayed using a Time Distance Diagram (TDD) or a Resistance/Reactance Diagram (RX Diagram). A TDD (see Figure 4) shows the distance reach of the relay on the x-axis and the tripping time for the relay on the y-axis. An RX Diagram (see Figure 8), with resistance on the x-axis and reactance on the y-axis, shows the area of resistance and reactance covered by each of the relay’s zones and the position of faults relative to the relay zones.

**Analysis of the Protection Requirements**

The 38kV relay on the Tower Hill outlet at Dunrath, before the wind farm is connected, must provide primary protection for the Dunrath to Tower Hill 38kV feeder and for the Tower Hill 38kV busbar. It must provide backup protection for the 10kV busbars at Tower Hill and for the Tower Hill to Kilog 38kV feeder. The 38kV relay on the Kilog outlet at Tower Hill must provide...
primary protection for the Tower Hill to Kilog 38kV feeder. It must provide backup protection for the 10kV busbars at Kilog.

**Effect on the Tower Hill Relay at Dunrath**
Connecting the wind farm to Tower Hill 38kV substation will cause the impedance relay (Siemens 7SA511) on the Tower Hill outlet at Dunrath to **under-reach** (Relay1 in Figure 3). This is as a direct consequence of the reduced fault current contribution from the source, for faults along the Tower Hill to Kilog 38kV feeder, due to the connection of the wind farm.

Figure 4 shows the TDD for the Tower Hill impedance relay at Dunrath before the wind farm is connected. This illustrates that the relay is providing the required primary and backup protection.

Figure 5 shows the TDD for the Tower Hill impedance relay at Dunrath when the wind farm is connected. This illustrates that the relay is no longer providing the required protection, because Zone 3 of this relay is only reaching 95% of the distance to Kilog. Prior to the wind farm connection zone 3 was reaching 110% of the distance to the Kilog.

**Effect on the Kilog Relay at Tower Hill**
Connecting the wind farm to Tower Hill 38kV substation will increase the short circuit level of any faults occurring in feeders fed via Tower Hill. Considering that the Kilog relay at Tower Hill is an overcurrent relay (Areva MCGG Relay), the increased short circuit levels, as a result of the wind farm, will cause the relay to **over-reach**.

Figure 6 shows the overcurrent characteristic for the Kilog overcurrent relay at Tower Hill before the wind farm is connected. Faults A and B, are a line to line fault at Kilog 38kV and a three phase fault at Kilog 38kV, respectively. Faults C and D are a line to line fault at Kilog 10kV and a three phase fault at Kilog 10kV, respectively. According to Figure 6 faults A and B will be tripped instantaneously, fault C will be tripped in 2.8 seconds and fault D will be tripped in 2.4 seconds. Thus this Kilog MCGG overcurrent relay at Tower Hill provides the required primary and backup protection.

Figure 7 shows the overcurrent characteristic for the Kilog overcurrent relay at Tower Hill with the wind farm connected. According to Figure 7 faults A, B and D will be tripped instantaneously, fault C will be tripped in 2.3 seconds.
Therefore, the increase in short circuit levels, caused by the addition of the wind farm, means that Kilog MCGG overcurrent relay at Tower Hill will now trip instantaneously for 10kV faults. The Distribution System Protection Policy stringently demands that 38kV relays do not trip instantaneously for medium voltage faults because this can result in miss-coordination between 38kV and medium voltage relays.

**Recommendations**

The connection of the wind farm to Tower Hill 38kV substation causes the impedance relay (Siemens 7SA511) on the Tower Hill outlet at Dunrath to under-reach. As such, adequate backup protection for the end of Tower Hill to Kilog 38kV feeder and for the Kilog busbar is not provided. In order to provide the appropriate backup protection the zone 3 reach of the relay should be increased, so it will reach the 38kV busbar at Kilog when the wind farm is installed. However, the Distribution System Protection Policy states that the reach of a 38kV impedance relay must be held back at least 15% from the fault impedance of the closest medium voltage fault. At present the Tower Hill relay at Dunrath is set to 85% of the fault impedance to the 10kV busbar at Tower Hill, see Figure 8. Accordingly, the zone 3 of this relay cannot be increased any further. Therefore the only way to provide backup protection for the Kilog relay at Tower Hill is to install an additional relay on the Kilog outlet at Tower Hill i.e. duplicate protection.

Note: also shown in Figure 8 is the position of the 38kV faults at the Kilog 38kV busbar before (B) and after (B’) the connection of the wind farm.

**CONCLUSION**

Adding distributed generation to the 38kV distribution network in Ireland creates a situation where networks that were designed primarily as tail, radial or open radial networks become looped networks. As a result, distributed generation can cause relays in a protection system to under-reach or over-reach. This has been illustrated in this paper, by sample calculations and an actual protection review (using CAPE software).

In order to ensure that the connection of distributed generation does not inhibit the performance of the protection system, a study to assess the actual impact on the protection system must be completed before any generation is connected. The protection review will determine the impact on the protection performance and recommend if an upgrade of the protection system is required, such as: revision of existing relay settings, addition of new relays to the network or the upgrade of existing relays.

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