DETAILED ANALYSIS OF THE IMPACT OF DISTRIBUTED GENERATION AND ACTIVE NETWORK MANAGEMENT ON NETWORK PROTECTION SYSTEMS

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ABSTRACT

Following the deregulation of the energy market and the political drivers to mitigate the effects of climate change, a significant increase in the amount of distributed generation connected to power distribution networks is being witnessed. This, in conjunction with network automation, has various potential impacts on the performance of the network protection system.

While several papers describe the possible consequences of high penetrations of DG on traditional protection schemes, this paper attempts to fully quantify and demonstrate potential problems. To achieve this, a rural overhead distribution network has been modelled and its protection system has been designed and modelled in accordance with prevailing utility protection policy. Using this modelling environment, a number of different scenarios have been simulated in order to show when and how the DG penetration levels and/or changes to the configuration of the network affect the protection system.

Following on from these analyses, the consequences of DG in conjunction with network automation are presented and guidance is provided relating to the levels of DG that may be connected before protection problems will be experienced.

INTRODUCTION

The amount of distributed generation (DG) connected to utility distribution networks is progressively growing, mainly due to deregulation of the energy market, political drivers and financial incentives. In the UK, DG has significantly grown in the last 10 years and accounted for 17.9% of the total installed power capacity of 78,255 MW in 2009 [1].
The connection of DG to the distribution system can significantly impact upon the steady state and transient behaviour of the network. This is dependent on DG capacity and penetration levels, type of generator, the method of interfacing the generator to the network and the position of connection. DG has positive and negative impacts: positive impacts potentially include provision of voltage support, improved power quality, reduction in network losses, release of addition transmission and distribution capacity and improved reliability; negative impacts include public and utility personnel safety issues, damage to plant in the event of unsynchronised reclosure, protection performance degradation, etc. [2], [3]. This paper focuses on the effect of DG, in conjunction with other influencing factors such as active network management and network automation, on overcurrent protection systems with automatic reclosure, as typically applied to UK distribution networks. The possible impacts of DG on overcurrent protection systems utilising relays, multi-shot recloser circuit breakers, pole mounted automatic reclosers (PMAR) and slow blowing fuses have been analysed in [4], [5] and [6]. Fuse-fuse, recloser-fuse and relay-relay coordination issues are discussed in [4] and [5].
The impact of synchronous machines on network protection is analysed in [6], which illustrates the possibility of blinding (non-operation) of network protection and false tripping (mal-operation), typically as a result of sympathetic and incorrect tripping of protection (feeder or DG interface) for faults on adjacent lines.
The IEEE 34 node test network [7] with added DG has been utilised to investigate possible protection coordination problems between fuses and auto-reclosers in [8]. Similar research activities are presented in [9] and [10], where other realistic network models have been used to investigate the impact of DG. All of these papers analyse the behaviour of traditional protection systems and have described possible problems such as blinding of protection, false tripping and miscoordination between protection devices, e.g. between auto-reclosers and slow blowing fuses.
This paper describes research work that has been undertaken to fully investigate and quantify the impact of DG on protection in a UK context. To achieve this, an overhead rural distribution network has been modelled and its protection system has been designed in line with present UK overcurrent protection practices. Commercially available protection relays, pole mounted autoreclosers and automatic sectionalisers have been modelled and their performance has been investigated through simulating a total of 120 scenarios with different levels of DG penetration and position of circuit breaker and switches. Then, for each scenario various fault conditions have been simulated resulting in over 24,000 individual fault simulations being carried out.

TEST CASE NETWORK

The test case network used to analyse the impact of DG is the overhead rural distribution network, "OHA Network", as specified in the United Kingdom Generic Distribution Network (UKGDS) [11].
As shown in figure 1, the network consists of three main feeders and several long spurs. The network is operated in radial mode and the topology can be changed by moving the position of normally open points (NOP).
Both 33/11 kV transformers have a 12MVA rating, with 8.5% per-unit reactance, delta-star winding configurations and solid earth connections.
The lengths of the feeders are 7, 5 and 4km for feeders A, B and C respectively. The maximum length of any spur is 4 km. Feeders A and B have a rated load current of 400A, Feeder C has a rated load current of 250A and all spurs have a rated load current of 100A.

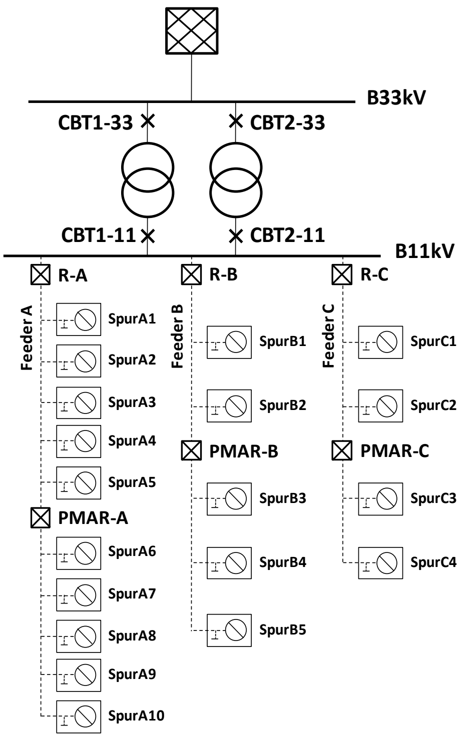

Figure 1 UKGDS OHA distribution network

Traditionally, overhead distribution feeders have been protected using a multi-shot auto-reclosing circuit breaker at the source end of the feeder, PMARs in series (used on longer feeders which can be split into individual sections) and slow blowing fuses on the spurs; these are situated close to the feeder-spur junctions.
UK utilities have estimated that approximately 50% of sustained 11kV overhead circuit outages are due to non-permanent faults. There are several reasons for this, mostly associated with the poor performance of slow blowing fuses and oil insulated PMARs. For this reason, utilities are replacing oil type PMARs with more modern SF_6 type PMARs and fuses with spur sectionalisers.
In this research, a modern protection policy has been applied to accurately represent present-day networks and possibly networks of the future. As shown in figure 1, each feeder is protected by a multi-shot circuit breaker/recloser at the source end and by a PMAR situated at approximately 50% along the length of the feeder. Spurs are connected to the main feeder through spur sectionalisers rather than via traditional slow blowing fuses to reflect modern protection policy. Protection settings have been calculated in accordance with utility policy. Figures 2 and 3 present respectively the phase overcurrent and earth fault protection applied to feeder A.

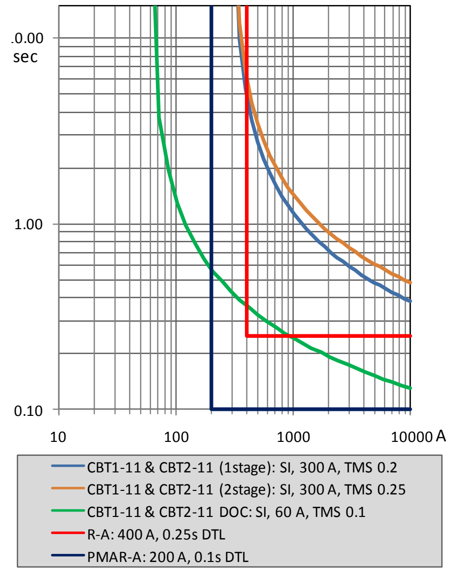

Figure 2 11kV Busbar and Feeder A Phase Overcurrent Protection Settings

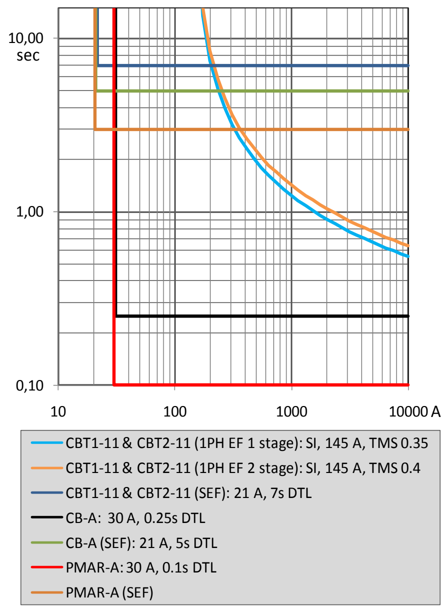

Figure 3 11kV Busbar and Feeder A Earth Overcurrent Protection Settings

DG units with a relatively low power rating are normally protected against network disturbances by a very sensitive instantaneous overcurrent relay in order to prevent islanded operation and/or damage to the network from sustained generator-supplied fault current.
For DG units with relatively larger ratings, utilities require the generators to contribute to the stability of the network and to remain connected during certain disturbances. This capability is known as “fault ride through” and is achieved by de-sensitising certain generator protection functions such as under-voltage, under-frequency and loss of mains. Due to the continued increase in DG penetration, utilities in future may extend fault ride through requirements to smaller power generating units in order to minimise unnecessary and nuisance tripping.
In this work, generator protection has been coordinated with the network protection and all generators with a rating of greater than 500kVA have protection set to ensure fault ride through capability in accordance with [12].

SIMULATED SCENARIOS

To quantify the impact of DG on network protection, several different scenarios have been simulated with two types of DG:

A. Inverter interfaced generators (e.g. photovoltaic generation, electric vehicle to grid).
B. Synchronous and induction generators connected directly or through a step up transformer to the utility network (e.g. combined heat and power (CHP), biomass and landfill generators).

The overall level of DG penetration has been simulated from zero up to a combined total capacity equal to 100% of the network load capacity in steps of 5%.
To study the impact of network automation in conjunction with DG, more scenarios have been added to reflect changes in the topology of the network, i.e. closing and shifting the positions of normally open points (NOP).

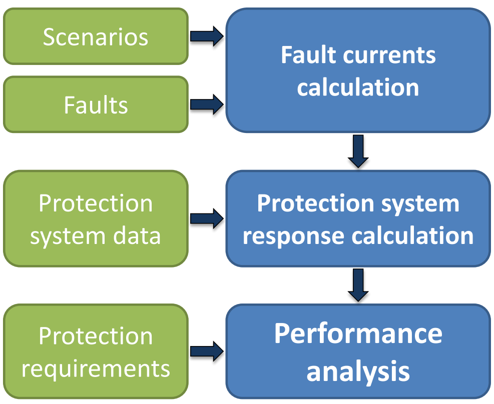

Figure 4 Protection system performance analysis

As shown in figure 4, several faults have been simulated for each scenario, including three phase, phase to phase and phase to earth faults. The calculated fault currents have been used to determine how the protection system responds with the protection settings shown in figures 2 and 3. Then the protection system response has been analysed to check the correctness of operation, the coordination between protection devices and the fault clearance times.

FINDINGS

Fault current levels

The results of the simulation show that for three phase and phase to phase faults, the connection of DG to the faulted feeder results in an increase of fault current on the feeder between the DG and the fault location, and a decrease of the fault current measured by the feeder protection for faults situated upstream of the DG and fault locations. The connection of DG to adjacent feeders generally increases fault current on the faulted feeder and decreases the fault current supplied thought the 33/11kV transformers. The relative impact on fault current levels depends both on the penetration and the location of the DG. These changes to fault current levels and flows have different potential impacts on the protection system. The following subsections describe and quantify different protection issues.

Sympathetic tripping

Sympathetic tripping can occur when the contribution of DG to a fault in an external protection zone, for example for a fault in an adjacent feeder, may lead to a situation where non-directional overcurrent relays mal-operate at the same time as, or before, protection on the faulted feeder, which is an obvious malfunction of the overall protection scheme.
The results of the simulations of phase to phase and three phase faults show that for synchronous generators connected through step-up transformers, sympathetic tripping begins when DG penetration levels reach 45%, while for inverter interfaced generators, sympathetic tripping is not experienced, even at 100% penetration. Figure 5 presents the incidence of sympathetic tripping for different levels of synchronous DG penetration.

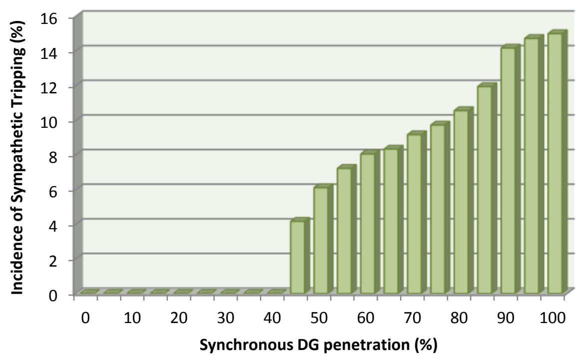

Figure 5 Incidence of sympathetic tripping

For network phase to earth faults, DG interface transformers are typically delta connected on the HV side; accordingly there is no DG earth fault contribution and no effect on the network earth fault protection.

Overload tripping

Overload tripping may occur if DG interface protection operates (either correctly or incorrectly) and results in the addition of previously "hidden" load that was offset from the upstream feeder loading by the DG output. This was observed in the scenarios where DG penetration exceeded 55% and network automation was available to reconfigure the network after a permanent fault. For example, consider figure 1, when the following two faults happen in sequence:

1. Permanent fault at the beginning of feeder B;
2. Three phase fault at the beginning of feeder C.

After fault 1, when the auto reclose sequence terminates, feeder B's main circuit breaker locks out, the network automatically reconfigured by closing the NOP at the end of feeder A and opening the first switch downstream of the permanent fault in feeder B.

Feeder A becomes longer, with a total load higher than its load current rating. However, the DG "hides" an element of this load from the feeder upstream of the DG position and the network continues to operate. When fault 2 occurs and the DG interface protection trips, the load current of feeder A increases, causing a protection trip due to overload.

CONCLUSIONS

The outcomes show that existing overcurrent protection systems are suitable for low levels of DG penetration.

Considering three-phase and phase to phase faults, sympathetic tripping results when synchronous DG penetration exceeded 45% of the installed load on the feeder; for inverter-interfaced generators, no sympathetic tripping is observed.

Overload tripping due to false tripping of generator interface protections arises when the total load of a feeder is larger than the load current rating of the feeder, but DG effectively "hides" or offsets an element of the total load. Overload tripping can occur when the DG interface protection mal-operates due to a fault in adjacent lines or transients in the network.

Further problems observed, but not reported in this paper due to space restrictions, include non-coordination of protection devices after reconfiguration of the network, sympathetic tripping of spur sectionalisers when DG is connected to the spurs, and false tripping of directional overcurrent relays at the LV side of 33/11kV transformers due to power flow from 11kV to 33kV network under both normal and 33kV fault scenarios.

Several possible solutions can be adopted to address these protection issues. One very attractive solution is to continue using overcurrent protection, but with the addition of directional elements and centralised adaptive protection, which monitors the network and the protection system and amend the settings as topology of the network or connection of DG units change. However, issues associated with the potential loss in security through the use of communications must be addressed.

ACKNOWLEDGMENTS

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