# Virtualized wide-area protection for distribution networks and effective anti-islanding of distributed energy resources using 5G communication

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***Abstract*— Protection and control of distribution networks need to be enhanced as the amount of distributed energy resources (DERs) grows and, at the same time, reliability of electricity supply is becoming increasingly important. This paper proposes a protection concept that improves the operation of DER anti-islanding protection and utilizes virtualization and 5G communication.**

**All protection functionalities are virtualized which means that they can be deployed on any hardware that hosts a suitable virtualization environment and fulfils the hardware requirements (computational capacity etc.). Applications from different vendors can be hosted on the same hardware. In this paper, virtualized protection applications include functions which operate based on local measurements (feeder protection at the substations, DER protection at DER sites) and communication-based wide-area protection scheme.**

**The developed wide-area protection scheme includes transfer trip, rate of change of frequency (ROCOF) based blocking and safe reclosing. This functionality ensures the prevention of unintentional islanding and unsynchronized reclosing and, at the same time, keeps the DERs connected during wide-area disturbances. Information is exchanged between sites using Routable Generic Object-Oriented Substation Event (R-GOOSE) messaging over a 5G slice. The developed protection concept has been verified in a real-time digital simulation (RTDS) laboratory environment.**

***Index Terms*—Centralized protection, distributed energy resources, IEC 61850, virtualization, wide-area protection**

## I. INTRODUCTION

Electricity distribution networks are undergoing major changes due to the ambitious Net Zero targets. As a result, there is a need to accommodate an increasing amount of distributed energy resources (DERs) that alter the power flows and fault currents in distribution networks. To address this, distribution network operators are transitioning to distribution system operators (DSOs), who will accommodate increasing amounts of DERs without a need for expensive network reinforcement and will enable DER provided services to support the power system operation. This requires revising the existing distribution network operation, protection and control solutions and also adding novel functionality such as active network management (ANM). This paper concentrates on protection aspects of distribution networks with DERs and proposes a novel protection concept that utilizes industry advances in virtualization and 5G technology. The work has been conducted as a part of a large-scale innovation project Constellation [1] that develops and demonstrates decentralized protection and control architecture in which several solutions can utilize the same computational hardware resources and communication infrastructure.

Currently, distribution network protection is usually achieved by using intelligent electronic devices (IEDs) that are responsible for protecting one feeder. These IEDs operate based on local measurements at each bay and have visibility only towards the one feeder they are monitoring and protecting. Protection functionalities can also be centralized on a single unit at a substation, which enables protection solutions that require broader visibility for the whole substation [2], [3]. Both the decentralized IEDs and the centralized protection unit currently use dedicated hardware on which no other functionality can be executed. However, when the increasing amount of DERs creates a need to decentralize distribution network control beyond the control center, using dedicated hardware for all solutions (existing and new) would lead to having a large amount of computational hardware from different vendors at the substations. A solution to this challenge is to utilize virtualization technology that has been developing rapidly and is now capable of hosting also applications that have rigorous real-time and reliability requirements. Virtualization decouples software from the

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underlying hardware and enables deploying various applications from different vendors on the same hardware.

Virtualization can be based on virtual machines or containers and there is a wide range of commercial and open-source virtualization solutions available. Virtualization is a mature technology for non-real-time applications and an enabler for modern cloud infrastructure. Substation automation, however, has different requirements than the typical cloud applications and, therefore, it is vital to select the right virtualization solution and to configure it correctly so that real-time guarantees are never compromised.

The protection concept described in this paper virtualizes existing distribution network protection functions and adds new functionality to enhance the operation of anti-islanding protection. Anti-islanding protection is required to prevent unintentional islanding of distributed generation (DG) units. However, most of the local monitoring based anti-islanding protection schemes, such as rate-of-change frequency (ROCOF), fail to detect islanding when the imbalance between local generation and demand are of minor scale [4]. On the other hand, there has also been concerns of cascading unwanted tripping of DG units due to wide-area disturbances [5]. The proposed communication-based wide-area anti-islanding protection concept tackles these challenges by utilizing Routable Generic Object-Oriented Substation Event (R-GOOSE) messaging over wireless 5G between the distribution network substation and the DER sites. Transfer trip functionality is used to disconnect islanded DG units, while ROCOF-based blocking is used to keep the DERs connected during system-wide events. A safe reclosing functionality, which is used to prevent unsynchronized reclosing, is also included. The developed concept also includes a communication supervision functionality for verifying that the exchanged R-GOOSE messages are being correctly received. Local ROCOF based anti-islanding protection at the DER sites will operate as back-up protection and will be always active unless blocked by the wide-area ROCOF based blocking functionality.

The paper will, at first, describe the virtualized protection concept and the wide-area protection functionality in detail. Thereafter, real-time simulation results are presented.

## II. Virtualized Protection Concept

The protection concept depicted in Fig. 1 virtualizes the whole protection functionality i.e., protection functions for the substation bays are not associated to dedicated physical relays but to a common hardware platform that has suitable capabilities. Substation computers that host a virtualization

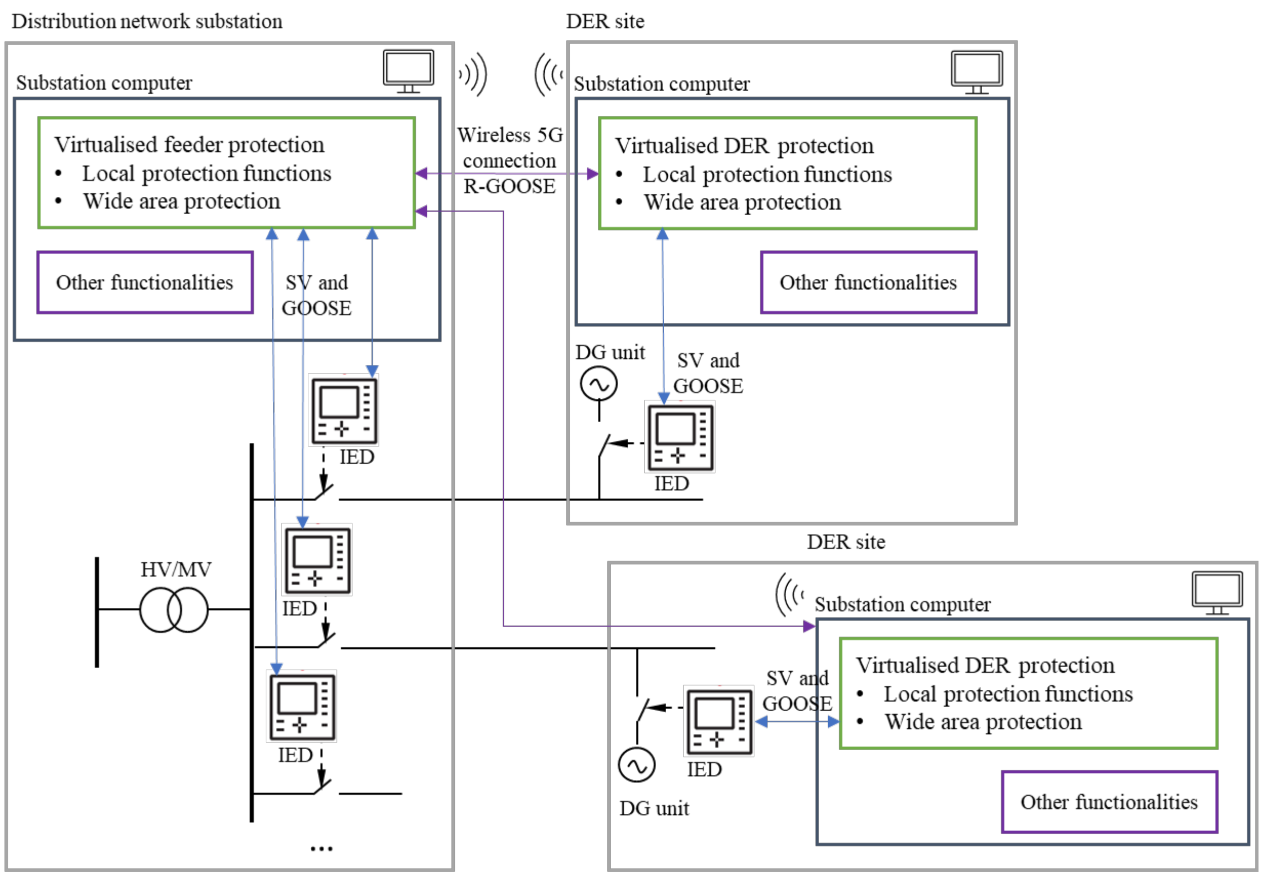


Figure 1. The decentralized protection and control architecture in which intelligence is added to substation computers located at distribution network substations and DER sites.

software environment are installed both at distribution network substations and at DER sites. Protection functionality is implemented on these substation computers while IEDs at each bay act as an interface that receives process data and controls the switchgear. Virtualized protection applications include functions operating based on local measurements (feeder protection at the substations, DER protection at DER sites) and communication-based wide-area protection.

The virtualization environment in substations will also host other functionalities such as active network management. Current legacy systems have a number of separate protection and control cubicles for various functions such as protection, automatic voltage control and substation control systems. The virtualized solution can combine this into one system. This will reduce the substation footprint and in time provide an opportunity to combine engineering resources to be more efficient.

### A. *Virtualizing protection applications*

Protection applications have very stringent real-time and reliability requirements because failure in the operation of protection can compromise the safety of the distribution network. If protection fails to disconnect a faulty network segment, substantial damage to network components can occur, fires can be started, and people can be exposed to danger of electric shock which can in worst case lead to death. Hence, protection needs to always operate correctly, and the virtualization solution needs to support this.

To guarantee real-time performance in the proposed setup (Fig. 1) it is important to consider the following aspects:

- Voltage and current measurements from the IEDs at each bay need to be received with a consistent and low enough network latency so that input data for the protection algorithms is available in a timely manner.
- Access to the computing hardware must be available when the application needs it so that calculations can be always completed within the required time. There needs to be mechanisms to reserve both central processing unit and memory resources.
- Accurate time synchronization using precision time protocol (PTP) is required. In cases where redundancy is implemented through having parallel substation computers, also support for parallel redundancy protocol (PRP) needs to be available.

The mainstream virtualization case does not optimize for any of these and, therefore, special care needs to be taken when setting up the virtualization environment.

The selected virtualization solution is operating at hardware level i.e. is a virtual machine based solution. Several virtual machines were briefly analyzed and VMware ESXi [6] and KVM [7] are the solutions that were selected for further studies. Both are capable of providing the required real-time performance if properly tuned and supported by suitable hardware. Operating system level virtualization i.e. container based solutions have also been studied earlier and provide another viable option [8]. Moreover, virtualization technologies are constantly developing and will provide even more possibilities for smart grid use cases in the future. For instance, scalability of solutions on different hardware platforms will improve. This will enable both advanced high-end solutions for situations when extensive computational power is needed and simpler low-cost solutions for less demanding cases.

## III. Wide-Area Protection Functionality

The wide-area protection proposed in this paper can improve the operation of anti-islanding protection through utilizing messages exchanged between distribution network substations and DER sites equipped with substation computers. Protection logic located at distribution network substations differentiates between events when the DER feeder is faulty (and the DER unit should be disconnected) and when the disturbance originates from the regional transmission system or adjacent feeders (in this case, the DER unit should remain connected). R-GOOSE over 5G technology will be used to send transfer trip and block signals to the DER units. The DER sites will also leverage local anti-islanding protection that is a virtual application running on the DER substation computer. This function is blocked if the distribution network substation measurements indicate that the disturbance originates outside the DER feeder. As a result of this new functionality, the DER benefits from reduced outages, while the electricity network benefits from the increased reliability of the intelligent services provided by DER.

### A. *Operational principle*

The wide-area anti-islanding protection scheme includes a transfer trip functionality that aims to prevent unintentional islanding. Also included is a ROCOF based blocking scheme to prevent disconnecting DERs during wide-area disturbances and adaptive reclosing to prevent unsynchronized reclosing. The basic idea of the protection scheme is detailed in Fig. 2.

#### 1) *Transfer trip*

The performance of local anti-islanding protection methods is dependent on the power imbalance between islanded generation and demand. When this local active and/or reactive power imbalance is exceptionally large, the voltages and/or frequency drift out of the utilized protection thresholds in a short time. However, local anti-islanding protection

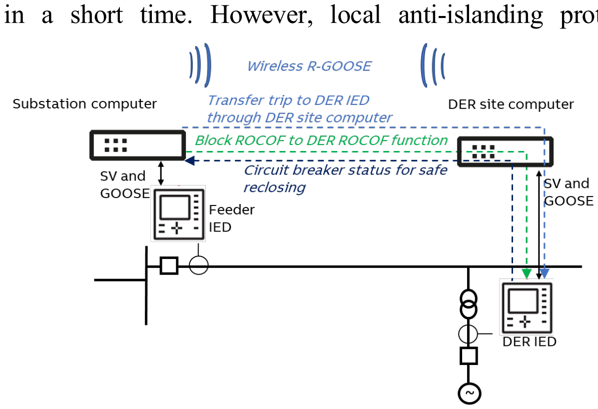


Figure 2. Proposed anti-islanding protection scheme.

operation times may be significantly prolonged, or anti-islanding protection may even wholly fail to detect islanding when the power imbalance is of the minor scale. The solution is to apply a dedicated transfer trip feature included in the protection scheme. This transfer trip functionality ensures that a trip signal is sent to the DER circuit breaker whenever the protected DER feeder becomes isolated from the main grid due to a fault. This solution ensures that islanding is always detected rapidly and reliably, irrespective of the local power imbalance.

*2) ROCOF based blocking*

ROCOF is commonly applied as anti-islanding protection. It has significantly better sensitivity to detect unintentional islanding compared to plain voltage magnitude and frequency protection. Nevertheless, it can also cause unwanted tripping of DER in case of system-level disturbances. In the method proposed in this paper, the distribution network substation virtualized protection is set to monitor the ROCOF value to differentiate which oscillations in ROCOF are caused by upstream wide-area disturbances. Whenever an actual islanding event occurs, the oscillations in frequency and ROCOF index in the islanded circuit are not detected by the main area site protection function. However, when neighboring feeder faults or system-wide disturbances cause the ROCOF index oscillations, the ROCOF index fluctuation is seen at the DER and substation sites. Thus, whenever the monitored ROCOF at the distribution network substation exceeds the utilized threshold for a predefined time, the substation virtualized protection sends a "block ROCOF" command to the DER site. Provided that the received block command at the DER site is up to date (the communication supervision logic is detailed in section III.B), the command temporarily blocks the local ROCOF-based anti-islanding protection. This concept is largely based on the COROCOF concept, which was presented in [9].

*3) Safe reclosing*

Unsynchronized reclosing is often one of the critical concerns regarding DG related protection challenges. Islanded DER and other network components may experience severe damage due to out-of-phase reclosure. This concern can be managed by ensuring that all DERs are tripped within the open time of automatic reclosing dead time. In the proposed method, the DER sites shall be configured to send their circuit breaker statuses to the distribution network substation. This information supports determining whether the DERs are connected and can be analyzed to either raise the alarm to SCADA or to automatically prevent circuit breaker (CB) reclosing at the substation if any DER sites remain connected.

### *B. Wireless communication over 5G*

5G mobile networks can provide reliable and low latency wireless communication and, therefore, be utilized in applications with strict reliability and real-time requirements. Utilizing 5G for power system protection has been studied in [10], and the results indicate that cellular networks can provide a communication platform for distribution networks. For highly critical applications such as line differential protection or transfer trip, 5G standalone (5G SA) deployment should be used and methodology to guarantee quality of service (QoS) for the critical applications should be included.

The proposed wide-area protection functionality will use a 5G SA network with network slicing capability. Network slices are logically independent networks where reliability and latency guarantees can be provided, and critical communication can be prioritized. The network slices can utilize the same physical network infrastructure with other services. The needed functionality at full extent will be available at least in 3GPP R16 [11] networking equipment.

When blocking protection functions over a wireless 5G network, the blocking messages must be reliable. The reason is that outdated blocking messages could potentially prevent the correct operation of ROCOF-based anti-islanding protection. Because of this, a dedicated communication supervision logic based on continuous R-GOOSE messaging between the two substation computers has been included to the implemented protection concept. If the continuous messages are not received for a defined time, the communication supervision function raises a communication failure alarm. This alarm is latched for a defined reset period. Whenever the communication failure alarm is active, the block ROCOF messages will be ignored. More sophisticated communication supervision mechanism could include interaction with communication network components or utilize time information carried with messages. These options may be implemented in the future.

## IV. TESTING RESULTS

The lab testing results presented in this paper concentrate on the wide-area protection functionality verification. During the Constellation project, virtualized wide-area protection will be demonstrated in two trial areas located in UK Power Networks' distribution network. The distribution network model analyzed in this section is based on one of the trial sites.

### *A. Simulation setup*

A real time simulator and two centralized protection and automation computers were used for conducting the simulation studies of this paper. In this setup, one of the centralized protection units was configured to protect and control the 33 kV substation (the two busbars of this substation are denoted as MAIN 1 and MAIN 2 in Figure 4). The transfer trip logic, as well as the wide area disturbance detection, were also configured to this IED (denoted as centralized protection unit #1 in Figure 3). The other IED in the setup (denoted as centralized protection unit #2), was configured to protect the four DG units in the simulated distribution system. Note that in practice there will be separate IEDs at each DG site in the actual pilot, but it was sufficient to use only one of these IEDs in the studies of this paper. This simplification was possible since it was possible to configure this IED#2 to subscribe measurements from all four DG unit locations via IEC 61850-9-2 sampled value streams. Each sampled value stream included phase currents and voltages, the residual current and residual voltage. Similarly, IED #1 was set to subscribe the simulated voltages and currents from each of the 33 kV bays connected to the busbar sections MAIN 1 and MAIN 2. All the digital signal exchange between

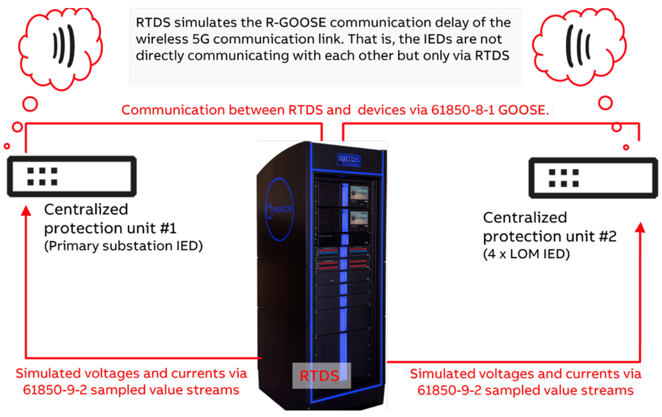


Figure 3. Overview of the utilized laboratory test setup.

the simulator and the IEDs was established via 61850-8-1 GOOSE in this simulation setup. However, GOOSE communication will be replaced by R-GOOSE and wireless 5G link in the final setup. Thus, to also be able to study the communication supervision logic related issues, the RTDS was set to emulate the behavior of the 5G network. This was done so that IEDs in the setup were only communicating with RTDS and not directly with each other at all. The RTDS was then set to delay the signals that were meant to be sent from one IED to another (e.g., transfer trip and block messages).

## B. *Simulation results*

This chapter firstly presents how the wide area disturbance logic (ROCOF based blocking) can be used for avoiding false tripping of DG units. In the example scenario, the power system frequency falls at such a rate of change that it causes all the DG units in the studied system to be unwantedly disconnected. The same scenario is then repeated while enabling the wide area disturbance detection logic to illustrate how the logic can aid in avoiding false tripping of DER. Finally, a fault scenario resulting to the islanding of one of the DG units is simulated for illustrating the functioning of the transfer trip logic. Figure 4 illustrates the structure of the studied network and the locations of the four DG units in the model.

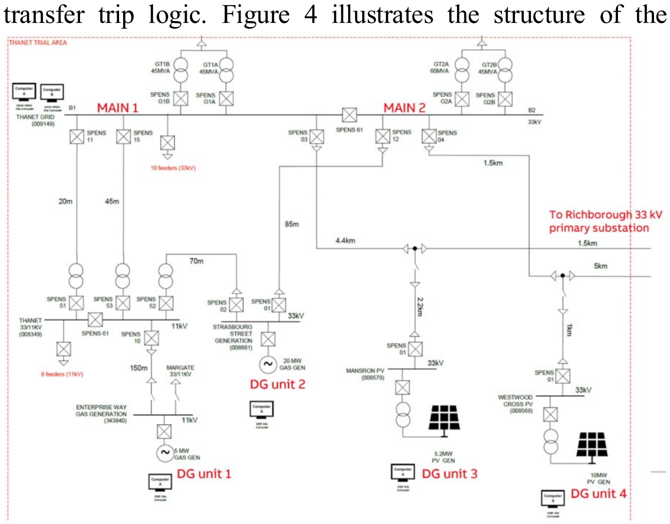


Figure 4. Single line diagram of the simulated network model. There are four DG units in the simulation model.

Figure 5 presents a reference case illustrating how a system wide frequency oscillation may result to unwanted tripping of DG units. In this example, the system frequency decreases from 50 Hz/s to 49 Hz/s at a rate of change of -2 Hz/s as illustrated in the uppermost graph of Figure 5. Consequently, all four DG units in the examined system see a ROCOF of approximately -2Hz/s as illustrated in the second graph of Figure 5. Note that ROCOF index in the figure is not exactly the ROCOF computed by the IEDs but instead simply an index computed using simple logic blocks in RSCAD (the graphical user interface for RTDS). Anyhow, the local ROCOF-based anti-islanding protection is triggered and causes all four DG units in the modelled system to falsely trip as presented in the lowermost graph of Figure 5.

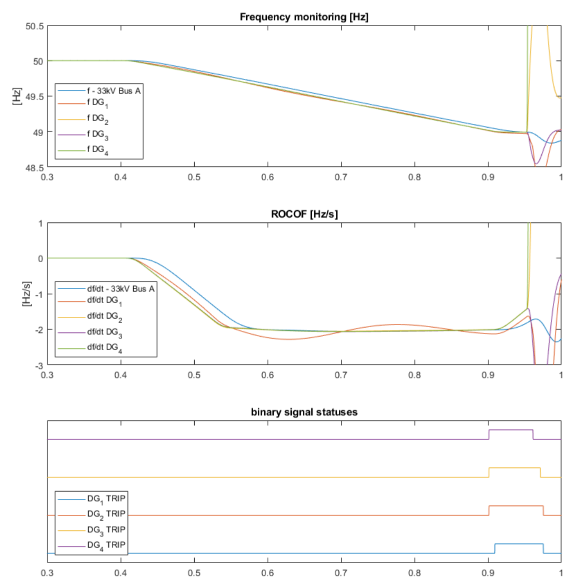


Figure 5. A reference scenario illustrating how a system wide frequency oscillation may result to tripping of DG units. In this scenario, the system frequency falls steadily from 50 Hz to 49 Hz at a rate of change of -2 Hz/s. Consequently, all four DG units in the network are tripped because of local ROCOF tripping.

In order to prevent such unwanted tripping, the wide area detection logic was then enabled, and the same simulation was repeated. This scenario is presented in Figure 6. This time the wide area disturbance is detected by the primary substation IED, which then sends blocking messages via GOOSE to all four DG units as illustrated in the lowermost graph. Consequently, no unwanted tripping occurred. Note that GOOSE will be replaced by R-GOOSE in the final implementation.

The following example illustrates how the transfer trip logic behaves when DG unit 3 becomes islanded as a result of a three-phase fault at the tail part of feeder SPENS 03 (SPENS is an abbreviation for substation plant equipment numbering system). Firstly, the overcurrent protection function instance which was set to protect the feeder SPENS 03 detected the fault and issued a trip command as well as a command to open the corresponding circuit breaker CB SPENS 03 (denoted as

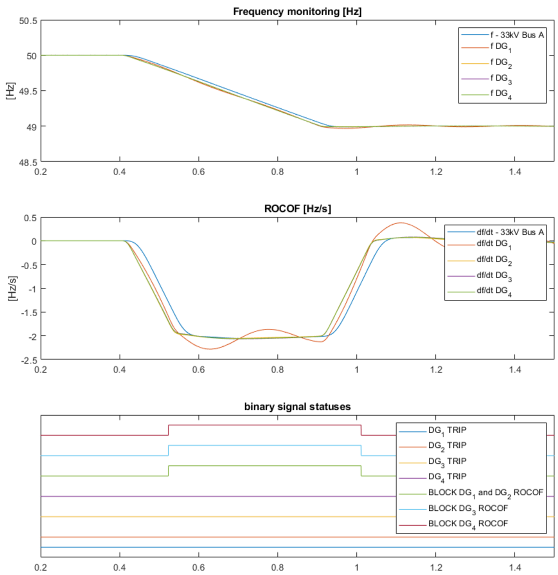


Figure 6. An example of the functioning of the wide area disturbance detection logic when the power system frequency falls from 50Hz to 49Hz at a rate of change of -2Hz/s. The logic detects the ROCOF oscillations at the main area substation (33 kV busbar) and blocking messages are consequently sent to all four downstream DG units successfully. Note that the block signals in the figure represent the received signals at DG sites (the simulated communication delay was 10 ms in this simulation scenario).

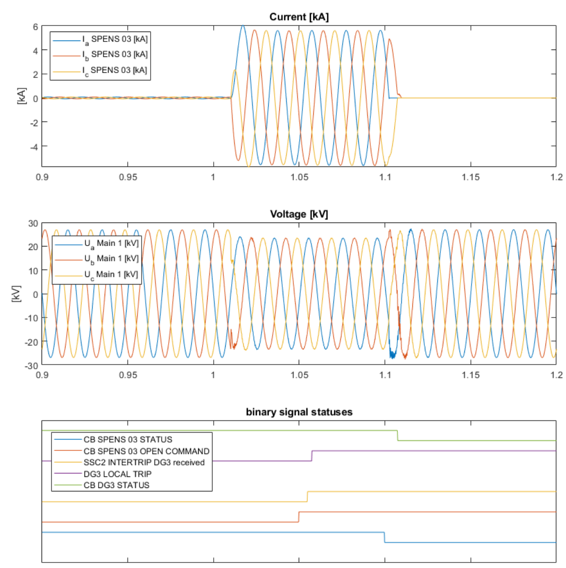


Figure 7. An example of the functioning of the transfer trip logic when a fault at the tail part of feeder SPENS 03 resulted to an islanding condition for DG unit 3. This three phase fault was detected and tripped by bay SPENS 03 overcurrent protection in IED#1. The tripping then resulted to CB SPENS 03 OPEN COMMAND, which is visible in the lowermost graph. Consequently, IED#1 sent a transfer trip command to DG unit 3 which resulted to tripping of DG 3.

"CB SPENS 03 OPEN COMMAND" in the lowermost graph of Figure 7). Almost simultaneously, the transfer trip logic in the primary substation computer concluded that DG 3 was to be islanded as a result of CB SPENS 03 opening, and consequently sent a transfer trip command to the DER site computer for disconnecting DG unit 3. The simulated communication delay in this scenario was 5 ms, and the DER site computer thus rapidly received the transfer trip command (denoted as "SSC2 INTERTRIP DG3 received" in the lowermost graph of Figure 7) from the primary substation computer. After a few ms delay, the DER site computer consequently issued a local trip command (denoted as "DG 3 LOCAL TRIP" in Figure 7). The CB opening delay in the modelled system was set to 50 ms, and the circuit breakers CB SPENS 03 and CB DG3 thus opened 50 ms after the received "CB OPEN" commands.

## C. *Integration testing and real network trials*

The testing results presented in this paper concentrate on verifying the operation of wide-area protection functionality. The next step of the Constellation project will be integration testing in a laboratory environment, with the virtualization environment hosting all the functionalities being developed. After that, demonstrations will proceed to trial tests at the Power Networks Demonstration Centre (PNDC) in Scotland and then at trial sites located in UK Power Networks' distribution area to verify the Constellation solutions in a real operational environment.

# V. Conclusions

The increasing amount of DERs is creating a need to enhance distribution network protection and control solutions. The existing functionalities will need to be altered, while completely new functionalities will need to be added to guarantee resilience and efficient operation of the future smart distribution networks. New technology advances in other industries such as software engineering (virtualization) and telecommunications (5G) can be utilized to support accommodating the increasing amount of DERs cost-efficiently and with less investments on hardware.

This paper describes a new protection concept that virtualizes all protection functionalities and enhances the operation of DER anti-islanding protection. When protection functionalities are virtualized, they can be deployed on any hardware that hosts a suitable virtualization environment and fulfils the hardware requirements (computational capacity etc.). This enables hosting several applications from different vendors on the same substation computer and, hence, the number of devices at the substations and DER sites decreases and computational and communication resources can be more efficiently utilized. The implemented virtualized protection concept includes functions based on local measurements and a wide-area anti-islanding protection scheme that includes transfer trip, ROCOF based blocking and safe reclosing and exchanges information between sites using R-GOOSE messaging over 5G. The wide-area protection functionality guarantees that DERs are disconnected when they are islanded but remain connected during wide-area disturbances. In this paper, the proposed protection concept is tested using RTDS lab testing environment and at later stages of the Constellation project, testing will proceed to integration testing and finally to real distribution network demonstration.

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