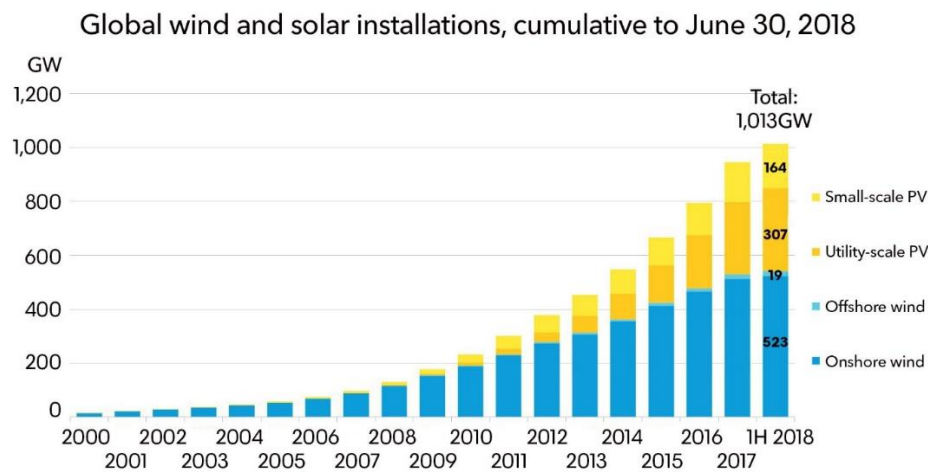

Transmission line protection for systems with high penetration of inverter-based resources

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1 INTRODUCTION

Some of the main characteristics of Smart Grids are the high level of penetration of distributed energy resources (DERs) and the requirements for improved reliability of the electric power system under different abnormal conditions. The DERs are of different sizes and types and are being connected at all different levels of the electric power system – transmission, distribution and low voltage. This introduces significant challenges for protection systems at the transmission and distribution level of the system which need to be considered in the engineering of the protection devices and systems.



Source: Bloomberg NEF. Note: 1H 2018 figures for onshore wind are based on a conservative estimate; the true figure will be higher. BNEF typically does not publish mid-year installation numbers.

Fig. 1 Wind and solar installations around the world

In order to remain in service following a short circuit fault the DERs need to be able to withstand the voltage drop until the fault has been cleared by the protection and the circuit breaker. Considering that the protection operating time depends on the type of protection, location of the fault, type of fault and fault parameters, it is clear that these factors need to be analyzed in order to identify the requirements for improvement in the fault clearing time.

The first part of the paper describes what is known as the ride-through characteristic of the DERs and the impact on the operation of the protection and control system on the ability of a DER to remain in service.

The second part of the paper discusses advanced protection functions in multifunctional IEDs and how they can be used to improve the performance of the protection system.

IEC 61850 is the dominant communications protocol recognized as one of the cornerstone technologies for the Smart Grid that brings significant benefits to the industry and allows the more efficient integration of devices of different types into systems. The paper describes the characteristics of the high-speed peer-to-peer communications defined in the standard and how they can be used in protection schemes to reduce the fault clearing time.

The next section of the paper describes different protection schemes that can be implemented in substations in distribution systems with high penetration of distributed energy resources. A substation with two power transformers and a distribution bus with sectionalizing breaker is used as an example. Different protection schemes using IEC 61850 GOOSE messages are described and it is demonstrated that they can significantly reduce the fault clearing time compared to the conventional distribution protection hardwired solutions, thus preventing the tripping of the DERs during the voltage drop resulting from the fault.

The paper then analyses the use of GOOSE messages in communications-based protection schemes at the transmission and distribution level that will have an impact on the DERs..

The use of accelerated protection schemes based on what is known as a wide-area GOOSE is described later in the paper.

The last section of the paper describes the methods and tools for performing testing of distributed protection schemes.

2 RIDE-THROUGH CHARACTERISTIC

Distributed generators are being typically connected to sub-transmission or distribution systems. The definition of such systems varies between utilities and in some cases systems with voltages as high as 138 kV may be considered as distribution. The addition of distributed generators has a significant effect on the system. The levels of short circuit currents, the dynamic behaviour of the system following such faults, the coordination of protective relays are affected and have to be considered in the selection of the protection system. Line protection settings and criteria should take into account in-feed effect, possible power swings and generator out-of-step conditions.

The increased fault clearing times that are caused by the in-feed effect of a distributed generator may not be acceptable to customers with sensitive loads. The voltage sag is experienced not only by users on the faulted feeder, but also on the adjacent feeders, connected to the same distribution system.

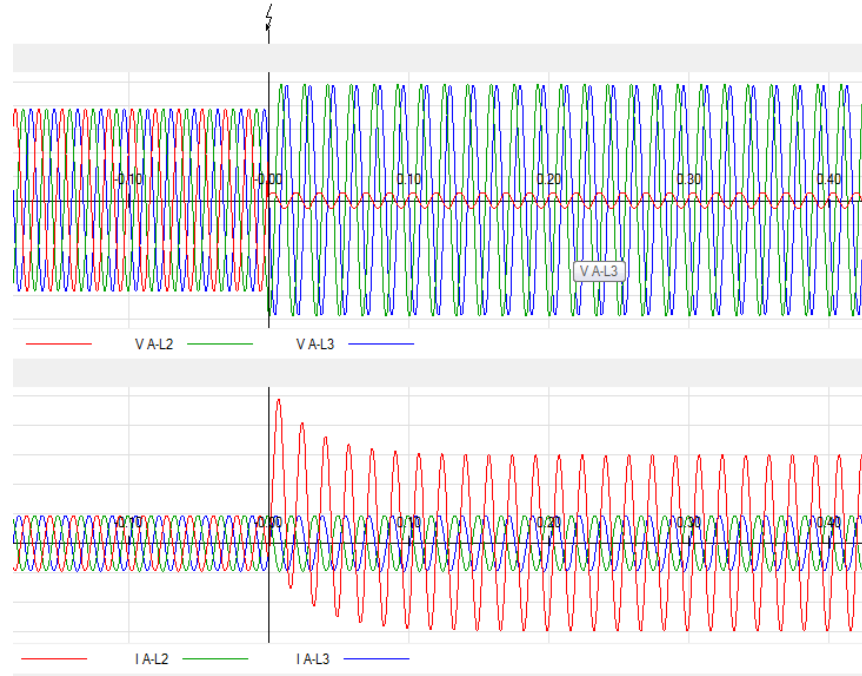


Fig. 2 Impact of single-phase-to-ground fault

Figure 2 shows the areas of impact of voltage sags or swells on sensitive equipment and demonstrates that the impact depends on two characteristics. The first characteristic of a voltage sag – the depth – is a function

of the type of fault, fault location and the system configuration. It will also be affected by the state of the distributed generator – if it is in service or not. Single phase-to-ground faults lead to voltage sag in the faulted phase and to voltage swell in the healthy phases. The level of voltage increase is also affected by the grounding of the interface transformer and should also be taken into consideration.

The same two characteristics of the fault also have an impact on the ride-through capability of the DER. Figure 3 shows an example of a ride-through characteristic.

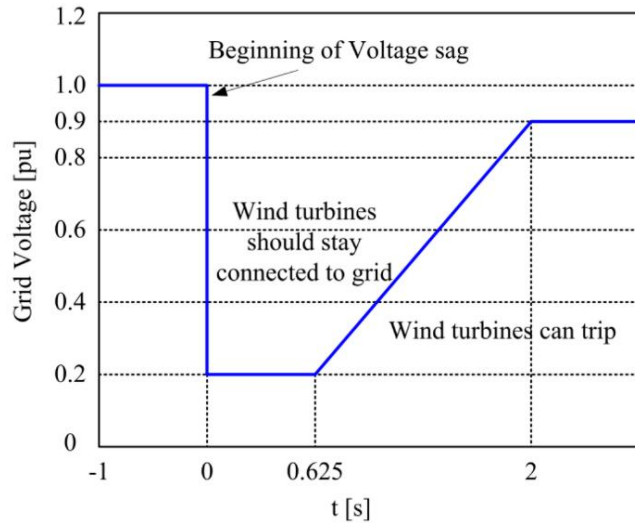


Fig. 3 Ride-through characteristic

The ride-through characteristic includes two areas defining the required response of the DER when a short circuit or another abnormal condition occurs.

The first area is the ride-through area when for a short period of time after the fault inception and depending on the level of the voltage drop the DER should stay connected to the grid.

The second area is where the DER can trip if the voltage drop is deeper or lasts longer.

The ride-through characteristics are different for different countries, as shown in Figure 4.

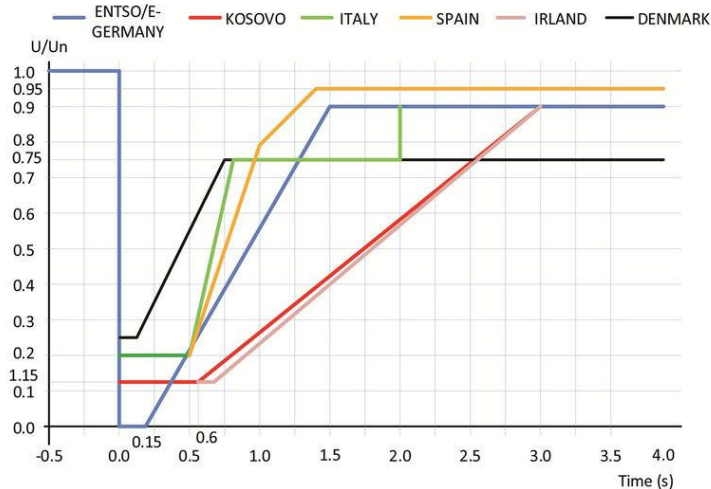


Fig. 4 Ride-through characteristics of different countries

The voltage drop is something that we cannot control, but we have to study in order to be able to predict or estimate the effects of different faults on the sensitive equipment. The second characteristic of the voltage sag – duration – is the parameter that we can control by properly applying the advanced features of multifunctional protection relays.

The distributed generator interconnection protection is subject to many papers, as well as standardization work, such as IEEE P-1547. It is clear that the location of the fault and the infeed from the generator will lead to increase of the fault clearing time and coordination problems. This depends more specifically on the type of distributed generator and its interconnection with the electric power system.

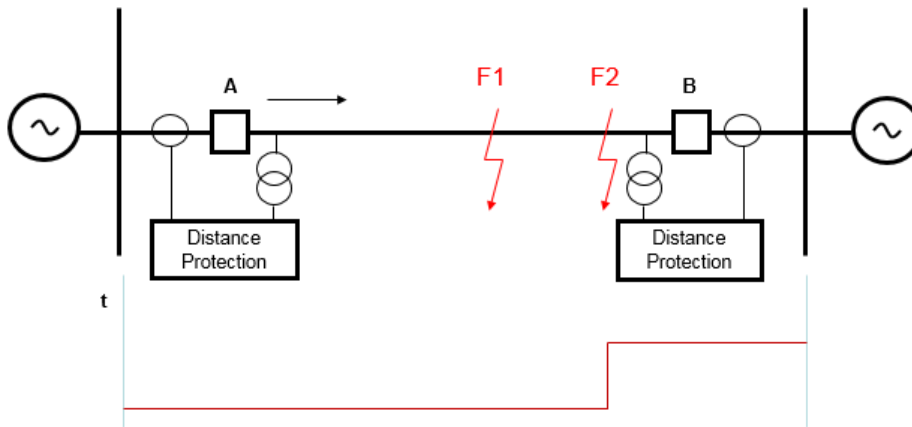


Fig. 5 Distance protection of transmission line

However, it is not only the distribution feeder protection that needs to be accelerated. When a short circuit fault occurs on a transmission line connected to a substation with DERs connected at the distribution level, the voltage drop caused by the fault needs also to be considered in the analysis of the performance of the DER and its ability to ride through the fault.

When the fault is in Zone 2 of the protected transmission line (especially on shorter lines) the time delayed trip will depend on the time delay setting which may be in the range of 300 – 400 msec. Such a delayed trip will result in the duration of the voltage sag experienced by a DER in the tripping area of the ride-through characteristic. An accelerated protection scheme can significantly reduce the fault clearing time and bring it within the stay connected area of the characteristic.

3 ACCELERATED DISTANCE PROTECTION SCHEMES

Conventional zone distance protection (Fig. 66) does not provide instantaneous tripping for all faults on the protected transmission line due to the fact that typically the last 20% of the protected line is covered by the Zone 2 element that typically operates with a time delay of 300-400 ms.

Communications based distance protection schemes, where a signal from the protection relay at one end of the line is sent to the protection relay at the other end of the line, allow considerable improvement in the overall fault clearing time for any fault within the zone of protection, and they do not require high-speed communications essential for line differential protection. This is because the signaling channel in these distance protection schemes only transmits simple ON/OFF data (from a local protection device) to the remote end protection device that is used to accelerate in-zone fault clearance or prevent operation for external faults.

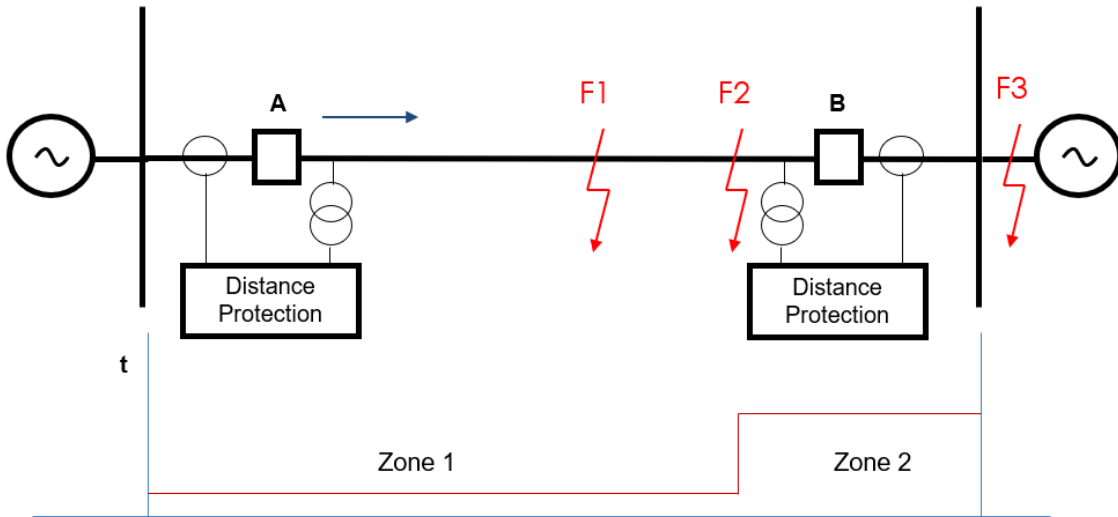


Fig. 6: Typical Transmission Line Zone Distance Protection

These accelerated teleprotection schemes can be grouped into three main operation modes: Intertripping, Permissive and Blocking. The protection function that sends the permissive or blocking signal to the remote end determines the type of scheme used. If this is a distance element, we usually talk about Permissive Underreaching or Overreaching schemes, and Blocking schemes. If a directional element is used to initiate the transmission of a signal to the remote end of the protected line, it is a Directional Comparison scheme. Directional comparison schemes can be Permissive or Blocking, with directional elements initiating the signal transmission and providing the supervision at the receiving end. There can be several types and combinations of permissive and blocking logic implemented in protection schemes.

In **Intertripping**, (direct or transfer tripping) applications, the command from one end of the line is not supervised at the remote receiving end by any protection relay and simply causes a remote breaker trip operation. Since the received signal is not checked by the remote protection device, it is absolutely essential that any noise on the signaling channel is not seen as being a valid signal. In other words, an intertripping communications channel must be very secure. An example of direct or transfer trip is when a line breaker at one end of the line fails to operate and a signal is sent to trip the breaker at the other end of the line.

In **Permissive** applications, tripping at the remote end of the line is only permitted when the command coincides with a protection operation at the receiving end. Since this applies a second, independent check before tripping, the signaling channel for permissive schemes does not have to be as secure as for intertripping channels. An example of permissive tripping is Zone 2 directional permissive overreach transfer tripping (POTT), where a fault is in Zone 2 of a relay and operation of the relay is accelerated by receiving the Zone 2 operating signal from the other end of the line.

In **Blocking** applications, tripping is only permitted when no signal is received, but a protection operation has occurred. In other words, when a command is transmitted, the receiving end device is blocked from operating even if a protection operation occurs. Since the signal is used to prevent tripping, a blocking channel must be fast and dependable. An example of blocking tripping is Zone 2 directional blocking tripping, where a fault is in Zone 2 of a relay and operation of the relay is accelerated by not receiving the Zone 3 (reverse looking) operating signal from the other end of the line.

4 WEAK INFEEED LOGIC

One of the concerns of the protection community related to the high levels of penetration of inverter-based energy resources is that when a fault occurs on a transmission line, some distance protection elements will operate with a delay, and as a result, expose the DERs in the neighboring system to lower voltage levels that may be in the tripping zone of the ride-through characteristic. For example, with the distance protection

scheme shown in Fig., a fault at F1 will be seen by the protection relays at both ends of the line in Zone 1 and it will be cleared without any significant time delay. For a fault at F2 it will be seen in Zone 1 by the relay at end B, but in Zone 2 by the relay at A, thus leading to a delayed tripping of that breaker.

Accelerated transmission line protection schemes are typically used to reduce the fault clearing time for faults in the Zone 2 of the distance protection. However, such schemes require the Zone 2 distance element at both ends of the line to operate, which results in the sending of a permissive signal to the remote ends as described above. In this case the fault clearing time will depend on the Zone 2 starting time and the communication channel delay, which will be much faster than the Zone 2 tripping time.

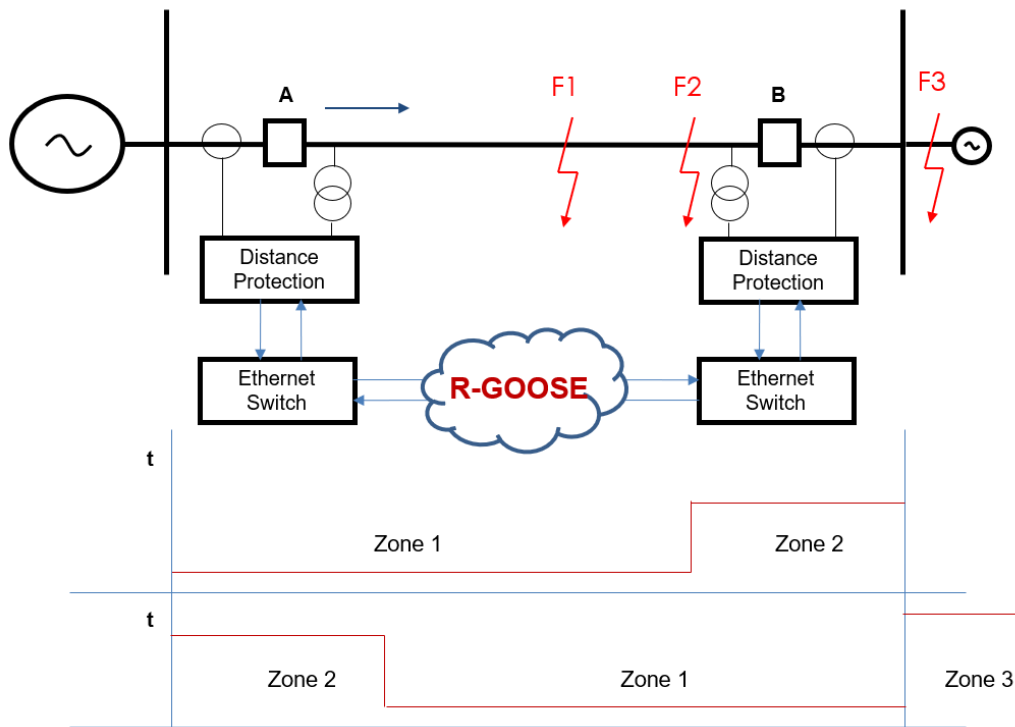


Fig. 7: Accelerated Distance Protection Scheme with Weak Infeed

If end B of the transmission line (Fig.7) is connected to a substation in an area with a high penetration of inverter-based distributed energy resources, for a fault at F2, it will be seen in Zone 2 of the relay at line end A with a strong source and send the permissive signal to the weak end relay B. Because of the weak source at B, the fault may not be seen by Zone 1 or Zone 2 of protection relay B because of the low fault current level, so a traditional directional POTT scheme will not operate.

To solve this problem, weak infeed logic is implemented by using a permissive Zone 2 trip signal from A to operate relay B if the reverse looking Zone 3 of the protection at B has not operated, indicating that the fault is on the protected line. The weak infeed logic will trip breaker B and then send a transfer trip signal back to A for permissive accelerated Zone 2 tripping at A. In this case the fault clearing time will be increased by the communication time from B to A, but will still be much faster than the Zone 2 tripping time at A.

Considering that typically a Zone 2 time delay is in the range of 300-400 ms the operating time of this logic will be much faster, around 70-80 ms, which will keep the fault clearing time within the most stringent 160 ms tripping delay specification in the IEEE 1547 inverter ride-through characteristic.

5 WIDE AREA IEC 61850 GOOSE

While the benefits of accelerated transmission line protection schemes have been known for many decades, their implementation typically has been limited by the fact that they require a communication channel, which can be quite expensive. The good news is that developments in the IEC 61850 standard can help solve the requirement for low latency end-to-end communications between substations.

The IEC 61850 GOOSE message was designed for peer-to-peer communications within the substation over a LAN, and because of that, it uses a three layer stack and MAC multicast. This is not suitable for messages that need to be sent over a wide area network. For that reason, additional features are required to support GOOSE transmission over wide area networks. Some network routers designed for use in the power utility field provide features to wrap GOOSE messages into IP packets and transmit them over a WAN.

5.1 GOOSE over MPLS

Multiprotocol Label Switching (MPLS) is a packet-forwarding technology that uses labels to make data forwarding decisions. MPLS networks became the focus of evaluation and deployment in many power utilities since they provide connectivity for all kinds of services within a utility, not just protection.

With MPLS, the Layer 3 header analysis is performed only once (when the packet enters the MPLS domain). Label inspection drives subsequent packet forwarding. In the traditional 7 layer OSI model, datalink Layer 2 includes protocols, such as Ethernet, which can carry IP packets, but only over simple LANs or point-to-point WANs.

The network Layer 3 includes Internet-wide addressing and routing using the Internet Protocol (IP). MPLS operates between these traditional layers, providing additional features for the transport of data across the network. Because of that, MPLS is sometimes called a “Layer 2.5 networking protocol”. This technology allows the engineering of paths between substations that can transport layer 2 traffic through the WAN, thus effectively extending the LAN into remote substations. IEDs communicating via GOOSE can therefore exchange information with remote devices, just as if they were connected to the same local network.

5.2 R-GOOSE

The technical report IEC 61850 90-5 Use of IEC 61850 to transmit synchrophasor information according to IEEE C37.118 is the document that also defines the methods for transmitting GOOSE messages over wide area networks based on IP solutions. This report selected UDP/IP as the option to transmit data over WANs. The GOOSE messages based on this technology became known as Routable GOOSE or R-GOOSE.

The Internet Protocol (IP) is a Layer 3 protocol. The Network layer adds the concept of routing above the Data Link layer. When data arrives at the Network layer, the source and destination addresses contained inside each frame are examined to determine if the data has reached its final destination. If that is true, this Layer 3 formats the data into packets delivered up to the Transport layer. The IP allows the routing of data packets (IP packets) between different networks over any distance.

The User Datagram Protocol (UDP) is a Transport Layer 4 network protocol. While TCP (Transmission Control Protocol) is a connection-oriented protocol that first requires establishing communications between a client and a server, UDP is connectionless, which makes it more suitable for GOOSE communications. UDP network traffic is organized in the form of datagrams. A datagram comprises one message unit. The first eight (8) bytes of a datagram contain header information and the remaining bytes contain message data.

A UDP datagram header consists of four (4) fields of two bytes each:

- source port number
- destination port number
- datagram size
- checksum

The UDP checksum protects the message data from tampering. The checksum value represents an encoding of the datagram data calculated first by the sender and later by the receiver. If the UDP checksum does not match, it will indicate that the data has been tampered or corrupted during transmission. In UDP, the checksum is optional as opposed to TCP where it is mandatory. The many working applications of the IEEE C37.118 protocol confirm that the use of UDP for the streaming of synchrophasor data is a proven method that can also be used for the routable GOOSE. Considering the importance of the checksum as a cyber security tool, IEC 61850 8-1 Edition 2.1 defines it as mandatory for IEC 61850 implementations.

6 TESTING OF WEAK-INFEED LOGIC SCHEME

A test system designed for the testing of distributed accelerated protection systems based on IEC 61850 has multiple components that are needed for the testing of the individual functions, as well as the complete scheme application. A simplified block diagram of such a system is shown in Figure 8.

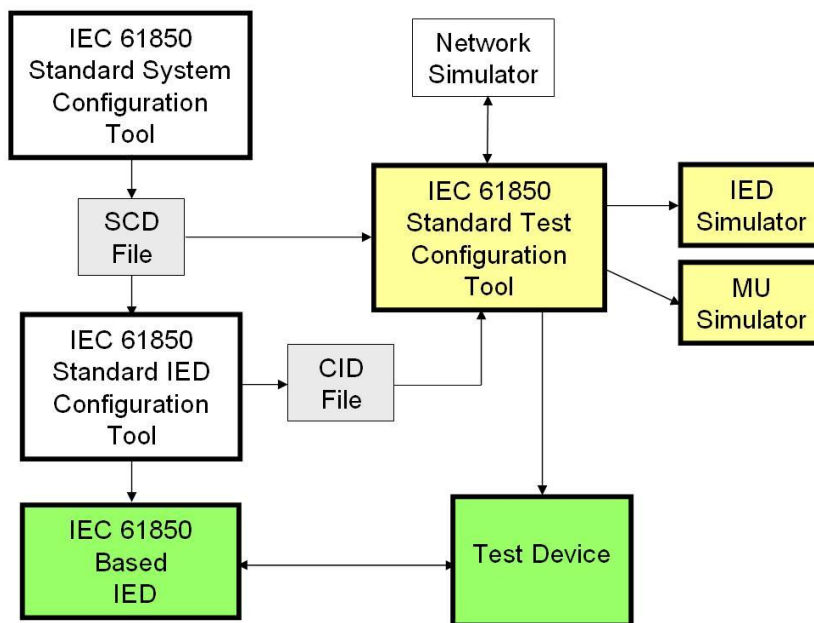


Fig. 8 Test system/configuration tool, simplified block diagram

The first component of the test system is the test Configuration Tool. It takes advantage of one of the key components of the IEC 61850 standard – the Substation Configuration Language. The Configuration Tool is used to create the files required for configuration of different components of the test system. It imports or exports different configuration files defined by Part 6 of IEC 61850.

The test system Configuration Tool reads the information regarding all IEDs, communication configuration and substation description sections. This information is in a file with .SCD extension (for Substation Configuration Description) and is used to configure the set of tests to be performed. The IED configuration tool sends to the IED information on its instantiation within a substation automation system (SAS) project. The communication section of the file.

The second component of such a system is a Simulation Tool that generates the current and voltage waveforms for each of the required test cases. The specifics of each simulated test condition are determined by the complete, as well as the configured functionality of the tested device or application. They are reflected in an electric power system model which as a minimum includes the protected transmission line and

equivalent sources at each end. If available, it is preferred to use a more detailed model of the system where the line is located.

Using the network model the testing tool performs a transient simulation which is used by the test device to produce current and voltage signals or in the case of IEC 61850 based solutions the corresponding sampled values. For the permissive or blocking signals required for the testing of the accelerated protection schemes the test device uses hard-wired interfaces or GOOSE messages. The test cases as a minimum should include simulate faults at F1, F2 and F3 combined with receiving or not of a permissive signal.

During the development of the protection scheme the testing is performed in the laboratory and may be done using only one or both protection devices.

During the commissioning of the protection system it is important to perform end-to-end testing running the transient simulation with GNSS synchronized devices located in the substations at both ends of the protected line. This is essential for the schemes that are implemented using R-GOOSE because of the dependence of the latency on the path through the wide area network. The same test needs to be performed numerous times to get a good understanding of the range of scheme operating times.

7 CONCLUSIONS

DER inverters compliant to the IEEE 1547-2018 standard will be able to provide more capability and flexibility in operation of the electrical grid, however, high penetrations of DER can affect conventional protection schemes. With the requirement for IEEE 1547 compliant inverters to include a communication interface, and options for wide-area communications, such as IP-based IEC 61850 GOOSE, more advanced and intelligent protection schemes can be implemented.

While the complexity of protection schemes can be alleviated with peer-to-peer communications to exchange monitoring and control data, the design and operation of the grid of the future is likely to include some form of integration, coordination and optimization of protection and control schemes along lines and feeders, among substations and across service regions.

Future protection and control systems may include a hierarchical or distributed architecture to provide more computing and data analytics capabilities at the grid-edge to support the necessary technical and commercial functions to operate the grid. We will likely see more integration of protection schemes to coordinate DER control in the next generation of transmission and distribution management systems.

Using communications-based protection schemes with weak infeed logic can ensure that the requirements for fast fault clearing will be satisfied even in areas with high penetration of inverter based DERs. The efficiency of such applications can be significantly improved with R-GOOSE messages.