How Utilities enable savings by investing in the digital intelligent grid towards a self-healing distribution network

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ABSTRACT - *In most of the Countries worldwide, delivering electricity in a safe and reliable way is becoming a priority challenge for Distribution Utilities. The gradual shift from conventional sources of energy i.e. coal power plants or nuclear to renewable energy and distributed generation (DG) concepts are introducing further variables to such challenge, which needs to be taken into consideration. Several measures can be introduced to optimize the reliability of the network and improve SAIDI and SAIFI indexes i.e. network automation, zone concept, fault detection isolation and restoration by means of different equipment and techniques, and the choice needs to be a technical-economical evaluation based on a clear return of investment.*

A general approach is presented in the paper together with some down to earth examples and case studies, to support utilities to approach current and future issues, paving the way for further discussion and research on the topic.

I. INTRODUCTION

Energy markets are undergoing many changes in order to adapt themselves to VUCA environments (Volatile, Uncertain, Complex and Ambiguous). Electric grid is becoming more and more dynamic and difficult to predict: in this challenging environment, transmission and distribution utilities are asked to keep stability and reliability at high levels, avoiding interruptions and intermittency in energy flow. Some conventional power plants fueled by coal, lignite or uranium, are being decommissioned in western countries, affecting the security of supply and reserve margin levels. These changes need to be introduced and maintained by system operators, and each country has a slightly different approach to these challenges [1].

The green economy powered by wind, water and sun (which are by definition intermittent and depending on weather), is introducing new challenges for utilities, since the grid we know today is not yet able to fully control and manage a massive integration of renewable energy. Without a robust planning of the network structure together with the ability to balance continuously energy supply and demand, wind or solar energy sources can have a profound negative impact on grid operations, reliability and power quality and can force utilities to make costly and inefficient adaptations to current spot conditions.

This paper presents an approach on how the operation of the distribution network and quality of service improves with deeper automation of the network in a safe and cost effective way. Several reflection points are discussed together with some examples on how to minimize the number of disturbances and outage times experienced during them.

II. INDUSTRY TRENDS AND CUSTOMER NEEDS

The electric infrastructure is critical for the development of any country: population growth and industrial development of certain areas are calling for an increasing demand for energy. DSOs (Distribution System Operators) are facing many challenges during their daily business to ensure a good service without major energy interruptions. Not only they need to produce more energy, they also need to deliver it in a safe and reliable way to customers and businesses.

In order to reach the desired level of service quality it is first of all necessary to quantify it. Two KPI are the most relevant for DSO operations: SAIDI and SAIFI.

The *System Average Interruption Duration Index* (SAIDI) is commonly used as a reliability indicator by electric power utilities. SAIDI is the average outage duration for each customer served, and is calculated as:

$$SAIDI = \frac{\sum U_i \cdot N_i}{N_T}$$

Where N_i is the number of customers and U_i is the annual outage time for location i, and N_T is the total number of customers served. In Figure 1 it is possible to see some SAIDI values in some of the main Countries worldwide, while in Figure 2 the situation is presented just for the Countries in Europe.

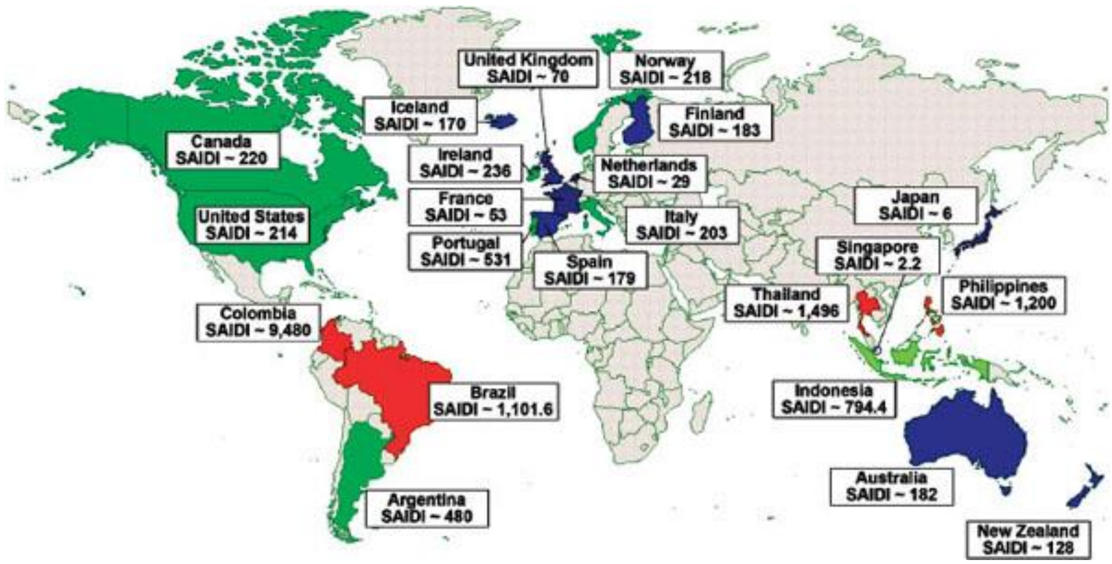

Fig. 1. SAIDI from 1992 to 2001 (excluding exceptional events) [2]

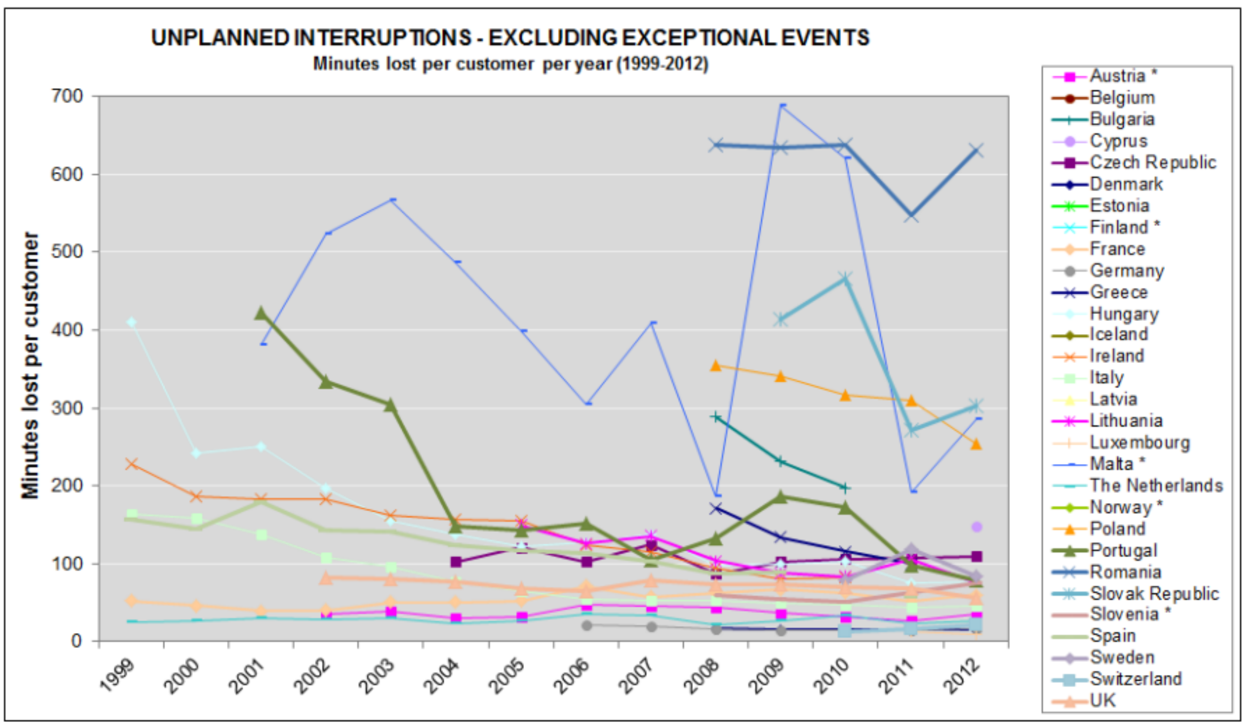

Fig. 2. SAIDI from 1999 to 2012 (excluding exceptional events) [3].

In other words,

$$SAIDI = \frac{Sum\ of\ all\ Customers\ interruption\ durations}{Total\ number\ of\ Customers\ served}$$

SAIDI is measured in units of time, often minutes or hours. It is usually measured over the course of a year, and according to IEEE Standard 1366-1998.

The *System Average Interruption Frequency Index* (SAIFI) is also used as a reliability indicator together with SAIDI. SAIFI is the average number of interruptions that a customer would experience, and is calculated as:

$$SAIFI = \frac{\sum \lambda_i \cdot N_i}{N_T}$$

Where λ_i is the failure rate, N_i is the number of customers for location i and N_T is the total number of customers served. In Figure 3 it is possible to see some SAIFI values in some of the main Countries worldwide, while in Figure 4 the situation is presented just for the Countries in Europe.

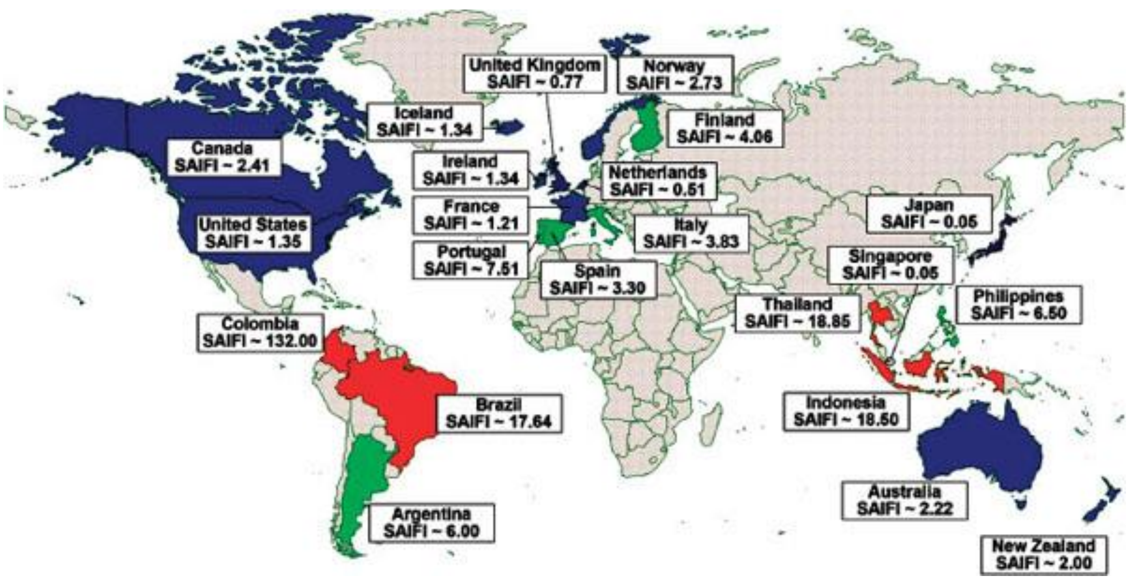

Fig. 3. SAIFI from 1992 to 2001 (excluding exceptional events) [2].

In other words,

$$SAIFI = \frac{Total\ Number\ of\ Customers\ interruptions}{Total\ Number\ of\ Customers\ served}$$

SAIFI is measured in units of interruptions per customer. It is usually measured over the course of a year, and according to IEEE Standard 1366-1998 the median value.

The lower those indexes are the better is the service that DSOs offer to their customers. It should not come as a surprise that Countries such as United States or Japan which are implementing network automation strategies since many years have much better SAIDI and SAIFI values of other less developed Countries. In Europe it is clear the investment trend towards lower values of SAIDI and SAIFI.

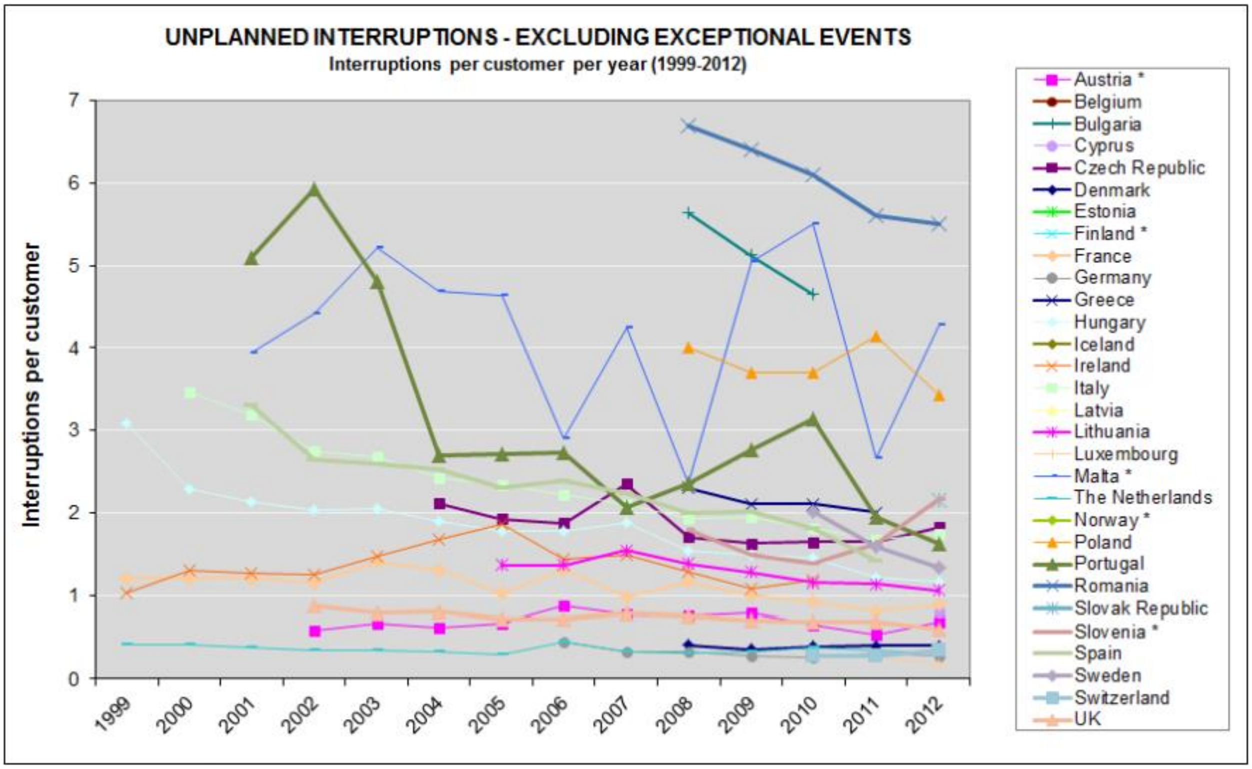

Fig. 4. SAIFI from 1999 to 2012 (excluding exceptional events) [3].

A. How to improve energy supply reliability

Bad results in SAIDI and SAIFI values are impacting the DSOs in several ways: loss of revenues due to non-distributed energy, increasing operational costs due to frequent emergency restoration events (increasing with geographical distribution of the network and rural areas), fines from electrical authorities if the values fall below some acceptable thresholds, etc.

As it is possible to see in Figure 5, most of the MV network in Europe is still composed of overhead lines, which will be the focus of this discussion. MV overhead lines are much cheaper than underground cables to install, but generally more prone to faults. Faults on overhead lines can be classified as transient (80%), semi-permanent (10-15%) and permanent (5-10%). Transient faults are commonly caused by lightning, strong storms causing momentary flashover, temporary contact with objects such as trees or animals. Transient faults normally disappear in less than one second. A small tree branch falling on the line could cause a semi-permanent fault, as the fault can last 1-2 seconds until the branch has burned. Permanent faults can be caused i.e. by a broken conductor falling to ground or a car crashing into a pole. As discussed later, reclosers can support in clearing temporary and semi-permanent faults, but in case of a permanent fault, human intervention is needed to clear it and restore the power [4].

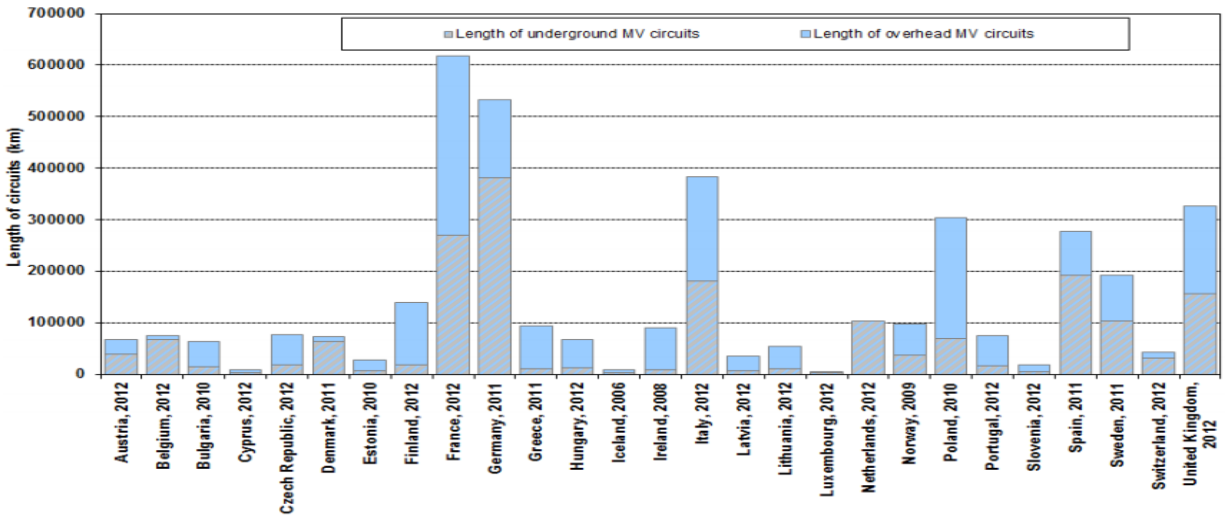

Fig. 5. Length of MV circuits in Europe [3].

Several options can be evaluated by DSOs to improve the system reliability, especially when overhead distribution networks are concerned.

- *Build additional primary substations* – The probability of failure is proportional to the length of the feeder. Installing new substations will segment the feeder in more (shorter) parts, but it is generally too expensive to be implemented.
- *Create additional feeder circuits* – Reducing the number of customers per circuit it is generally less effective than building additional primary substations, and still expensive.
- *Implement vegetation management plan* – This is normally done and essential to reduce the likelihood of having faults on the overhead networks.
- *Move from overhead lines to underground cables* – While in some Countries and especially in densely-populated areas Utilities are moving underground, the cost of using MV underground cables for long-length feeders outside the main cities is enormous. Further to that, a significant redesign of the network would also be required.
- *Use feeder automation solutions* – This is a cost effective way to improve the reliability and availability of the MV network. Reclosers, switches, sectionalizers, used to implement grid automation schemes can be integrated with the existing mechanical and electrical configuration of the network without major disruption and cost.

III. FAULT DETECTION

Detection is at the base of any feeder automation solution. Without detection there could be no isolation and restoration, as the protection and control system is not aware of the condition of the network. On feeder automation products and solutions, currents and voltages are normally measured by different means i.e. CT/VT, capacitive or resistive voltage dividers or current sensors such as Rogowski.

Together with a sensitive detection of current and voltage values, it is fundamental to have an advanced intelligence able to adapt to different network characteristics and able to discriminate down to the most challenging faults i.e. intermittent, low current, non-predictable behavior. As an example, in case of compensated networks, earth-fault is one of the most challenging to detect and analyze by currently available technology.

New multi-frequency admittance (MFA) function is proposed with the following advantages:

- It can detect continuous (stable) earth faults with fault resistance up to 10 kohms.
- It can detect and operate selectively during restriking/intermittent earth faults.
- It can operate correctly during various compensation levels of the system, from unearthed to fully compensated operation.

In order to meet the above requirements, multi-frequency admittance MFA-based earth-fault detection method was chosen. The MFA-function consists of two main elements: the directional element and the current magnitude supervision element, which are shown in Figure 6 [5].

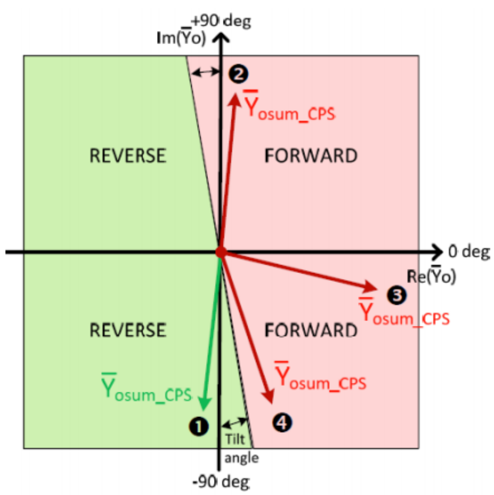

Fig. 6. Illustration of the operation characteristics of the MFA-function [6]

The novel algorithm combines optimal transient and steady state performance into one function. The operation of the algorithm is based on multi-frequency neutral admittance measurement using the cumulative phasor summing technique. The main advantage of the used concept is that it provides valid measurement results regardless of fault resistance value and fault type, whether the fault has permanent, transient or an intermittent character. It also simplifies the applied fault indication scheme, as there is only one earth fault function to protection engineer [5].

IV. FDIR BY MEANS OF THE ZONE CONCEPT

It is necessary to have a broader view of the whole distribution network and its capability to limit the impact of disturbances to as small areas and as few consumers as possible.

The Zone concept provides a model for dividing distribution networks into zones, separated by active and intelligent components, in order to handle fault situations in an optimal way. Optimal in this context means least affected consumers, fast power restoration and, finally, minimal dependency for personnel availability. The active and intelligent node components, the data communication between these nodes and the substation, and the control center with appropriate software form the corner stones of the zone concept.

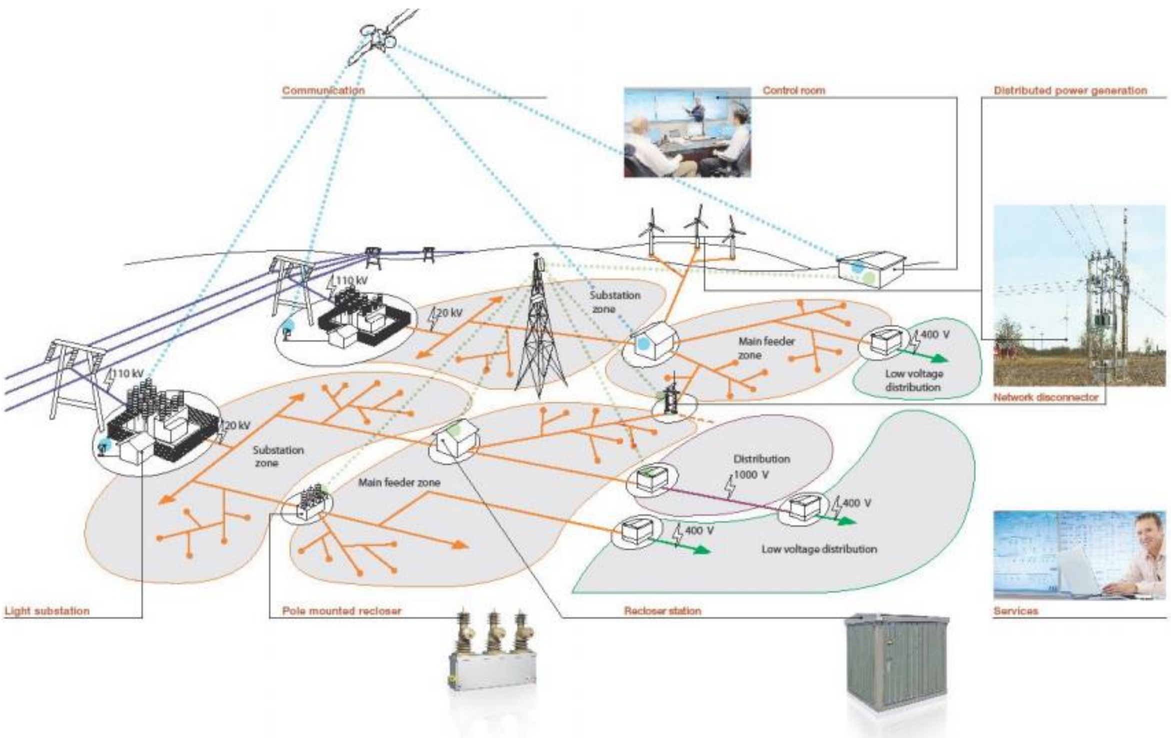

Fig. 7. Main components of the zone concept [6].

Rapid evolution of communication technologies, such as LTE (Long Term Evolution) mobile network, deployment of public wireless networks etc. have made it possible to build the needed applications. This is particularly important for DSO, as they are faced with the increasing demand for a more reliable power supply and lower operational costs.

Between the zones, zone dividers with protection and breaking/reclosing or only disconnecting capabilities are located. All zone dividers are provided with facilities for remote communication for transfer of status indications, control commands, measurements, etc. required by the application. Depending on the capability of the zone divider equipment the zone on the downside is either a protection zone or a control zone. Today the ongoing increase of distributed energy resources put special demands on the flexibility of the equipment functionality and adaptability.

A. Zone Concept Pilot case

The concept was piloted on two rural area feeders in Kirkkonummi, Finland. The target of the pilot project was to verify the functionality of the concept. The feasibility of the concept pilot was analyzed with LuoVa, ABB's reliability analysis software. The program calculates Customer Interruption Costs (CIC). The results show that it would pay off after 6 years, with an interest rate of 8%. [6]. Such calculation was supported by the customer as well.

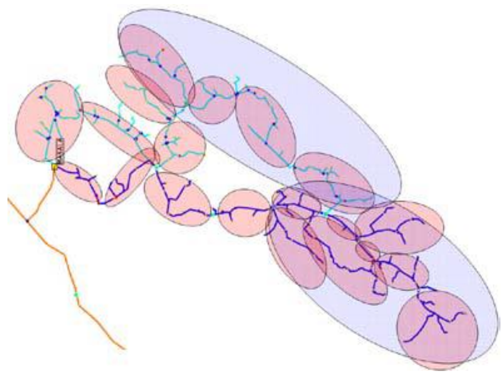

Fig. 8. Protection areas of the piloted feeders. Red zones indicate disconnector protected areas and blue zones recloser areas [6].

V. Fault Detection Isolation and Restoration, FDIR

A further step in the application of the zone concept is the application of Fault Detection Isolation and Restoration techniques, enabling the utility to quickly identify the location of a fault, isolate it, and restore power wherever possible by rerouting the flow of power on the distribution grid through unaffected areas. FDIR has two main goals: further limit the size of impacted areas and safely speed up the restoration of power to all customers not affected by the permanent fault.

Below in Figure 9 it is possible to understand the huge difference represented by the implementation of FDIR on the distribution network. Without FDIR a fault in a specific feeder will affect all the users in all the branches. The DSO will acknowledge the permanent failure after 5-10 minutes due to the calls received by customers, travel to site of the specialized crew takes another 15-30 minutes (more if remote areas); 15-20 minutes are necessary to locate the fault and another 10-15 minutes to manually re-configure the network to provide power to customers on the healthy sections of the feeder. After 1-4 hours of repair time and manual operations, the whole feeder is back to normal operation. In order to do some calculations let us assume 80% of the customers connected to the feeder are on the healthy sections and 20% of the customers are on the section affected by permanent failure. This leads to the fact that 80% of the feeder customers will have power back after 45-75 minutes, while the remaining 20% after 100-300 minutes.

With FDIR the smart network composed by smart devices i.e. sectionalizers, switches with FPI functionalities, will detect the fault, locate it and quickly reconfigure the network to restore power to the 80% of the customers on the healthy feeders within 1-5 minutes. Since the system will communicate the location of the fault, the specialized crew can travel directly to the right location, even improving the time needed to restore power to the 20% of customers left.

In order to monetize this assumptions we can consider that for a utility the cost of an outage by kWh stands between 2$ and 20$, with normal values below 10-12$ [7]. If we assume 1000 is the total number of the customers and an average consumption is 2kWh/customer and cost of outage is 10$/kWh it is possible to say:

Cost without FDIR = 800·1h·2kWh·10$/kWh + 200·5h·2kWh·10$/kWh= 36.000$

Cost with FDIR = ~~800·0h·2kWh·10$/kWh~~ + 200·4h·2kWh·10$/kWh= 16.000$ **-55%!!**

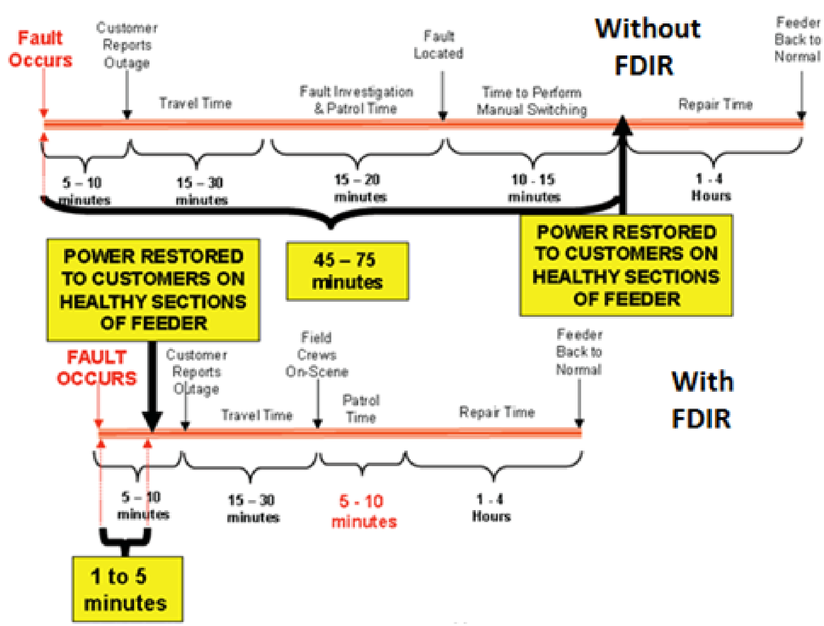

Fig. 9. Typical utility response time with and without FDIR [8].

In order to understand how it is possible to implement FDIR in an overhead network, it is very important to introduce the important concepts of recloser and sectionalizer.

- *Recloser* – The automatic circuit recloser is a device with the necessary intelligence to sense overcurrents to time and interrupt fault currents, and to re-energize the line by reclosing automatically. If a fault is permanent, the recloser locks open after a preset number of operations (usually three or four), isolating the faulted section from the main part of the system. Reclosers are recognized by electric utilities throughout the world as an essential device for achieving their prime goal: providing maximum continuity of electric service to their customers simply and economically.
- *Sectionalizer* – The sectionalizer is a circuit-opening device used in conjunction with source-side protective devices, such as reclosers or circuit breakers, to automatically isolate faulted sections of electrical distribution systems. Sectionalizers are able to measure the current flowing in the line through sensors or current transformers and are equipped with a tripping mechanism triggered by a counter or a timer. Each sectionalizer detects and counts fault current interruptions by the recloser (or circuit breaker). After a pre-determined number of interruptions, the sectionalizer will open, thereby isolating the faulty downstream section of the circuit, allowing the recloser to restore supply to the other non-fault sections. In order to enable advanced functions of fault passage indication or for other scope, the sectionalizer can also measure voltage on one or both sides. The word sectionalizer defines a functionality more than a product, and several products on the market can fulfill this requirement with different advantages and characteristics.

Fig. 10. Different type of products used for FDIR.

Introducing reclosers in the distribution grid it is already a big step change towards higher reliability, as this would mean getting rid of the temporary faults with no or minor impact on customers. Reclosers are normally put at the beginning of new or particularly problematic feeders (to prioritize the investments) and they can also be installed in series from the beginning of the feeder to the end of the feeder. To achieve the required coordination on series reclosers, the operating time of each recloser must be faster than any upstream device and slower than any downstream device. This ensures that only the recloser immediately upstream of the fault will trip. A safe margin (approximately 200 ms) between operating times of successive devices must be maintained for all fault levels on the network being protected. Pre-programmed Inverse Definite Minimum Time (IDMT) protection curves or definite time to trip are used for phase and earth fault protection. These protection curves allow close orchestration with substation protection relays and other protection devices.

The best results are achieved with the correct coordination of reclosers and sectionalizers downstream, installed in strategic locations i.e. at bifurcations, or to split the network into more sub-areas. The use of sectionalizers permit, in case of a permanent fault, to limit the number of customers affected by it. Some utilities even use reclosers as sectionalizers (as they have all what it takes to function as sectionalizers), but generally this is not the optimal economical solution.

In order to understand how this recloser-sectionalizer coordination is achieved using a real case, let us consider a feeder with a recloser and three sectionalizers.

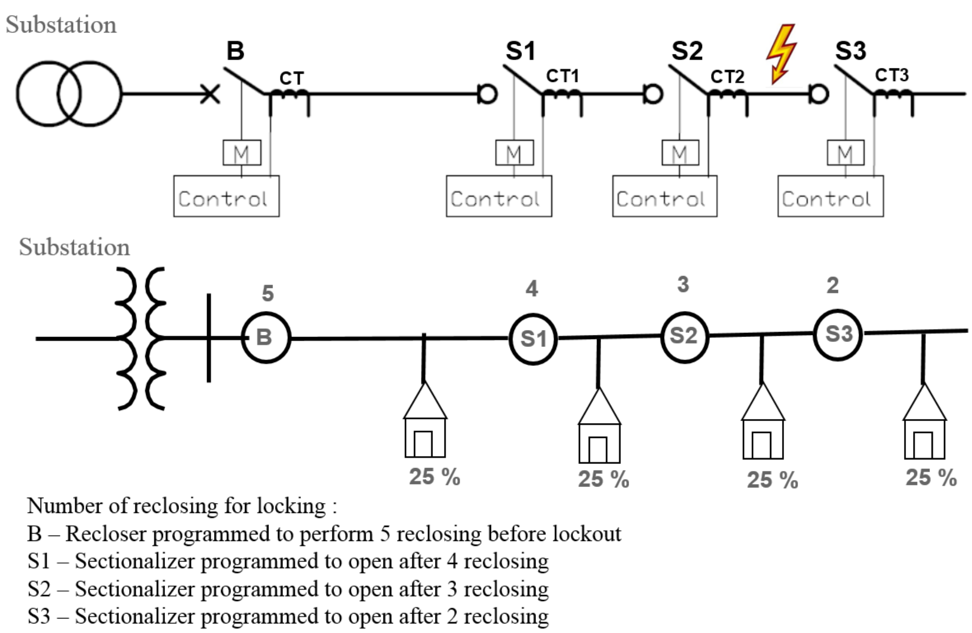

Fig. 11. Feeder with recloser and sectionalizers.

The sectionalizers can use different logics to operate as they can measure voltage, current, both voltage and current, depending on technology and customer preferences. The measurement of current on the three phases is widely used and also very effective, for this reason it will be considered for this example.

As it is possible to read in Figure 11, each sectionalizer is equipped with a control receiving the current measurement as an input. Customers are supposed evenly distributed in the four sections of the feeder, and the sectionalizers are programmed so that moving downwards the feeder they are set with a decreasing number of counting. If the permanent fault is between the S2 and S3 sectionalizers and we only have a recloser (or a circuit breaker) in the substation with no sectionalizers, this would mean that 100% of the customers would lose power.

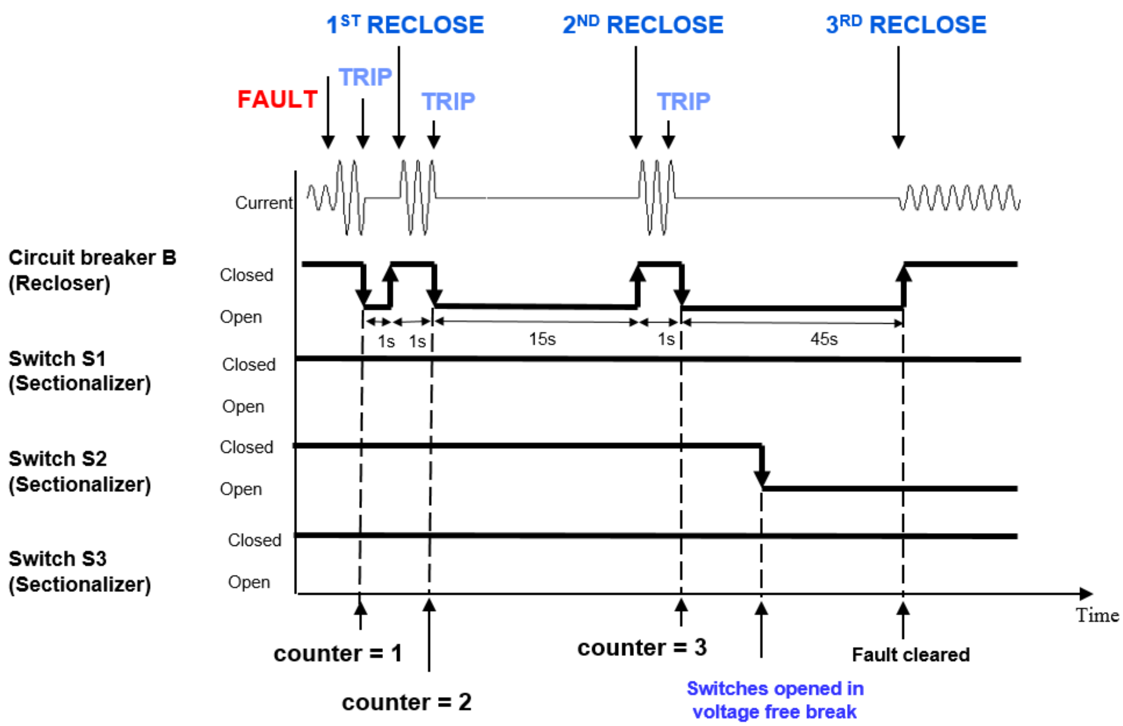

Fig. 12. Feeder with recloser and sectionalizers behavior during a permanent fault.

As it is possible to see in Figure 12, after just 63 seconds, 50% of customers are back to normal operation, and this definitely reflects on SAIDI and SAIFI indexes. The use of such system will allow a faster identification and better continuity of service for the other branches that the recloser is feeding. Further to that, if the end of the feeder as it is showed on the picture is i.e. connected to another feeder in a sort of open loop network, the DSO might decide to feed the last part of the feeder from another point and further restore power to another 25% of customers. This would mean only 25% of customers will be affected by the permanent fault, the ones between the S2 and S3 sectionalizers.

One important topic that has not been mentioned so far is the remote control and communication: several type of solutions can be used.

Isolated equipment with no communication – Reclosers and sectionalizers will take actions based on the current/voltage input they see on the system. The case study presented above did not need communication, as both sectionalizers and recloser can work independently.

Peer-to-peer communication between devices (GOOSE) – The reclosers and sectionalizers might be connected together and communicate when some abnormal condition is arising. This will ensure coordination and limit the time needed to reconfigure the network after the fault. A major drawback of this solution is that the GOOSE communication works as a stand-alone network: if one relay is replaced there is the need to reconfigure the system.

Decentralized communication (station level) – The devices i.e. reclosers and sectionalizers in a certain area of the network are connected to a substation automation device (hardware based or cloud based) via whatever communication media (preferable public mobile network). This device has the intelligence needed to analyze the new configuration of the network after the fault and reconfigure it based on load, presence of Distributed Energy Resources (DER), number of customers affected etc. An approach to this configuration is proposed in the next section of the paper.

Centralized communication (SCADA) – Implementing a SCADA system is quite often very expensive, but it offers the advantage of being in full control centrally of all the data coming from all the feeders on the network. Network restoration algorithms can be implemented directly on the SCADA system.

Functionalities and benefits	**No FDIR**	**FDIR with no communication**	**FDIR with peer to peer between devices (GOOSE)**	**FDIR with decentralized communication**	**FDIR with SCADA supervision**
Ensure coordination among devices i.e. reclosers, sectionalizers	No	No	Yes	Yes	Yes
Fault event and location available from remote	No	No	No	Yes	Yes
Time to reach the after-fault configuration	Very High	Medium	Medium	Low	Low
Possibility to reconfigure network from remote	No	No	No	Yes	Yes
Information and monitoring available centrally	No	No	No	Yes	Yes
Management of distributed generation variable	No	No	No	Yes	Yes
Cost of implementation	None	Low	Low	Low/Mid	High

Tab. 1. Comparison between different levels of network management solutions.

Smart grid is definitely far from being a one-solution-fits-all. DSOs should determine through a careful analysis which devices to install and the communication option that offers the best advantages based on the distribution network configuration. For some important feeders or parts of the network, even a huge investment can have a quick payback if it is drastically increasing SAIDI and SAIFI values, while for some extreme rural overhead networks a recloser protecting the line and a few electronic sectionalizers can simply do the job without any major issue.

VI. Smart FDIR with DER using Substation Automation Device

It is also possible to control a group of reclosers, sectionalizers and substation circuit breakers in a determined geographic area or adjacent feeders by means of a substation controller [9]. The last mile communication between each equipment and the substation automation device can be done with i.e. LTE, new 5G, radio, etc. Communication infrastructure need to implement effective cyber security architecture, which is an additional challenge. The data processing and intelligence is built onboard of the substation automation device, and data are handled in a way that only relevant information (already processed) are sent to the SCADA so that it is not overloaded.

The substation automation controller can be hardware based or cloud based. In this latter case, the advantages for the customers are better robustness, portability and cost. This solution reduces engineering support and recurring costs as any modification on products connected to the substation automation device will not be reflected on the SCADA. It also provides a base support for future communications investments and for applications such as asset health condition monitoring and Volt/VAr Control.

As already explained the fault isolation will be done by the combination of switches and reclosers as already explained. For the controller the fault condition can be triggered with different events i.e. with recloser lockout status, substation breaker trip signal or sectionalizer status. The controller knows the pre-fault system status (configuration, loads and sources). A complex feeder can have multiple restoration paths, and it generally include several “open tie switches” used for network reconfiguration. Load restoration will be done based on the load current capacity check based on the pre-fault load current, it is supported single or multi-path restoration (unserved loads are picked up by multiple feeders). The substation automation controller is also able to modify the setting group of the related sectionalizers or reclosers based on the new reconfigured network after the fault.

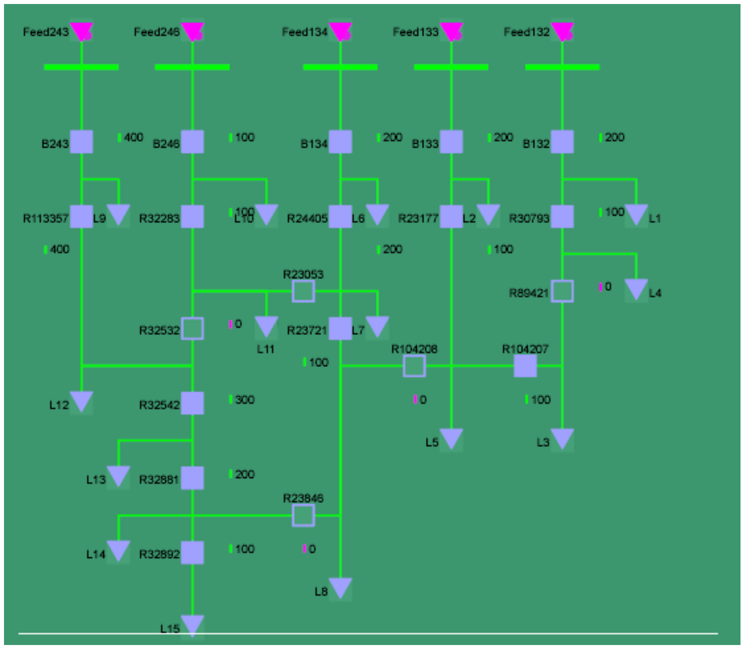

Fig. 13. Cloud solution of substation automation controller HMI with DER integration using FDIR algorithm with self-healing scheme [10].

This solution needs initial low capital investment and it is specifically suggested for problematic feeders. A limited number of devices can be connected to the same controller.

In a distribution network with Distributed Energy Resources (DERs), when a short-circuit fault occurs, the magnitude and direction of fault current may be different from the fault current of distribution network without DERs. Under this circumstance, the coordination of recloser and sectionalizer or fuses might be lost [11].

The advantage of using a substation automation device during restoration is that the condition of the network before/after the fault are analyzed in real time (DER can vary quite quickly over time) and decision can be taken accordingly. It can even be possible that, due to the particular configuration, location of the fault and DER/loads, the substation automation device can even decide to run particular feeders or part of the network in island mode until the fault has been cleared. The application of this solution has certainly a positive impact on utilities SAIFI and SAIDI valued towards a better service for their customers.

Green and distributed energy represents the future but it poses new challenges to DSOs towards good reliability indexes with the lowest possible cost of operation. FDIR technologies and intelligent controllers are technologies that are already available today to support utilities to solve the issues of tomorrow.

VII. Conclusion

The grid is changing and evolving and a reliable supply of power is more and more central to businesses and people. This pushes Countries and electrical distribution utilities to invest in smart grid technology to move towards a more flexible and reliable grid. Prosumers, will require a more dynamic control of their generation and consumption and we will see additional challenges in the next years with further penetration of DER.

A precise, sensitive and timely detection of anomalous condition, together with FDIR is the proposed solution to increase reliability of the DSO infrastructures and optimize SAIDI and SAIFI indexes with a limited investment and a good ROI. Communication will play a central role in this process as it enables distribution utilities to further optimize the flow of information and a consistent decision making process.

New cloud solutions will ensure a rapid evolution of FDIR using highly redundant computational capabilities. This future proof technology helps to gradually improve the electric grid operation and economic performance maintaining backward compatibility to the legacy devices with affordable investments and fast return.

VIII. References

[1] E. Software, "The western european energy markets," ABB, Europe, 2017.

[2] EPRI, "Distribution Reliability Index Tracking within the United States," Institute Electrical Power Research, Palo Alto, 2003.

[3] Council of European Energy Regulators, “CEER Benchmarking Report 5.1 on the Continuity of Electricity Supply,” Brussel, 2014.

[4] V. J. Vijay Shah, "Improved Power Availability for Smart Cities," *Ieema journal,* vol. 9, no. 1, p. 125, september 2017.

[5] J. S. M. S. Goran Leci, "Advanced automation with zone dividers deployment in distribution networks," ABB, Finland.

[6] K. K. A. K. G. W. Pekka Manner, "Towards self-healing power distribution by means of the zone concept," in *21st International Conference on Electricity Distribution*, Frankfurt, 2011.

[7] C. Wolfram, “Measuring the Economic Costs of Electricity Outages,” Energy Institute at Haas, 2012. [Online]. Available: https://energyathaas.wordpress.com/2012/11/04/measuring-the-economic-costs-of-electricity-outages/. [Accessed 20 April 2018].

[8] K. H. L. a. J. H. Eto, "Understanding the Cost of Power Interruptions to U.S.," Berkley Lab., 2004.

[9] ABB, "Fault detection isolation restoration Strategies," Automation & Power World, 2012.

[10] ABB, "COM600 Product Guide".

[11] X. Y. a. Z. L. Wu Lei, "Effects of Distribution Generator on Feeder Automation and Its Solution".

[12] Y. Bhamare, "5th Annual Conference on Power Distribution," Power Distribution, India, 2010.