Applying Self-Healing Schemes to Modern Power Distribution Systems

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***Abstract*— Self-healing schemes in the context of power distribution systems have the objective of performing fault location, isolation, and service restoration in an automated fashion, i.e., without (or with limited) distribution system operator and repair crew intervention. Some of the intrinsic benefits of this smart distribution technology are increased reliability due to outage duration reduction, more efficient use of personnel and resources (crews, operators, vehicles, etc), and increased operational flexibility. Reliability is naturally increased since less time is needed for locating and isolating faulted feeder areas, as well as for restoring customers located on healthy feeder sections. Self-healing schemes are an inherent part of the Smart Grid and are expected to play a fundamental role in modern and future distribution systems. It is worth noting that the switchgear technology (protective and switching devices, including adaptive protection), sensors, enterprise systems and communications infrastructures required for the implementation of self-healing schemes represent the basis for the execution of other smart distribution applications such as automated system reconfiguration and optimization. Therefore, a growing number of self-healing projects are being implemented by utilities as part of their power delivery modernization plans. This paper discusses the estimation of reliability benefits of self-healing schemes, with emphasis on Fault Location, Identification and Service Restoration (FLISR) applied to real distribution feeders.**

***Index Terms*-- Smart Grid, smart distribution systems, distribution automation, self-healing technologies, distribution reliability**

I. INTRODUCTION

SELF-HEALING of power delivery systems is a concept that enables the identification and isolation of faulted system components and the restoration of service to customers supplied by healthy elements. This activity may be conducted with little or no human intervention and has the objective of minimizing interruptions of service and avoiding further deterioration of system reliability. Self-healing of power distribution systems is conducted via Distribution Automation (DA), specifically through smart protective and switching devices that minimize the number of interrupted customers during contingency conditions by automatically isolating faulted components and transferring customers to an optional source when their normal supply has been lost. Optional sources may include neighbor feeders and Distributed Energy Resources (DER) such as Distributed Generation (DG) and Distributed Energy Storage (DES) [1], [2]. For this reason some authors prefer to use the term "self-restoration" instead of self-healing. It is worth noting that the implementation of self-healing in distribution systems requires schemes that are flexible enough to adapt to changing system loading and configuration conditions (including automatically modify protection settings) and operate distribution system components within their ratings.

Distribution Automation (DA) is a set of technologies that enable an electric utility to remotely monitor, coordinate, and operate distribution components in a real-time mode from remote locations. DA includes substation, feeder and customer automation. DA is a vital component for achieving the self-healing capabilities, high reliability and power quality of the smart grid, as well as for allowing the integration of DER. DA driving forces are: a) addressing the needs of the smart grid pertaining to service reliability and power quality, b) regulatory incentives and penalties, and c) pressure to cut costs and optimize operations. DA benefits can be classified in functional and monetary and they are a function of the specific application to be deployed. One of the most popular DA applications is Fault Location, Isolation and Service Restoration (FLISR).

II. SELF-HEALING OF DISTRIBUTION SYSTEMS

Self-healing or self-restoration ranges from conventional approaches such as automatic load transfer and loop sectionalizing to more advanced agent-based restoration schemes, including DER intentional islanding. Self-restoration can be implemented by utilizing only switches (no fault current detection or interrupting capability), only reclosers or a combination of both. The advantages of using switches for conducting self-restoration is that it avoids dealing with issues pertaining to protection coordination that may occur when power flow through a device is reversed due to transferring load to a neighbor feeder. If not properly taken into account this situation may lead to miscoordination and/or nuisance tripping of reclosers. However, modern remote-controlled reclosers allow overcoming this issue, being the drawback the need to calculate and program different overcurrent protection settings depending on the potential feeder configurations. This can be overcome by the implementation of adaptive protection systems. New technologies, including pulse and single-phase reclosing provide additional alternatives for implementing self-restoration schemes. Although single-phase reclosing allows detecting and isolating only the affected phases in single-phase or two-phase fault conditions, there are practical

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limitations such as crew safety that avoid implementing this type of operation for self-restoration purposes, and limit it only to specialized applications.

The concept of self-restoration in distribution systems seems more suitable for urban and suburban feeders where open ties and alternative supply routes are available, but not to rural feeders where radial distribution is predominant. However, even in the latter case, the implementation of microgrids and intentional islanding of DG and DES may help minimize reliability impacts, successful experiences in this regard have been reported in the literature [3]. Furthermore, in the case of urban and suburban distribution feeders, alternatives such as close-loop operation of medium-voltage feeders may also be implemented in the context of self-restoration while attaining other benefits such as improved system efficiency. It is worth noting that there are a series of difficulties to implement such operation [4]. However, new technologies and growing real-time monitoring and control capabilities are increasing the feasibility of utilizing this type of operation (thus far limited to specialized applications) on a broader fashion.

A key aspect of self-restoration when applied to distribution systems is the need to identify fault locations and if possible anticipate fault occurrence. Numerous proposals and commercial products are available in this area, and different levels of fault location capabilities are becoming available not only on field level devices such as modern microprocessor-based relays and reclosers, but also on Distribution Management Systems [5]. This includes either fault or outage location. Fault location aims at pinpointing faulted feeder components (pole, distribution line, etc), while outage location has the goal of identifying the protective device that has operated to isolate the fault. Here it is worth remembering that not all protective devices are monitored in real-time, thus outage location is aimed at assisting the distribution system operator in detecting the operation of this type of devices and confirming the operation of those that are supervised in real-time. Given the diverse topological features of distribution feeders and limited real-time information that historically have been available at distribution system level, most proposals for conducting fault or outage location rely in the combined utilization of short-circuit current, power flow, historic reliability indices, heuristics and expert knowledge, for pinpointing faults. These proposals apply a variety of methodologies ranging from signal processing and system analysis to computational intelligence for processing the available data and handling uncertainties to identify the most likely fault location [6].

The proliferation of distribution equipment with monitoring capabilities, such as modern reclosers and switches, Intelligent Electronic Devices (IED) such as voltage and current sensors, faulted circuit indicators, DER, and the growing utilization of SCADA and Advanced Metering Infrastructure (AMI), is helping utilities overcome the traditional real-time supervision limitations of distribution systems and allowing the implementation and increased accuracy of fault location algorithms. Moreover, the growing interest in applying Phasor Measurement Units (PMU) to distribution systems is expected to provide with an additional high-definition data source that could be used for conducting not only more accurate state estimation and fault location. Evidently, the consolidation and analysis of these diverse and unsynchronized data sources represents a challenge itself. The fault anticipation concept, on the other side, has been studied in numerous publications and experimental results have been encouraging, but it has not seen wider practical implementation yet [7], [8].

An additional consideration for self-restoration implementation in distribution systems is selecting the most suitable DA system architecture. Proposals range from centralized approaches, where data are gathered and processed at distribution operation center or distribution substation level, to local processing and analysis at feeder or device level (peer-to-peer) [9]. Each proposal has advantages and disadvantages and there are numerous commercial products that utilize either approach [9] - [11]. Local processing via hierarchical utilization of "agents" is seeing growing interest and support. Similarly, hybrid approaches such as local implementation of self-restoration combined with centralized processing and analysis have been explored as well [12].

Another important aspect for self-restoration implementation is the selection of the switchgear and protective device technology. Early technologies relied on detecting and counting loss of voltage, reclosing attempts, and using time delays to infer the state and operations of devices (switches, reclosers) located on neighbor feeder sections [13]. Most recently, peer-to-peer communication among distribution automation switches and reclosers has become a popular alternative. This has risen a further consideration with regards to the communication technology to be utilized, which is very diverse and includes radio, cellular, microwave, Wi-Fi, WiMAX, DSL, Power Line Communication (PLC), etc.

There are several additional practical aspects that need to be considered when implementing self-restoration, besides the DA system architecture and switchgear and communication technology and to be used, it is necessary to consider loading ratings and voltage limits, since transferring load to a highly loaded and long feeder may end up generating power quality complaints (low voltage in this case), protective device nuisance tripping, or causing additional equipment faults and outages due to accidental equipment overloading. This is where centralized feeder analysis, e.g., at distribution substation level, plays an important role.

III. Fault Location, Identification, and Service Restoration (FLISR)

The smart grid concept is driving the implementation of a series of self-restoration schemes in the form of DA applications. The most popular of these is FLISR, which consists of the utilization of advanced protective and switching devices to automatically locate and isolate faulted feeder sections and restore the maximum number of customers possible located on healthy sections. FLISR applications range from half-loop and full-loop schemes to advanced "agent-based" approaches.

There is a growing trend in the industry for implementing FLISR as well as other DA schemes. This is due to several reasons such as the access to incentives provided through government-funded programs [14], the maturity of DA technologies and the availability of a variety of communication technologies that facilitate its implementation. FLISR benefits include [9]:

a. Functional benefits:
- Improve SAIDI, SAIFI, and other reliability statistics
- Reduce "energy not supplied" (kWh)
- Provide "premium quality" service
- Reduce fault investigation time

b. Monetary benefits:
- Increase revenue (sell more energy)
- Reduce customer cost of outage
- Additional revenue from "premium quality" customers
- Labor/vehicle savings
- Achieve regulatory incentives (when available)

Figure 1 shows the advantages of implementing FLISR versus conventional operation for a typical distribution feeder. When conventional operation (without FLISR) is used, there is a need for investigating the specific fault location and conducting manual switching to isolate the faulted area and restore service to customers located on healthy feeder sections. In this case customer trouble calls may play an important role, and human intervention, either for fault location or switching operations to restore service, is vital. FLISR on the other side allows detecting faults and restoring affected customers faster and with limited human intervention. When FLISR is used power is quickly restored to customers located on healthy sections of a feeder. Moreover, the faulted area is delimited by the FLISR scheme, this reduces the time required for fault investigation and patrolling. Moreover, if FLISR switching and protective devices are monitored in real-time then there is no need to wait for customer trouble calls to dispatch crews. Therefore, besides its obvious reliability benefits FLISR also has a direct impact on reducing operators and crews' workload, which increases efficiency and reduces operation costs.

Reliability benefits of FLISR (reduction on frequency and duration of customer interruptions) can be estimated by conducting a *predictive reliability analysis* that compares the existing reliability of a study area versus the expected reliability after implementing the proposed FLISR schemes. The overall objective of this approach is to identify those locations and combinations of devices that attain the greatest cost-benefit ratio. The existing reliability of a system can be determined by using the feeders' historical reliability indices, since reliability may exhibit noteworthy variations, even during consecutive years, it is recommended to use the average of the reliability indices for the most recent years, for instance the last three to five years. These average values are assumed to be representative of the existing system reliability, and are used as targets for calibrating the feeder models [15]. Calibration is accomplished by iteratively adjusting the reliability parameters of the feeder models, i.e., the failure rates and Mean Times To Repair (MTTR) of distribution components (lines, protective and switching devices, voltage control and regulation equipment) until the reliability indices calculated by the software tools match the reliability targets.

Once the feeder models are calibrated, then a series of simulations are conducted for several combinations of FLISR schemes. Then, costs and benefits are estimated for each FLISR scheme combinations and finally, the ones that attain the largest cost-benefit ratio, i.e., greatest $/reliability improvement unit, are identified. This can be a challenging task when numerous schemes are deployed on a feeder system, the interactions among schemes, and the combination of alternatives requires using detailed models and tools that allow specifying how automated switches and reclosers should work together. Furthermore, additional variables such as feeder loading and voltage limits must be considered by the algorithms.

Existing software tools allow identifying benefits of half-loop and full-loops schemes, however, the level of complexity required for evaluating the benefits of numerous FLISR schemes is generally available only at academic level. Attaining this modeling and analysis capability requires further development of existing predictive reliability algorithms used by commercially available distribution software.

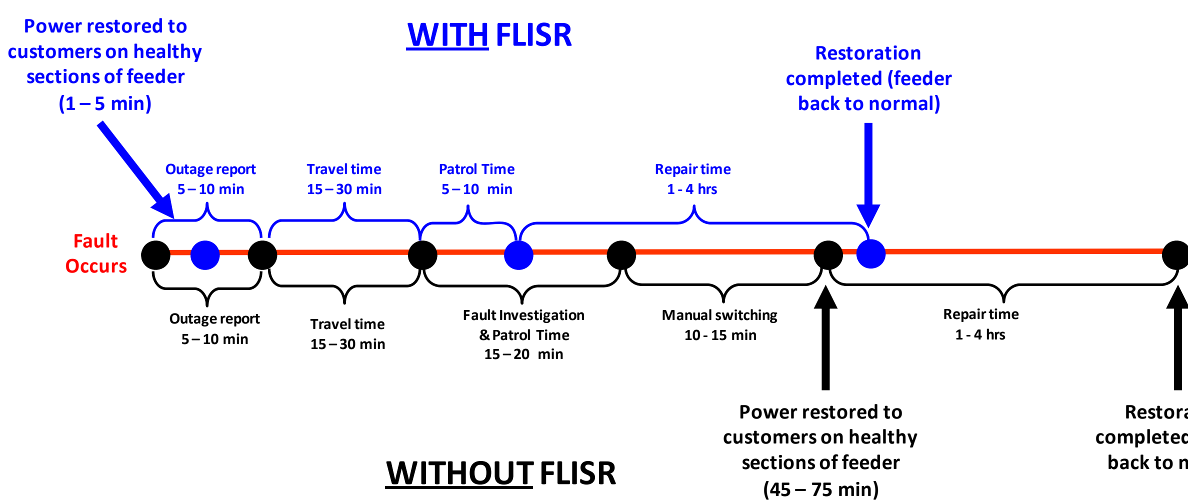

Figure 1. Comparison of reliability improvement due to implementation of FLISR versus conventional restoration [9]

Figure 2 shows an example of the reliability levels of a real distribution system area that includes 19 feeders (12.47 kV) before and after implementing a portfolio of half-loops and full loop schemes. The feeder areas highlighted in blue and red represent sections with good and bad reliability, respectively. These results were calculated by using a predictive reliability analysis that takes into consideration the reliability parameters of system components and feeder loading. This means that if a load transfer to or from a neighbor feeder leads to a system component rating violation, then it is not allowed. The results show that the implementation of FLISR leads to evident reliability improvements. These results can be used to determine cost-benefit ratios and prioritize and select those schemes that attain maximum benefits.

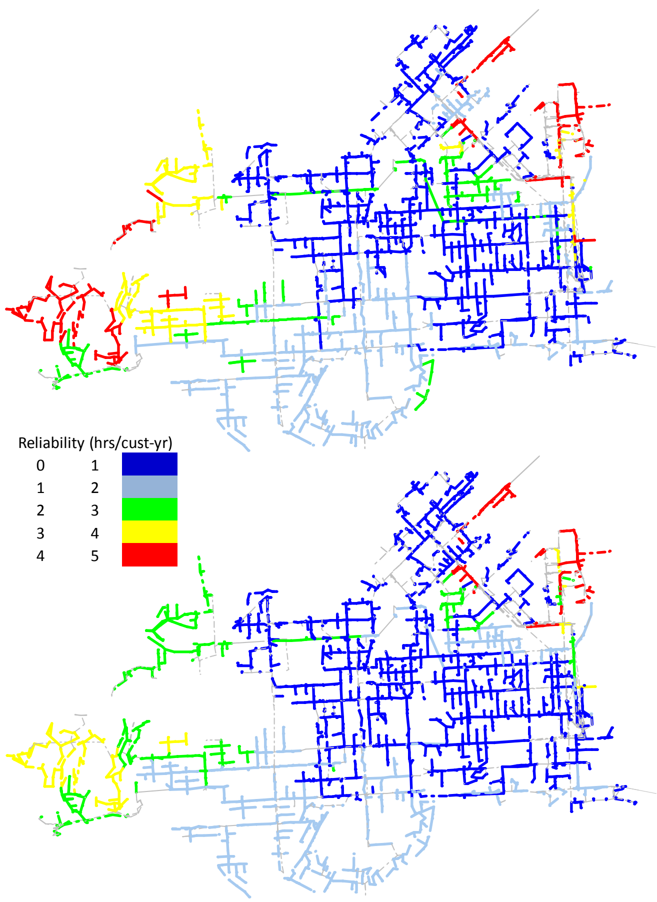

Figure 2. Reliability improvement before (above) and after (below) the implementation of a portfolio of full-loop and half-loop schemes

IV. Conclusions

The modernization of the power distribution grid has prompted the implementation of self-restoration technologies, particularly FLISR, for improving reliability and power quality and increasing operations efficiency. In the specific case of reliability, the benefits provided by these technologies can be estimated via predictive reliability models. Calibration of such models requires using historical reliability data to estimate existing system reliability and the ability of simulating the operation of FLISR schemes. The latter implies being able to model switching times of protective and switching devices, travel times, inspection times and taking into account feeder loadings and equipment ratings. Modern commercial tools allow conducting this type of analysis for relatively simple FLISR schemes. However, evaluating benefits of more complex schemes such as the ones envisioned by the smart grid paradigm require further research and development of analysis tools.

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VI. Biographies

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