Smart Grid Self-healing Implementation for Underground Distribution Networks

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***Abstract*—** Electric Distribution utilities are facing increasing need for substantial changes to embrace smart grid technologies to meet growing energy demand, power supply quality and integration of renewable energy resources to reduce carbon footprint. Self healing distribution Automation can achieve significant improvement of network availability, reliability and consumer satisfactions by considerable reduction customer minutes lost (CML). This paper evaluates different self healing solutions for underground distribution network and Cost-effective distribution automation strategy. The paper also presents selection criteria for optimal allocation of feeder Remote Terminal Units (RTU) in order to minimize interruption cost and Customer minutes lost.

I. Introduction

Today's Distribution network design has many limitations for demand side management and efficient operation. There are few monitoring devices that can provide visibility of the network conditions to operation control centers or distribution management systems (DMS). Demand side management is currently based on historical data and predictions rather than real time information. Fault management and supply restoration completely done in manual manner which lead to long power interruption and increased customer minutes lost. Many utilities around the world include GCC region started Distribution Automation projects In order to improve network performance for fault management which can be represented in terms of customer minutes lost (CML), System Average interruption duration index (SAIFI) and average outage duration. Other drivers to such projects are increasing energy demand due to economic growth and the urge to improve supply availability, power quality and eventually customer satisfaction.

II. Automated Distribution Network

Automation of MV and LV distribution networks is essential in realization of smart grid. The distribution network in Dubai mostly consists of underground cables, unlike overhead line distribution, the failures in distribution cables networks are permanent faults only and locating such faults manually is time consuming. There are different strategies for distribution automation aiming to minimize faults outage time and reduce CML. Ideally all distribution substations will be automated but it is neither affordable nor economically feasible to automate all secondary distribution substations. It is essential for each power utility has to come up with a cost-effective strategy to address the main operational issues of fault management and enhance distribution network reliability. Figure 1 shows the basic conception of utility investment feasibility for reliability improvement against customer interruption cost.

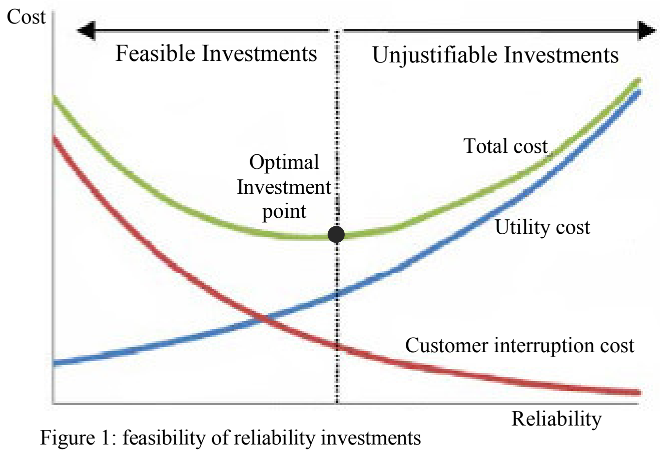

Figure 1: feasibility of reliability investments

The basic distribution automation strategy which has been in use for long time was to introduce remote fault passage indicators (FPI) using GSM communication for medium voltage overhead lines and underground cable networks as demonstrated in [1], [2] and [3]. Remote FPI will help dispatches in operation control centers to reduce fault localization time and crew traveling time which result in shorter interruption duration, in Stedin distribution network around 20% outage time reduction were achieved using this strategy [4].

The commonly used distribution automation (DA) strategy is to remotely control RMU load break switches by retrofit the old equipments in secondary distribution substations and introduce motorized actuator. This strategy introduces further enhancement to CML or SAIDI because it is not only reducing fault localization time and interruption duration (r_i) but also it reduces the number of interrupted customers (N_i) since the operator can isolate faulty section and restore the supply to healthy part of the feeder.

$$\text{SAIDI}=\sum_i r_i\, N_i/N_T$$

Where i represents an interruption event, r_i is the interruption duration for each interruption event, N_i is the number of annual interrupted customers for each sustained interruption and N_T is the total number of customers served.

In the view of smart grid, the evolving distribution automation strategy is the self healing automation system where further enhancement to CML is not only possible but power quality and network disturbances can also be improved.

III. SELF HEALING DISTRIBUTION ARCHITECTURES

Self healing is vital feature of smart distribution grid; it repents the immune system of the power system where substantial power security and reliability levels can be achieved. Self healing distribution system has two main functions; self-prevention and self-recovery. Self-prevention means real-time performance evaluation and continuous optimization during normal operating condition. There are many initiatives and pilot implementation and self healing concept. This paper will focus on the main initiatives in MV/LV distribution network as follows:

a) Fault location, isolation and service restoration (FLISR)

Self-recovery refers to automatic fault detection, isolation and supply restoration (FLISR) during disturbance or fault conditions. There are currently several implementations of FLISR systems in Overhead lines [5] and underground cable distribution network [1], [3] and [6]. The different implementations of self healing architectures can be categorized in three main categories:

- Centralized (Intelligent switching algorithm resides in DMS).
- Distributed (Intelligent switching logic located in master substation).
- De-centralized (Peer to Peer Approach)

Centralized Arctiture require powerful DMS and Distribution SCADA System in order to process intelligent switching algorithms. No actions can be taken without control center knowledge which provides maximum operator visibility for all network reconfiguration and conditions. The cost of DMS system is high but the cost per substation automated is relatively low. On the other hand, switching since all signals are communicated back to control center which add latency and require high bandwidth communication. Other DA applications such as automatic Vot/Var control and optimal feeder reconfiguration can be implemented efficiently in centralized arctiture.

In Distributied Arctiture, a master substation is configured for group of DA substations to control the switching algorithimes then report back to DMS system. In this case switching decision and control is distributed over a number of master sustations rather than centralized in DMS system. The communication is made over relatvely short distances which lead to faster performance compared to centralized approach.Typical implementation is to locate the master station at primary substation (33Kv or 132/11 Kv) and communicate over radio or WIMAX to DA subsations then communicate from master station to control center via fiber optic, in case it is already avaliable at primary substation, or through GPRS. Operator visibility of the network is limited and there a chance that operations will not be reported to control center in case the communication between control center and master station is interrupted.

De-centralized Arctiture is implemented as peer to peer communication between DA substations, the switching alogtrithim is distributed amoung feeder subsaions. Communication manly occures between peers substations over short distances which lead to high speed performance and lowest service restoration time. This approach provide great support for micro-grid concept and it doesn't require distribution SCADA system however the cost per substation is relativly high compared to centrlized and distributed approachs.

De-centralized (peer to peer) approach can be explained by fault scenario shown in Figure 2 below where cable earth fault occurred between RMU1 and RMU2. In this case CB1 will be tripped and all consumers up to normally open point (NOP) will be interrupted. The self-healing algorism is initiated by CB tripping event, then upstream iteration starts where each substation's RTU analyses its FPI signals and communicate to upstream substation's RTU to identify fault location and isolate upstream fault, in this case left hand LBS of RMU2 will be opened and NOP will be closed to restore customers connected to RMU2. Downstream iteration then carried out where each peer check its conditions and communicate to downstream peer to isolate the faulty section and restore the normal supply conditions, in this case LBS of RMU1 will be opened and CB1 will be closed to restore the supply to all consumers. The maintenance group can then be dispatched to the faulty feeder section for necessary cable repair.

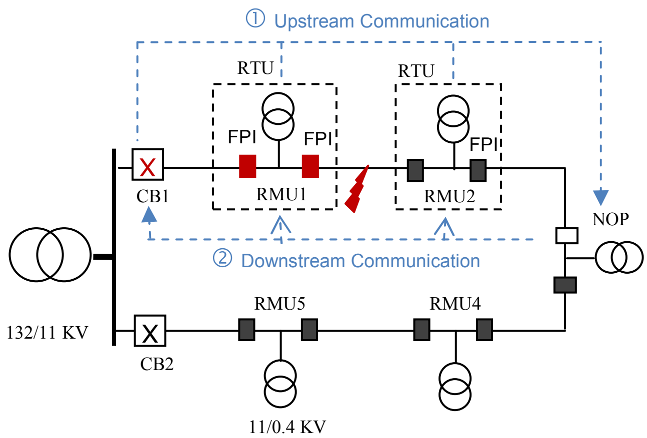

Figure 2: Communication Layers of self healing Architectures

There are practical examples of different self healing implementation using RMU load break switches for cost reduction and investment optimization to retrofit existing substation rather than replacements [3]. There are also some examples of self healing projects using circuit breakers [6], which will improve both SAIDI and SAIFI significantly; however the cost need to be studied compared to additional reliability improvements. Finally, there is no ideal architecture that fits all utilities; the optimal decision depends on many factors such as, aspired level of smart grid penetrations, operation dispatching issues, performance, integration of distributed generation and micro grid support.

b) Automatic Grid Recovery (AGR)

Automatic Grid Recovery is a remarkable initiative of Grid4EU smart grid. The main objective of AGR is to "Enhance the observability and control the low and medium voltage distribution networks building on a multi-layer solution for smart metering implementation" [8]. AGR also aim to enhance effective real time demand side management, enable the integration of EVs in the LV/MV network and achieve more engagement of the customer. The scope of AGR is to recover automatically as much customers as possible in a short time after a "Definitive trip" in Medium Voltage Grid. AGR will be implemented by IBERDROLA as pilot project in Spain for 20 secondary distribution substations, and up to 200 clients with smart meters [8].

The restoration process of AGR will have several stages, for which a proposal is included below:

- Create a sequence (and allocate an identifier number) for new trips.
- Verify if it should process the trip (do not re-try a restoration for a tripped switch, which the automatic restoration has "successfully" processed previously within a configurable time span).
- Notify the operator by start and stop messages and by highlighting the affected feeder within the displays.
- Locate the fault and try to restore the supply downstream from the tripped switch as far as possible
- Locate an open switch, which will allow supplying the feeder upstream to the fault (locating a breaker to isolate the fault and try to connect the rest of the feeder to the power supply).
- Analyze a trip if a previous switching action has caused it. If a previous switching action has caused the trip, the AGR must look for an alternate switching action. If a previous switching action did not cause the trip, it is a new one.[8]

IV. SELECTION OF ICT TECHNOLOGY

Information and communication technology is probably the most challenging part in distribution automation and self healing implementation. Communication reliability and ability of DMS system to process enormous amount of MV/LV substation data are critical factors in successful DA projects. The multi layer communication model adopted in AGR approach as shown in Figure 3 provides common infrastructure for integrated implementation of different smart grid applications. The communications involved in Grid4EU demo3 can be classified in the following three groups:

a) Power line communications (MV and LV): It covers the communications based in BPL technologies between secondary substation nodes (SSNs) MV and meters based in PLC technologies (LV).

b) SSN/Dispatcher communications: It covers the communications between the SSN and the system used by the dispatcher (AMM System and DSO SCADA).

c) AMM/DSO-SCADA communications: It covers the communications between the dispatcher systems involved in the demo. (AMM System and DSO SCADA).

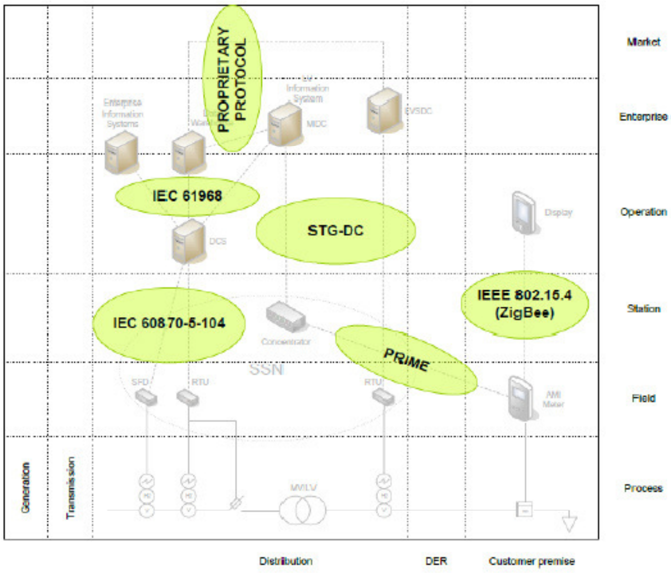

Figure 3: Communication Layers of Automatic Grid Recovery System [8]

Electric distribution utility has to decide which communication media to choose based on aspired level of smart grid penetration. Distribution grid automation is very demanding in terms of communication requirements, typically high level of availability, high capacity (>1Mbps) and low latency (<50ms) depending on the services implemented in the Smart Distribution Grids[8].

Most smart distribution grid communications requirements can be fulfilled by private networks (utility owned), the availability and performance of private network is controlled by utility and reliability is ensured for mission-critical applications. However, the required investment to establish private communication need to be analyzed carefully. However, there will still be an important role for public cellular networks to play in augmenting private networks to achieve better coverage. Table 1 below summarizes the difference between public and private communication networks.

Description	Public Networks	Private Networks
Communication media	Cellular networks (GPRS, UMTS, WIMAX, etc.), Leased Lines, Internet, etc.	Fiber optic, Broadband PLC, Wireless Networks (Meshed Radio, Tetra, etc)
Initial cost	Low CAPEX	Higher CAPEX
Running cost	OPEX / monthly fees	No monthly fees (Future upgrades may be required)
Maintenance	Low maintenance cost	High Maintenance cost
Performance	Limitations concerning Reliability, availability, security, bandwidth, latency, etc.	Better availability, Reliability superior latency and Integrated security. Critical traffic is properly prioritized.
Smart Grid Application	for augmenting the private networks, applications with standard communication Requirements (AMI backhaul, monitoring, etc.) and back up Operation	for mission critical Smart Grid applications with strict requirements on reliability and Performance (e.g. distribution automation, wide area Monitoring, control and protection)

Table 1: Comparison of Public against Private Communication Networks

V. SELECTION CRITERIA FOR DA SUBSTATIONS

As discussed, it is not feasible to automate all distribution substations, selection criteria are required to optimize distribution automation architecture and prioritize the allocation of automated and monitoring substations.

Practical qualitative and quantitative criteria were formulated so that substations of selected MV rings could be ranked to determine the optimal number motorized control points and monitoring RTUs to be installed. The objective functions were defined in order to minimize SAIDI and outage cost per substation C_{pi} as represented in below formula [7].

$$C_{pi}=C_1+r\,d^k \quad \$/kW$$

Where C_1, k Factors depends on Load type, d Interruption duration (Average) and r is Kwh rate ($/Kwh) [7].

The qualitative and quantitative ranking score for each substation is based on the following criteria:

- Load type
- KVA capacity and Loading %
- Number of customers per each substation
- Substation accessibility
- Upstream Cable length
- Historical failure data

A software tool was developed to simply qualitative and quantitative evaluation as shown in Figure 4.

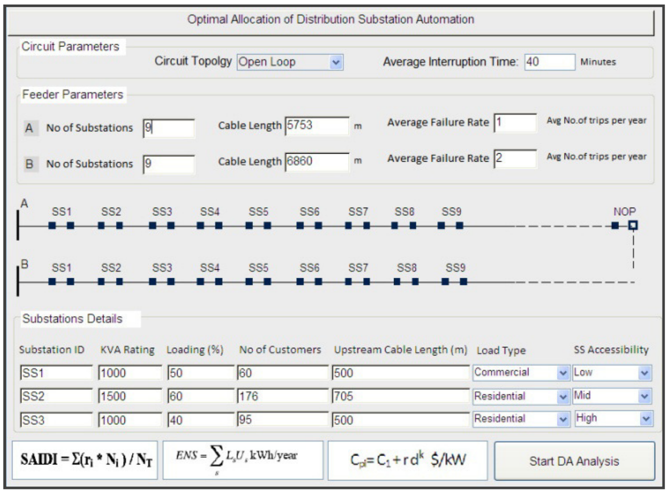

Figure 4: software tool for qualitative and quantitative evaluation of substations ranking

VI. PILOT DISTRIBUTION AUTOMATION PROJECT

A pilot distribution automation project was initiated by Dubai Electricity and Water Authority (DEWA) in 2010 for MV network consist of 38 secondary distribution substations (11/0.4 kV) connected in open ring topology with three redial feeders and two normally open points (NOP) to be operated as radial feeder in a ring configuration for reliability as shown in figure 5.

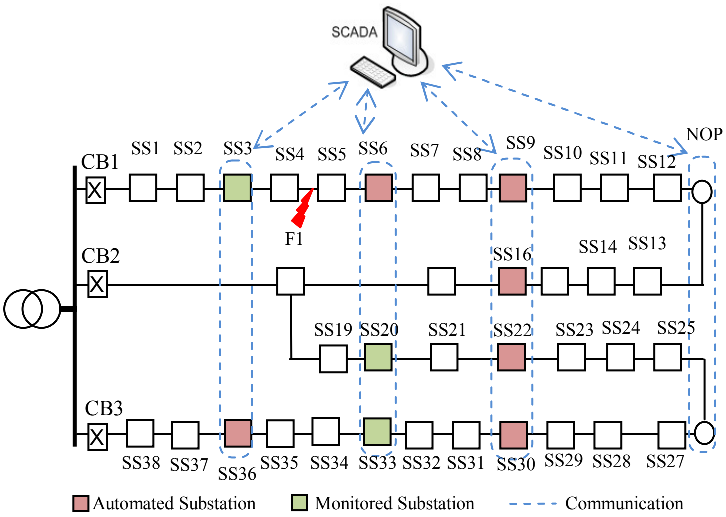

Figure 5: Selected MV network for DEWA pilot DA Project

Cost-effective approach to minimize customer minutes lost and reduce outage duration was adopted by dividing each feeder into three sections using automated substation. Monitored substations with fault passage indicator (FPI) were introduced in the middle of long sections in order to reduce fault localization time. The existing substations were retrofitted and equipped with smart distribution automation system comprise of the following:

- RTU controller and GPRS modem
- Fault Passage indicator (FPI)
- Voltage presence sensor (or voltage monitoring relay)

- Motorized actuator for the ring main unit (RMU).
- UPS system with backup batteries.
- Modbus Power quality meter in selected substation

Other substations were selected for remote monitoring of FPI for better fault localization. Monitored substations have the similar system of automated substation expect for the Motorized actuator in order to enable flexibility and scalability in case of ring reconfiguration.

Figure 6 illustrates an overview of automated secondary distribution substation is shown in where existing FPI and load break switches of RMU were retrofitted in order to minimize the cost of ownership and balance between initial investments (CAPEX) and running cost include operational and maintenance costs (OPEX). GPRS communication was selected for this project for faster implementation and to reduce the initial investments. However, there are limitations related to latency, availability and security. The availability of Cellular network during critical fault management functions is not guaranteed. Cyber security were addressed by ensuring that all communication was routed via private VPN, SIM cards with static IP were installed in automated substations in order to minimize cyber security risks.

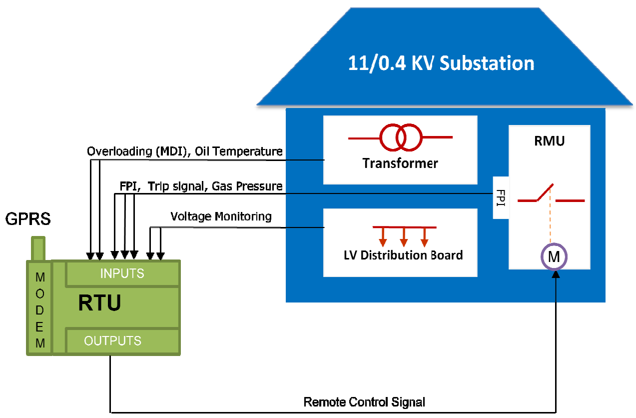

Figure 6: Automated distribution substation overview

The self healing concept is implemented in centralized approach through distribution management system (DMS) and SCADA system. The communication protocol supported by DMS is IEC 60870-5-104 over GPRS. The pilot project were evaluated based on two parameters, percentage of power restored using automated substations and reduction in service restoration time. Table 2 shows typical percentage power restored based on different simulated fault scenarios in each feeder section; the fault scenario in first feeder section (F1) is demonstrated in figure 5.

Feeder CB tripped	Fault Scenario	Simulated Fault Location	% Power (kVA) restored in 2 minutes using DA
CB1	F1	SS4-SS5	48%
CB1	F2	SS7-SS8	52%
CB1	F3	SS10-SS11	46%
CB2	F4	SS13-SS14	54%
CB2	F5	SS19-SS20	78%
CB2	F6	SS24-SS25	50%
CB3	F7	SS28-SS29	72%
CB3	F8	SS32-SS31	52%
CB3	F9	SS36-SS37	75%

Table 2: Percentage power restored based on different simulated fault scenarios

In average 59% of interrupted power was restored within two minutes by means of the DA system, around 40% CML improvement for the selected MV ring was achieved.

VII. CONCLUSION

In this paper, different self healing architecture were discussed and centralized self healing approach in underground distribution cable network was implemented as a pilot project for evaluation and to gain experience in smart grid technologies and reliability improvement. Practical selection criteria for DA devices allocation were presented in order to reduce CML and minimize interruption cost with feasible utility investments.

Effective Change management is important for successful implementation of Distribution Automation and self healing projects. The change of fault management techniques, network operator's role, maintenance requirements and organizational changes should be addressed at early project stage.

The limitations of centralized self healing approach to support micro grid operation and implications of distributed generation on the system design need further study. However, it is essential for utilities to develop long term strategy for smart grid before project large roll out.

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