# Improving Reliability and Quality of Supply(QoS) in Smart Distribution Network

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***Abstract*—Smart distribution grids will be a combination of existing electrical networks controlled by distributed software applications communicating via communication networks. This means that not only the reliability of individual technologies are crucial, but the interoperability is also pivotal for the robustness of the smart distribution network. These individual research areas (electrical network, distributed software controller and communication network) have their corresponding fault handling strategies and several proven solutions exist to ensure reliability. The objective of our work is to integrate the solutions from these individual technologies. We focus on the interoperability and integration of individual fault handling strategies that are essential for improving the reliability and robustness of the overall smart distribution network.**

**In this paper, we describe our approach in creating a single solution from the existing individual strategies to create a robust smart distribution network. We also present the details of the demonstrator design that is being built to evaluate our approach.**

***Index Terms*—reliability, reconfiguration, availability, graceful degradation, network planning,distributed control, interoperability**

## I. INTRODUCTION

Today, energy production and distribution undergoes a paradigm change comparable to the change from line-based to package-based communication in information and communication technology (ICT). There is an immense need to move from traditional, centralized, static energy grid towards a decentralized and dynamic grid, which gives more freedom to producers, distributors, and consumers [1] [2]. The distributed control of supply and use of small to medium size renewables are the major challenges in the smart energy distribution systems.

In developed nations, an unreliable power supply culminates to economic losses. On the other hand, in developing nations, meeting the energy demand is a major challenge. While the European continent faces the challenge of improving reliability of excessive green energy in the network, Indian infrastructure requires smarter control operations to address the inadequacy of electricity. Given the diverse nature of power grids in Europe and India, renewable integration and enhancing availability of the network are the most pressing issues for both sides. Therefore, the reliable supply of the energy in distribution network requires strategic planning of electrical system and new control methods of utilizing possibilities enabled by ICT.

For electrical distribution systems, network reconfiguration approach is usually done to improve voltage profile, minimize loss, and ensure higher reliability of the power supply [3]. Possible network configurations are generated based on several constraints, such as maintaining radial structure of the network, location of controllable switches, status of the feeders, etc [4]. With increasing penetration of distributed generators (DGs) and the associated uncertainties in the generation and load, the need for real-time monitoring and control appears pivotal. A well-laid communication system and the associated information technology (IT) infrastructure is essential for the successful implementation of such real-time monitoring and control system.

In the following sections we will discuss the overall scope of our work on improving the reliability and quality of supply (QoS) in the smart distribution network. Section II describes the building blocks of the smart distribution network. Thus highlighting the gaps in the current research. In section III, research challenges are described in designing a solution that considers the crucial aspects of the each element explained in section II. In section IV we discuss the interoperability issues among the existing solutions and how they can be combined to find a novel solution for improving reliability of the network. Finally, based on our experience, a short summary and conclusion of our work is provided in section V.

## II. ELEMENTS OF SMART DISTRIBUTION NETWORKS

A smart distribution network is essentially a combination of three main technologies: existing electrical system with or without smart devices, software system for smart and distributed control and adaptive, self-configurable communication network, which allows the interaction between the other two.

In this section, the interaction of the three different technologies are highlighted as an enabler for the evolving role of electrical distribution network. Figure 1 shows the envisioned distribution network, in which smart nodes can be monitored with the help of distributed software application. Intelligence can be added by applying control algorithms on these smart nodes.

*Existing physical system (hardware)* in the distribution network is largely centrally controlled. With increasing prevalence of small-medium scale DGs, distributed control of DGs require context awareness. This implies that the smallest consumer in the distribution network must be aware of all the connected DGs, which may act as alternate energy providers. To enable the consumers to interact with each other, a distributed software application is envisioned.

*Middleware or software application* monitors and maintains the status of generation and consumption of energy. Based on this information, decisions of selling or buying energy from DGs can be made. These control algorithms not only add smartness to the system, they also make the system robust by including fault detection and mitigation strategies.

In real life, these consumers can be situated far from each other. Hence, there is a need for robust and reliable *communication network* to collect the information and operate in real-time. The communication network can be either wired or wireless and it should be adaptable based on the requirements between the entities.

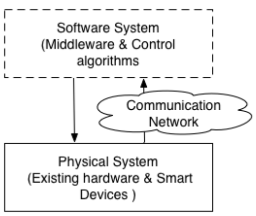


Fig. 1. Elements of smart distribution network

There are several existing approaches to improve reliability in these individual technologies. Table I gives an overview of the research focus of the key scientific projects. It clearly shows that the majority of effort was on developing solution in only one or two technology. Since the power grid is considerably stable in Europe, most of the research is focused on the ICT.

TABLE I
CHALLENGES OF THE SMART DISTRIBUTION NETWORK

| Research Project | Software Systems | Communication Technologies | Power System Technologies |
|---|---|---|---|
| FINSENY[5] | ✓ | ✓ | |
| AmI-MoSES[6] | ✓ | | |
| IMPONET[7] | ✓ | | |
| INTEGRIS [8] | ✓ | ✓ | |
| NEMO & CODED [9] | ✓ | ✓ | ✓ |
| eTelligence [10] | ✓ | ✓ | ✓ |
| ADDRESS [11] | ✓ | ✓ | |
| SEESGEN-ICT [12] | ✓ | ✓ | |

## III. CHALLENGES IN DESIGNING THE SMART DISTRIBUTION NETWORKS

The overall objective is to enhance the cost-effectiveness, efficiency, and reliability of the power distribution systems having significant penetration of DGs. Monitoring the network with extensive use of ICT, detecting and locating faults for abnormal operating conditions, taking timely actions to control the network in a distributed manner and optimizing the performance of the network through reconfiguration are some of the key challenges in the ongoing work.

Table II represents the key technological challenges that need to be addressed:

TABLE II
CHALLENGES OF THE SMART DISTRIBUTION NETWORK

| | |
|---|---|
| Data handling | |
| | -Data representation and format |
| | -Data accessibility |
| | -Data latency |
| | -Data lifetime including data cycle |
| Smart devices for monitoring & control | |
| | -Reliability |
| | -Regulatory laws in the deployed region |
| | -Costs |
| | -Smart meter design |
| Communication Infrastructure | |
| | -Design and Architecture |
| | -Heterogeneous protocol support |
| | -Self-organization |
| | -Delay-minimization |
| | -Fault tolerance |
| | -Scalability |
| | -Secure connectivity |
| Middleware | |
| | -Design & Architecture |
| | -Distributed deployment |
| Automation & intelligent control algorithms | |
| | -Network reconfigurations in distribution network |
| | -Performability and dependability issues |
| | -Failure modes, effect and analysis |

### A. Data Handling

**Data representation and format:** The data from smart meters is used for several purposes such as automation, fault detection and visualization of the network for smart monitoring and control. It is crucial to identify the type and frequency of data required for various functionalities. Simple data (Voltage, Current) can be used to monitor the loads in the network, whereas aggregated data can be used to monitor the general health of the entire network.

**Data accessibility:** Distributed data storage is another important aspect of efficient data handling. Data storage provides raw data from metering devices and the aggregated data for decision-making. The graphical user interface to visualize the actual status of the network helps in analyzing the status of the network.

**Data latency:** A detailed study of the requirement of data for various processes must be done to detect faults like overvoltage situations, for which the real-time data is required. On the other hand, for theft detection near-real time data is suitable.

**Data lifetime including data cycle:** The data storage requirements in terms of the decision to store the data forever or periodically stash data to a central repository. This decision depends on factors like the computing power of the smart devices and the intermediate data collectors.

Research in the Big Data community is mainly focused on these data handling issues.

### B. Smart devices for monitoring and Control

Metering capabilities such as the ability to detect two-way flow of energy, secure communication to send and receive information and being tamper-proof play an important role in the smart grids. Therefore, the following issues are important when designing smart meters.

**Smart meter design:** Key attributes while designing a metering device.

**Intelligence:** Design the local intelligence required for the smart meter to achieve several requirements.

**Reliability:** Details of the design decisions addressing reliability of the device.

**Regulatory laws of the deployed region:** Flexibility of the design to incorporate the region specific standards.

### C. Communication Infrastructure

The communication backbone for the devices, aggregators, and control stations to interact with each other must be made adaptable to achieve the required functionality. The communication architecture has to be designed to integrate heterogeneous devices, support dynamic needs, achieve different functionality through adaptive communication technology and deliver real time monitoring and control with respect to the adaptive delay constraints and throughput. This network should be designed to be secure, fault tolerant and scalable.

### D. Middleware

System architecture from the ICT perspective should enable data collection, data provisioning and carrying out control algorithms. Following aspects require careful considerations.

**Design and architecture:** Various design issues such as dependability, modularity and distributed deployment should be considered. A software control application should be flexible to support heterogeneous hardware platforms. Moreover, it should be technology-agnostic in order to integrate foreign libraries/APIs, protocols and communication platforms etc. Component-based or service based architectures are well-known choices as the software architecture design principles.

**Distributed deployment:** In smart grids, the architecture of a single unit of smart node and the network architecture are equally important. Approaches like fractal architectures are emerging, which allows the compositionality of similar smaller sub-systems to create a hierarchical system [13].

### E. Automation and Intelligent Control Algorithms

Data acquisition and analysis make base for smart actions such as reconfiguration, graceful degradation, fault detection etc.

**Performability and dependability issues:** This issue corresponds to the robustness of both the software application and the design of control algorithm which increases the availability and reliability of the distribution grid. If a certain section of the distribution grid fails, then sectionalizing parts of the grid to isolate the problem is done with the help of control algorithms. Such control strategies either require *real-time* or *near real-time* or *some-time* data.

### F. Failure modes, effect and analysis

A smart distribution network can have various sources of faults (hardware, software and communication networks). For instance, a line breakage fault pose power outage situation, which can be dealt with reconfigurations strategies. Whereas, communication network failures will pose a major disruption to monitoring and alarming systems. In contrast, the failure of software systems will lead to absence of data which can affect the implementation of control signals. Therefore, these individual strategies must be combined to develop an integrated fault handling strategy for a robust smart distribution network.

The challenges listed in this section are active areas of research. In our study, we identify and combine relevant solutions.

## IV. Proposed approach

In smart grid control systems, communication and traditional power engineering are increasingly in continuous interaction. As the progress is from enhanced data acquisition towards real-time use of data, time-criticality of functions is also increasing. The current state of the art does not employ wireless sensors at a fine granularity for real-time data collection and control.

The need to control significant masses of active smart grid components (like PV units, electric vehicles) has increased exponentially. The knowledge about different consumer and producer profiles in combination with their flexibility will enable the introduction of new control strategy on microgrid / island level. Furthermore, distributed decision mechanisms based on real-time sensing can serve to identify causes and locations of grid problems in real time or to increase the level of confidence for grid recovery actions. In this section, we discuss our approach based on the challenges elaborated in Section III.

One of the major goal of our work is to establish a crucial relationship between the methodologies developed and the plausibility of solution using low-cost sensors. This includes validation using demonstrator and simulation both at the component and at the system level.

### A. Smart Metering Devices

The measurement and collection of data at the node-level must be done irrespective of the underlying hardware. The proposed solution for such smart metering devices has two components i.e. *Metering device* and *Metering collector*. Figure 2 shows the Voltage and Current values of the node by the *metering device*. These values are forwarded to the *metering collector* connected via Ethernet. A metrology processor is used to measure Voltage, Current, Energy values irrespective of the sensor type. A *metering collector* collects the data from metering device in order to combine information to be dispatched for various purposes.

### B. Design of the Smart Distribution Network

The design of the proposed demonstrator includes several considerations such as real-time monitoring of loads, renewable energy sources, health of smart meter, transformer, and distribution poles, real-time simulation and detection of line

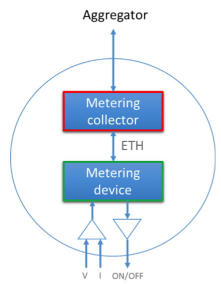


Fig. 2. Metering device showcasing both monitoring and control signal.

faults, power thefts, real-time control of energy usage per load, islanding a microgrid based on the energy availability and reconfiguration of energy flow using tie lines. The demonstrator should be also capable to perform real-time communication between different heterogeneous entities and provide real-time storage and data analysis of the electrical distribution parameters. Based on the real-time data analysis the demonstrator should be able to provide real-time control of different entities and equipments in the distribution grid.

Considering all the above design parameters we proposed a 15-Bus outdoor, overhead line based electrical sub-distribution system with real loads as the demonstrator for this work. The system is a secondary distribution network, 415VAC 3-Ph 4-Wire overhead line system. Source power to the demonstrator is obtained from a dedicated feeder provided from the sub-station. Figure 3 shows the physical layout of the planned demonstrator. It has thirteen load points and three renewable

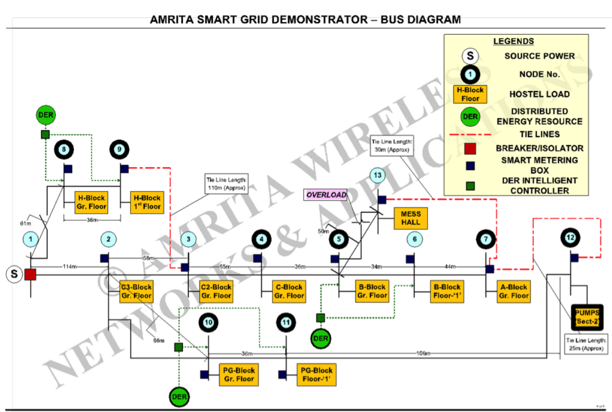


Fig. 3. Single line diagram of the Test Distribution Grid Model at Amritapuri Campus in Kerala.

energy source points. The electrical poles with overhead lines connect the loads. Each pole that is acting as a node consists of a manual isolating device and a smart metering box. The manual isolating device could be a breaker, which would help to isolate the smart metering box for carrying out live maintenance. The intelligence of the system resides in the smart metering box enabled with ICT.

Faults to be simulated in the demonstrator are line breakage and overload due to over current faults. A switching device, which can be controlled remotely is used to emulate a line breakage condition. For overload due to over current, the current threshold value for tripping is set slightly lower than the peak current, e.g., at 75-80% of the peak current so as to carry out the tests in a controlled manner. The demonstrator will allow isolating each node remotely, if the need arises. Tie-lines in the demonstrator help in emulating the reconfiguration solutions, in case of the outages in the power grid.

### C. Logical Layout of the Smart Distribution Network

In figure 4 the physical nodes at Layer-0 are referred as *Intelligent nodes*. These node are monitored by the smart measuring device. All the raw data generated from measurements is sent to the *Aggregator* at Layer-1. The communication between the *Intelligent node* and the *Aggregator* is via a secure channel using a defined set of data objects. Intelligent node configuration parameters and control actions for switching are received by *metering collector* from *Aggregators*. Another

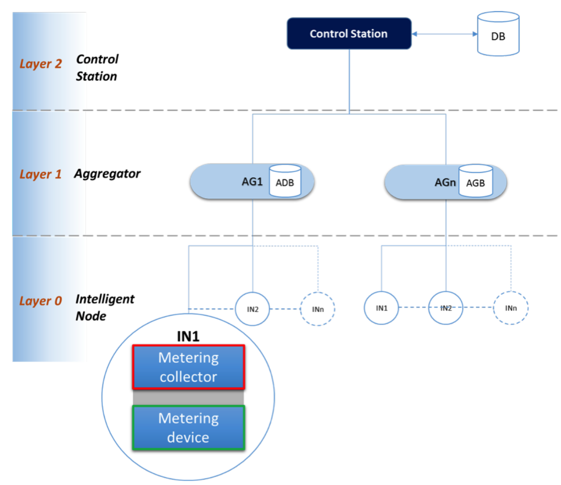


Fig. 4. Hierarchal layout of the test distribution network, showcasing the real-time monitoring and control of physical nodes.

functionality of an *Aggregator* is to act as an information gateway for several nodes connected to it. This allows the *intelligent nodes* to communicate with each other through *Aggregator*. The role of the *control station* is to monitor the complete sub-distribution networks, activities of Aggregators and *Intelligent nodes*. The complete information of the network, routine data backups from the Intelligent nodes and Aggregators are maintained by the control station. A user friendly data visualization can provide a better monitoring and help in maintaining the health of the complete network.

The flexibility of this approach eases the process of expandability, addition, removal of nodes and layers and, importantly, a fault isolation of any node or branch of the ICT infrastructure, keeping observability and controllability of the network without compromising its overall integrity.

### D. Heterogeneous Communication Network

The performance of a smart grid will depend on a reliable, robust, and scalable communication network. The requirement for each subsection of the distribution grid is very unique. The acceptable latency for monitoring, detection and control of each of the functionality will differ with respect to its impact on the reliability and robustness of the grid. The complete communication network uses different communication technologies such as Wi-Fi, Zigbee, and Cellular technologies.

The different protocols will be developed for adaptive routing, self organization of heterogeneous network, delay minimized data aggregation, localization and time synchronization of the network.

### *E. Distributed software application*

The reliability of the smart distribution network depends on two main areas: a stable electrical grid and the software application which provides smart control to the electrical grid. The software application should be flexible and modular. We propose component-based architecture [14] for smart grid monitoring and control. Figure 5 shows the functional components of the middleware developed to monitor and control the Intelligent nodes, Aggregators and the control station. At level-0, the role of the middleware is to communicate and receive data from the devices. The devices include the smart metering devices, DGs, and other controllable and uncontrollable loads. At level-1, the main functionality of the middleware is to extract knowledge from the raw data received from Intelligent nodes. This information is then used for carrying out reconfiguration to improve quality of supply or for theft detection etc. At level-2, visualization of complete network is the key functionality that is required for constant monitoring of the network. Another important functionality is the calculation of online reconfiguration to improve network reliability.

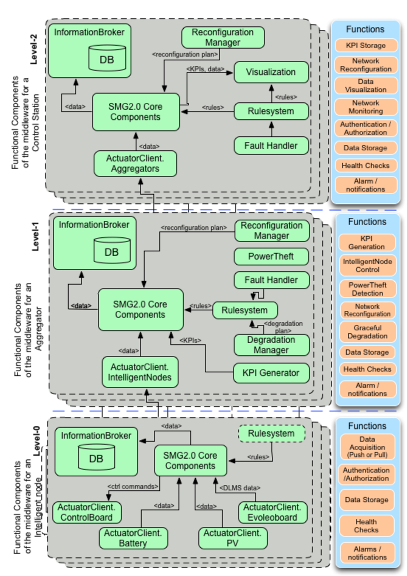


Fig. 5. Component-based architecture of SMG2.0 middleware for hierarchal monitoring and control.

### *F. Reconfiguration of the distribution network*

Network reconfiguration has been one of the key components in the distribution automation system [15] [16] [17] [18]. In a network reconfiguration process, the topology is altered by opening or closing either sectionalizing switches or tie switches, while meeting the load requirements and maintaining the radial nature of the network. Multiple objectives can be achieved during this process, such as the minimization of real power loss in the network, minimization of the voltage drops along the lines, and maximization of the reliability of the power supplied to the consumers. Maximum utilization of the DGs with renewable energy sources will also be ensured in the reconfiguration process. The reconfiguration process can be formulated as an optimization problem, as shown below.

$$Minimize J = w_1 J1 + w_2 J_2 + w_3 J_3 \tag{1}$$

where $J_1$ is the total real power loss in the system,$J_2$ is the sum of squares of voltage drops along the distribution lines, and $J_3$ is a measure of the unreliability of the power supplied to the consumers in the distribution system; $w_1$ ,$w_2$ ,$w_3$ are the weights assigned to the corresponding objective functions. The above multi-objective optimization problem can be solved by using some optimization technique using computational intelligence, such as the Particle Swarm Optimization (PSO) method. The network reconfiguration can be done both during normal conditions and during post-fault conditions. The reliability of the reconfiguration approach is evaluated using the probabilistic reliability model as in [4].

### *G. Graceful degradation*

Another approach of improving the reliability of the network, is by maximizing the use of DGs. During power outages i.e. fault at the feeder level or during line breakage, the connected renewables can be used. Due to unpredictability of DGs, a storage unit can be used as a backup resource. Since storage unit can provide support only for a fixed amount of time, the scheduling of tasks can be planned in such a way that the crucial tasks remain functional for as long as possible. This approach is referred as graceful degradation, since the performance of the system is lowered intentionally [19] [20].

### *H. Faults and fault handling strategies*

Improving the reliability and the Quality-of-Service(QoS) requires an in-depth understanding of faults and factors that affects them. Our focus is to combine the approaches of fault localization in distribution network and model-based fault detection approaches in software system. For instance, the physical faults such as line breakage or failure in feeder or over-voltage situations are handled by network reconfigurations. In communication network, time-outs are a way of detecting missing data packets or connection issues.

### *I. Evaluation through Simulation*

To correspond with the above mentioned drivers, operation and planning systems need to be more integrated. Integrated power system simulation and communication emulation environments support such development. Only few integrated simulation systems exist and they are not often applied to Smart Grid research activities. Integrated simulation between power system and communication network has been done e.g. [21] [22].

Bringing together simulation studies for power and communication systems offers more benefits on both sides. The objective is in having real integrated environment, where systemic interactions can be studied effectively. Another significant research step is in the remote use of simulators that help in distributed decision-making and identifying the cause and locations of grid problems.

In the reconfiguration phase, communication has a very central role. As the fault has been automatically isolated, power delivery is restored for as many customers as possible. This is made by remote-controllable switches via communication.

As our approach relies on microgrids during network outages, the requirements for communication will be much stricter. We are seeking for a dynamic formation of microgrid according to current status in the network. Thus, the size of the microgrid would be decided according to current DG generation, storage capacities and loads. This requires accurate real-time measurements and controls.

In this project, we apply Advanced PROcess Simulator (APROS) [23] simulation environment for the studies of power system and communication network. The advantage of APROS is that it can be used to combine power system and communication network simulation and it also has a possibility to use emulated communication channels. This enables an integrated simulation of whole cycle including control and measurement loops as indicated in figure 6.

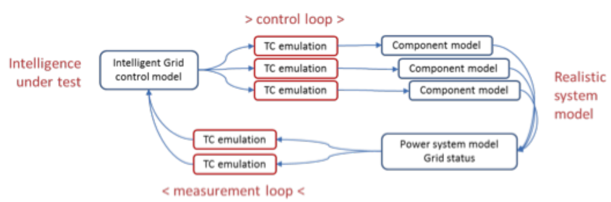


Fig. 6. Emulated communication channels integrated in APROS simulation enviroment.

Figure 7 presents a typical simulation case in which a microgrid controller is utilizing measurements and controls via different communication channels is studied.

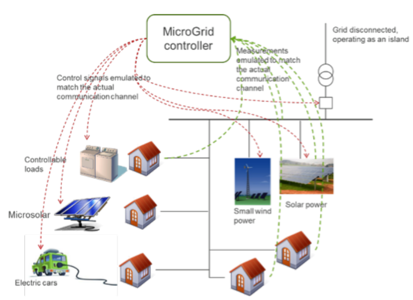


Fig. 7. Example of microgrid controller simulation case.

## V. Conclusion

In this paper, we presented an overview of our approach to improve reliability and availability of smart grid systems. We described that power outages can be rectified using the combination of control algorithms such as reconfiguration, real-time monitoring, graceful degradation mechanisms and theft detection. To gain increased confidence in the proposed methodologies, the developed hardware and software tools will be tested in close loop with real-time power system simulators, and also in actual distribution systems. The results of the research add strategic cross-domain (Power-ICT) insights towards a better utilization of existing European infrastructures that are able to handle the high availability and reliability requirements of the future real-time smart electrical system. Our research will also serve as a benchmark for Indian power sector to adopt, demonstrating the benefits of smart grids and paving the way for a reliable power system that better meets the growing demands of the people.

## VI. Acknowledgement

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