CHAPTER-1

INTRODUCTION

1.1 GENERAL

The concept of smart grid will be incomplete without complete automation of distribution networks. A smart distribution system should be capable to monitor from the control centre, consumers demand, voltage, frequency and power factor accurately on regular basis. This seems possible with installation of smart meters that are capable to record these variables and send them to Central Data Collection System (CDCS) through fast satellite communication link. Smart meters give information regarding consumption of energy in real time to all consumers through display device. To enable remote monitoring of substation, Automatic Meter Reading (AMR) may be interfaced by Data Collection Devices (DCDs) installed at substations, which may further be transmitted to Central Data Collection System (CDCS) through two-way communication link. A smart meter may be defined in terms of its capability as *"An electronic device that records in real-time, energy consumed, voltage, current, and power factor for system monitoring, customer billing, and is capable of interacting with consumers and suppliers at regular intervals through a bi-directional communication link."*

A smart distribution network architecture requires two-way flow of electricity and informations between electrical power suppliers and consumers, and should be capable to deal with distribution system challenges such as load balancing, protection of feeder against overcurrent, theft detection through automatic monitoring and control. Phasor Measurement Units (PMUs) may be installed at substations to measure time stamped voltage and current phasors, and these measurements may be interfaced with smart meters at consumer premises through bi-directional communication protocols.

1.2 LITERATURE SURVEY

For efficient monitoring and control of consumers in real time, existing Special Energy Meters are to be replaced by Smart Energy Meters which are to be accessible to distribution control centre through communication link [1]. Distribution control centre could have application softwares which include billing, addressing power quality issues. Smart meters are able to send their readings over communication lines [2] and recognize addresses to activate/deactivate internal modules. To have that capability, Automatic Meter Reading (AMR) requires a specific infrastructure which would make it bidirectional. The communication network can be wired like Ethernet, Power Line Carrier (PLC) or wireless like Wireless Fidelity (WIFI), Global System for Mobile (GSM), Zigbee. Radio Frequency (RF) and Power Line Carrier (PLC) communication have generally been used [3]. Implementation of AMR using PLC has been used in measuring gas, electricity and water consumption in most of the countries, as complexity and cost reduces. For interfacing smart meters [4] and managing collection of data globally and automating billing, a wireless energy meter with its communication capabilities is designed which monitors the meter readings regularly without manual intervention. Furthermore, a new technology is also implemented that works on Short Message Services (SMS), which intimates the customers about the consumption of their energy via a short SMS [5]. The technology called Bluetooth wireless sensor network is used for the collection of widely distributed sensors, monitors energy used at each home and passes all stored data through the communication network to a control centre. This system consists of meters, relay, a ZigBee operated wireless sensor network and GSM [6]. A prototype Automatic Meter Reading system using power lines and frequency shift has been proposed [7]. Optimal rescheduling of residential micro-grid based on readings obtained from smart energy meters has been considered where temperature dependent loads have been included [8].The communication existing between the data concentrator and data collectors can also be implemented using PLC in an AMR system connected to master station through General Packet Radio Service (GPRS). To reduce Aggregate Technical and Commercial (AT&C) losses in power distribution sector, an AMR system based on GPRS technique [9], where smart metering system is interfaced with Photo Voltaic (PV) energy system and data acquisition, may be helpful. Home automation special and smart energy meter has been presented [10]. A new framework has been developed by using hidden Markov model that manages end user privacy in measurements through meters [11]. A cost effective energy management system is also designed that uses rechargeable battery [12] and different protocol like Efficient Privacy-Preserving Protocol for Smart Metering Systems (EPPP4SMS) [13]. Smart grid pilot programs are presented with regards to smart grid technologies in which utilities can interact with customer meters and provide solutions for improvement [14]. Standalone AMR system has been proposed that enables control of AMR using Supervisory Control and Data Acquisition (SCADA) system [15] and also realizes some of the smart grid goals [16]. For smart metering, different protocols have been presented that implements Internet Protocol version 6 (IPv6) allowing maximum flexibility [17]. Smart home energy management using Zigbee communication has been proposed [18]. A digital technology that includes Zigbee and WIFI for home automation has been proposed [19]. Non-Intrusive Load Monitoring (NILM) has been suggested to determine the operation of individual loads in buildings [20] which also tracks power consumption. A smart metering device that can be designed based on waveform based estimator to determine power consumed by variable power demands, has been proposed [21]. The implementation of electric energy quality meter has been proposed through hardware reconfiguration computing [22]. The integration of AMR technology with the outage management system has been presented [23]. Smart meters for hydro system have been proposed [24].

Automatic Meter Reading (AMR) with its interface meters (Smart Energy Meters or SEM) and data collection from Data Collecting Devices (DCDs) at substations may be quite fruitful in monitoring consumers. Implementation of these projects would enrich India with advanced capabilities of remote monitoring and control of its substations, with centralized data collection &processing, and this would reduce the maintenance and monitoring costs over time, thereby improving overall efficiency of the grid.

Distribution automation system comprised of advanced sensors and communication technologies should be capable of monitoring customers remotely. Bi-Directional flow of information should take place between supplier and customers in a smart distribution system. A framework for autonomous demand-side management, which adopts a structure with admission control, load balancing, and demand response management has been presented in [25-26]. But, the issues related to appliance modelling, implementation of reliable cross-standard networking platforms,

distributed system-wide demand response management algorithm to coordinate the operation of residential Home Load Management (HLM) modules in a smart grid has been presented [27-28]. In [27-28], the HLM modules are embedded in customers smart meters. Based on prices announced by the utility, smart meters optimize the daily operation of household appliances and send back the scheduled load profiles. Then, the total load profile is calculated and released by the utility based on scheduled load profile of different consumers. The proposed algorithm enhances the total load profile, network voltage magnitudes, network losses, and service reliability. But, the proposed method is not capable of considering network constraints and not ensures simultaneous flattening of load voltage profile of all the three phases. Also, various network challenges, such as load balancing, overcurrent protection, and theft detection, have not been considered. Different techniques have been used for phase identification to balance the particular phase in smart distribution grids [29-32]. However, these approaches do not investigate the performance using real metering data obtained from both transformers and homes. A cost efficiency concept as a metric of the economic efficiency of the electricity consumption to optimize the consumption benefit per unit cost has been proposed [33]. The cost efficiency varies with different consumption patterns and is sensitive to behaviours of load shifting. However, along with load balancing and shifting, the author only considers the residential consumption, but it can be extended to the commercial consumption scenarios and industrial consumption scenarios to achieve better economic efficiency for business companies and industrial producers. Also, this approach does not investigate the performance using real-time metering data. The basic considerations for the smart metering applications in commercial and residential buildings have been elaborated [34]. However, various network challenges such as load balancing, overcurrent protection, and theft detection have not been considered, and the author does not investigate the performance in real time system. A comprehensive survey of smart metering and electricity smart meter data analytics has been presented [35]. Several different dimensions to smart meters including the smart meter technology have been highlighted, but the author does not consider the privacy of the customers and also does not consider the real-time communication protocols for the transfer of data. And, also, the author does not consider the capability of the smart meter that automatically handles the situation of protection against overcurrent and theft. The author proposed a smart meter which can achieve good compression rates, also offering observability features in medium voltage and low voltage networks Distribution Management System (DMS)/SCADA [36]. In this way, smart metering becomes an enabler of real-time voltage control required by modern active distribution grids. But, the author does not consider the real-time communication protocols for the transfer of data. And, also, the author does not consider the capability of the smart meter that automatically handles the situation of protection against overcurrent and theft. Clustering of customers may reduce computational requirements, thus may be suitable for analysis of real-time networks. A finite mixture model based clustering of residential customers using smart meter measurements considering the behaviour of customers in different periods has been proposed [37]. However, clusters so formed have not been tested in monitoring, control, and protection of real-time systems. The possible adverse consequences for power quality of introducing smart distribution-grid technologies and applications have been considered [38]. But the authors did not carry out results for the real-time system, and also, did not consider the different challenging issues like balancing of load, protection against overcurrent, and detection of theft. A general protection scheme for loop-based microgrids have been proposed [39] and applied the proposed approach to a microgrid that is owned and operated by Illinois Tech. The proposed protection scheme analyses the differences in voltages, currents, and frequencies between grid-connected and island modes. However, authors did not include various operating conditions, such as unbalanced loads, different earth-connection systems, specific control strategies, large harmonics, and fault current limiters and verification of results with the real-time system. An efficient communication-based protection scheme for radial distribution lines that implements common directional overcurrent relays, assisted by intercropping and blocking transfer functions have been proposed [40]. However, various network challenges such as load balancing, and theft detection have not been considered, and the authors did not investigate the performance in real time system. A Directional Overcurrent (DOC) relay-based Regional Area Protection Scheme (RAPS) for a modern distribution system incorporating high penetration of Renewable Energy Sources (RESs) have been proposed [41]. Protection components and the sensitivity-preferred setting principle utilized in local relays are presented. Then, a RAPS is proposed to accelerate fault isolation and enhance protection coordination. It is achieved by exchanging the pick-up signal and fault direction information from local relays within each predefined regional area. However, authors did not consider the case of overcurrent. A novel consumption pattern-based energy theft detector has been presented [42], which relies on the predictability of the customer's normal and malicious usage patterns. Using distribution transformer probability of energy theft are short listed, and by monitoring abnormalities in consumption patterns, suspicious customers are identified. However, these approaches do not investigate the performance using real-time smart metering data. It also doesn't give theft notification with time 't' to the control centre and also to the customer. A stochastic Petri has been used in [43], to detect and localize the occurrence of theft in grid-tied microgrids. The development of a cost-effective electricity theft detection and prevention system using the Internet of Things (IoT) technology have been presented [44]. A data analytics method for detecting various types of electricity thefts have been presented in [45], by using novel data mining techniques, i.e., Maximum Information Coefficient (MIC) and clustering fast search algorithm. But, these methods don't focus on the overcurrent protection of the feeder and the load balancing. The impact caused by the Distributed Generators (DGs) on the Overcurrent Relays (ORs) performance for Distribution Systems (DSs) protection has been presented [46]. The impact of the installation of DG in Central Java region, on the coordination of protection on the radial distribution network, has been studied in [47], showing that the existing protection coordination settings still work properly for protection coordination settings after the installation of DG.

In the Wide area Monitoring System (WAMS), it has been possible to continuously monitor the health of power system networks using synchrophasor technology. A Wide Area Monitoring System (WAMS) consists of geographically dispersed Phasor

Measurement Units (PMUs) which are able to perform time stamped phasor measurements within a microsecond through Global Positioning system [49]. Role of PMU and WAMS technology in power quality estimation, protection and control of power system networks has been presented [50-51]. Discrete Fourier Transform (DFT) based LABVIEW model of PMU using non-recursive and recursive algorithms has been developed [52]. Possibility of PMU placements in distribution systems has been considered [53]. In [54], feasibility of PMUs in smart grid architecture has been presented. A MATLAB based PMU simulator for state estimation in a three-phase network using greedy algorithm and integer programming has been presented [55-56]. The main computational algorithms involved in the phasor measurement process are illustrated using a MATLAB based PMU simulator [57]. A novel method of incorporating the phasor measurements and the results of the traditional state estimator in a post-processing linear estimator has been proposed [58]. The performances of a PMU prototype based on a synchrophasor estimation algorithm conceived for the monitoring of active distribution networks, as well as its experimental application during some intentional islanding and reconnection tests of an urban medium voltage power network has been described [59]. Development of test platforms for PMU-based wide-area monitoring and control applications have been proposed [60-62].

According to C37.118.1-2011 Std. of IEEE [63], PMUs are capable of giving universal time-tagged frequency estimation, its Rate of Change of Frequency (ROCOF), Phasors of currents and voltages. The high rates of reporting as well as accuracy of the PMUs data make PMU suitable for operators of distribution & transmission networks for real-time monitoring, control and protection functionalities [64-66]. Communication protocol IEC-61850 allows a control & protection application which gives immense results compared to conventional solutions. High - speed communications between

IEDs connected between substations based on Local Area Network (LAN) on the exchange of Generic Object Oriented Substation Event (GOOSE) messages successfully used to replace conventional hardwares for various control & protection applications. Sampled Measured Values (SMV) communicated from Merging Units (MUs) to various protection equipments at the substation replaces the copper wiring between the Current Transformers/Potential Transformers (CTs/PTs) in the yard of substation and the IEDs [67-70].

1.3 MOTIVATION

From the limited literature survey carried out in this thesis, it is observed that implementation of Automatic Meter Reading (AMR) technique may be quite useful in automatic monitoring and control of substations through transmission of informations from smart meters at consumer premises to Data Collecting Devices (DCDs) installed at substations that may be transmitted further to Central Data Collection System (CDCS) through bi-directional communication link.

From literature survey, it seems that past work in the area of distribution automation system has certain limitations like not considering the case of load shedding/load reconnection based on the availability of power. Distribution networks are prone to several challenges such as overcurrent through feeder resulting in overheating of conductors, unbalancing of loads on three phases, power thefts due to illegal connections. Reduction of available power at the substation due to under voltage requires some of the loads to be switched OFF to protect various equipments against under voltages. Similarly, increase of available power caused by over voltage requires switching ON of some new loads to protect equipments against over voltages. Handling all such problems through manual switching are time consuming and prone to mistakes thus causing aggravation of situation. Therefore, complete automation of distribution network is the need of the hour where such problems may be automatically detected and controlled. Consumer premises may be provided with smart meters which are capable to interface with controllers at the substation and distribution transformer (DT), through fast bidirectional communication link either wired or wireless. Controllers at the substation and distribution transformers (DTs) having application softwares dealing with distribution network challenges such as overcurrent monitoring and control, load balancing, power theft detection may generate control decisions based on received informations, and automatic implementation of control measures may be processed, accordingly. Most of the challenges may be handled by local controller at distribution transformers, whereas, remaining may be tackled by master controller at the main substation. Thus, distribution networks may be saved against outages/ deterioration of power quality caused due to such problems.

PMUs may play an important role in real time monitoring, control and protection of distribution networks through its time-stamped phasor measurements. It seems that very limited effort has been made in exploiting role of PMUs in automation of distribution system.

Therefore, motivations behind the work carried out in this thesis are:

- To investigate the benefits of implementation of smart metering scheme in Indian power system through case studies performed at some ongoing Automatic Meter Reading pilot project in India.
- To suggest a smart distribution network architecture that is capable to carry bi-directional flow of electricity and informations between consumers and suppliers through fast communication link, and is capable in automatic monitoring, control and protection of distribution system.

- To develop model of PMU in MATLAB/SIMULINK and LABVIEW that can be used to study effectiveness of PMUs in monitoring, control and protection of distribution networks in smart grid architecture.
- To propose a communication-assisted scheme for automation of distribution networks using Phasor Measurement Units.

1.4 ORGANIZATION

The thesis has been organized in following six chapters:

Chapter 1 presents a comprehensive literature survey on related work, and sets motivation behind work carried out in this thesis.

Chapter 2 presents a case study for implementing an Automatic Meter Reading (AMR) project that has been carried out in south area of Delhi. This project proposes a use of SYNC interface communication unit i.e. SYNC 2000 data concentrator unit and SYNC 5000 meter data acquisition system. These units may collect the data from the meters, convert it into the Device Language Message Specification (DLMS) protocol and transmit it to the Northern Regional Load Dispatch Center (NRLDC), which may act as the Central Data Collection System (CDCS).

In chapter 3, a smart distribution system with two-level control architecture has been proposed, where, secondary controller (master controller) installed at substation checks availability of power and decides load shedding/load reconnection based on that. Primary controller (local controller) installed at distribution transformer performs tasks of load balancing, overcurrent protection of feeder and power theft detection in the real-time framework. In the proposed architecture, all customers have been provided with smart meters that are capable to interface with the local controller in a bidirectional fashion. All local controllers can interface with the master controller in a bidirectional manner. The two-way flow of information has been proposed to take place through Informations and Communication Technology (ICT). Case studies have been performed on a test distribution network comprising of two identical areas each having 21 loads. Simulations have been carried out on a developed MATLAB/SIMULINK model of the test system, and results have been validated on eMEGASim® OP5600 OPAL-RT real-time simulator.

Chapter 4 presents the MATLAB and LABVIEW models of PMU that have been developed in this work to estimate phasors by use of Discrete Fourier Transform (DFT) using non-recursive as well as recursive algorithms.

In chapter 5, a modified architecture of the distribution system has been proposed, where Phasor Measurement Unit (PMU) has been placed at the main substation receiving supply from the grid through the incoming feeder, as well as at all Distribution Transformers (DTs). PMU installed at the main substation is linked to master controller (secondary controller) through IEC-61850 communication protocol. PMUs placed at DTs are connected to the corresponding local controller (primary controller) through the IEC-61850 communication protocol. Estimated voltage and current phasors together with frequency are transmitted from PMU to the local controller through IEC-61850 communication protocol. Controllers perform different tasks based on the data received from PMUs. Each local controller is linked to master controller as well as to all smart meters placed at loads supplied by the DT. Bidirectional exchange of information takes place between master and local controllers as well as between local controller and smart meters. Available power at the substation and distribution transformer is calculated in real-time with the help of PMU measurements.

Finally, Chapter 6 concludes the thesis with its important findings and observations, and suggests future research required to be carried out in this direction.