Ethernet-Based Communications Network for Teleoperation of Renewable Energy Technologies in Hybrid Mini-Grids

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ABSTRACT

Ethernet-Based Communications Network for Teleoperation of Renewable Energy Technologies in Hybrid Mini-Grids

Mohammad Reza Sharafat

Renewable energy technologies (RETs) such as wind and photovoltaic (PV) have great potential for reducing the cost and environmental impact of electricity production in stand-alone power systems (mini-grids). However, due to fluctuating nature of RETs, and the various constraints of diesel power plants, a suitable communication system is required for better coordinating the operation of the various sources and controllable loads so as to increase diesel fuel displacement without compromising the power quality.

A framework for designing and dimensioning a communications network for supervision and control of hybrid mini-grids as well as for choosing the network's components and interfaces (including the data acquisition systems, modems, network hubs and switches, communications media and channels, etc.) is presented. In this framework, standard technologies and readily available communications units and subsystems are chosen with a view to satisfy the requirements and assumptions. In doing so, the hardware components needed for implementing such a network are identified, and various software pieces are written to integrate all elements of the network. A set of performance measures that are normally used to assess the performance of data communications networks is identified, and their values are obtained via extensive tests.

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I would like to dedicate this thesis, to the soul of my late grandfather, who passed away while I was writing this thesis.

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LIST OF ACRONYMS

AMR	Automatic Meter Reading
APC	Active Power Curtailment
BPL	Broadband Power Line
BPSK	Binary Phase Shift Keying
CdTe	Cadmium Telluride
CFS	Carrier Frequency System
CIGS	Copper-Indium-Gallium-Selenide
EWH	Electric Water Heater
FSK	Frequency Shift Keying
Genset	Diesel Engine-Generator Set
GUI	Graphical User Interface
HMG	Hybrid Mini-Grids
HV	High Voltage
LAN	Local Area Network
LV	Low Voltage
MAN	Metropolitan Area Network
MPPT	Maximum Power Point Tracking
MV	Medium Voltage
OFDMA	Orthogonal-Frequency-Division-Multiplexing Access
PLC	Power Line Communication
PV	Photovoltaic
PWM	Pulse Width Modulation

RCS	Ripple Carrier Signaling
RET	Renewable Energy Technology
WPAN	Wireless Personal Area Network

CHAPTER 1

INTRODUCTION

1.1 A Brief Primer on Renewable Energy Technologies (RETs)

Ever since the first power station in the world was built in 1881 to generate electricity from hydro power in Niagara Falls, there has been a steady increase in the demand for more electric power in all continents. With the start of Edison's bulb commercialization and opening of the Pearl Street power station in New York in 1882, there has been a steady diversification of energy sources that today include coal, nuclear, natural gas, hydro power, petroleum, solar energy, tidal harness, wind, and geothermal sources for electricity production. However, more than 80% of the electricity worldwide is generated by heat engines that mainly rely either on fossil fuels or nuclear fission for generating heat needed by the steam turbine that was invented in 1884 [1]. Such widespread use of fossil fuels has contributed to serious problems for the environment, and the recent mega earthquake in Japan has forced many countries to abandon their plans for future nuclear plants, and some have even decided to gradually phase out their existing ones.

In contrast, the use of renewable energies for electricity production has been on the rise steadily. This is because such energies are free and abundant, and their use is neither detrimental to the environment (as is the case of using fossil fuels), nor entail possible catastrophes (as in the case of using nuclear material). However, renewable sources of energy, such as solar and wind, are highly fluctuating, and their hours of peak production in general do not coincide with the hours of peak demand. Hence, appropriate techniques should be used to make them more useful and efficient. In this thesis, the focus is on generating electricity via photovoltaic panels that directly convert solar irradiance to electricity. It is interesting to note that the photovoltaic phenomenon was first observed in 1839, long before building the first power station in 1881 powered by fossil fuels [2].

Grid-connected solar photovoltaic (PV) power generation is the fastest growing of all renewable energy technologies with a 60% annual average growth rate for the five year period ending in 2009 [3]. This is in spite of the fact that generating electricity via photovoltaic panels is costly in terms of the required capital expenditure; but their operating costs can be insignificant as compared to other existing power sources. In many cases, home owners are provided with financial incentives in terms of tax relief or loan subsidies to acquire and install photovoltaic panels at their premises. As a result, photovoltaic panels are spread over in many sparse locations. In order to somehow compensate for the high costs of purchasing and installing solar panels, two approaches have been taken by the industry, namely to improve the efficiency of converting sunlight to electricity and to optimize the operation of photovoltaic panels via utilizing appropriate measurement and control schemes.

Photovoltaic panels are made of either crystalline silicon or thin film. Crystalline silicon panels come in two different types, namely, monocrystalline silicon or multicrystalline silicon. The manufacturing process for the latter is less complicated and so the panels are more affordable, but they are less efficient. Thin film panels come in three different types, namely, cadmium telluride (CdTe), amorphous silicon, or copper-indium-gallium-selenide (CIGS). Thin film panels are the least costly, hence are very popular, but are less efficient as compared to crystalline silicon panels. The efficiency of crystalline silicon panels is in the range of 13-19% as compared to 2-14% for thin film panels [4]. Besides, crystalline silicon panels are smaller, and need less space and shorter wirings.

Typically, each photovoltaic panel is composed of 30-36 photovoltaic cells, each producing 0.5 to 0.6 DC Volts and 1 to 1.5 Watts at 25° C. The cells are connected in series to form a solar module. Solar modules are connected in parallel to form a string, and strings are connected in parallel to form a PV panel, resulting in 15-18 volts and 30-50 Watts per panel [5], [6]. A panel's voltage is determined by the number of modules in each string, and its output current is determined by the number of parallel strings in the panel. Photovoltaic panels need to be tilted to maximize the received irradiance from the sun. The tilt angle depends on the geographical location and on the time of the year, e.g., in Winter, it should be the latitude + 23° while in Summer, it is the latitude – 23° [7].

A DC-AC converter (inverter) is used to convert the DC voltage produced by photovoltaic panels into an AC voltage. This can be done in either three-phase or in single phase, depending on the grid. The objectives of the converter is to convert the output of the solar array to either a sinusoidal voltage at a given frequency, if it is in stand-alone mode, or a sinusoidal current in phase with the grid voltage if it is in grid connected mode.

Although it is possible to utilize a battery bank beside each inverter site to store the excess energy generated by photovoltaic panels, this is neither cost effective, as it requires additional capital and operational expenditures for batteries and their maintenance, nor environmentally friendly as batteries are potentially hazardous for the environment.

1.2 A Brief Primer on Hybrid Mini-Grids (HMGs)

An autonomous mini-grid is defined as an integrated solution that meets the energy needs of a group of consumers, such as a neighbourhood, or a town [8]. In other words, it is a local stand-alone electricity grid. A mini-grid that utilizes different technologies in the supply side is called hybrid mini-grid (HMG). In this thesis, the focus is on HMGs that use photovoltaic panels in their supply side together with the diesel engine-generator sets (gensets) in remote communities. Fig.1.1 illustrates a one-line diagram of such a hybrid mini-grid.

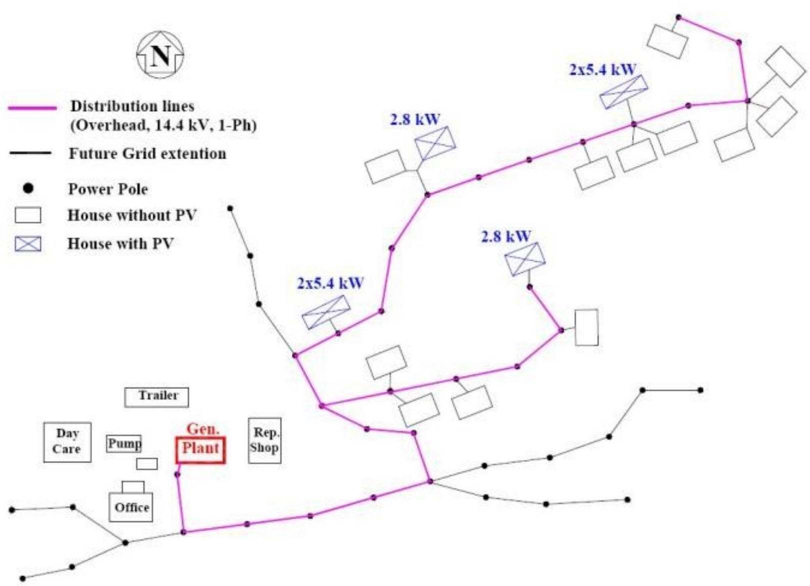

Fig. 1.1- One-line diagram of the photovoltaic hybrid mini grid [9]

In photovoltaic panels, the relationship between sun's irradiance, the temperature, the panel's voltage, and its output current supplied to the grid is nonlinear. In order to get the maximum possible power from photovoltaic panels, a technique called maximum power point tracking (MPPT) is used, which is based on measuring the panels' output voltage and applying an appropriate load to adjust the panels' output current (which the inverter draws) so that the panel's output power is maximized under any given environmental condition. This is shown in Fig. 1.2, where the maximum power corresponds to the knee of the voltage-current curve for different levels of sun's absorbed irradiance.

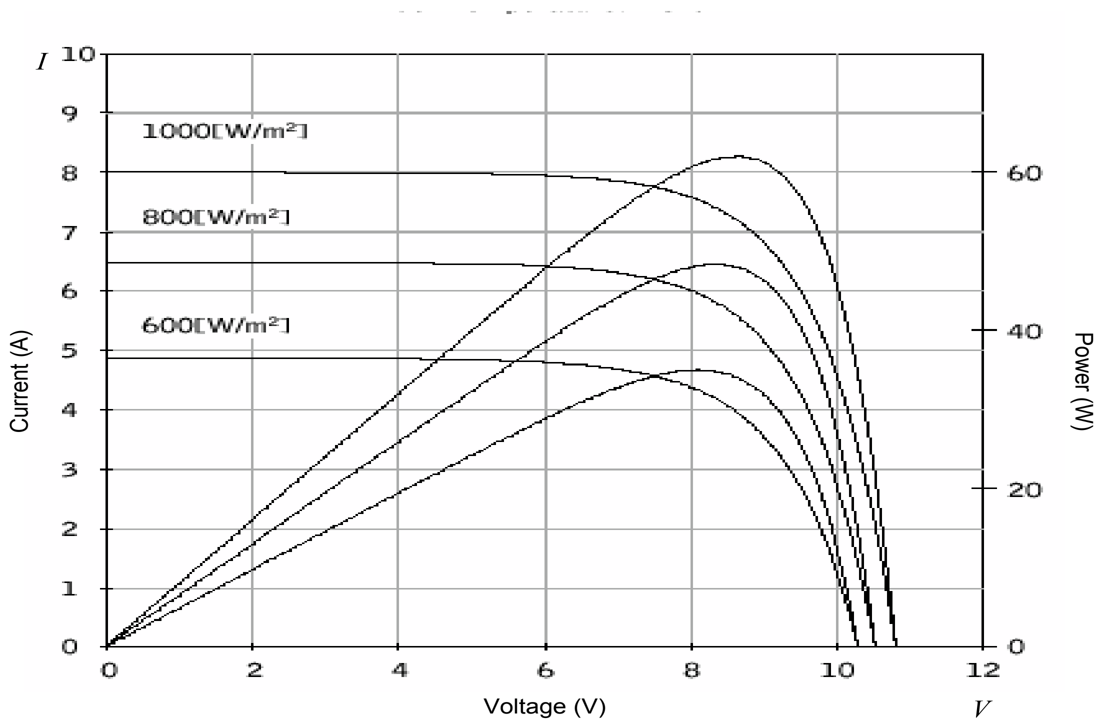

Fig. 1.2- Dependence of the power generated by photovoltaic panels on voltage, current, and absorbed irradiance

An important issue in community type hybrid mini-grids with dispersed photovoltaic panels is overvoltage prevention. Usually in a hybrid mini-grid, either a diesel generator set (genset) or a battery form the grid, establishing the grid frequency which is followed by other sources, such as PV and wind. There are two main methods to control the inverters in a mini-grid. One is called “master-slave” mode, and the other one is called “multi master” mode. The characteristics of each along with their advantages and disadvantages are explained next.

Master-Slave Mode:

In this mode, parallel operation of the inverters is made possible through a master inverter that sets the frequency, and other inverters (called slaves), follow this frequency. In this way, power sharing between inverters has to be managed through a supervisory control center. This master-slave mode of operation requires a reliable and fast communication link between the master unit and each of the salve units. In general, the master-slave mode of operation has the following main characteristics:

1) Simple control algorithms are implanted in inverters.
2) A complex supervisory control center is needed.
3) It may be difficult to expand the system.

Multi Master Mode:

In this mode of operation, the need for reliable and fast communication links is relaxed, as inverters individually decide how much power should be injected into the grid based on locally measured quantities (such as terminal voltage, and frequency) and a droop function for balancing active and reactive power. It is evident that ideally the multi-master inverters should respond to load variations, by increasing or decreasing their injected power proportionally to their rated capacities, what can be set on their droop factors or slopes. As a result, a supervisory control center is tasked to set appropriate parameters such as the no-load frequency and the droop factor of each inverter, meaning that only slow communication links are needed to update these parameters and improve system performance in terms of energy management and power quality. In some cases, a supervisory controller is not used and the grid frequency is not regulated. It varies as the balancing power from the grid forming inverters varies. The up side of this feature is that the grid frequency becomes an indication of the amount of the net active power available in the mini-grid. When the RETs produce more power than the loads' consumption, the frequency tends to increase. Conversely, when there is a shortage of active power in the system, the master battery inverters have to inject more power in the system, which decreases the grid frequency.

Overall, the multi master mode of operation has the following features:

1) More sophisticated control algorithms are implemented in inverters.
2) A simplified supervisory control center is needed.
3) Expanding the system is not technically difficult.

In the sequel, two scenarios of mini grids in remote communities are described in which multi master mode of operation are needed.

Multi master mode of operation can be utilized to operate the inverters in the mini-grid of a remote community. It has been shown in [10] that in low voltage (LV) distribution systems, voltage is related to active power (instead of reactive power). Hence, in order to prevent overvoltage incidents, active power injected by PV inverters needs to be controlled. In doing so, an emerging technique called active power curtailment (APC) is applied, in which, the grid voltage at each PV inverter site is used, rather than the frequency as in master battery inverters, to curtail the amount of power that the respective inverter injects into the grid. In this way, overvoltage incidents are prevented. This is done by adjusting the droop coefficient of each PV inverter in such a way that the injected power is below the MPPT power by an amount that is sufficient for overvoltage prevention. Formula (1) below describes the operation of APC:

$$P_{inv} = P_{MPPT} - m \times (V - V_{cri}) \qquad (1\text{-}1)$$

where P_{inv} is the injected power by the PV inverter, P_{MPPT} is the maximum power that can be supplied by the inverter, m droop coefficient of the inverter which is the slope of the active power versus voltage ($\Delta P/\Delta V$), and V_{cri} is the critical voltage beyond which the injected power should be decreased. The values of V_{cri} and m in (1) is set by the supervisory control center. Note that (1) is not valid when the bus voltage is less than V_{cri}, meaning that the PV inverter would inject maximum power when there is no risk of overvoltage. It has been shown in [10] that adjusting the droop coefficient for each inverter (instead of setting a common droop coefficient for all inverters) can result in a more balanced effort by the PV inverters, in terms of the amount of active power curtailed, for preventing overvoltage occurrences in a radial distribution system with multiple dispersed PV inverters.

In addition to active power curtailment, secondary loads such as electric water heaters (EWHs) are utilized for power balancing and frequency control of mini grids in remote communities [11]. In this way, EWHs are integrated in the demand side (load side) of a mini-grid that is composed of a genset and photovoltaic inverters. In doing so, EWHs that normally operate based on a reference temperature, need to function according to a temperature vs. frequency droop curve. In this manner the reference temperature is set based on the frequency of the grid, and this reference temperature determines how much power should be drawn from the mini grid. In such cases, it is the mission of the supervisory control center to adjust the droop and other relevant parameters of EWHs, so that frequency of the mini grid is controlled and power mismatches can be balanced with controllable demand.

1.3 Why Communication Networks Are Needed for Supervision and Controlling of RETs in HMGs?

Photovoltaic systems and inverters can either be co-located in one place or dispersed. In co-located systems, it is relatively simple to send reference signals for the droop control. This is not so easy in dispersed systems. In this thesis, the case of an autonomous mini-grid that comprises sparsely spread photovoltaic panels and inverters together with a power station that utilizes fossil fuel for its generator is considered. For minimizing the active power curtailment in each location that houses a set of photovoltaic panels and their corresponding inverters, certain values of interest, including the converter's voltage, current, and frequency need to be measured and transmitted to the supervisory control station for analysis so that appropriate control signals can be generated and sent back to the respective units. Subsequently, appropriate commands issued by the supervisory control center need to be transmitted back to each location. The main functions of the supervisory control center can be summarized as receiving (and storing) the information sent by photovoltaic panels and other main system units, processing the received information with a view to monitoring and controlling photovoltaic panels and their respective system units, and sending appropriate commands to each location. Information processing and storage at the supervisory control center is beyond the scope of this thesis. Instead, we focus on design and implementation of a communication network for hybrid mini grids.

When existing communications infrastructures are readily available at each location that houses a set of photovoltaic panels, e.g., in urban areas, the problem is reduced to designing appropriate interfaces and using suitable protocols. However, in remote areas that such infrastructures are scarce and location-dependent, one has to consider what communication media (channel) is available at each location. In other words, the communication network may use different type of communications media (e.g., the telephone network, the Internet, fiber optic links on the power grid (OPGW), etc.) for transferring information and control commands between each location and the supervisory control center. Such a hybrid network that comprises of different communications media (channels) should function seamlessly. In the sequel, a typical scenario for mini grids in remote communities is further elaborated.

In many cases, two or more diesel powered gensets are used to supply the mini-grid [9]. When the demand approaches 85% of the gensets' rated capacity, another genset is added, which might lead the gensets to operate under light load with increased fuel consumption. Each genset, however, is required to operate with a minimum load of 40-50 % of its rated capacity to prevent carbon buildup and premature aging of the engine [12]. This can be enforced by utilizing dump loads, which not only waste the costly fuel and damage the environment, but may not prevent over-voltages, as dump loads are usually located close to the gensets. Alternatively, secondary (lower priority) controllable loads can be used, which does not involve wasting energy [11]. Nevertheless, utilizing renewable sources of energy such as photovoltaic panels in the supply chain of the mini-grids can potentially mitigate the above mentioned problem by providing the grid with the needed extra capacity at appropriate times, e.g., at peak hours. In this way, the need for more gensets is delayed until the demand for additional power reaches a certain level that would not require dump loads. In essence, although employing photovoltaic panels and their associated systems causes a reduction in the output power of the genset, and as a result, in less fuel consumption, however, unfortunately, this is not proportional to the decrease in active power produced by the genset, since the efficiency of the diesel gensets, in kW/liter, usually increases with the generated/output power. As stated earlier, it is very desirable to apply active power curtailment to each inverter by adjusting its droop coefficient individually to prevent overvoltage occurrences while sharing the power curtailment effort among all PV inverters. Moreover, transmitting appropriate commands to manage controllable loads [11] provides the opportunity to react to local voltage and frequency differently depending on the time of the day and configuration of the system.

Finally, another important fact is that renewable sources of energy are intermittent and fluctuating. Introducing such uncertainties could cause voltage rises and revere power flows in the grid that may lead to genset and inverter trippings. Such instances can be avoided by adding appropriate monitoring and control to the grid, so that their undesirable effects can be reduced to acceptable levels. From the above, it is evident that there is a need for a communications network for monitoring and control in a hybrid mini grid. In what follows, the required features of such a communications network are presented.

1.4 Required Features in Terms of Functional, Operational, and Technical Specifications

Below is a list of features identified by the Ontario Smart Grid Forum [8] regarding the communication requirements of the smart grid:

1. The communications network should support a two-way flow of information at the required data rate between the supervisory control center and each inverter.
2. The communications network should accommodate different devices and technologies offered by various suppliers.
3. The communications network should be based on open standards so that the risk of stranded technologies is minimized, and various devices could be deployed.
4. The communications network should use standardized communications protocols.
5. The communications network should be fast deployable, robust, and scalable.

1.5 Problem Statement

The problem is to design a cost-effective communications network for monitoring and control of RETs in the form of photovoltaic power generating units in hybrid mini grids. In doing so, two scenarios are considered: the case of a remote community with sparsely spread units and relatively long distances (a few kilometers) between each unit and the supervisory control center, and the case of a suburban area where the units are concentrated within a relatively small area and the distance between each unit and the supervisory control center is less than a few hundred meters. The following assumptions are taken into account:

1. The power generating RET grid consists of *N* PV sites and one supervisory / control center.
2. The HMG is not connected to other national or regional grids, and is not affected by them.
3. Monitoring and control of PV sites can be done by using slow communications as stated by the IEA-PVPS Task 11 [13]. This means that the supervisory control center expects to receive measured values of interest (e.g., voltage, and current) from each PV site at intervals of 5 seconds or less.
4. The distance between the supervisory control center and the farthest PV site in the remote community (Scenario 1) is in the order of few (less than 10) kilometers [14].
5. The distance between the supervisory control center and the farthest PV site in the suburban area (Scenario 2) is below 100 meters [10].
6. The designed communication network is deployed at laboratory environment to demonstrate the design principles and to measure its performance.
7. The cost-effectiveness of the proposed design means that only readily available technologies, systems, units, and modules should be utilized in the communications network.
8. No battery bank for storing of unused electricity in the grid is considered with a view to reducing the costs and complexity of HMGs.
9. The capital expenditure for implementing the communications network (including the data acquisition system, network interfaces, local cables, and other communications subsystems) should not exceed $2000.00 per PV site.

10. The control of PV sites by the supervisory control center is done by adjusting each PV's droop parameters based on received measurements of other local quantities. However, the manner in which measured values of interest are used to derive control commands and signals will not be considered in this thesis, as it is beyond its scope.
11. Security issues are beyond the scope of this thesis.

1.6 Contributions of this Thesis and Its Outline

A framework for designing and dimensioning a communications network for supervision and control of electricity generating units and controllable loads in hybrid mini grids as well as for choosing the network's components and interfaces (including the data acquisition systems, modems, network hubs and switches, communications media and channels, etc.) is presented. In this framework, standard technologies and readily available communications units and subsystems are chosen with a view to satisfying the requirements and assumptions that were stated earlier. In doing so, the hardware components needed for implementing such a network are identified, and various software pieces are written to integrate all elements of the network. A set of performance measures that are normally used to assess the performance of data communications networks is identified, and their values are obtained via extensive tests.

The rest of this thesis is organized as follows. Chapter 2 is a review of relevant literature, and a description of each existing solution's strengths and weaknesses. In Chapter 3, an overview of the proposed approach is presented, followed by Chapter 4 where its details are explained. Chapter 5 contains quantitative assessments of the proposed framework, followed by conclusions and future work in Chapter 6.

CHAPTER 2

LITERATURE REVIEW

The literature on communications networks for electricity grids is mainly focused on tailoring existing communications media for either of the following two different applications. The first application is the one used by the electricity distribution system for management and control of electricity grids or introducing new services on the electricity distribution network, such as two-way automatic meter reading (AMR), outage detection, demand side management, power quality management, etc. The second one covers in-home applications, such as broadband surfing, television over the Internet, online gaming, home security / monitoring, wireless range extension, etc. [15]. An ideal communications media for the electricity grid is the electricity grid itself, where data pertaining to the supply or consumption of electricity can be transferred from one point (the source) to the other (the destination) by utilizing the metal conductor that also transports electric energy. The technique is called power line carrier or power line communication (PLC) and has already been used by electric utilities for load control and remote meter reading. However, existing PLC systems seem to be insufficient or inappropriate for the objective of this thesis, which requires more frequent message passing (at least one message per 5 seconds for the objectives of this thesis as compared to infrequent load control at peak consumption hours, and for meter reading every 15 minutes). In what follows, a brief review of promising and relevant cases that are reported in the literature is presented.

In [16], an assessment of communication methods for smart electricity metering in the U.K. is presented, where wired communications (i.e., power line communication) and different variants of wireless communication (i.e., low power wireless, ZigBee (IEEE 802.15.4), Z-Wave, and mesh networks) are described and compared. The focus in [16] is on “the last mile” of the communication network connected to the metering device, and it is shown that possible interference from consumer products operating in unlicensed frequency bands renders the use of wireless links for this purpose problematic. It concludes the PLC can be a suitable candidate for communicating with metering devices, provided that it can operate in relatively low bandwidth channels in the sub 100 kHz region of the spectrum, and robust coding techniques are used. It is evident from the conclusions in [16] that even for meter reading (whose requirements are far below those of this thesis), existing PLCs are problematic and need to undergo further developments, entailing significant costs. In [17], the use of narrow band power line communication systems for long haul networking is shown to suffer from serious reliability and throughput issues, and a scheme is proposed to cover short haul (a few hundred meters) communications via power line or wireless networks. In [18], a scheme is proposed to use broadband power line communication (BPL) for meter reading every 15 minutes for distances up to 100 meters. In [19], an orthogonal-frequency-division-multiplexing access (OFDMA)-based scheme for low voltage power line communication systems is proposed and emulated in the laboratory environment, and is claimed that it is suitable for smart meter reading, but no coverage range (distance) is mentioned. In [20], it is shown that existing PLC modems developed for domestic applications may not be suitable for transmitting information in industrial applications that require a reach of few hundred meters, and it is proposed that using pulse width modulation (PWM) may be useful in such applications. Again, this needs further developments, entailing significant costs. Since the emphasis in [16]-[20] is on the last mile of the communication network, they are not applicable to the scope of this thesis, which is the establishment of a wide area network encompassing a limited number of PV sites and for more frequent measurements (5 seconds in this thesis versus 15 minutes for smart metering and smart power consumption in [18].

In [21]-[23], communication networks that are suitable for power quality monitoring systems are presented. Power quality monitoring involves measurements of up to 40 harmonics of the voltage waveform, which generates significant amount of data that need to be transmitted via the communication network. This entails very high data rates in the network, which is far above the data rate of one set of data every 5 seconds for the application of this thesis. It is evident that network requirements for power quality monitoring are fundamentally different from those for actively controlled RETs, meaning that a network that is appropriate for the former is not necessarily suitable or appropriate for the latter.

In [24], the need for providing security in communication network that are used as part of power system is described and its implications are elaborated. Security concerns are most relevant when public communication networks are used, where hacking, eavesdropping, denial-of-service attacks, etc. are expected. In order to address this important point, as it will be shown in Chapters 3 and 4, the proposed design is based on dedicated point-to-point distributed Ethernet connections, which may not be accessible to the public (hence, such links are potentially more immune to security threats that are prevalent in public data networks. Moreover, existing and readily available tools, such as firewalls, or intrusion detection systems can be utilized to improve network security even further.

Recently, there has been much attention to developing new products and services by utilizing in-building electricity network for in-home applications, such as broadband surfing, online gaming, home security / monitoring, wireless range extension, etc. [15]. The technique is called broadband PLC, and the objective for such efforts is to use the home's electricity grid as a communications media, which is already available in all corners, hence providing coverage to blind spots in wireless local area networks, or removing the need for new wideband cabling in the building. Since in such cases the distances are limited (below 100 meters), such products are not useable for monitoring and control of hybrid mini-grids that span much larger distances (in the order of a few kilometers). Broadband PLC has also been used for last mile access [25] in some cases that customers in one area are served by a common medium-voltage (MV) to low-voltage (LV) transformer; which is the normal practice in some European countries, but not in North America.

PLC suffers from signal attenuation caused by transformers and other devices in the frequency spectrum that is suitable for communications purposes. This results in significant reductions in the data rate for long distances, meaning that PLCs are suitable for a few isolated links, where each link is physically separate and independent of other links. Clearly, this is not the case for hybrid mini grids, where the distribution grid feeds multiple customers situated one after the other, and the link for each customer is partially shared by other customers.

As stated earlier, PLC has been used by electric utilities for load control and remote meter reading or for data transmission. The technique is called narrow-band PLC, and it requires deployment of repeaters and couplers. As such, its use requires the additional capital expenditure and their corresponding operations and maintenance costs [26]. Narrow-band PLC is classified into two categories: 1) Low data rate narrowband PLC that employs a single carrier and the transmission rate is around a few kbps, used by electric utilities for remote meter reading [26], and 2) High data rate narrowband PLC that employs multi carriers and its transmission rate is up to 500 kbps [25], [26]. For narrowband PLC, the technologies used are carrier frequency systems (CFS) and ripple carrier signalling (RCS) [27]. CFS is used in high-voltage (HV) segments of the grid in the frequency range of 15–500 kHz; and RCS is mainly used at medium-voltage (MV) and low-voltage (LV) segments of the grid in the frequency range below 3 kHz [27]. In contrast, broadband PLC utilizes frequencies in the range of 1-34 MHz, resulting in the data transfer rate in the order of 4-20 Mbps [25].

In [27]-[28], a hybrid wireless-broadband power line is proposed for rural areas. A wireless local area network (IEEE 802.11 a/b/g) is used to transmit/receive data at the customer site which bypasses the medium voltage (MV) to low voltage (LV) transformer that serves the customer. In this way, severe signal attenuation in high data rates caused by the transformer is avoided. On the MV segment, a wireless transceiver together with a broadband PLC is used. In order to overcome the coverage (distance) limitation of the broadband PLC, at regular intervals of approximately 1 km, one repeater is employed, which regenerates the attenuated input information on its output. Although this scheme solves the problem of limited coverage by broadband PLCs, but it requires that all repeaters function properly at all times in the rough terrain that the medium voltage (MV) grid spans. As an example, if the operational availability of a repeater is 99.9%, a cascade of 110 repeaters used in [16] would have an operational availability of $(0.999)^{110}$ = 89.6%, meaning that in each day, the network is down for almost 2.5 hours. Clearly this is unacceptable for mission critical applications such as grid monitoring and control; and requires frequent inspection and repair, which involves significant operations and maintenance costs in addition to the initial capital expenditure. Even for shorter distances of a few kilometers, all repeaters should operate properly at all times, resulting in significant operations and maintenance costs that stem from the need for frequent inspections by technical staff.

The use of PLC and its potential undesirable side effects are discussed in [25] by the Australian Communications Authority, where the risks of interference on other radio communications services, caused by the use of unshielded power lines in broadband PLCs are discussed. Impedance mismatching of devices that are connected to the network can create nulls at particular frequencies, which will prevent those frequencies to be used for communications [25]. The locations and the depths of those nulls depend on where a device is plugged into the network and on other devices that are connected to the network [25]. In order to overcome the above difficulties, the broadband PLC uses a number of carriers in parallel, so that the data is spread over a wider range of frequencies and allowing individual carriers to turn on and off with less impact on the overall data rate [25]. This causes undesirable interference on other radio communications services licensed in the vicinity of the broadband PLC modems, which is inherent in the use of orthogonal frequency division multiplexing scheme as described above. If narrowband

PLC is utilized, then the risk of undesirable emissions is low, as the attenuation of the signal will be low due to the fact that utilized frequency is in the range of 9-500 kHz, resulting in fewer nulls in the network [25], but then the data rate is severely reduced. This is because of the fact that since the communications media (the distribution grid) is shared by all PV sites, existing narrow band PLC's data rate of a few kbps needs to be divided by the total number of PV sites to obtain the data rate for each PV site. For a typical case of 30 PV sites, the data rate for each PV site is clearly well below the required data rate.

In [29], power line communication is proposed to meet the networking requirements of energy management in the smart grid and automation systems, and an overview of the requirements for power line communication to become an enabler for advanced control and measurement systems is presented in [30]. The above mentioned requirements include the need to access thousands of nodes within 5 seconds, and the strict need for real time and reliable communications for switching between electric utilities, and for maintaining grid stability. As can be seen, these requirements are quite different from the networking requirements of a hybrid mini grid, both quantitatively and qualitatively. While the proposed solution in [29] (which is to use narrowband PLCs supplemented with various techniques described in the sequel to overcome the inherent shortcomings of narrowband PLCs) is useful and interesting for some applications, using power line communication for data transmission introduces ripples and glitches on the measured values, which may cause undesirable consequences. In [29], it is stated that using a single carrier (instead of multi carriers) together with flooding of messages is a more suitable scheme for large PLC networks. Flooding is an algorithm for transmitting a message from a source to its destination by sending it through every possible link without any distinction between possible different routes. It reports that because of the time varying communication channel in PLCs due to electrical load variations, all network nodes need to be constantly monitored. Besides, to improve network availability in the case of node failures, redundant communication paths are needed (meaning that each node should at least have two electricity feeds) [29]. The proposed scheme involves complicated and numerous changes in existing access techniques, and is more suitable to cases that involves mainly one-way communications, or simple sensors and infrequent commands such as airfield ground lighting systems. Besides, its cost seems to be prohibitive due to the fact that various complicated modifications in existing schemes are needed to adapt the proposed solution to each environment, meaning that its customer base are limited and the development and overhead costs are divided between few customers as compared to readily available modules whose customer base is extensive and the development and overhead costs per user are insignificant.

In [16] it is reported that PLC can be used for remote meter reading, but it has to be robust against undesirable or unpredictable effects in the grid and the bandwidth has to be low, to reduce the risk of interference from in-house equipment that operates in the unlicensed frequency bands (e.g., WiFi transceivers, WiMax transceivers, wireless medical devices, wireless monitoring devices, etc.). It also states that broadband PLCs could cause harmful interference to other communications networks and systems, and the coverage distance is quite limited as there is significant signal attenuation. On the other hand, narrowband PLCs do not have the high data rates that are needed in many applications. It proposes to use a modified orthogonal frequency division multiplexing to achieve a better signal to noise ratio and higher data rates by using the entire available frequency spectrum. Again, similar to the case for [29], the cost per user is higher than that of readily available modules and systems that benefit from a large existing customer base.

In [17], the results of field-trial measurements of PLCs in Victoria, Australia are reported. It is mentioned that narrowband PLC on the low voltage grid employing fixed carrier frequencies suffer from serious reliability and throughput issues, and consequently it is suggested to use the orthogonal frequency division multiple access (OFDMA) technique to overcome the above mentioned problems. Their proposed scheme was simulated, but was not implemented in practice. The report emphasizes that narrowband PLC is cost effective, at the expense of reliability and throughput. It further states that the most commonly used PLCs utilize single carrier systems in which frequency shift keying (FSK) and binary phase shift keying (BPSK) modulation techniques are employed, which are suitable for time-invariant single channels. The communications media in PLC systems can be viewed as a single channel that encompassed the available frequency band, or can be divided into multiple channels each using a portion of the available frequency band. Moreover, although a communication channel in PLCs between two points vary with time due to external effects (such as electrical load variations, interference from nearby transmitting devices, etc.), for simplicity, it is sometimes assumed to be time-invariant. This, however, may not be the case in practice for PLC channels due to electrical load variations and other unpredictable / undesirable events.

Wireless networks have also been considered as an alternative. In [31], it is stated that a communications network that serves the power grid should cover all nodes in the latter. This is true for any solution that mandates homogeneous media in the network, such as what they considered in [31]. However, this is not the case for the proposed solution in this thesis. This may require deployment and installation of additional repeaters / base stations that can be costly in terms of capital expenditure as well as operating costs. It is also mentioned that wireless cellular networks can be utilized instead of point-to-point wireless links. Today, wireless cellular networks are widely used in many locations, but this may not be the case in remote locations with sparsely spread and small populations, where the return on capital expenditure for deployment of wireless cellular networks may be very discouraging. Besides, quality of service in wireless links may deteriorate with weather conditions [32] as wireless signals attenuate heavily when humidity is high.

In [33], a wireless sensor network is considered in smart grids in which wireless sensors are deployed at critical nodes to monitor the status of vital equipment. It is mentioned that such networks are flexible, and can be rapidly deployed, but continuously providing power to such wireless sensors may be problematic. This is because of the fact that typically, wireless sensor networks do not have power supplies in their nodes (to reduce costs), or in this case, the respective power supply would be very expensive, meaning that if electricity to nodes are supplied by the power grid, it entails addition costs that may not be acceptable. The network also suffers from harmful interference caused by other wireless devices and networks.

In [34], various potentially useful technologies such as wireless local area network (LAN) based on IEEE 802.11 (also known as WiFi), wireless metropolitan area networks (MAN) based on IEEE 802.16 (also known as WiMAX), and wireless personal area networks (WPAN) based on 802.15.4 (also known as ZigBee) are reviewed. Although wireless technologies may have significant benefits, such as rapid deployment [34], for the case of power systems in particular, conventional wireless technologies may suffer from low data rates, harmful interference, and security issues.

Considering the above, and as summarized in Table 2.1, existing solutions and approaches in the literature are either insufficient or inappropriate for the objective of this thesis, which is the need for a reliable, efficient, and cost effective communications network in hybrid mini grids that stems from the necessity for active power curtailment in renewable energy technologies to avoid overvoltage instances in the grid. Moreover, the communication network can be used to update the droop parameters of renewable sources of electricity [10] and manage controllable loads [11] so that they can react to local voltage and frequency differently depending on the time of the day and configuration of the system. Besides, a comprehensive framework for communications networks for electricity grids that covers not only the communications media, but also includes network software as well is very desirable and is still under-developed. In Chapters 3 and 4, a framework for networking that can accommodate different communications media that may be available between inverter sites and the supervisory control center is developed. Specifically, since Internet does not suffer from any of the stated shortcomings for existing PLC and wireless technologies, the proposed framework is implemented when Internet connections are available at inverter sites and at the supervisory control center, and the results are presented in Chapter 5.

Table 2.1 - A Comparison of existing solutions proposed in the literature for communication networks for electricity grids

	Aggregate Data Rate	Coverage	Causes Harmful Interference	Security Issues	Cost	Reliability
Narrowband PLC	Low (a few kbps)	Limited, needs repeaters	Yes	Potentially Secure	High with repeaters	Low with repeaters
Broadband PLC	High (a few Mbps)	Limited, needs repeaters	Yes	Potentially Secure	High with repeaters	Low with repeaters
IEEE 802.11 (WiFi)	High (a few Mbps)	Limited (<100 meters)	No	Potentially unsecure	Low	Relatively High
IEEE 802.16 (WiMax)	High (a few Mbps)	Extensive (a few km)	No	Potentially unsecure	Potentially High	Relatively High
IEEE 802.15.4 (ZigBee)	High (a few Mbps)	Limited (<100 meters)	No	Potentially unsecure	Low	Relatively High

CHAPTER 3

THE PROPOSED NETWORKING APPROACH: THE BIG PICTURE

3.1 Overview

The proposed approach is based on obtaining sampled values of interest, e.g., measured RMS voltages, from any given inverter site and providing such values to the supervisory control center. The supervisory control center is tasked with receiving relevant information from all inverter sites and feed them with pertinent control commands so that each site performs efficiently and reliably. Such information and control are exchanged via any existing communications media between the two locations by utilizing Ethernet networking technologies that cover all network layers from the application layer to the physical layer.

It also employs polling at the supervisory control center to obtain the measured values from each inverter singularly and in circular order. Polling is a process in which the supervisory control center at regular intervals requests each inverter site to provide it with its information. This would guarantee fairness in communicating with all inverters in a timely manner. The proposed framework is capable of sending inverter settings from the supervisory control center to the respective inverter, updating the droop parameters of renewable sources of electricity [10], and transmitting appropriate commands to manage controllable loads [11] so that they can react to local voltage and frequency differently depending on the time of the day and configuration of the system. As such, the network is half-duplex, meaning that the system provides communication in both directions, but only one direction at a time, which is needed in this application. In doing so, the emphasis is on developing a cost effective approach by utilizing existing and readily available hardware modules and system software, but developing vital missing software elements needed for an operational system in this thesis.

Considering the nature of required communications between each inverter and the supervisory control center, the proposed network topology is hub-and-spokes, as shown in Fig. 3.1 below. The hub is the supervisory control center and each inverter communicates only with the hub through a communication media (spoke) between the two. In the hub-and-spokes network topology, communications between entities are limited to those between the hub and each entity that is connected to the hub via the corresponding spoke. This simplifies the network topology by removing unnecessary links between inverter sites, and considering only the links between the hub and inverter sites.

The proposed framework can work with any communications media between an inverter and the supervisory control center. The media does not need to be the same and uniform for all inverters, provided that for each media, appropriate interfaces are used at both ends. Moreover, the media's length is not a limiting factor, provided that in each case, the respective interface can drive the media for its entire length.

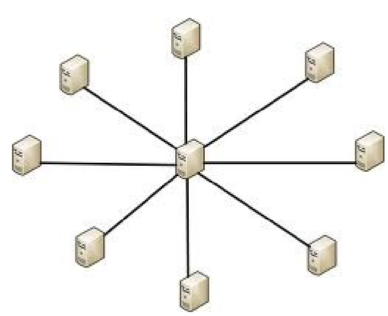

Fig. 3.1 – The proposed network topology

Ethernet, which is a packet switching technology, is widely used for many diverse applications, and hence is very cost effective. Although the term “Ethernet” is used to denote a local area network (LAN), and hence one may think that its reach is limited to a few hundred meters, but as will be shown in this thesis (Chapter 5 where the supervisory control center (the hub) can be located practically anywhere), “Ethernet technologies” can be properly utilized in such a way that the physical reach of the network is arbitrarily extended. In this way, one benefits from inexpensive and readily available technologies. This is in contrast to developing new technologies that would be exclusively used for establishing a communications network that is useful for hybrid mini grid applications. Ethernet has been proposed to be utilized in smart grids [35] due to its efficiency and cost-effectiveness (in terms of its required capital expenditure as well as its operational costs) as compared to legacy alternatives such as the traditional circuit switching or time division multiplexing, its capability to handle diverse services such as voice, data, or video services, and its easy plug-and-play mode of operation. One cannot ignore the fact the IP-based networks that utilize different techniques, such as tunneling and gateway solutions are increasingly being considered for satisfying the requirements of smart grids [36]. Tunneling is a mechanism to establish a virtual pipe (connection) between two points through which information can be exchanged. The important feature in tunneling is that the two end points do not have to use the same protocol as the one that is normally employed by the connecting pipe. This is vital in the scheme proposed in this thesis, as the two end points are Ethernet segments, while the pipe is the IP-based Internet. Another approach for information exchange between two points via a network that utilizes a different protocol than the two end points is to utilize a gateway for protocol conversion.

Tunneling is more cost effective when the additional hardware and software cost of gateway is not justified. In this thesis, Ethernet networking together with the tunneling scheme is employed for data transport, as Ethernet-based hardware modules and interfaces are readily available, and the networking requirements of hybrid mini grids can be satisfied efficiently and cost effectively. In this framework, each node (the supervisory control center or any inverter) is an Ethernet segment, meaning that an Ethernet interface connects each node to its respective communications media. The reach of an Ethernet segment is about 100 meters, which far exceeds the distance between each data acquisition system and its interface to the network (e.g., its modem) located nearby. The reach of Ethernet segments can be properly extended by using appropriate modems or interfaces (such as connection to the Internet).

The rate of data transmission for each link depends on the respective communications media. Since the application of interest in this thesis only needs slow communications, most of the existing communications media and technologies can be utilized in the proposed framework.

3.2 System Components

The proposed framework consists of the following components.

1. A voltage sensor for each phase at each inverter site to measure the inverter's output voltage.
2. A current sensor for each phase at each inverter site to measure the inverter's output current.

3. A data acquisition system with an Ethernet port at each inverter site.

4. An Ethernet interface to the communications media at each inverter site.

5. A communications media (link) from each inverter site to the supervisory control center. This link may be a dedicated one, or a shared one where other services / applications may be accommodated depending on the latter's requirement.

6. An Ethernet interface to the communications media at the supervisory control center. The link(s) from the supervisory control center to the inverter site(s) can be individual to each inverter site, meaning *N* individual links to the supervisory control center as shown in Fig. 3.2, or can be aggregated to a single link by utilizing the Internet or through the use of the point-to-multipoint service in a wide area network as shown in Fig. 3.3.

In this thesis, a scheme in which the links between the inverter sites and the supervisory control center are aggregated into a single link (the single link scheme) is implemented (Fig. 3.3) by utilizing the Internet, the details of which are explained in Chapter 4.

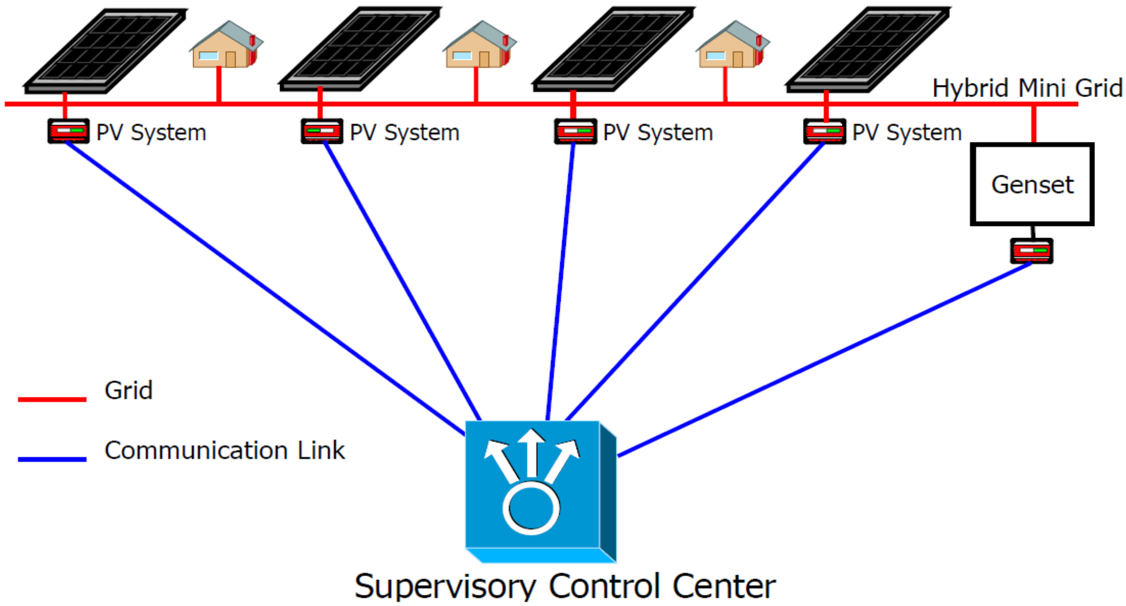

Fig. 3.2 – Communications network with multi-links to the supervisory control center.

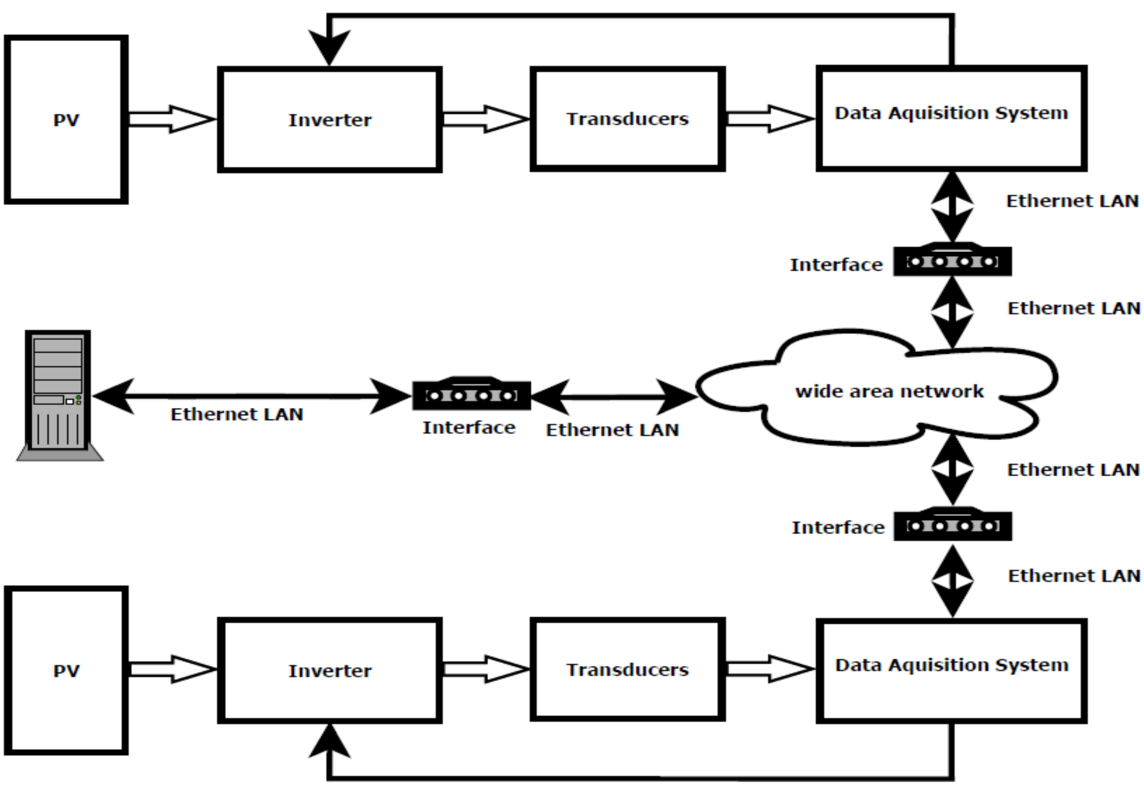

Fig. 3.3 – Communications network with a single link to the supervisory control center.

CHAPTER 4

THE PROPOSED NETWORKING APPROACH: THE DETAILS

4.1 Information Flow

Information flow in the proposed network is two ways, i.e., from each inverter to the supervisory control center, and from the supervisory control center to each inverter, but one at a time. In other words, half-duplex links are utilized. Moreover, since there is no need for any information flow between the inverters, the hub-and-spokes network topology is chosen in this thesis. Because of the nature of the application, the amount of information originating from each inverter and terminating at the supervisory control center is much more than the adjustments / settings sent from the supervisory control center to each inverter. In other words, the traffic is bi-directional but not symmetric. Asymmetric traffic, which is a fact in this case as well as in many other cases, affects network engineering and dimensioning when the network is expected to carry significant amounts of information, e.g., for power quality management, but not in this case.

4.2 The Hardware

In this section, starting from the inverter towards the supervisory control center, various hardware modules that are used in the proposed framework are presented and explained.

4.2.1 Sensors

Two types of transducers are used to facilitate sampling and measuring the values of interest at each inverter site.

4.2.1.1 Voltage Transducer

A voltage transducer that works based on the Hall-effect is used to isolate and scale down the inverter's output voltage so that it would not exceed the upper bound of input voltage to the data acquisition system. The Hall-effect is an electromagnetic phenomenon where a voltage proportional to the current that passes through the primary circuit of the transducer is generated in the secondary circuit of that transducer. The maximum input current for a bounded voltage value to be measured (and hence the maximum output voltage of the transducer) is set by an external resistor R connected in series with the primary circuit of the transducer. In this thesis, the voltage transducer model LV 20-P made by LEM is used at the inverter site, and the measured voltage at the secondary circuit of the transducer is scaled and isolated from the rest of electronic circuitry via operational amplifiers as shown in Fig. 4.1. The combination of the voltage transducer and its associated circuitry is called the voltage sensor in this thesis.

4.2.1.2 Current Transducer

A current transducer is also used at each inverter site to measure the current supplied to the grid by the inverter. This transducer also utilizes the Hall-effect for measuring the current without affecting the supplied current. A current carrying conductor (the primary circuit of the transducer) generates an electromagnetic field, which in turn is used to generate a current at the secondary circuit of the transducer. This current is passed through a resistor, whose voltage is proportional to the current passing through the primary circuit of the transducer. In this way, the current that is supplied to the grid is measured by way of a voltage that is proportional to the primary circuit's current. In this thesis, the current transducer model LA 55-P made by LEM is used at the inverter site, and the measured voltage at the secondary circuit of the transducer is scaled and isolated from the rest of electronic circuitry via operational amplifiers as shown in Fig. 4.1. Their associated circuitry is the same as the one shown in Fig. 4.1, except that as per the manufacture's recommendation, the value of R2 in the circuitry for the current transducer is 100 Ohms, instead of 150 Ohms in the circuitry for the voltage transducer. The combination of the current transducer and its associated circuitry is called the current sensor in this thesis.

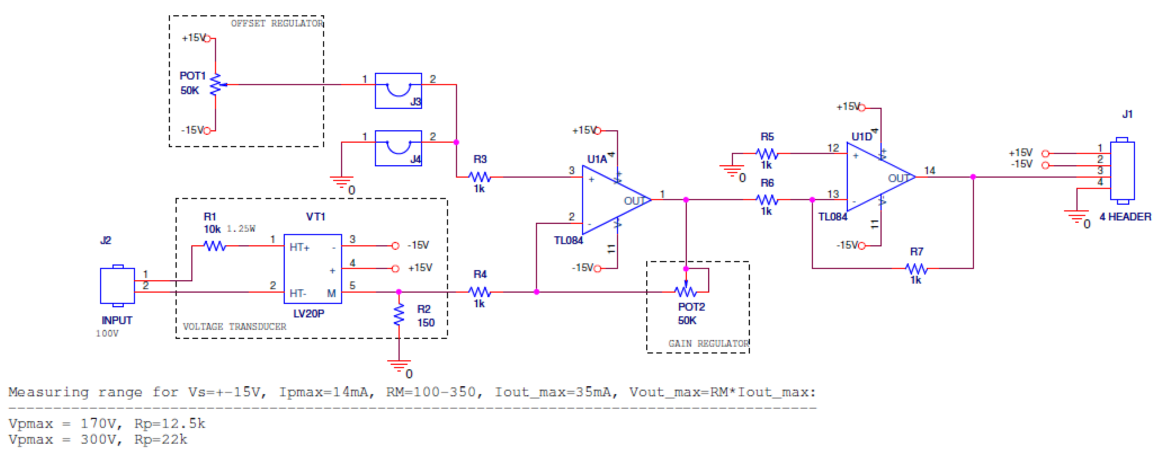

Fig. 4.1 – The voltage transducer and its associated circuitry

4.2.2 Data Acquisition System

The measured instantaneous voltage and current values at each inverter site need to be preprocessed to obtain values that are of interest at the supervisory control center, e.g., RMS values, and to reduce the amount of data to be transmitted from each inverter to the supervisory control center. This is typically done by employing a data acquisition system, which takes samples of the measured values at regular instances, and performs appropriate calculations on the sampled values to obtain RMS values.

In each data acquisition system, there exist three main modules, namely, an analog to digital converter that converts sampled analog values to digital ones that can be used for calculations, a processor module that performs calculations on the digital samples, and a digital to analog converter that converts digital values to analog ones. The analog to digital converter is typically characterized by the number of bits in its digital output. A 12 bit analog to digital converter has a resolution of 1 part in 4,096 bits, which for 250 Volts translates into 61 mV. This is more than adequate for the purposes of this thesis, but is typical for analog to digital converters. The processor module employs a CPU and the memory needed for its efficient operation. There are many choices for the CPU in a data acquisition system, and more powerful CPUs mean more expensive systems. In choosing a data acquisition system, one has to take into account the required processing power for existing and future applications on the system with a view to maintaining the cost within the available budget.

In addition to the above, in the proposed framework, the data acquisition system must have an Ethernet port that is used to exchange information between the inverter site and the supervisory control center. Without this Ethernet port, data transmission between the source and the destination would become complicated, tailor made, and expensive. In this thesis, the data acquisition system consists of an LR-F2812 DAQ daughter card made by Link Research and an F2812 eZdsp^{TM} board made by Spectrum Digital. The CPU in the F2812eZdsp^{TM} board is an TMS320F2812 made by Texas Instrument. Fig. 4.2 shows the block diagram of the F2812 eZdsp^{TM} board.

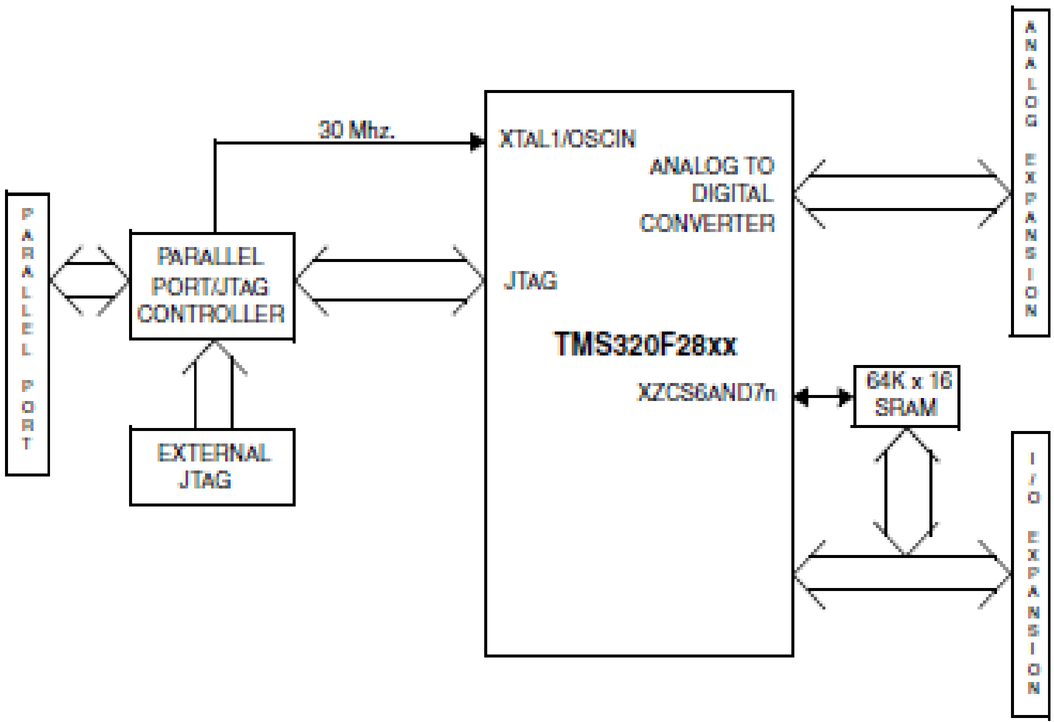

Fig. 4.2 – Block diagram of eZdsp F2812 [37]

In order to program the data acquisition systems in all inverter sites, there is also a need for an eZdsp^{TM}DSP development system made by Spectrum Digital, Inc. This development system is a software package that runs on a personal computer that is connected to the respective data acquisition system at the inverter site via a RS232 cable. The development system is needed to program and debug the data acquisition system, and is removed from the inverter site after the data acquisition system is up and running at each inverter site. The LR-F2812 DAQ is a 14-bit data acquisition for multi-phase power system applications. The board contains four 14-bit analog to digital converters and eight 14-bit digital to analog converters. Each analog to digital converter can operate at up to 100,000 samples per second sampling rate. The board is designed to support a maximum of 8 analog to digital converters and 8 digital to analog converters via expansion boards.

4.2.3 Sampling Rate

Measured instantaneous values need to be sampled at regular intervals, and sampled values are used for further processing. Nyquist theorem states that the sampling rate should be at least twice the highest frequency component of interest, beyond which there is no useful information. As such, the sampling rate depend on the application, for example in power quality management, sampling rate is very high, resulting in large amounts of sampled values per second, which require very high speed communication links. For preventing overvoltage incidents via active power curtailment, and for demand side management via adjusting droop parameters sent to controllable loads, which are of interest in this thesis, the sampling rate is set at 24 samples per line cycle, which is sufficient to capture harmful overvoltage incidents in a timely manner. As will be shown later in Section 4.4.1.1, this sampling rate of 24 samples per line cycle can accommodate extreme fluctuations in the grid's frequency with minimal impact on the accuracy of calculated RMS values.

4.2.4 Ethernet Interface

Depending on the communications media, which is discussed in the sequel, there may be a need for an Ethernet interface to connect the Ethernet segment at the inverter site to the communications media. The same is true for the Ethernet segment at the supervisory control center. As discussed in Chapter 2, neither existing PLC nor wireless technologies are suitable choices for the communication media that is needed in general to connect an inverter site to the supervisory control center. As an alternative, in this thesis, the proposed framework is implemented in an Internet environment, i.e., the communications media is the Internet. In such a case, the need for Ethernet interfaces vanishes. However, when other types of communications media is used, such as the telephone network, fiber optic cables, or power line carriers when distances are below their practical range, a suitable modem and other ancillary modules and units are needed. Such interfaces depend on the particular communications media, and should be selected as such. Fig 4.3 shows the LR-F2812 DAQ daughter card along with the Ethernet port made by Link Research on top of the F2812 eZdsp™ board made by Spectrum Digital. Fig 4.4 displays the voltage sensors and current sensors, and Fig 4.5 shows the voltage source inverter alongside the inductors and capacitors employed to filter out the harmonics.

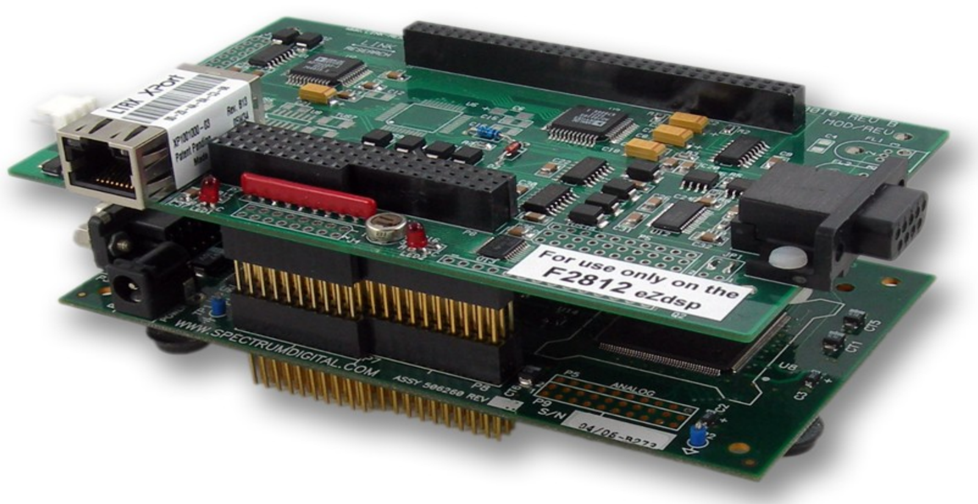

Fig. 4.3 – LR-F2812 DAQ daughter card with the Ethernet port on top of the F2812 eZdsp™ board

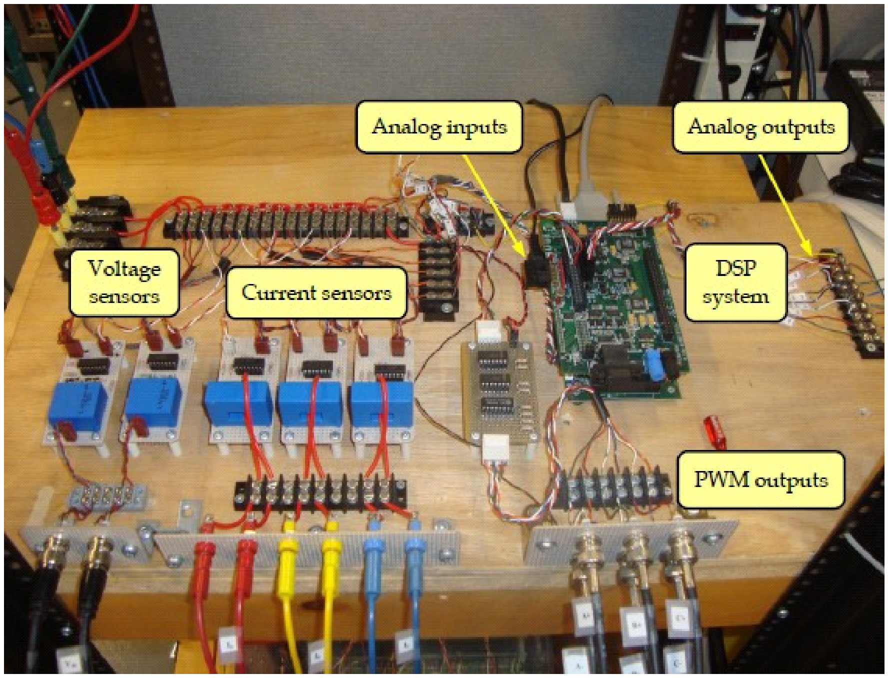

Fig. 4.4 – Voltage sensors and current sensors utilized on the system setup

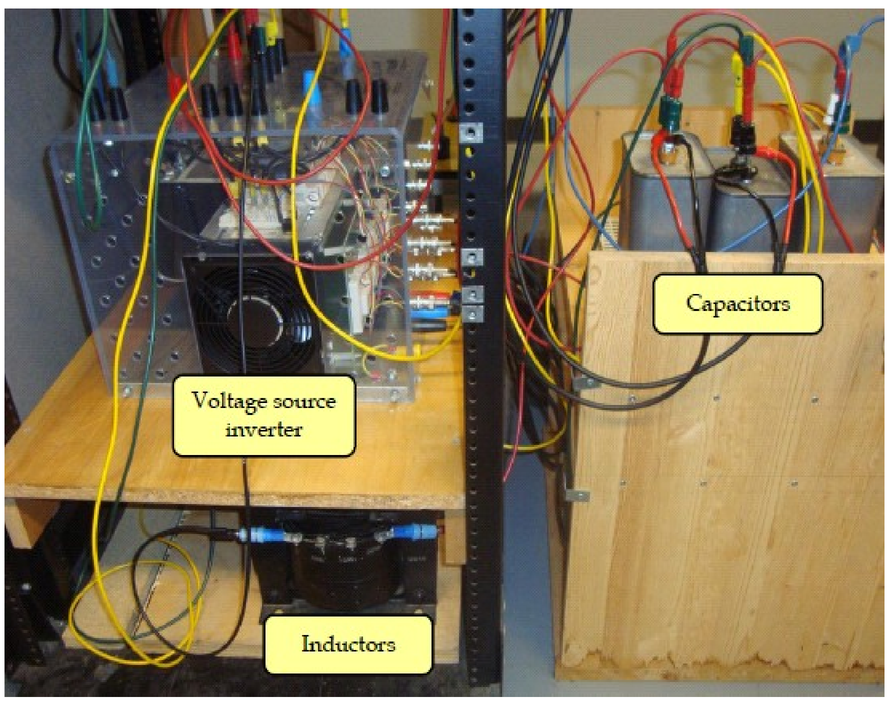

Fig. 4.5 – Voltage source inverter alongside the inductors and capacitors employed to filter out the harmonics

4.3 Communications Media

In the proposed framework, it is possible to have inhomogineous communications media depending on what is available at each inverter site. In other words, if a telephone line is available at one inverter site with a corresponding telephone line at the supervisory control center, an Internet link is available at another inverter site with a corresponding Internet link at the supervisory control center, and a fiber optic link connects the third inverter site to the supervisory control center, all of them can be accomodated in the proposed framework. Of course, for each case, a suitable Ethernet interface that matches the available communications media should be carefully selected, and information exchange at the supervisory control center should also be managed accordingly. In this thesis, for conveneince, Internet links are chosen for information exchange between inverter sites and the supervisory control center.

4.4 The Software

4.4.1 Data Acquisition System

In Section 4.4.1.1, the design and implementation of the software running in the data acquisition system is explained. The rationale behind the given design is given in Section 4.4.1.2.

4.4.1.1 Design

The data acquisition system is composed of several software modules that run at the inverter site. The software system is written in the C language and uses a proprietary compiler that comes with the hardware described in Section 4.2.2. The software modules in the data acquisition system are described as follows:

Initialization

The initialization module resets the CPU by changing its configuration to the default. It then proceeds with configuring the sensors and setting up some interrupt modules for reading and performing calculations on the voltage and current values. Subsequently, it starts listening (checking) on the Ethernet port for new incoming TCP connections. This is because establishing a connection between two end points (i.e., between an inverter site and the supervisory control center) in an Internet environment that uses the TCP protocol in its transport layer and the IP protocol in its network layer (i.e., the well known TCP/IP network) is done at TCP layer. As soon as a TCP connection is established with the supervisory control center (meaning that from this point in time, data can be exchanged between the inverter site and the supervisory control center), it proceeds to the main module.

Interrupts

Interrupts are used for running regularly timed tasks, such as reading voltage and current values from the sensors and calculating appropriate values. The sensor values are read from the device registers into the local memory of the "reading interrupt" program. The "reading interrupt" program runs every 0.69 ms, which corresponds to a sampling rate of 1440 samples per second for the grid frequency of 60 Hz, and the voltage and current RMS values calculation is based on the last 24 samples read from the sensors. The inter-interrupt period of 0.69 ms is based on a sampling rate of 1440 samples per second for the grid frequency of 60 Hz. For extreme variations in the grid's frequency, the chosen sampling rate of 1440 samples per second is more than sufficient to capture corresponding variations in instantaneous voltage and current values, hence the inter-interrupt period of 0.69 ms can accommodate such variations in grid's frequency. Variations in the grid's frequency is regulated by IEEE Standard 1547, and its permissible range is from 59.3 Hz to 60.5 Hz. Within this range, the sampling rate of 1440 samples per second results in the exact RMS values for the grid's frequency of 60 Hz. In the event that variations in grid's frequency exceed the above mentioned bounds so that there would be 23 samples per cycle or 25 samples per cycle, corresponding to the grid's frequency of 62.6 Hz and 57.6 Hz, respectively, as will be shown in the sequel, the error in RMS values caused by considering 24 samples (instead of 23 or 25 samples) are within 1.5% of its exact value as shown below, which is considered as acceptable [38].

Voltage RMS values are calculated by $V_{\text{rms}} = \sqrt{\frac{1}{24}\sum_{k=1}^{24}(v_k)^2}$, where v_k is the k^{th} sampled value. When there are 23 samples in one cycle, the maximum value of error in the calculated RMS value happens either when the 24^{th} sample is the maximum instantaneous voltage value, denoted by $v^{\max}$, or when it is the minimum absolute value of 0 volts. For the case of maximum instantaneous voltage value, the exact value of V_{rms}, denoted by $V_{\text{rms}}^{\text{exact}}$, is equal to $V_{\text{rms}}^{\text{exact}} = \sqrt{\frac{1}{23}\sum_{k=1}^{23}(v_k)^2} = \frac{v^{max}}{\sqrt{2}}$. Hence, the error in the RMS value, denoted by ε, is

$$\varepsilon = \frac{v^{max}}{\sqrt{2}} - \sqrt{\frac{1}{24}\sum_{k=1}^{24}(v_k)^2} = \frac{v_{max}}{\sqrt{2}} - \sqrt{\frac{1}{24}\sum_{k=1}^{23}(v_k)^2 + \frac{(v^{max})^2}{24}} =$$

$$= \frac{v^{max}}{\sqrt{2}} - \sqrt{\frac{1}{24}\left(\frac{23 \times (v^{max})^2}{2} + (v^{max})^2\right)} = -0.015v^{max}. \quad (4\text{-}1)$$

For the case of the minimum absolute voltage value of 0 volts, the exact value of V_{rms}, denoted by V_{rms}^{exact}, is equal to $V_{rms}^{exact} = \sqrt{\frac{1}{23}\sum_{k=1}^{23}(v_k)^2} = \frac{v^{max}}{\sqrt{2}}$. Hence, the error in the RMS value, denoted by ε, is

$$\varepsilon = \frac{v^{max}}{\sqrt{2}} - \sqrt{\frac{1}{24}\sum_{k=1}^{24}(v_k)^2} = \frac{v^{max}}{\sqrt{2}} - \sqrt{\frac{1}{24}\left(\frac{23 \times (v^{max})^2}{2}\right)} = +0.015v^{max}. \quad (4\text{-}2)$$

Similarly, when there are 25 samples in one cycle, the maximum value of error in the calculated RMS value happens when the missed 25th sample is either the maximum instantaneous voltage value, denoted by v^{max}, or the minimum absolute voltage value of 0 volts. For the case of maximum instantaneous voltage value, the exact value of V_{rms}, denoted by V_{rms}^{exact}, is equal to $V_{rms}^{exact} = \sqrt{\frac{1}{25}\sum_{k=1}^{25}(v_k)^2} = \frac{v^{max}}{\sqrt{2}}$. Hence, the error in the RMS value, denoted by ε, is

$$\varepsilon = \frac{v^{max}}{\sqrt{2}} - \sqrt{\frac{1}{24}\sum_{k=1}^{24}(v_k)^2} = \frac{v^{max}}{\sqrt{2}} - \sqrt{\frac{1}{24}\left(\sum_{k=1}^{25}(v_k)^2 - (v^{max})^2\right)} =$$

$$\frac{v^{max}}{\sqrt{2}} - (\sqrt{\frac{1}{24}\left(\frac{25 \times (v^{max})^2}{2} - (v^{max})^2\right)} = +0.015\, v^{max}. \quad (4\text{-}3)$$

For the case of minimum absolute voltage value of 0 volts, the exact value of V_{rms}, denoted by V_{rms}^{exact}, is equal to $V_{rms}^{exact} = \sqrt{\frac{1}{25}\sum_{k=1}^{25}(v_k)^2} = \frac{v^{max}}{\sqrt{2}}$. Hence, the error in the RMS value, denoted by ε, is

$$\varepsilon = \frac{v^{max}}{\sqrt{2}} - \sqrt{\frac{1}{24}\sum_{k=1}^{24}(v_k)^2} = \frac{v^{max}}{\sqrt{2}} - \sqrt{\frac{1}{24}\left(\frac{25 \times (v^{max})^2}{2}\right)} = -0.015\, v^{max}. \quad (4\text{-}4)$$

As can be seen from the above, the system obtains RMS values with an accuracy of 1.5% even when the grid's frequency varies between from 57.6 Hz to 62.6 Hz. As such, there is no need to consider the effects of grid's frequency variations on RMS values obtained above.

Main Module

The main module runs right after the initialization module. The main module is responsible for reading incoming packets from the supervisory control center and reacting to them. The module consists of an infinite loop. In each iteration of the loop, the module first checks to see if there is any new data in the incoming TCP buffer. If there is, then it proceeds to read one byte from the buffer (each command from the supervisory control center has a length of one byte). Then, based on the type of command, it performs the appropriate action. For example, when the read byte is equal to ASCII value of character "Z", the supervisory control center is asking for the latest RMS values of voltage and current to be sent. In this case, the module copies the locally stored RMS values onto its local outgoing TCP buffer. Each RMS value is a 2 byte integer (short integer). Hence, considering that there are three RMS values for each of voltage and current (one for each phase), a total of 12 bytes are written to the local outgoing TCP buffer. The operating system of the data acquisition system then takes the data from the local TCP buffer and writes it to the TCP channel.

4.4.1.2 Rationale

In order to obtain the values of interest, e.g., instantaneous values of three phase voltages and currents, and their corresponding RMS values in a timely manner, a scheme is devised by which a mix of interrupt and polling techniques are employed. The reason for doing so is that some of the tasks at the inverter site need to be done on regular timed intervals (e.g., sampling the instantaneous voltage and current values), while the rest need to be done continuously (e.g., monitoring the incoming TCP buffer for new packets). The timing and performance requirements of the tasks at the data acquisition system require the use of both interrupts and polling. For instance, sampling of voltages and currents must occur on fixed time intervals and should be lightweight tasks; hence, the use of interrupts. On the other hand, the receiving channel must be continuously monitored for new data from the supervisory control center. There is a need to use polling for monitoring of new packets for the following three reasons:

1. The transmission rate of the supervisory control center is variable in time. Hence, if the incoming buffer is checked using interrupts, the interrupt interval may be too long and the incoming packets may be lost as a result of a buffer overflow.
2. A short interrupt timer is not efficient either. At the beginning and at the end of each interrupt, the state (also called the context) of the CPU needs to be saved, and subsequently restored when the interrupt is finished. This process is called context-switching, and is needed so that the execution of the interrupted software can be resumed from the same point at a later time. Context-switching is a costly operation (i.e., it needs significant resources

(mostly memory), and is time consuming) and if the interrupt timer is too short, then the time needed for context-switching may overwhelm the CPU. This can result in unexpected behavior by the program, most notably a non-recoverable crash.

3. The response-time of the data acquisition system is directly tied to its read/write speed onto the network socket. If a polling scheme is used, then the read speed is very close to the throughput of the Ethernet port since the packets are read as they arrive. However, if an interrupt-driven scheme is used, then the maximum read speed is equal to the frequency at which the interrupt is fired; a much lower rate than the throughput.

Hence, using polling results in shorter response-times and better read/write rate. Fig. 4.6 is a finite state machine graph representing interactions between concurrent processes in the system. The flowchart of the software developed for Fig. 4.6 is shown in Fig. 4.7, with the flowchart of the interrupt process shown in Fig. 4.8, and the pseudo code at the data acquisition side is presented in Fig. 4.9.

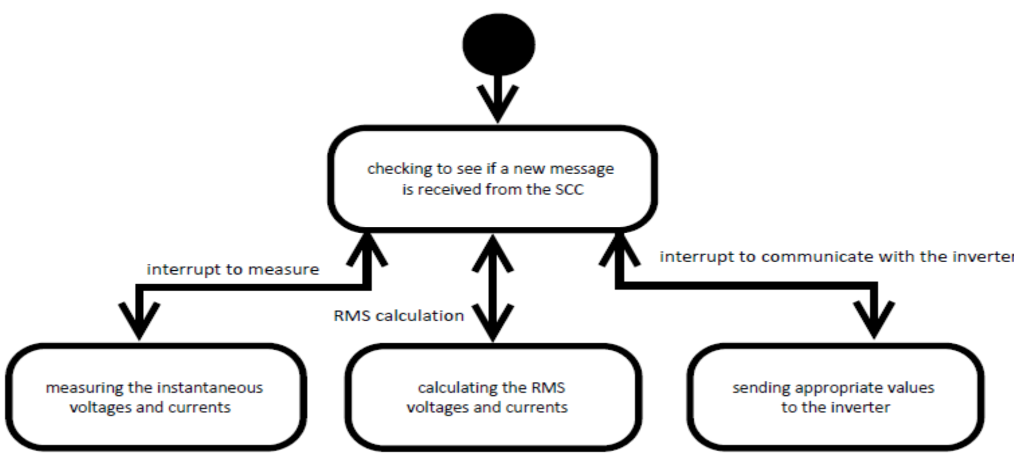

Fig. 4.6 – Finite state machine graph representing interactions between concurrent processes within the data acquisition system.

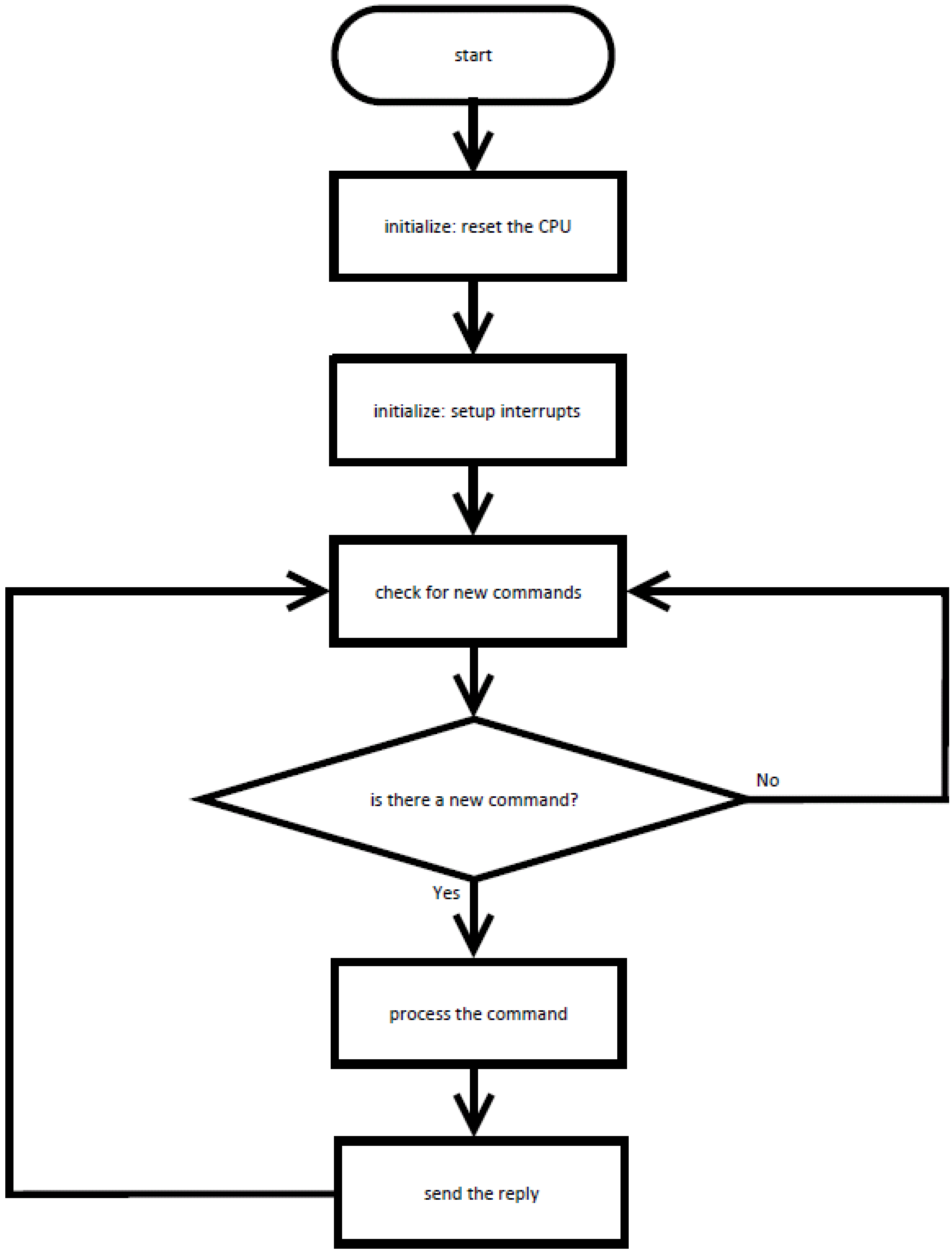

Fig. 4.7 – The flowchart of the software implemented at the data acquisition side

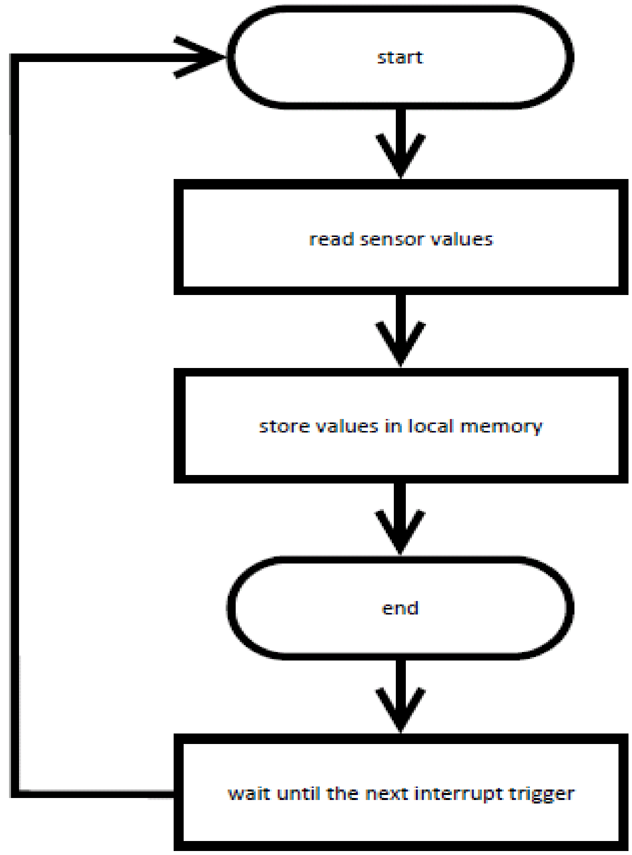

Fig. 4.8 – Flowchart of the interrupt process

```
for(;;)
{
      if a message from the SCC is in the buffer
      {
            execute the corresponding message
            informe SCC of the action perfored
      }
      else
      {
      }
}
interrupt
{
        measure the three phase voltage and current
}
interrupt
{
         communicate with the inverter
}
```

Fig. 4.9 – Pseudo code at the data acquisition side

4.4.2 Supervisory Control Center

The supervisory control center is a software system written in MATLAB. It is responsible for obtaining RMS values of voltages and currents from the inverter sites in a reliable manner. The RMS values are polled when the user requests them. Hence, the supervisory control center provides a graphical user interface (GUI) so that the user can use the software more easily. The graphical user interface (GUI) is shown in Fig. 4.10.

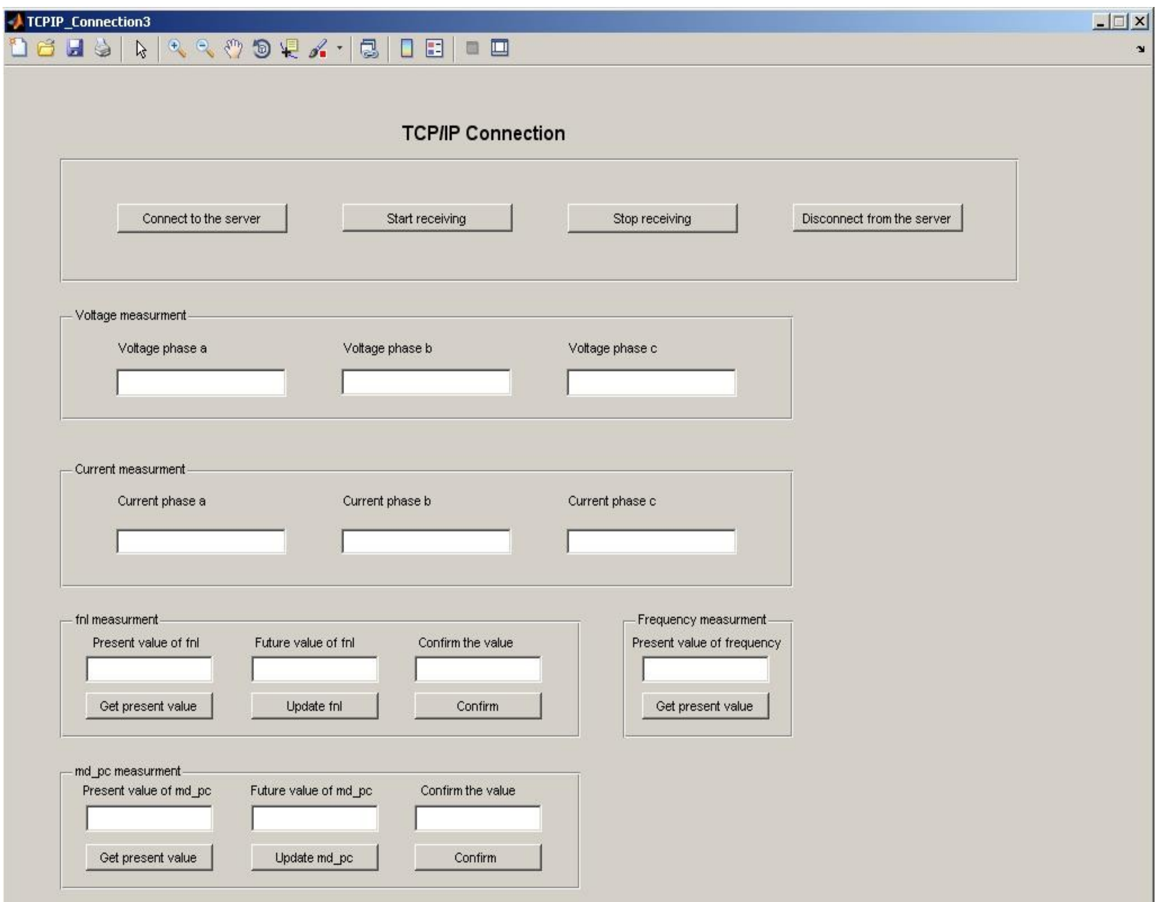

Fig. 4.10 – Graphical user interface (GUI) at the supervisory control center

After the user runs the software at the supervisory control center, he/she must start a TCP connection between the supervisory control center and the inverter site as is shown in Fig. 4.11. The idea behind this is to establish a dedicated and secure tunnel between the two ends while physical segments in the Internet link may be carrying other information unrelated to the application of interest in this thesis. As explained in Chapter 3, tunneling is a mechanism to establish a virtual pipe (connection) between two points through which information can be exchanged. In establishing a virtual pipe, as a standard practice, the data is encrypted, so that it would be immune to eavesdropping; hence a dedicated and secure tunnel. This is done via a permanent TCP connection between the source and the destination, which is used for exchange of information. Fig. 4.12 shows the sequence for establishing the permanent connection between the supervisory control center and the inverter site, and its pseudo code is presented in Fig. 4.13.

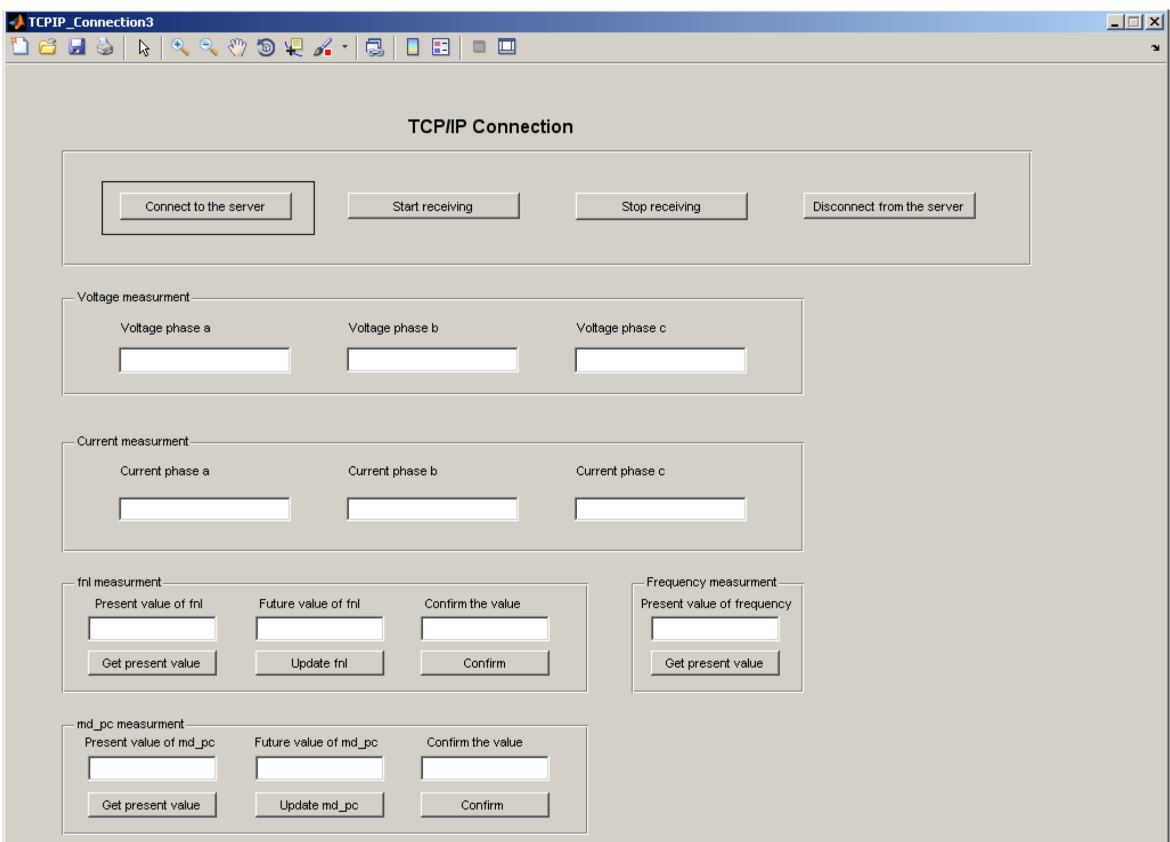

Fig. 4.11 – Establishing TCP connection with the inverter via the GUI at the supervisory control center

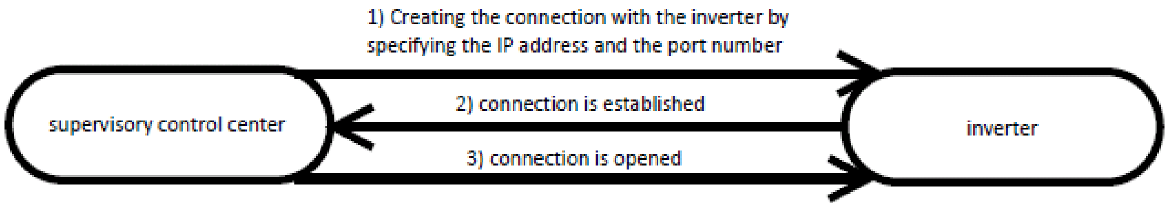

Fig 4.12 – Sequence of establishing TCP connection between the supervisory control center and the inverter

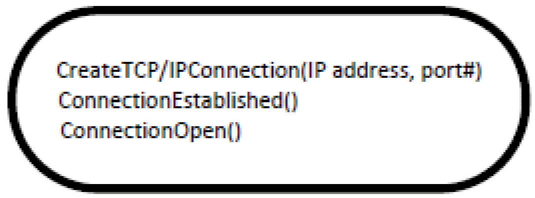

Fig 4.13 – Pseudo code for establishing TCP connection from the supervisory control center to the inverter

The inverter site must be actively listening for incoming TCP connections in order for the TCP connection to be successfully established (see Section 4.4.1.1 *Main Module*). The TCP connection has a buffer size of 96 bytes, enough for handling 8 responses from the inverter site. Due to the fact that the inverter site sends one response per request, the allocated buffer size is sufficient and prevents buffer overflows.

After a TCP connection is established, the user can request for the latest data via the graphical user interface (GUI) as shown in Fig. 4.14. After the user clicks the appropriate button, a request for updated data is sent to the inverter site. The request/receive mechanism used is as follows. The one byte command (in this case, the ASCII value of character "Z") is written to the local TCP buffer at the supervisory control center. This buffer is monitored regularly by the operating system and if there is any data in the buffer during each check, that data is written to the TCP channel. After the command is written into the local TCP buffer, the module waits for up to 900 milliseconds, as it was determined experimentally (enough time for the operating system to write that byte into the TCP channel and for the inverter site to respond), before checking the TCP buffer for a response from the inverter site. If the supervisory control center determines that the expected information was not received, it assumes that its request for information was lost or was not properly received / processed by the data acquisition system, and repeats its request for information. This repetition is vital to make sure that those anomalies due to noise or congestion in the communications media or caused by busy processes at the destination are treated properly and compensated for in the system.

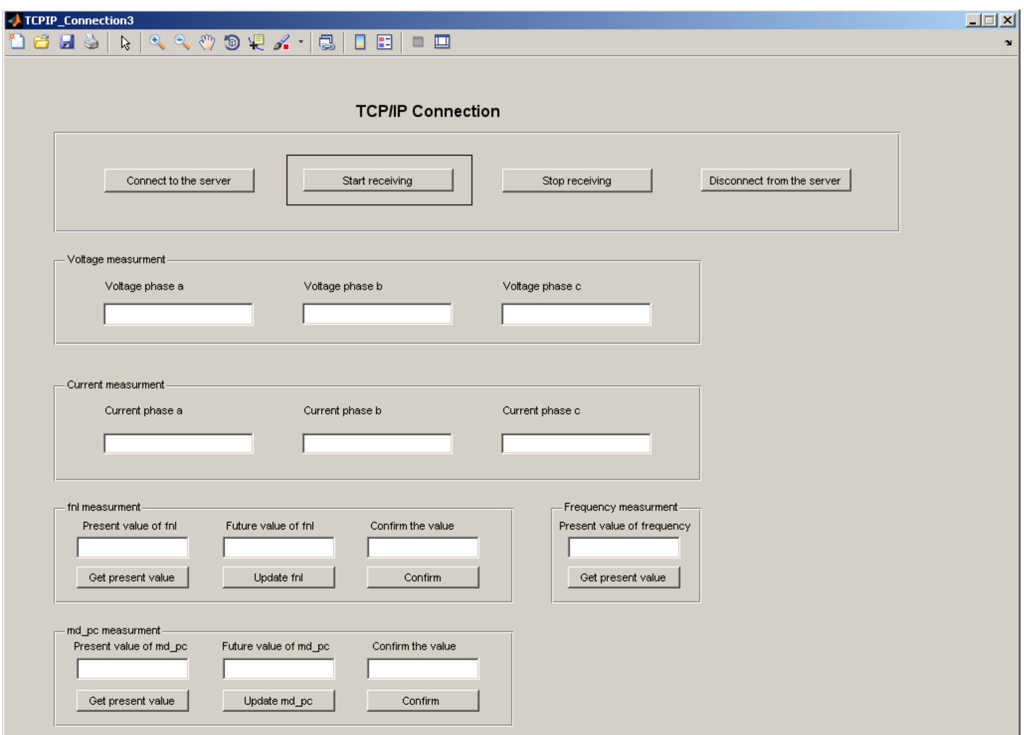

Fig. 4.14 – User requesting the inverter to send RMS values of three phase voltages and currents

If a response is received from the inverter site after the waiting period, the supervisory control center starts reading 12 bytes of data (2 bytes for each value, 6 values in total) from the incoming TCP buffer. The read byte stream consisting of 12 bytes are de-serialized (unmarshalled) into 6 values and stored into 6 local registers and displayed to the user via the GUI. The flow chart of the software on the supervisory controller side is shown in Fig. 4.15

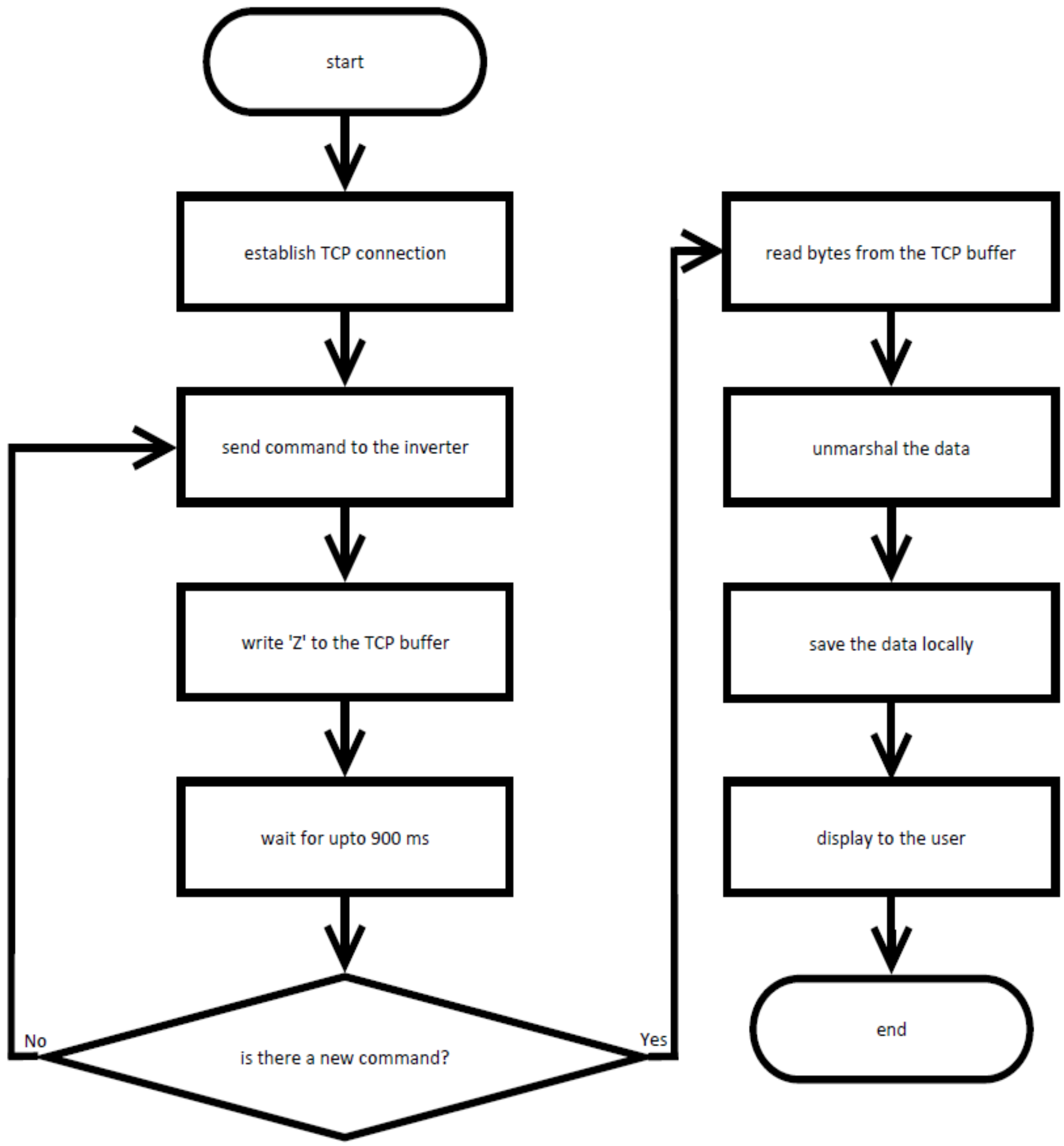

Fig. 4.15 – Flowchart of the software implemented at the supervisory control center

CHAPTER 5

MEASUREMENTS AND PERFORMANCE

5.1 Performance Measures

Performance measures describe the scalability of the system as a whole. However, definitions of performance metrics are very tied to the component that is being measured. Hence, system components are divided into three separate categories:

1. The supervisory control center.
2. The PV inverter site.
3. The communication link connecting the above components.

The performance metrics of elements in each category are measured and presented in the following sections.

5.2 Communication Software at Supervisory Control Center

The communication software at the supervisory control center is tasked with setting up TCP connections to the set of PV inverter sites and polling the sites on demand to collect information pertaining to their status. Hence, it is natural to gather performance metrics relating to the following aspects:

- Set-up time of a TCP connection
- Time to write to a TCP socket
- Time to poll a TCP socket
- Time to read from a TCP socket
- Memory and CPU usage at the supervisory control center

The measurements were made on a PC whose configurations are shown in Table 5.1. For measurements, the PC at the supervisory control center was directly connected to the PV inverter via an Ethernet cable, unless indicated otherwise. This was done to avoid fluctuations due to network settings and to find the maximum performance of the system for benchmarking.

Table 5.1 – The configuration of the PC for the supervisory control center

Parameter	Value
Operating System	Windows XP
CPU	3.4 GHz
RAM	1.99 GB

5.2.1 Setup-Time of TCP Connection

The setup-time of the TCP connection was measured 20 times in quick successions, and measurements are shown in Table 5.2. The mean setup-time was 40.39 ms with a standard deviation of 1.892 ms. The setup-time of a TCP connection depends heavily on network conditions. In the presented measurements, a direct connection is used, which is the best setting in terms of delay, throughput, and reliability. Hence, the above values can be considered as optimal.

Table 5.2 – Setup time of TCP connection

No	Setup Time of TCP Connection (ms)
1	40.975
2	42.641
3	41.907
4	46.575
5	40.969
6	41.187
7	40.385
8	40.060
9	40.230
10	41.659
11	38.987
12	39.358
13	40.161
14	38.966
15	38.930
16	38.269
17	38.772
18	40.150
19	38.601
20	39.054
Average	40.390
Standard Deviation	1.892

5.2.2 TCP Write-Time

The time needed to write to a TCP socket is divided into two items, namely, the time needed to write to a local TCP buffer and the time needed for the data in the buffer to be written to the channel. The TCP write-time is measured 20 times. The mean was 3.11 ms with a standard deviation of 0.946 ms. The measurements are given in Table 5.3. Note that there is little variation in the write-time, and that can be attributed to the network being highly stable and the systems being in steady state. Hence, the abovementioned measurements of the write-time can be considered as optimal.

Table 5.3 – TCP write time

No	TCP write time (ms)
1	3.458
2	2.714
3	2.665
4	2.694
5	2.859
6	3.031
7	2.707
8	2.793
9	2.683
10	2.761
11	2.787
12	2.775
13	2.747
14	3.277
15	3.267
16	3.041
17	2.741
18	2.873
19	6.997
20	3.233
Average	3.110
Standard Deviation	0.946

5.2.3 TCP Polling-Time

After sending a status request to the PV inverter, the supervisory control center constantly polls the incoming TCP buffer for data from the PV inverter. The polling operation checks the number of unread bytes in the incoming TCP buffer, and if the expected number of bytes exist in the buffer, the supervisory control center reads the data and stores it locally for later use. The expected number of bytes for a three phase system in this thesis is 12 = 3 × (2 × the number of quantities for each phase) (which are voltage and current). It is vital that the polling operation be short enough, otherwise the entire operation may take longer than what is needed for accurate and timely data capture.

TCP polling-time is measured 20 times. Its mean value was 2.42 ms and its standard deviation was 0.533 ms. The TCP-polling time for the 20 measurements are shown in Table 5.4. Note that the polling time is stable.

Table 5.4 – TCP polling-time

No	TCP polling time (ms)
1	2.614
2	2.673
3	2.792
4	2.806
5	2.641
6	3.213
7	2.774
8	2.812
9	2.640
10	3.604
11	2.597
12	1.763
13	1.912
14	1.944
15	1.830
16	1.851
17	1.821
18	1.857
19	2.469
20	1.858
Average	2.42
Standard Deviation	0.533

5.2.4 TCP Read-Time

If there are enough bytes in the incoming TCP buffer (after polling), the bytes are read from the buffer and stored locally. It is important that the polling and reading rate is faster than the receiving rate of data at the supervisory control center, so that the TCP buffer does not overflow between consecutive polls. If the TCP buffer were to overflow, the supervisory control center would read unaligned data, leading to wrong values being read.

In the case of RMS values, the supervisory control center expects 12 bytes each time it asks for the status of the PV inverter. The TCP read-time is measured 20 times, and it was verified that that during each read, there are 12 bytes in the buffer to be read so the read operations would not stall. The TCP read-times are displayed in Table 5.5. The mean TCP read-time is 3.42 ms with a standard deviation of 1.144 ms.

Table 5.5 – TCP read-time

No	TCP read time (ms)
1	3.570
2	3.031
3	2.926
4	2.943
5	3.106
6	3.192
7	3.509
8	3.203
9	3.246
10	2.933
11	2.930
12	3.140
13	3.434
14	3.602
15	2.943
16	2.995
17	8.184
18	3.464
19	3.122
20	2.939
Average	3.42
Standard Deviation	1.144

5.2.5 Memory and CPU Usage

The memory and CPU usage is measured at the supervisory control center for three traffic scenarios described below.

- **Standby**: The supervisory control center is running with an active TCP connection between itself and the PV inverter site, but no data is being sent between the pair.
- **Normal**: Same as the standby mode, but with requests being sent at a rate of 1 request per second.
- **Stress test**: Same as the normal mode, but requests are sent at the maximum possible rate.

The results of the experiment are shown in Table 5.6. It is evident that as the interval between the requests is reduced, the system uses more memory and CPU.

Table 5.6 – Memory and CPU usage under various conditions

	Memory (MB)	CPU Usage
Standby	194	1 %
Normal	195	2 %
Stress Test	200	6%

5.3 Communication Software at PV Inverter Sites

The communication software at each PV inverter site is tasked with two main issues:

- Using timed interrupts to poll its sensors at regular intervals to get updated values of instantaneous voltages and currents.
- Using an infinite loop to check the incoming TCP buffer for commands from the supervisory controller center and to reply in a timely manner.

Due to limited processing power of CPUs at the inverter sites, the set of metrics that can be measured is restricted compared to the supervisory control center. Hence, the following two metrics are measured at each inverter site:

- Time taken to read sensor values in timed interrupts
- Time needed to calculate the RMS values of currents and voltages

5.3.1 Sensor Read-Time

The instantaneous values of voltage and current are regularly read from the registers of the respective sensors and stored in the local memory of the main module of the communication software at the PV inverter site. These values are later used to determine the RMS values sent to supervisory control center. The time needed to read the sensor values is a key measure, since it determines how often one can read the sensor values. Table 5.7 shows the time taken to read sensor values for 10 different instances.

Table 5.7 – Sensor read time

No	Sensor Read-Ttime (ns)
1	333
2	271
3	292
4	292
5	271
6	271
7	271
8	250
9	250
10	271
Average	277.2
Standard Deviation	24.091

5.3.2 RMS Calculation Time

The time needed to calculate the RMS values is important because it is the limiting factor on the response time of the communication software at the PV inverter site. Table 5.8 shows the amount of time taken to calculate the RMS values.

Table 5.8 – RMS calculation time

No	RMS Calculation Time (µs)
1	174
2	140
3	141
4	174
5	145
6	141
7	140
8	154
9	145
10	141
11	161
12	141
13	161
14	141
15	141
16	141
17	141
18	142
19	141
20	140
Average	147.25
Standard Deviation	11.24

5.4 Communication Network Performance Indicators

Performance of each network is characterized by a set of indicators that are particular to that network. For communications networks designed for supervision and control of electricity grids, a set of such performance indicators are identified in IEEE Standard 1547.3 [39], that comprises of throughput, latency, and reliability. In the following subsections, the definition of each of the above mentioned parameters is provided along with their corresponding measurements. Performance indicators are measured for three different scenarios to investigate the effect of distance between the source and the destination on the measured metrics. These three different scenarios are:

1) The supervisory control center and the PV inverters are in close proximity to each other, and the coverage distance is less than 100 meters (the suburban scenario). In this scenario, Ethernet networks are directly connected to each other.

2) The distance between the supervisory control center and the inverters are in the order of km, and private communication links (meaning that the supervisory control center and the inverters, and a limited number of users are the only entities that are using the communication link) are utilized.

3) Public communication links between the supervisory control center and the inverters have been utilized, meaning that others whose work is irrelevant to the application of interest in this thesis may be using the network as well.

In all the above mentioned scenarios, wired networking connection is employed to avoid variations in wireless channels. Besides, the raw bit rate on the direct connection scenario (100 Mbps) and the private link (100 Mbps) is much higher than that of the public link scenario (5 Mbps). Each of the above scenarios has been tested on three different days, on each day 20 tests have been performed, and each test was composed of sending 1000 requests for status to the inverter. In what follows, measurements of performance indicators are presented and discussed.

5.4.1 Throughput

Throughput is the amount of information that can be continuously sent through the network, and is normally measured in Kilo bits per second (Kbps) [39]. Throughput can be specified by its maximum value, its nominal value, or its minimum value. The throughput value is specified from the end-user point of view (i.e., raw data rate), but actual network throughput measurements include protocol overhead and repeated packet transmissions due to errors.

In each scenario, the throughput of the link between the supervisory control center and the PV inverter site is measured by continuously sending status requests from the supervisory control center to the PV inverter site. These requests need to be replied to. The throughput is the amount of data sent (in bits) divided by the measurement period. The measurement period depends on the existing link (its raw bit rate and actual traffic on the link) between the supervisory control center and the PV inverter site in each scenario, and is so chosen so that the PV inverter site has enough time to provide the supervisory control center with the requested data. Throughput values are shown in Tables 5.9 to 5.16 for the three different scenarios. As can be seen in the above mentioned tables, Scenarios 1 and 2, (i.e., the direct Ethernet connection, and the private communication network) have a much higher throughput as compared to the case of public network. Note that throughput varies within a network as the network condition is not constant. Note that measured throughput values are far less than the raw bit rates.

5.4.1.1 Direct Ethernet Connection (Suburban Case)

Table 5.9 – Throughput of direct Ethernet connection measured on Sept. 8th

No	Throughput (bits/sec)
1	552
2	555
3	558
4	561
5	564
6	544
7	558
8	552
9	555
10	555
11	550
12	560
13	560
14	556
15	556
16	555
17	554
18	558
19	555
20	561
Average	555.95
Standard Deviation	4.465

Table 5.10 – Throughput of direct Ethernet connection measured on Oct. 8th

No	Throughput (bits/sec)
1	554
2	554
3	553
4	554
5	553
6	560
7	553
8	554
9	555
10	553
11	555
12	555
13	557
14	556
15	556
16	561
17	562
18	547
19	556
20	555
Average	555.15
Standard Deviation	3.248

Table 5.11 – Throughput of direct Ethernet connection measured on Nov. 8th

No	Throughput (bits/sec)
1	497
2	533
3	559
4	561
5	555
6	554
7	559
8	555
9	561
10	561
11	557
12	557
13	559
14	556
15	557
16	554
17	558
18	556
19	555
20	556
Average	553
Standard Deviation	14.41

5.4.1.2 Private Communication Network

Table 5.12 – Throughput of private communication network measured on Sept. 8th

No	Throughput (bits/sec)
1	539
2	541
3	539
4	540
5	539
6	539
7	541
8	540
9	540
10	539
11	539
12	540
13	535
14	537
15	540
16	538
17	540
18	540
19	540
20	538
Average	539.2
Standard Deviation	1.399

Table 5.13 – Throughput of private communication network measured on Oct. 8th

No	Throughput (bits/sec)
1	540
2	543
3	501
4	540
5	540
6	539
7	539
8	539
9	539
10	539
11	539
12	541
13	538
14	539
15	539
16	539
17	539
18	540
19	539
20	538
Average	537.5
Standard Deviation	8.66

Table 5.14 – Throughput of private communication network measured on Nov. 8th

No	Throughput (bits/sec)
1	540
2	538
3	540
4	538
5	538
6	541
7	541
8	540
9	539
10	539
11	540
12	542
13	540
14	539
15	538
16	539
17	540
18	541
19	541
20	541
Average	539.75
Standard Deviation	1.20

5.4.1.3 Public Communication Network

Table 5.15 – Throughput of public communication network measured on Sept. 8th

No	Throughput (bits/sec)
1	207
2	207
3	208
4	207
5	196
6	213
7	213
8	214
9	215
10	214
11	215
12	175
13	149
14	150
15	151
16	151
17	150
18	150
19	175
20	174
Average	186.7
Standard Deviation	27.81

Table 5.16 – Throughput of public communication network measured on Oct. 8th

No	Throughput (bits/sec)
1	267
2	214
3	176
4	175
5	176
6	175
7	175
8	176
9	158
10	151
11	150
12	150
13	151
14	151
15	151
16	150
17	147
18	149
19	151
20	150
Average	167.15
Standard Deviation	28.91

Table 5.17 – Throughput of public communication network measured on Nov. 8th

No	Throughput (bits/sec)
1	164
2	169
3	167
4	164
5	174
6	168
7	130
8	114
9	115
10	115
11	116
12	150
13	151
14	168
15	158
16	164
17	166
18	165
19	128
20	172
Average	150.9
Standard Deviation	22.07

5.4.2 Latency

Latency is the time between the onset of a data request packet and receipt of requested packet at the supervisory control center; and can be specified by its maximum, its nominal, or its minimum value [39], normally measured in seconds. The measured value is the round-trip time plus the processing time at the inverter site. The processing time is very small compared to the round-trip time and can be ignored. From Tables 5.17 to 5.25, it is evident that Scenarios 1, and 2 (i.e., direct Ethernet connection, and private communication network) have a much smaller latency as compared to the case of public network. Note that for in public network, the latency varies considerably, while for the other two scenarios, it is stable.

5.4.2.1 Direct Ethernet Connection (Suburban case)

Table 5.18 – Latency of direct Ethernet connection measured on Sept. 8th

No	Latency (ms)
1	188.24
2	187.24
3	186.22
4	185.12
5	184.36
6	191.08
7	186.28
8	188.38
9	187.26
10	187.14
11	188.98
12	185.48
13	185.56
14	186.86
15	186.74
16	187.28
17	187.62
18	186.26
19	187.28
20	185.16
Average	186.92
Standard Deviation	1.532

Table 5.19 – Latency of direct Ethernet connection measured on Oct. 8th

No	Latency (ms)
1	187.31
2	187.33
3	187.83
4	187.50
5	187.77
6	185.41
7	187.67
8	187.28
9	187.19
10	187.86
11	187.10
12	186.96
13	186.45
14	186.89
15	186.76
16	185.06
17	184.60
18	189.66
19	186.62
20	187.16
Average	187.02
Standard Deviation	1.093

Table 5.20 – Latency of direct Ethernet connection measured on Nov. 8th

No	Latency (ms)
1	208.95
2	194.61
3	185.58
4	185.09
5	186.91
6	187.50
7	185.86
8	187.19
9	185.11
10	184.99
11	186.51
12	186.41
13	185.80
14	186.88
15	186.41
16	187.27
17	185.91
18	186.89
19	187.03
20	186.89
Average	187.88
Standard Deviation	5.343

5.4.2.2 Private Communication Network

Table 5.21 – Latency of private communication network measured on Sept. 8th

No	Latency (ms)
1	192.70
2	191.76
3	192.62
4	192.30
5	192.56
6	192.48
7	191.84
8	192.38
9	192.36
10	192.44
11	192.58
12	192.42
13	193.92
14	193.16
15	192.10
16	193.02
17	192.26
18	192.42
19	192.40
20	192.92
Average	192.52
Standard Deviation	0.472

Table 5.22 – Latency of private communication network measured on Oct. 8th

No	Latency (ms)
1	192.34
2	191.24
3	207.16
4	192.44
5	192.16
6	192.48
7	192.62
8	192.48
9	192.74
10	192.64
11	192.54
12	191.90
13	193.08
14	192.46
15	192.52
16	192.66
17	192.44
18	192.24
19	192.78
20	192.88
Average	193.18
Standard Deviation	3.31

Table 5.23 – Latency of private communication network measured on Nov. 8th

No	Latency (ms)
1	192.44
2	192.84
3	192.36
4	192.96
5	193.02
6	191.96
7	193.94
8	192.22
9	192.50
10	192.56
11	192.42
12	191.72
13	192.22
14	192.74
15	192.82
16	192.48
17	192.40
18	191.96
19	192.06
20	192.04
Average	192.48
Standard Deviation	0.492

5.4.2.3 Public Communication Network

Table 5.24 – Latency of public communication network measured on Sept. 8th

No	Latency (ms)
1	500.92
2	500.20
3	498.86
4	500.82
5	530.22
6	486.64
7	486.22
8	486.78
9	483.20
10	485.46
11	482.14
12	590.96
13	693.40
14	691.60
15	688.50
16	685.46
17	689.68
18	690.18
19	593.70
20	594.46
Average	567.96
Standard Deviation	89.44

Table 5.25 – Latency of public communication network measured on Oct. 8th

No	Latency (ms)
1	388.64
2	484.84
3	587.44
4	592.24
5	590.00
6	592.06
7	591.36
8	589.46
9	654.36
10	687.98
11	690.64
12	688.82
13	685.88
14	686.96
15	687.40
16	689.72
17	702.62
18	693.98
19	687.64
20	687.18
Average	633.16
Standard Deviation	82.48

Table 5.26 – Latency of public communication network measured on Nov. 8th

No	Latency (ms)
1	633.88
2	611.98
3	621.58
4	633.34
5	594.52
6	616.52
7	797.68
8	909.54
9	901.64
10	900.04
11	893.28
12	691.78
13	686.24
14	615.64
15	655.38
16	631.40
17	623.32
18	628.18
19	809.78
20	602.86
Average	702.92
Standard Deviation	116.68

5.4.3 Reliability

It sometimes happens that data that is sent by either the supervisory control center or the PV inverter site are lost in the communication channel and / or the processor. It is important to detect and recover from such occurrences in a timely fashion. The lightweight nature of the communication system at the PV inverter site prohibits it from doing any packet-loss detection and recovery. Hence, all such detection is done in the supervisory control center.

When the supervisory control center sends a data request to the PV inverter site, it waits for a set amount of time (waiting time) for a reply. If that time elapses (also known as time-out), it is assumed that either the request or the reply was lost in the communication channel and / or in the processing unit. At that point, the supervisory control center retransmits the request and waits for a subsequent reply.

The challenge in packet-loss detection involves setting an appropriate waiting time. If it is too short, the PV inverter site may not have enough time to reply to a request before the supervisory control center assumes the request/reply is lost (false positives). If the waiting time is too long, the supervisory control center becomes slow as it waits an excessive amount of time before it checks the incoming TCP buffer for new data.

Here, the packet drop rate is considered as a measure of reliability of the communication network and the processing unit. In doing so, the number of requests that are not acknowledged within the waiting time is counted. It is evident from Tables 5.26 to 5.34 that packet drop rate is fairly constant across the three different scenarios. Note that even though there are packet drops in the system, but that does not deteriorate the reliability of the system, since the system is recovered in a timely manner.

5.4.3.1 Direct Ethernet Connection (Suburban case)

Table 5.27 – Packet drop rate of direct Ethernet connection measured on Sept. 8th

No	Number of Packets dropped	Percentage
1	82/1000	8.2 %
2	67/1000	6.7 %
3	67/1000	6.7 %
4	64/1000	6.4 %
5	78/1000	7.8 %
6	68/1000	6.8 %
7	56/1000	5.6 %
8	65/1000	6.5 %
9	70/1000	7.0 %
10	60/1000	6.0 %
11	59/1000	5.9 %
12	70/1000	7.0 %
13	69/1000	6.9 %
14	71/1000	7.1 %
15	77/1000	7.7 %
16	68/1000	6.8 %
17	60/1000	6.0 %
18	64/1000	6.4 %
19	72/1000	7.2 %
20	65/1000	6.5 %
Average	67.6 / 1000	6.76 %
Standard Deviation	6.54 / 1000	0.654 %

Table 5.28 – Packet drop rate of direct Ethernet connection measured on Oct. 8^{th}

No	Number of Packets dropped	Percentage
1	58/1000	5.8 %
2	60/1000	6.0 %
3	73/1000	7.3 %
4	62/1000	6.2 %
5	59/1000	5.9 %
6	71/1000	7.1 %
7	62/1000	6.2 %
8	70/1000	7.0 %
9	65/1000	6.5 %
10	59/1000	5.9 %
11	70/1000	7.0 %
12	66/1000	6.6 %
13	68/1000	6.8 %
14	59/1000	5.9 %
15	72/1000	7.2 %
16	65/1000	6.5 %
17	73/1000	7.3 %
18	64/1000	6.4 %
19	59/1000	5.9 %
20	66/1000	6.6 %
Average	65/1000	6.5 %
Standard Deviation	5.1/1000	0.51 %

Table 5.29 – Packet drop rate of direct Ethernet connection measured on Nov. 8^{th}

No	Number of Packets dropped	Percentage
1	51/1000	5.1 %
2	65/1000	6.5 %
3	70/1000	7.0 %
4	63/1000	6.3 %
5	74/1000	7.4 %
6	66/1000	6.6 %
7	77/1000	7.7 %
8	70/1000	7.0 %
9	68/1000	6.8 %
10	79/1000	7.9 %
11	56/1000	5.6 %
12	58/1000	5.8 %
13	66/1000	6.6 %
14	74/1000	7.4 %
15	63/1000	6.3 %
16	53/1000	5.3 %
17	72/1000	7.2 %
18	71/1000	7.1 %
19	71/1000	7.1 %
20	68/1000	6.8 %
Average	66/1000	6.6 %
Standard Deviation	7.6 / 1000	0.76

5.4.3.2 Private Communication Network

Table 5.30 – Packet drop rate of private communication network measured on Sept. 8th

No	Number of Packets dropped	Percentage
1	66/1000	6.6 %
2	55/1000	5.5 %
3	71/1000	7.1 %
4	63/1000	6.3 %
5	63/1000	6.3 %
6	71/1000	7.1 %
7	57/1000	5.7 %
8	53/1000	5.3 %
9	52/1000	5.2 %
10	74/1000	7.4 %
11	63/1000	6.3 %
12	57/1000	5.7 %
13	64/1000	6.4 %
14	71/1000	7.1 %
15	56/1000	5.6 %
16	74/1000	7.4 %
17	64/1000	6.4 %
18	62/1000	6.2 %
19	52/1000	5.2 %
20	58/1000	5.8 %
Average	62.3 / 1000	6.23 %
Standard Deviation	7.21 / 1000	0.721 %

Table 5.31 – Packet drop rate of private communication network measured on Oct. 8th

No	Number of Packets dropped	Percentage
1	55/1000	5.5 %
2	59/1000	5.9 %
3	61/1000	6.1 %
4	68/1000	6.8 %
5	48/1000	4.8 %
6	65/1000	6.5 %
7	52/1000	5.2 %
8	47/1000	4.7 %
9	65/1000	6.5 %
10	55/1000	5.5 %
11	58/1000	5.8 %
12	60/1000	6.0 %
13	70/1000	7.0 %
14	66/1000	6.6 %
15	64/1000	6.4 %
16	68/1000	6.8 %
17	61/1000	6.1 %
18	71/1000	7.1 %
19	64/1000	6.4 %
20	76/1000	7.6 %
Average	61.6 / 1000	6.16 %
Standard Deviation	7.61 / 1000	0.761 %

Table 5.32 – Packet drop rate of private communication network measured on Nov. 8th

No	Number of Packets dropped	Percentage
1	62/1000	6.2 %
2	78/1000	7.8 %
3	59/1000	5.9 %
4	68/1000	6.8 %
5	60/1000	6.0 %
6	67/1000	6.7 %
7	70/1000	7.0 %
8	59/1000	5.9 %
9	62/1000	6.2 %
10	60/1000	6.0 %
11	61/1000	6.1 %
12	65/1000	6.5 %
13	53/1000	5.3 %
14	74/1000	7.4 %
15	66/1000	6.6 %
16	55/1000	5.5 %
17	61/1000	6.1 %
18	72/1000	7.2 %
19	65/1000	6.5 %
20	62/1000	6.2 %
Average	63 /1000	6.39 %
Standard Deviation	6.24 /1000	0.624 %

5.4.3.3 Public Communication Network

Table 5.33 – Packet drop rate of public communication network measured on Sept. 8th

No	Number of Packets dropped	Percentage
1	65/1000	6.5 %
2	56/1000	5.6 %
3	62/1000	6.2 %
4	74/1000	7.4 %
5	72/1000	7.2 %
6	75/1000	7.5 %
7	70/1000	7.0 %
8	57/1000	5.7 %
9	70/1000	7.0 %
10	67/1000	6.7 %
11	68/1000	6.8 %
12	60/1000	6.0 %
13	72/1000	7.2 %
14	71/1000	7.1 %
15	58/1000	5.8 %
16	59/1000	5.9 %
17	74/1000	7.4 %
18	73/1000	7.3 %
19	66/1000	6.6 %
20	68/1000	6.8 %
Average	66.8/1000	6.68 %
Standard Deviation	6.19 /1000	0.619 %

Table 5.34 – Packet drop rate of public communication network measured on Oct. 8th

No	Number of Packets dropped	Percentage
1	67/1000	6.7 %
2	51/1000	5.1 %
3	81/1000	8.1 %
4	69/1000	6.9 %
5	54/1000	5.4 %
6	60/1000	6.0 %
7	64/1000	6.4 %
8	66/1000	6.6 %
9	110/1000	11.0 %
10	82/1000	8.2 %
11	54/1000	5.4 %
12	66/1000	6.6 %
13	73/1000	7.3 %
14	76/1000	7.6 %
15	50/1000	5.0 %
16	76/1000	7.6 %
17	55/1000	5.5 %
18	61/1000	6.1 %
19	70/1000	7.0 %
20	65/1000	6.5 %
Average	67.5/1000	6.75 %
Standard Deviation	13.7 /1000	1.37 %

Table 5.35 – Packet drop rate of public communication network measured on Nov. 8th

No	Number of Packets dropped	Percentage
1	70/1000	7.0 %
2	65/1000	6.5 %
3	76/1000	7.6 %
4	80/1000	8.0 %
5	75/1000	7.5 %
6	66/1000	6.6 %
7	62/1000	6.2 %
8	67/1000	6.7 %
9	75/1000	7.5 %
10	66/1000	6.6 %
11	53/1000	5.3 %
12	78/1000	7.8 %
13	64/1000	6.4 %
14	53/1000	5.3 %
15	65/1000	6.5 %
16	82/1000	8.2 %
17	64/1000	6.4 %
18	67/1000	6.7 %
19	68/1000	6.8 %
20	73/1000	7.3 %
Average	68.4/1000	6.84 %
Standard Deviation	7.85/1000	0.785 %

5.5 Discussion

Three criteria are used as performance measures for the implemented communication network, namely, throughput, latency, and reliability. The above measurements indicate that the proposed scheme performs satisfactorily under different conditions as explained below.

5.5.1 Throughput

As can be seen in Tables 5.9-5.17, throughput values for the suburban scenario and for the private link scenario are approximately the same (about 550 bps for a single PV inverter site), but are substantially higher than those of the public link scenario (about 150-180 bps). Such differences are due to other sources of traffic on the public link that compete with the flow of data between the supervisory control center and the PV inverter site as well as to the differences in raw bit rates. This competition (and the resulting reduction in the throughput) increases the latency that may be attributed to lost packets, or to the contention between packets from other sources, or to the raw bit rate. When the number of PV inverter sites is increased, the throughput value for each PV inverter site remains the same. This is because of the fact that polling is utilized; hence, at each instant, only one PV inverter site is using the network link. However, as the number of PV inverter sites increases, it takes longer to poll a PV inverter site again, as other PV sites must be serviced before the supervisory control center polls that site again. This increases the period of time between two successive polls for any given PV inverter site. In spite of this, the latency for any given PV inverter site (defined as the time between a data request by the supervisory control center and provision of data by the PV inverter site) remains the same, and is independent of the number of PV inverter sites.

5.5.2 Latency

As can be seen in Tables 5.18-5.26, measured latencies for the suburban scenario and for the private link scenario are approximately the same (about 190 ms for a single PV inverter site), but are substantially lower than those of the public link scenario (about 570-700 ms). As stated above, such differences are due to other sources of traffic on the public link that compete with the flow of data between the supervisory control center and the PV inverter site, or to the raw bit rate. This would increase the latency. Note that even in the worst case, measured latencies for a single PV inverter site are well within the stated requirements in Section 1.5, i.e., the latency is still less than 5 seconds. As stated earlier, the latency for any given PV inverter site (defined as the time between a data request by the supervisory control center and provision of data by the PV inverter site) remains the same, and is independent of the number of PV inverter sites.

5.5.3 Reliability

As can be seen in Tables 5.27-5.35, the percentages of dropped packets for all three scenarios are approximately the same (about 6.5%). This is in spite of the fact that measured throughput values and latencies differ substantially across different scenarios. This means that in the three examined scenarios, packet drops are caused by insufficient processing power at the PV inverter site. In other words, the PV inverter site may be busy with other tasks, and cannot detect an incoming request for data, resulting in packet drops. However, since the packet recovery mechanism is implemented at the supervisory control center, packet drops at the rate of about 6.5% are easily recovered, resulting in a pro-rata increase in latency, which as discussed above, is still satisfactory.

CHAPTER 6

CONCLUSIONS AND FUTURE WORK

6.1 Conclusions

In this thesis, a framework for establishing a communications network for supervision and control of renewable sources of energy in hybrid mini grids was developed and presented. In the proposed framework, existing and readily available hardware and software modules are utilized and various software pieces are developed and written to integrate all elements of the network with a view to satisfy the problem statement's requirements and assumptions.

The proposed approach is based on obtaining sampled values of interest, e.g., measured RMS voltages, from any given inverter site and providing such values to the supervisory control center via any existing communications media between the two locations by utilizing Ethernet networking technologies. It also employs polling at the supervisory control center to obtain the measured values from each inverter singularly and in circular order. This would guarantee fairness in communicating with all inverters in a timely manner. The proposed framework is capable of sending inverter settings from the supervisory control center to the respective inverter. As such, the network is half-duplex. In doing so, the emphasis is on developing a cost effective approach by utilizing existing and readily available hardware modules and system software, but developing vital missing software elements needed for the application of interest in this thesis.

Considering the nature of required communications between each inverter and the supervisory control center, the proposed network topology is hub-and-spokes. The hub is the supervisory control center and each inverter communicates only with the hub through a communication media (spoke) between the two.

Furthermore, a set of performance measures that are normally used to assess the performance of data communications networks is identified, and their values are obtained via extensive tests. The results show that the proposed framework is capable of providing communications serviced between the supervisory control center and inverter sites in a stable, robust, and satisfactory manner.

6.2 Future Work

There are a number of issues that are still open problems in establishing a communications network for hybrid mini grids in particular and for smart grids in general. The most important one is that it is very desirable to use the grid itself as its communications media, i.e., removing the need for a separate media for the communications network. Existing power line communications systems either have insufficient bandwidth, or cover very short distances. The challenge is to develop a wide-band power line communications system that can cover long distances (in the order of tens of kilometers) in a secure manner, without causing unacceptable interference on other services, without producing undesirable distortions on the grid's voltage, and without compromising users' privacy. The problem is particularly aggravated by unavoidable use of transformers, switch gears, etc., and interconnection of high voltage transmission grids to medium and low voltage distribution grids.

Another topic that is still under-developed is security. Any publicly accessible network, irrespective of its communications media, is prone to hacking and unauthorized access. Two major concerns have been raised in this regard. First, consumers' privacy may be compromised in terms of their specific usage of electricity; and second, control and management of the grid and its integrity may be endangered by inadvertent or targeted attacks. A totally secure network is an ideal and theoretical concept, and any real network may suffer from security breaches. Fixing all security weaknesses is very expensive and continuously requires new hardware, new software, and manpower. It also creates overhead in the transmitted information, thereby efficiency is reduced.

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