

Designing and Testing of a Three-Phase AC Net Meter for V2G Application

A Thesis submitted in fulfillment of the requirement for the award of the degree of

DOCTOR OF PHILOSOPHY

in

ELECTRICAL AND INSTRUMENTATION ENGINEERING DEPARTMENT

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AUGUST 2023

Certificate

I, Amrit Pal Kaur, Registration No. 901904001, hereby declare that the thesis entitled **“Designing and Testing of a Three-Phase AC Net Meter for V2G Application”** submitted to the Electrical and Instrumentation Engineering Department at Thapar Institute of Engineering & Technology, Patiala, Punjab, India is an authenticated record of my own work for the award of the degree of **“Doctor of Philosophy”** under the supervision of Dr. Mukesh Singh. This report has not been submitted to any other Institution or University for award other degree.

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Acknowledgments

First and foremost, I would like to thank the God Almighty for giving me the strength, knowledge, ability, and opportunity to undertake this research study and to persevere and complete it satisfactorily. Without his blessing, this achievement would not have been possible.

I would also like to acknowledge my indebtedness and render my warmest thanks to my supervisor, *Dr. Mukesh Singh* (Professor, EIED, TIET), who made this work possible. Their friendly guidance and expert advice have been invaluable throughout all stages of the work.

I express my sincere gratitude to *Dr. R. S. Kaler*, the former head, *Dr. Mandeep Singh*, Ph.D. coordinator and members of my doctoral committee, *Dr. Nirbhowjap Singh*, *Dr. K. K. Gupta*, and *Dr. Sanjay Sharma*, for their constructive suggestions and for ensuring the correct pace of my work. I even sincerely thank *Dr. Sukumar Mishra* (Indian Institute of Technology, Delhi), *Mr. Sanket Karlekar* (Director, Aspirant Solutions, Pvt Ltd, Nashik, India), *Dr. Prashant Singh Rana* (Professor, CSE, TIET), and *Dr. Husanbir Singh Pannu* (Assistant Professor, CSE, TIET) for their valuable suggestions in the work and continuous support and encouragement. I am also obliged to the Director, *Dr. Padmakumar Nair*, DoRSP, *Prof. Dr. Rafat Siddique*, and the management of Thapar Institute of Engineering and Technology, who provided me with all the necessary resources and facilities to complete my work.

The greatest indirect contribution to this work has been from my mother, *Mrs. Karamjit Kaur*, and my father, *Capt. Kamikkar Singh*, who made me capable of reaching this point in life, and for giving me their kind support and love. I especially thank my nephew *Mr. Bhavandeep Singh* to adore what I do. I also want to thank my senior *Dr. Vinit Kumar* (Research Engineer at Aix

Marseille University) and my friends *Mr. Ravi Teja, Mr. Shahrukh Alam, Ms. Kratika Yadav, Mr. Sandeep Singh, Mr. Ashiq Bhat, Mr. Rahul Kamboj, Ms. Riya Sharma* and *Mrs. Reeta* for their constant encouragement and support throughout the journey.

I would like to thank *Council of Scientific & Industrial Research (CSIR)* and *Department of Science & Technology (DST)* for providing me with financial support in the form of a research fellowship to complete my Doctoral studies.

Place: Patiala

April, 2023


(Amrit Pal Kaur)

Abstract

In today's scenario, the estimated exponential growth of Electric vehicles (EVs) has raised concerns about the spike in electricity demand. Vehicle-to-Grid (V2G) technology has emerged as an effective solution that enables the EV as a prospective energy source irrespective of time and atmospheric conditions. It connects the vehicle to the grid in two operating modes: charging and discharging or V2G mode. While charging, EV acts as an electric load and draws current from the grid. In contrast, in discharging mode, EV acts as an energy source and feeds the current back to the grid when needed. The idea benefits to balance the electric grid by supplying the energy back to the grid in peak demanding hours. Overall, it enhances grid performance by improving grid efficiency, stability, and reliability. Establishing the V2G application involves three elements amongst the bidirectional intelligent metering plays a significant role. However, the lack of bi-directional metering concerning EV users and service providers deters the V2G applicability in real. Hence, bi-directional metering equipment and infrastructure are developed for the V2G application.

Firstly, the research aimed to design and develop a cost-effective Three-Phase AC Net Meter for easy acceptance of the V2G application in society. The Net Meter is developed at technology readiness level (TRL) 9 for V2G-enabled charging stations at levels 1 and 2. The compliance considers the automotive grade with the International Electrotechnical Commission (IEC) standards to assure class 1 accuracy. C2000 Digital Signal Processor (DSP) based TMS320F28069 microcontroller has reduced the cost involved with affecting the performance needed for the application. The prototype assures the automotive industry standards (AIS) for electromagnetic compatibility in the practical environment. In the software implementation, coherent sampling is adopted to

compute Fast-Fourier Transform (FFT). The choice of coherent sampling has reduced the overhead involved in identifying the suitable window for the application, and it changes the sampling rate with the change in the input frequency of the grid signal. The technique has shown better spectral resolution and harmonic detection.

In the second work, an internet-of-thing (IoT) based Net Meter is deployed as a data source and recipient of information between EV, grid operator, and EVSE for the V2G technology. The device enables real-time data accumulation and connects the BMS of the Li-ion battery using MODBUS-RTU protocol to read the battery status at regular intervals of time. The developed prototype is configured as both master-slave; it operates in master mode while initiating communication with BMS. The EV parameters fetching and evaluation help to establish a coordinated charging-discharging environment without compromising the battery life. Net Meter accounts for the energy required or will be generated by the EV when connected based on the requested operation. Besides, the device is embedded with a simplified software 2-point calibration process to accurately rescale the input sensors. The results have shown that the prototype has attained class 1 accuracy. Moreover, the ToU attribute is integrated to allow dynamic billing with evolving techniques and presents a protection mechanism against physical tampering at the EV prosumer end.

Lastly, the third work proposes a research methodology for optimal demand-side management (DSM) using EVs. Aggregators (AG) are programmed to generate time-of-use (ToU) based tariff rates to motivate the EV prosumers to participate in the V2G application. Concerning this, a novel mathematical model is proposed to calculate the tariff rates using EVs' peak and off-peak contribution coefficients. In addition, to mitigate the situation of simultaneous EV charging that may alter the consumption curve, a conditional prioritization is presented based on EVs' state-of-charge (SoC). The best and worst-case computational complexity in the proposed technique is $O(N)$ due to the involvement of the linear search algorithm. In the simulation, the AG manages the data from multiple IoT-based Net Meters and effectively reduces the peak consumption by 6%–7% with an elasticity of 0.45.

List of Publications

Journal Publications (SCI/SCIE)

1. Amrit Pal Kaur and Mukesh Singh, “Design and development of a three-phase net meter for V2G enabled charging stations of electric vehicles,” **Sustainable Energy, Grids and Networks**, vol.30, pp. 100598, 2022. (SCIE, IF-5.405)
2. Amrit Pal Kaur and Mukesh Singh, “Time-of-Use tariff rates estimation for optimal demand-side management using electric vehicles,” **Energy**, vol. 273, pp. 127243, 2023. (SCI, IF-8.857)

Conference Publications

1. Amrit Pal Kaur and Mukesh Singh, “IoT-Based Net Meter for Vehicle-to-Grid Application with Time-of-Use,” **2nd International Conference on Smart Technologies for Smart Nations**, 18-19 August, 2023, Amity Global Institute, Singapore.

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List of Abbreviations

AC	Alternating Current
ADC	Analog-to-Digital Converter
AG	Aggregator
AMI	Advanced Metering Infrastructure
ASIC	Application-Specific Integrated Circuit
BMS	Battery Management System
CCS	Code Composer Studio
COSEM	Companion Specification for Energy Metering
CT	Current Transducer
DC	Direct Current
DLMS	Device Language Message Specification
DR	Demand Response
DSM	Demand-Side Management
DSP	Digital Signal Processor
EMI	Electromagnetic Interference

EV	Electric Vehicle
EVSE	Electric Vehicle Supply Equipment
FAME	Faster Adoption and Manufacturing of Electric Vehicles
FAN	Field Area Network
FDST	Fast Discrete Stockwell Transform
FFT	Fast-Fourier Transform
FIR	Finite Impulse Response
FPGA	Field Programmable Gate Array
FT	Fourier Transform
G2V	Grid-to-Vehicle
HAN	Home Area Network
HT	Hilbert Transform
IA	Instrumentation Amplifier
ICT	Information and Communication Technology
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IEN	Intelligent Energy Network
IoT	Internet-of-Things
JSON	JavaScript Object Notation
Li-ion	Lithium-ion

LPF	Low Pass Filter
MDMS	Meter Data Management System
MQTT	Message Queuing Telemetry Transport
NSGM	National Smart Grid Mission
PIC	Peripheral Interface Controller
PV	Photovoltaic
RMS	Root-Mean-Square
RTC	Real-Time Clock
RTU	Remote Terminal Unit
SAE	Society of Automotive Engineers
SoC	State-of-Charge
SoH	State-of-Health
SPI	Serial Peripheral Interface
ST	Stockwell Transform
STFT	Short-Time Fourier Transform
TE	Tariff Elasticity
THD	Total-Harmonic Distortion
ToU	Time-of-Use
UART	Universal Asynchronous Receiver-Transmitter
V2G	Vehicle-to-Grid

VT	Voltage Transducer
WAN	Wide Area Network
WT	Wavelet Transform
ZCD	Zero Crossing Detector

Chapter 1

Introduction and Thesis Organization

The vast adoption of electric vehicles (EVs) and increased dependency on electronic devices have made the electricity demand a critical challenge. New techniques and concepts have revolutionized various applications in the smart city era. The primary aspect of the smart city is the smart grid which accomplishes automation and communication capability in the electric grid. The smart grid manages various energy resources such as wind, solar, coal, hydroelectric plants, and EVs, shown in Fig. 1.1. Here, the power distribution system is controlled intelligently through an intelligent energy network (IEN) that efficiently utilizes resources. The benefits of the smart grid have attracted many developed and developing nations to adopt this concept for providing intelligent solutions for power utilization. The government of India accelerated National Smart Grid Mission (NSGM) in 2015 to establish the smart grid environment in India [1]. NSGM's vision is a secure, adaptive, and sustainable ecosystem to provide a reliable energy system for all active stakeholders. The IEN deployment in the smart grid relies on the advanced metering infrastructure (AMI) to enable two-way communication over the distribution network. AMI targets energy monitoring and controls the flow of energy from the point of generation to consumption.

Among the aforementioned energy resources in the smart grid, EV growth is paramount to balance the grid. It has revolutionized the transportation system globally by reducing the environmental pollution. EVs are composed of a Lithium-ion (Li-ion) battery that charges through the

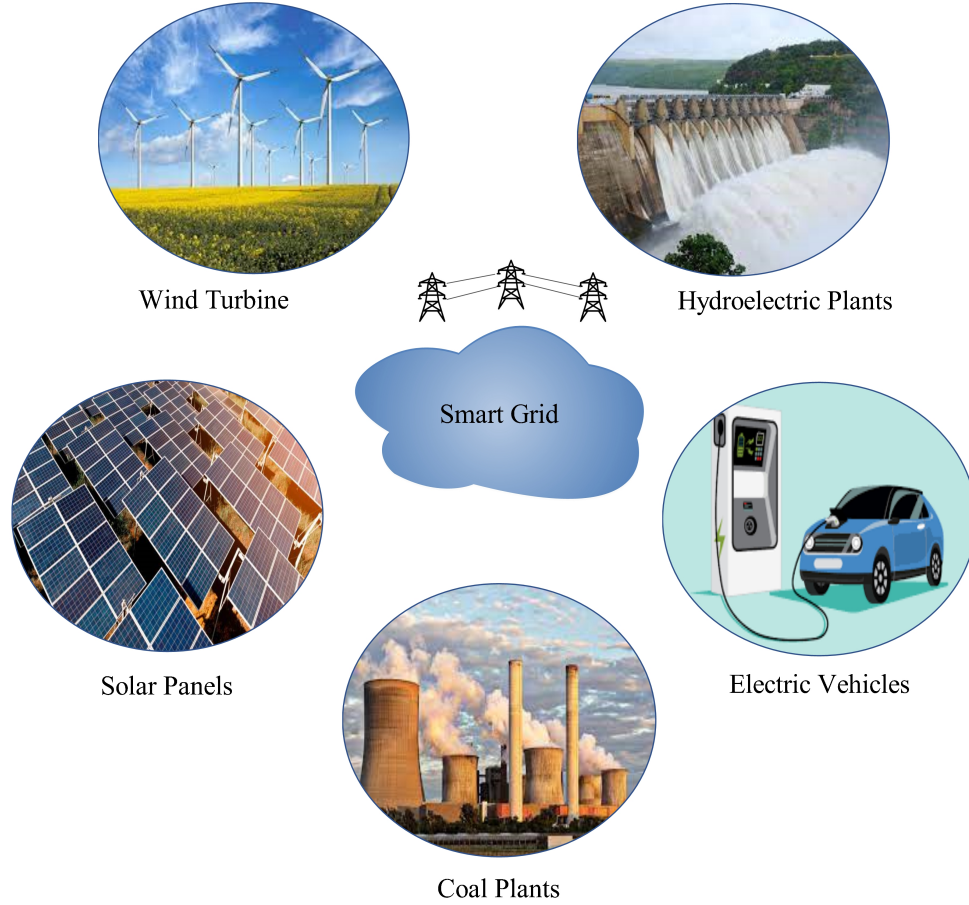


Figure 1.1: Energy resources managed by the smart grid.

electric grid to commute at a distance. Thus, it reduces greenhouse gas emissions and the dependency on fossil fuels. Various plans have been launched worldwide to raise the count of EVs on roads, focusing on the benefits of EVs. Globally, around 17 million EVs have been sold since 2012 and it is expected to reach 145 million by 2030. Even the Indian government has approved Faster Adoption and Manufacturing of EVs in India (FAME-India) with National Electric Mobility Plan 2020 aimed to release millions of hybrid vehicles and FAME II with a 3-year subsidy program [2]. Fig. 1.2 shows the annual EV sales till 2021 of countries such as India, Europe, and China. The extensive penetration of EVs in the smart grid raises the imbalance between the demand and supply of energy. This energy gap may lead to power outages in different areas and disturb the standard functionality of the smart grid. Analyzing EV growth, the anticipated rise in the EV market is around 20 million, which is 100 million tiny mobile energy storage with 5

TWh aggregated capacity by 2030 [3]. EVs as energy storage brings the concept of vehicle-to-grid (V2G) technology where EVs are considered an alternative energy source in the smart grid [4].

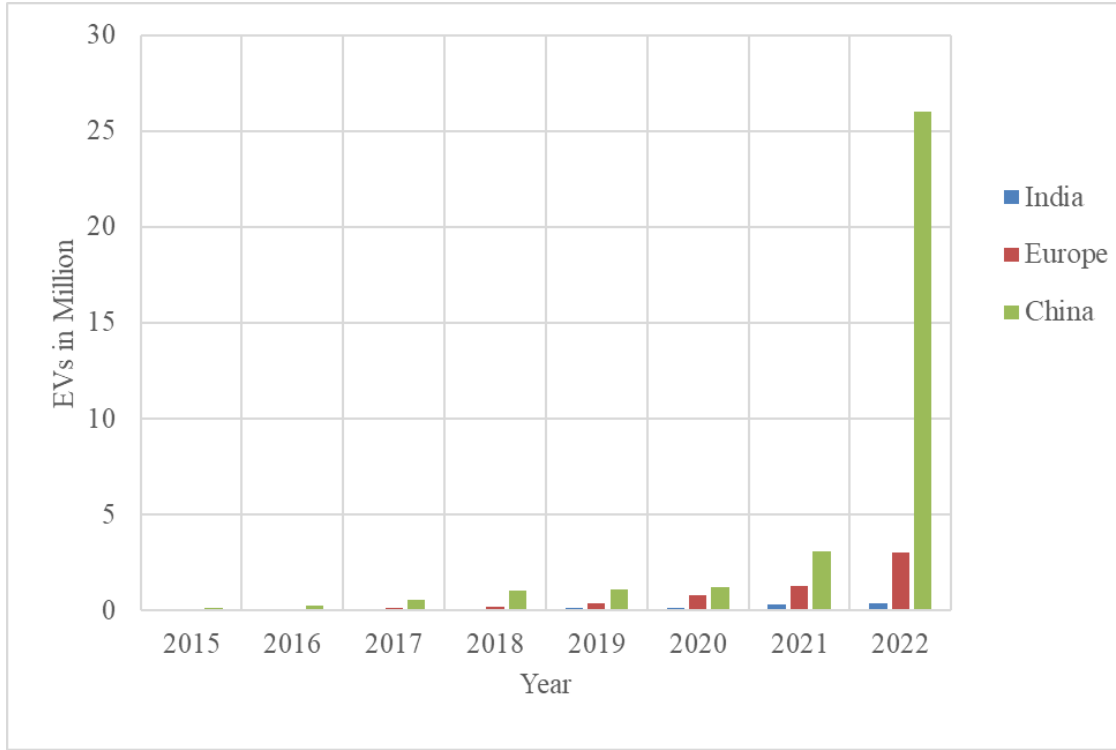


Figure 1.2: Annual growth of EV sales in different countries.

To cater to the increased energy demand due to the exponential growth of EVs, V2G is an emerging technique. It can regulate the power flow when the electricity demand is high by supplying the energy back to the grid. At present, one of the constraints in electrical engineering is the expansion and application of smart grids in V2G. The existing AMI can integrate the bi-directional functionality of EVs by configuring the information and communication technology (ICT) tools to withstand the V2G infrastructure.

1.1 Smart Grid

A smart grid is an electric grid with energy management capability from different conventional and non-conventional sources. It efficiently manages energy utilization based on the information available on energy generated and consumed [5]. Fig. 1.3 depicts all the smart grid entities gen-

erating information related to electric power generation and consumption. Table 1.1 presents the coverage range, data rate, and techniques supported by the networks in the smart grid environment. A wide area network (WAN) connects all the devices in a larger geographic area to communicate. It collects all information in the distribution network at the utility offices. A field area network (FAN) contains consumers' data and connects with the field control or intelligent devices. At the same time, a home area network (HAN) connects the home appliances and monitors the energy flow through smart meters that establishes the communication network. The information provided is significant for efficient energy utilization in the distribution network and improved reliability.

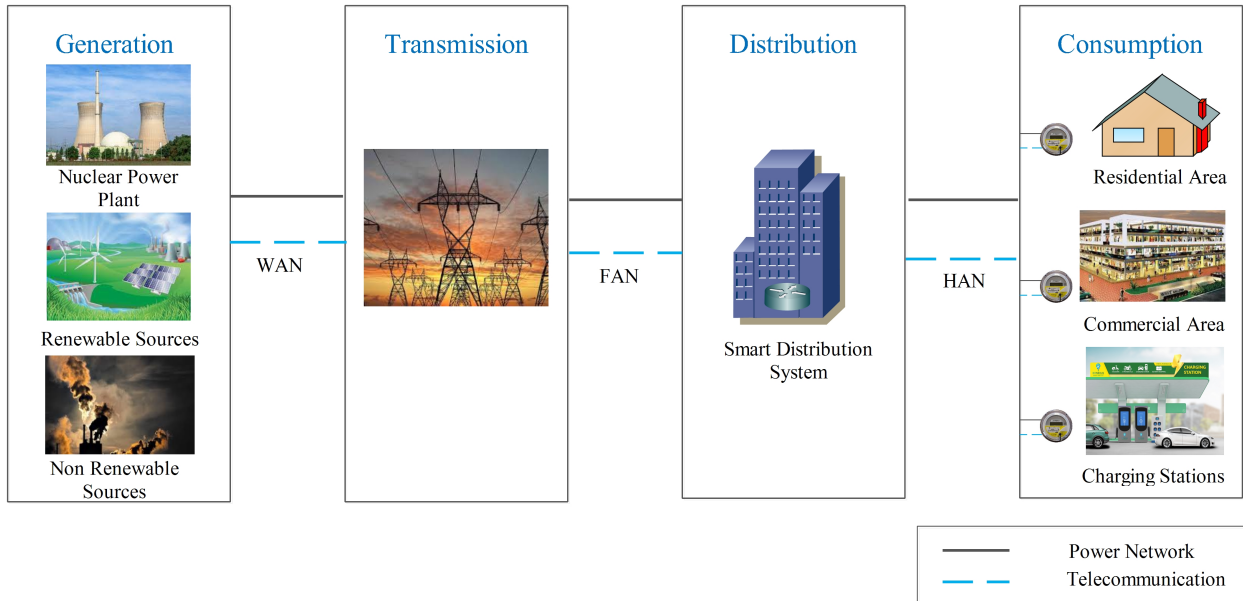


Figure 1.3: Smart grid communication system.

The smart grid has raised the opportunity of the energy industry to a new era of availability, efficiency, and reliability of the distribution system. The transition faces challenges in technology improvement, standards and regulations, and consumer awareness. The benefits of a smart grid include the following:

- Efficient energy utilization.
- Reduced operational and management costs for utilities.
- Lower tariff rates for consumers.

- Reduced stress on the nation's grid.

Table 1.1: Communication techniques used in smart grid.

Coverage Range	Network	Data Rate	Communication Technology
10-100 km	WAN	10 Mbps - 1 Gbps	Cellular Optical Fiber Cable Synchronous Digital Hierarchy
100 m - 10 km	FAN	100 kbps - 10 Mbps	WiMax WiFi Cellular PLC RF Mesh
1 - 100 m	HAN	1 - 100 kbps	WiFi ZegBee Bluetooth

The smart grids support different applications such as smart homes where the home appliances are controlled optimally, roof-top PV solar panels for bi-directional flow of electricity, EV smart charging, and emerging V2G technology. The complete establishment of a smart grid depends upon the data gathering and analysis carried out on AMI. It facilitates data collection, analysis, computation, and analytic exchange of information for the systematic use of electricity. However, the requirements of AMI vary for diverse applications concerning reliability, latency, and operable bandwidth.

1.2 Vehicle-to-Grid Technology

The growth of EVs and smart grid has led to the concept of V2G technology. V2G is the emerging field of research that integrates EVs in two operational modes to the smart grid: charging and discharging (as shown in Fig. 1.4). In charging mode, EV behaves like an electrical load since the battery draws power from the grid for mobility, which is the grid-to-vehicle (G2V) technique. On the other hand, in discharging mode, EV acts as a prospective energy source for injecting electricity back into the grid using the V2G technique [6]. Thus, V2G technology supports the bi-directional

energy exchange between the smart grid and EVs to balance the increased electricity demand. The idea benefits to 'balance' the national electricity network and generate revenues for the EV owners by supplying electricity in peak demand hours. It utilizes the EV battery to source the electricity in demanding hours irrespective of the time and atmospheric conditions compared to other renewable energy sources. It overcomes the restriction of using electricity anywhere instead of only where it is stored. V2G is still a developing technology; therefore, it is difficult to say about its adoption worldwide.

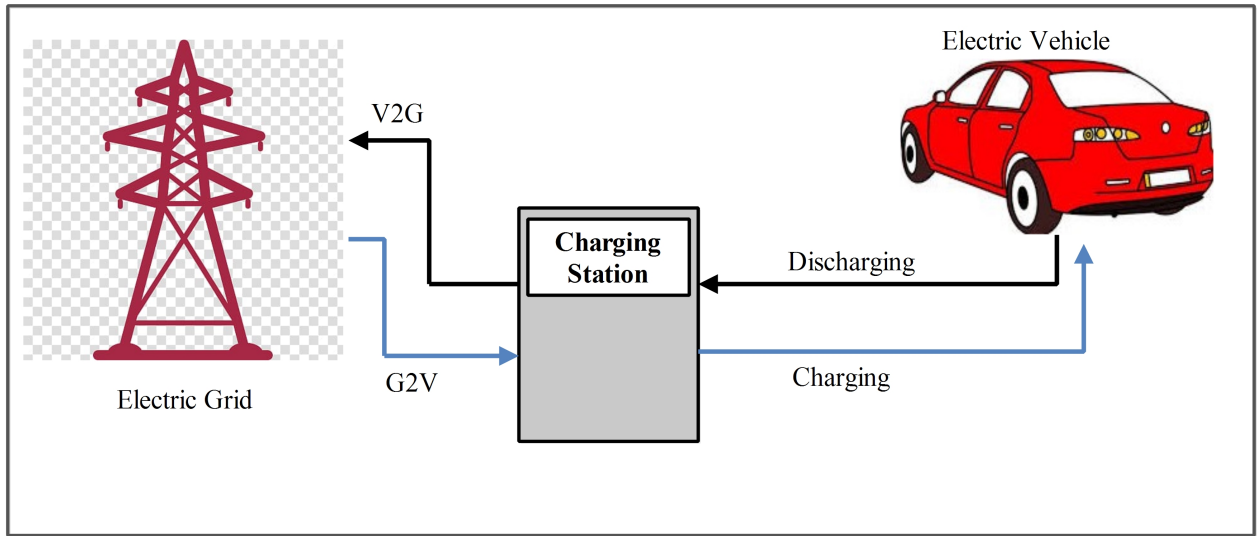


Figure 1.4: Operational modes of V2G technology.

Worldwide, countries are exploring the area of V2G technology to give an idea of the scope of development and performance in the existing smart grid infrastructure. In reference to the United States, the University of California San Diego has installed V2G chargers under 6 Nissan and 2 Honda V2G funded projects. Denmark and the United Kingdom have executed over 1500 V2G enabled chargers to test the performance of V2G. Similarly, the Indian government has supported various projects under the Department of Science and Technology to anticipate the need and analyze the challenges of V2G in the Indian grid. It is indispensable to consider that the V2G technique is in its developing stage. Research has initiated to lay hold of its successful establishment in society. The successful operation of V2G technology relies on three elements: power connection to the grid, control and communication between EVs and the grid operator, and on-board/off-board

intelligent metering [4].

1.2.1 Benefits of V2G

The establishment of V2G technology targets to balance the electric load by reducing the peak hours consumption of the electric grid. The technique benefits the grid performance and encompasses various advantages for EV owners and utility providers [7].

1. The existing renewable energy sources, such as wind turbines and solar farms, cannot guarantee constant electricity production. They repeatedly shut down when power generation exceeds the demand. EVs can store the excess green energy, and V2G will allow continuous supply.
2. V2G enables Demand-side Management (DSM) that helps to reduce the stress on the electric grid by supplying the energy back in peak demanding hours of the grid.
3. It enhances the sale of EVs by providing the opportunity to earn while feeding the energy back to the grid for EV owners. Thus, reducing the expense of ownership of fleets.
4. Energy providers can trade electricity and optimize overall consumption.

1.2.2 Demand-Side Management

DSM is an initiative to restructure the power system [8]. It aims to benefit both the electric grid and consumers by improving reliability and reducing electricity bills, respectively [9]. DSM controls the power consumption either centrally, where the grid side controls the load, or individually where the consumers proactively manage their energy consumption, known as demand response (DR) [10]. Fig. 1.5 illustrates a day's varying load consumption curve from the consumer's side. When energy utilization is more than the grid power supply capability, the peak hours and low demand are the off-peak hours. DSM aims to stabilize the load profile, reducing the grid's stress and improving the power quality. The trending usage of EVs and evolving V2G technique makes them

an appropriate choice for DSM without any substantial expansions in the grid [11, 12]. DSM using EVs supports DR, where EV owners voluntarily shift the EV charging from peak to off-peak hours and V2G mode, EV owners supply the EV battery energy to the grid in peak hours [13]. EVs are advantageous as it is available irrespective of the time or atmospheric condition and could support peak hours [14]. Dynamic pricing plays a significant role in stimulating the implementation of DSM using EVs. Here, the utilities charge more for electricity consumption in peak hours and low prices in off-peak hours.

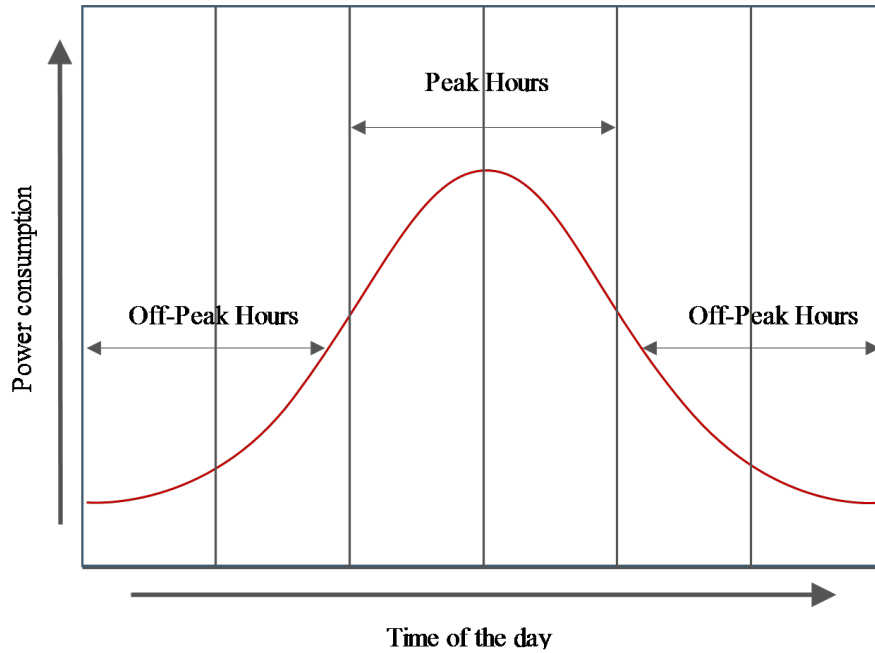


Figure 1.5: Typical consumption curve with peak and off-peak hours.

1.2.3 Challenges in V2G Application

The major challenges in the successful establishment of the V2G application are listed below:

1. **Effects on Electronic Equipment:** Existing EV chargers use unidirectional converters to charge the Li-ion batteries through the electric grid. These chargers failed to supply the stored energy of the Li-ion battery back to the grid and, thus, were replaced by the bi-directional converters. However, the bi-directional chargers are prone to noise and electro-

magnetic interfaces (EMI) due to high-frequency switching techniques used in the construction [15, 16]. Thus, it affects the performance of electronic devices in the infrastructure, resulting in malfunctioning and inaccurate monitoring. In addition, the shift towards fast charging infrastructure demands an acceptable performance of electronic devices.

2. **Battery Degradation:** EVs are composed of Li-ion batteries which are the prime resource of energy where it can be stored or retrieved when needed. The frequent charging-discharging cycles of Li-ion batteries may affect the battery life [17, 18]. Thus, efficient operation-ability demands close monitoring and controlled charging-discharging in the V2G application.
3. **Marketing Strategy:** EV prosumers are paid while discharging the battery back to the grid. If the EV owners generate high revenues covering their charging and battery cost, they participate in the process. However, it is equally important to recover the energy utility expense. Thus, deciding the appropriate tariff rates is essential to motivate EV prosumers to participate in the V2G application without affecting the grid performance [19].

In summary, the significant contribution is determined by the intelligent metering that initiates the controlled charging-discharging of EVs and aims to benefit both EV prosumers and service providers. The intelligent metering in V2G supports the bi-directional monitoring and communication feature that brings the net metering concept. However, the lack of bi-directional metering capability concerning EV users and service providers or compensation deter V2G applicability. Therefore, extending the AMI functionality to facilitate successful V2G establishment is necessary with negligible effect on the power quality and battery life. Thus, the Net Meter configuration concerning the V2G environment can play a vital role.

1.3 Advanced Metering Infrastructure

AMI describes two-way communication over a distribution network for controlled energy usage. It is the backbone of the smart grid incorporating supply and demand features by integrating renew-

able and non-renewable energy sources [20–22]. AMI targets remote meter reading for accurate billing and identifies network issues and electricity theft. The determining factors supported by AMI are efficient power utilization and emergency power supply during power shortages. It aims to resolve load-shedding problems by proactively managing power consumption. The basic building blocks of electrical AMI are energy consumption monitoring devices, data transmission networks, and meter data management systems (MDMS), as shown in Fig. 1.6. At the customer end, energy meters and sensors monitor the electricity consumption. The data transmission network establishes the communication channel for information transmission using power line communication, broadband over power lines, radio frequency, or public data networks. Finally, MDMS collects and stores the data obtained from multiple meters or sensors that users and other programs can retrieve.

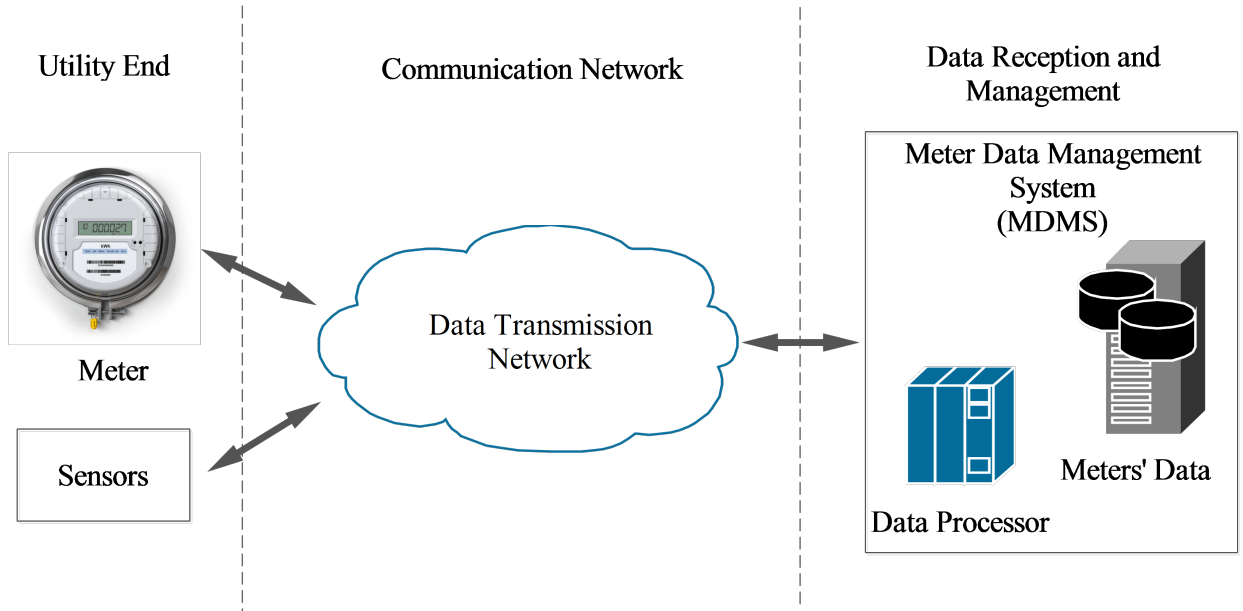


Figure 1.6: Building of advanced metering infrastructure.

AMI helps eradicate the need for on-site meter readings and the response to power outages. The smart meter is the primary ICT tool of AMI for information exchange and data accumulation. It enables energy monitoring, data collection, and transfer of information over the distribution network [23, 24]. Smart meters are electronic devices installed at the consumer end to support automated billing and control smart home appliances. In contrast, the conventional meter provides

only energy monitoring and fails to attain the automotive requirements of AMI [4,25,26]. Further, the smart grid enables the bi-directional flow of energy, which is presently observed in roof-top photovoltaic (PV) solar applications. It omits the investment cost behind energy storage devices and reduces consumer bills [27]. Net Meters installed at the consumer end allow the residential or commercial users to feed the excess energy back to the grid. These Net Meters are similar to smart meters, except they generate the net bill to be paid by the consumers. The emerging V2G application relies on the same principle where the bi-directional flow of electricity between the EV battery and the smart grid occurs. However, V2G is in the preliminary stage of development and requires a lot of effort in AMI to meet the challenges of intelligent metering in the application [23,24].

1.4 Net Meter

The fundamental component in the intelligent metering of V2G application is the Net Meter. Net Meter acts as a data source and is crucial in efficient energy utilization through bi-directional monitoring and communication [28]. These meters are similar to those installed in smart homes or buildings, except that they generate net bills. Smart meters assist residential or commercial consumers with energy consumption and control electrical appliances for efficient energy utilization. Similarly, Net Meters enable assistance to EV prosumers to determine the optimal time and controlled EV charging-discharging. However, both meters are different from automated meter reading devices that only communicate the amount of energy consumption to the service provider for billing. Traditionally, the Net Meters comprise input sensors, processing units, and communication modules in the AMI infrastructure, as shown in Fig. 1.7. Input sensors monitor the electrical quantities and convert them into the equivalent digital amount for data processing. The data processing unit evaluates the energy flow through the sensors and allows the information exchange over the network using communication modules.

The benefits of Net Meter include real-time monitoring and communication for remote billing,

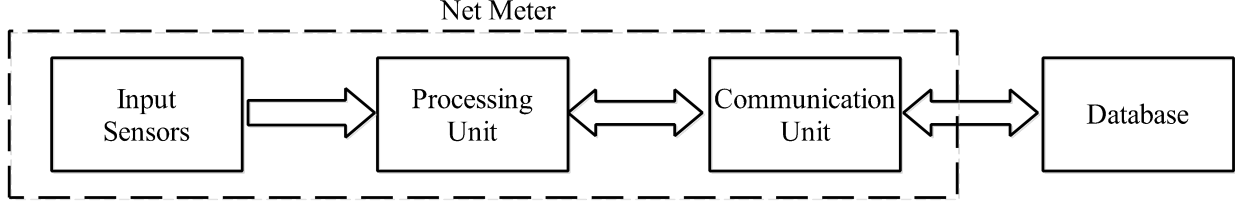


Figure 1.7: Basic components of Net Meter.

net metering, managing energy consumption, and optimizing grid performance. Overall, Net Meter works on measuring the import and export of energy that already exists in the roof-top PV solar application [20, 29]. However, the differences co-exist in the construction based on applications requirement. PV solar net metering is deployed using unidirectional converters and, thus, has low EMI [30]. In contrast, net metering in V2G is carried through bi-directional fast-converters that can be noise-prone and induce EMI and harmonics. The EMI may affect the performance of electronic devices in the infrastructure; thus, designing needs to reinforce as per the practical requirements. Therefore, considering automotive grade is essential to sustain a realistic automotive environment. Besides, the PV solar application communicates with the service provider to only transfer the billing quantities. In reverse, V2G requires bi-directional interaction for controlled charging-discharging and to know EV prosumer's behavior. Hence, including battery status monitoring along with the grid is vital to eradicate any malfunctioning in the process. In addition, the Net Meter in V2G must incorporate the mechanism to reduce the risk associated with the local distribution network due to the simultaneous charging of enough vehicles.

1.5 Role of Net Meter in V2G

EV integration with the smart grid profoundly changes the AMI that derives new information flow. AMI works on accumulating history, real-time data, and the computational and analytic environment for electric power [31]. It allows the efficient consumption and generation of electricity through renewable energy sources. EV integration in the distribution network leads to an increased data volume that may resolve with big data technology. Therefore, efforts are required

to adapt existing AMI to the varying operational scenarios. Fig. 1.8 shows the detailed V2G enabled charging infrastructure with integration of Net Meter. Generally, the Net Meter is equipped with a metering and communication module. The metering module performs energy measurement and accordingly generates billing quantities. The communication modules establish an interactive network between the smart grid, electric vehicle supply equipment (EVSE), and EV for controlled operation and database management. The detailed functionality of each is as follows:

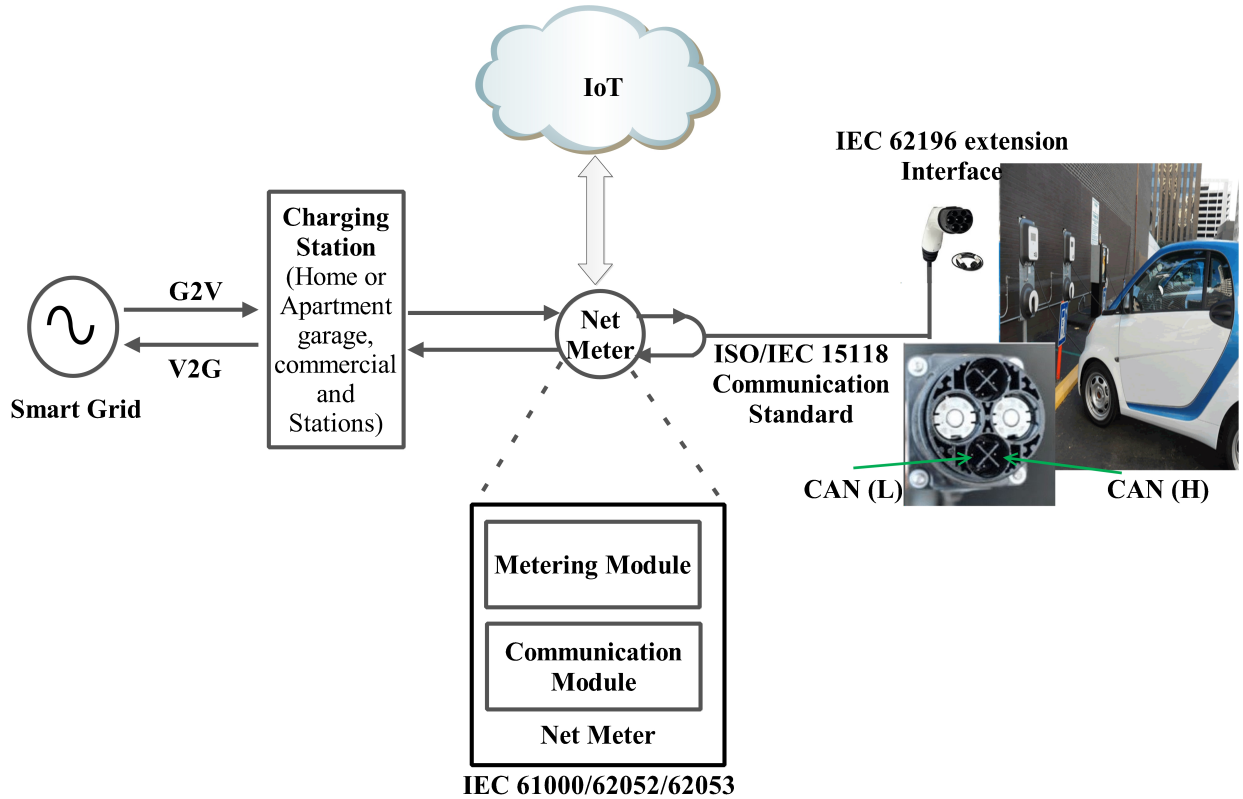


Figure 1.8: V2G enabled charging infrastructure with an integration of Net Meter.

1.5.1 Metering Module

The EV batteries are charged through the EVSE, the charging points. The supply to the EVSE is an alternating current (AC) through the electric grid. However, the batteries charges with direct current (DC) current. Thus, bi-directional electronic converters must be integrated to convert AC supply into DC and vice-versa. Grid connects the AC supply to EVSE at different levels as shown

in Table 1.2 [32–35]. Levels 1 and 2 are the AC chargers that charge the EV in slow or fast charging modes using an on-board charging facility (as shown in Fig. 1.9), respectively. Level 3 is the DC charger that charges the EV in ultra-fast mode using off-board converters (shown in Fig. 1.10, also known as an off-board charger). Levels 1 and 2 chargers with the maximum current capability of 80 A are preferably used at private and public facilities. Level 1 is served by single-phase circuitry, and level 2 is with single-phase (US) or three-phase (EU) circuits. Alternatively, level 3 is suggested for commercial and public locations powered by a three-phase supply with a maximum 200 A current rating. In all cases, the grid connects the AC supply to the EVSE, and the energy exchange is monitored using the AC metering module of the Net Meter for accurate billing. Thus, termed as AC Net Meter to monitor the energy exchange between EVSE and the grid.

Table 1.2: Levels of charging system.

Level	Power supply	Voltage range	Power level
Level 1	1-phase	120 V_{ac} (US) 230 V_{ac} (EU)	1.4kW (12A)
			1.9kW (20A)
Level 2	1-phase or 3-phase	240 V_{ac} (US) 400 V_{ac} (EU)	4kW (17A)
			8kW (32A)
			19.2kW (80A)
Level 3	3-phase	208-600 V_{ac} or V_{dc}	50kW
			100kW

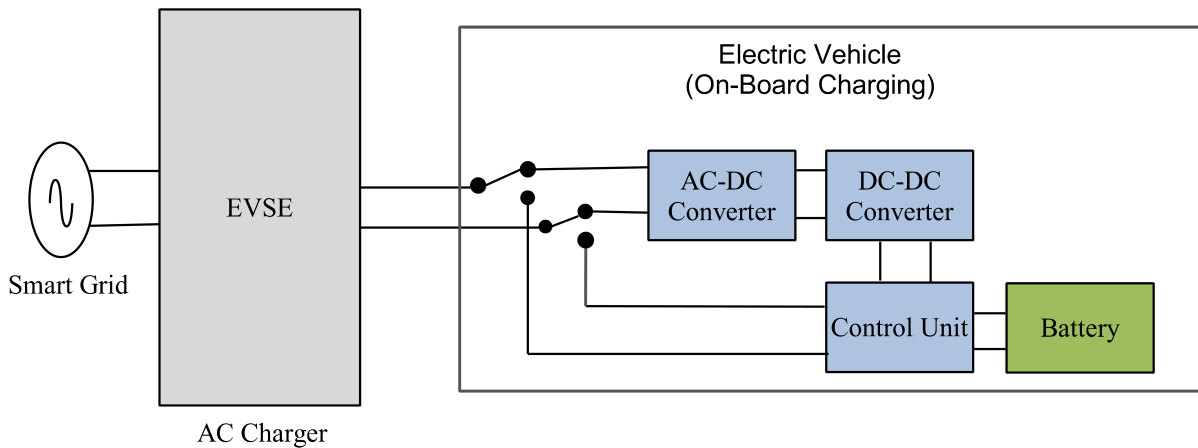


Figure 1.9: AC charger (Level 1 and 2).

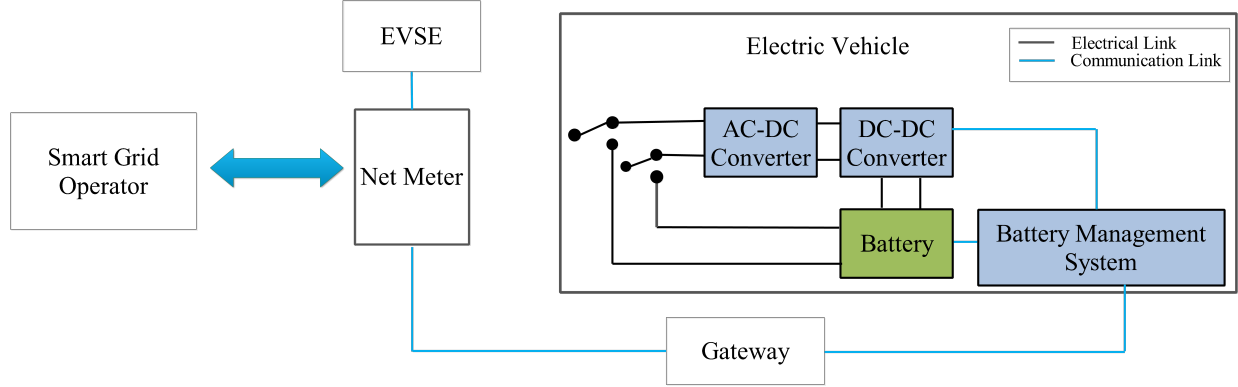


Figure 1.11: Net Meter communication link.

Table 1.3: Communication technologies suggested for V2G.

Technique	Wireless communication technology used	Rating of wireless communication technology	Control strategy used
Bi-directional V2G	ZigBee 868	MHz (Europe) 2.4 GHz (Worldwide)	Aggregated control strategies, Model predictive control algorithms
	Near field communication	13.56 MHz, 5-10 cm	
	Bluetooth	2.4 GHz	
	IEEE 802.11p	5.85-5.92 GHz 500-1000 m	
	WiMAX	2-6 GHz	
	Converged fiber wireless (Fi-Wi) communication	5 GHz, 10 Gb/s, 1-40 m	

to apply diverse computational and analytical strategies. In the V2G application, Net Meters can embrace EV charging-discharging scheduling to eradicate the grid's stress due to increased EV penetration. Besides, the charging at commercial places may interface enough vehicles simultaneously, introducing losses in the mechanism [36]. The Net Meter monitors grid performance and may help to overcome difficult situations. It detects the plugging/unplugging of EVs for desired billing and security mechanisms [37]. Considering the electricity theft detection mechanism at the EV consumer end is crucial. Electronic meters are promoted to mechanical tampering that introduces the transmission of incorrect metering information. Researchers are working on implementing data encoding-decoding strategies to reduce data corruption. However, physical tampering at the EV prosumer ends leads to the generation of incorrect data at the source itself. Here,

encoding-decoding techniques for secure data transmission failed to detect theft. Therefore, Net Meters' design plays a vital role in resisting any mechanical or electromagnetic tampering at the EV prosumer end.

1.6 Impact of Net Meter in V2G

The impact of integrating Net Meter in the V2G application incorporates EV prosumers' satisfaction, improved grid efficiency and reliability, and controlled EV charging-discharging. V2G acceptance will increase by gaining insights into the charging-discharging of EVs. Customized solutions can be provided to EV prosumers according to their active participation in the smart grid problem-resolving techniques. Net Meter generally influences EV prosumers and grid performance in the following ways.

- **Data source:** The increasing integration of EVs in the smart grid leads to big data for electrical applications. Net Meter is a data source and generates time series data for big data technology.
- **Improve grid resilience:** Net Meter allows bi-directional real-time communication or exchange of information in real-time. It helps to improve grid resilience and EV load management by allowing the retrieval of data quickly to rectify grid problems through controlled charging-discharging.
- **Grid efficiency:** Net Meter helps improve the grid's operational efficiency by identifying electricity theft, outages, and loss detection. It allows better EV load management to reduce the stress on the nation's grid.
- **Net Metering Scheme:** The integration of Net Meter on charging stations support the bi-direction flow of energy and data. Thus, implementing net metering schemes can benefit EV prosumers and grid operators.

- **DSM** The Net Meter integrates the bi-directional feature that enables the deployment of new models to leverage the EV prosumers for DSM, which includes DR and V2G.
- **EV prosumer satisfaction:** Net Meter helps to generate dynamic bills and revenues based on the EV prosumer's behavior in the smart grid. It motivates prosumers to participate and maximizes their benefits and satisfaction through reduced billing.

1.7 Challenges and Constraints

The major challenges that need to be addressed while deploying the Net Meter in V2G and supporting futuristic DSM with EVs in the smart grid are as follows.

- I. **Cost-efficient:** The device should be cost-effective as it is designed to serve one charging point instead multiple nodes. At residential places, the installation of Net Meter will be done by EV owners. Thus, cost-effective solutions will allow faster acceptance of the device in society.
- II. **Standardization:** The electrification of automobiles has introduced the set of International Electrotechnical Commission (IEC) and the Society of Automotive Engineers (SAE) standardization [38]. The purpose of designing a Net Meter in V2G should fulfill the requirements defined in IEC or SAE. It helps to improve the system's reliability.
- III. **Accuracy:** Available charging levels cover a more comprehensive range. Net Meter design should cover the broader range to serve different chargers and withstand around 80 A of constant current nominally. However, the increased operating range of energy meters has an adverse effect on the device's accuracy.
- IV. **Protection against tampering:** Plethora of work is underway for secure data transmission in the metering infrastructure. However, omitting corrupted data generation through Net Meters due to mechanical interface or EMI is a major concern.

- V. **Infrastructural performance monitoring:** Other than measuring the energy flow with high accuracy for bill generation, Net Meter must be capable of evaluating the frequency fluctuation and distortions introduced through the converters. These parameters are essential as they may affect the grid's performance.
- VI. **Interoperability:** Exchange of information among EVSE, EVs, and service operators becomes important to render the smart charging-discharging concept. The Net Meter should be compatible with communication protocols and connectivity of BMS and supports interoperability among smart grid or EV market operators.
- VII. **AMI integration:** Net Meters act as a data source for the market-end to monitor the EV prosumer's behavior for different EV applications. Using big data technology, it generates time series data for evolving computational and analytical techniques.
- VIII. **Real-time operational capability:** EV charging-discharging affects the grid performance due to their erratic behavior. It increases the stress on the distribution network system. Thus, managing EV charging-discharging in real-time improves grid stability.
- IX. **Dynamic billing:** Dynamic billing supports DSM for efficient electricity utilization. The Net Meter initiates the platform to generate bills at variable prices. However, bill generation in real-time with evolving pricing systems is challenging.
- X. **Tariff rates determination:** Tariff rates motivate EV prosumers to participate in DSM using EVs optimally. Determining convincing tariff rates plays a crucial role in DSM functionality.
- XI. **Security Mechanism:** Globally, EV charging is introduced at subsidized rates to raise the acceptance of EVs. The design of the Net Meter should integrate the security mechanism to reduce electricity theft.

1.8 Summary of Research Questions

From the above discussion, the Net Meter can help address various aspects of V2G technology. However, this thesis addresses the following research questions to validate the claim.

1. How the cost of Net Meter is reduced without affecting the performance so that the EV prosumers will easily accept it?
2. V2G infrastructural losses may affect the accuracy of the electronic devices. How does the accuracy of the Net Meter maintain to serve different high-power charging levels?
3. How the performance based on the power quality will be monitored using the Net Meter?
4. Does the Net Meter affect handling big data in a smart grid so that data processing time is reduced.
5. How the Net Meter interconnect the smart grid operator, EV and EVSE for smart charging-discharging?
6. How the re-scheduling of EV charging-discharging based on smart grid condition and EV battery status is managed by the Net Meter?

1.9 Thesis Organization

The thesis has been strategies as shown in Fig. 1.12. The following chapters help to resolve the challenges while integrating Net Meter in the V2G application.

1. Chapter 2: Literature Survey

The chapter overviews the preliminary research work in designing and developing Net Meter and its functionality in the V2G application. A relative comparison of existing approaches has been presented to determine the merits and demerits of various evaluation parameters.

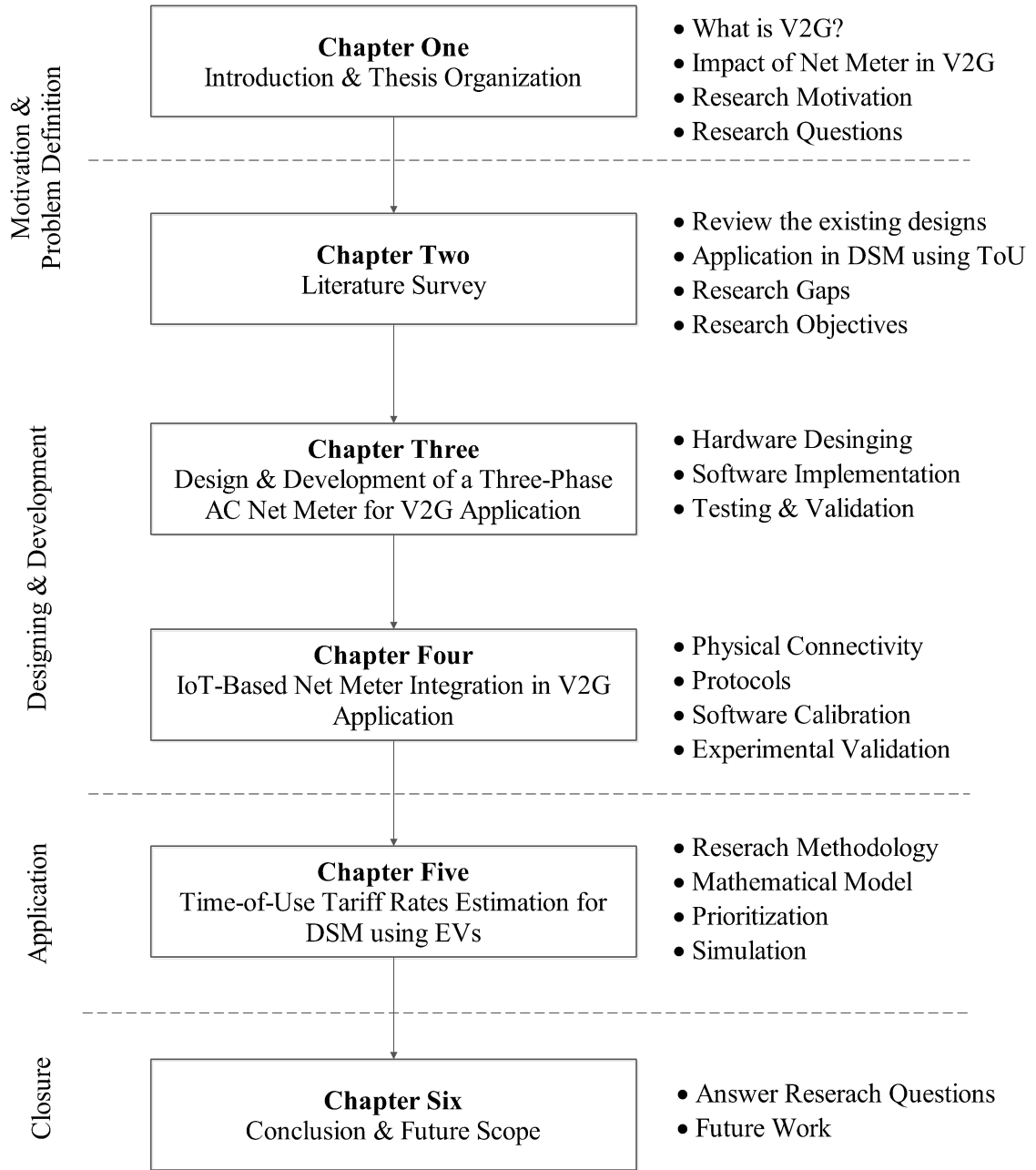


Figure 1.12: Thesis organization.

Based on the study, research objectives have been suggested to resolve the existing issues acknowledged in the research challenges.

2. Chapter 3: Design and Development of a Three-Phase AC Net Meter

In this chapter, the designing of a bi-directional Three-Phase AC Net Meter for V2G appli-

cations has been proposed. The prototype is developed to serve different EV charging levels with class 1 accuracy over a wider range.

3. Chapter 4: IoT-Based Net Meter Integration in V2G Application

In this chapter, an IoT-based Net Meter is discussed to meet the V2G application. Connectivity and compatibility of the device are presented, and a software calibration technique is proposed to re-scale the input sensors.

4. Chapter 5: ToU Tariff Rates Estimation for DSM using EVs

This chapter proposes a research methodology to set tariff rates for the V2G application. A mathematical model is presented with the simulation results. Time-of-Use and Graphical User Interface

5. Chapter 6: Conclusion and Future Scope

The chapter concludes the thesis by highlighting the contribution of the proposed research work. Moreover, the chapter presents the future directions in the research domain.

Chapter 2

Literature Survey

The chapter's preliminary research focuses on V2G technology and raising challenges in its successful establishment. Finally, the survey is presented in the design and development domain of Net Meter in V2G application¹. Moreover, the existing approaches used to motivate consumers to reduce the stress on the smart grid are analyzed. Overall, the literature contribution of the chapter is classified into different categories as given in Fig. 2.1. The first category provides an overview of the V2G technology defining its benefits and challenges in intelligent metering. The second category discussed the design and development of a Net Meter, which is further classified into three sub-categories: hardware configuration, metering algorithm, and communication. Then, the schemes used for DSM with EVs are summarized in the third section.

¹The content of this chapter are partly published in:

- A. Kaur, M. Singh, Design and development of a three-phase net meter for V2G enabled charging stations of electric vehicles, *Sustain. Energy Grids Netw.* 30 (2022) 100598.
- A. Kaur, M. Singh, Time-of-Use tariff rates estimation for optimal demand-side management using electric vehicles, *Energy* 273 (2023) 127243.
- Amrit Pal Kaur and Mukesh Singh, "IoT-Based Net Meter for Vehicle-to-Grid Application with Time-of-Use," 2nd International Conference on Smart Technologies for Smart Nations, 18-19 August, 2023, Amity Global Institute, Singapore.

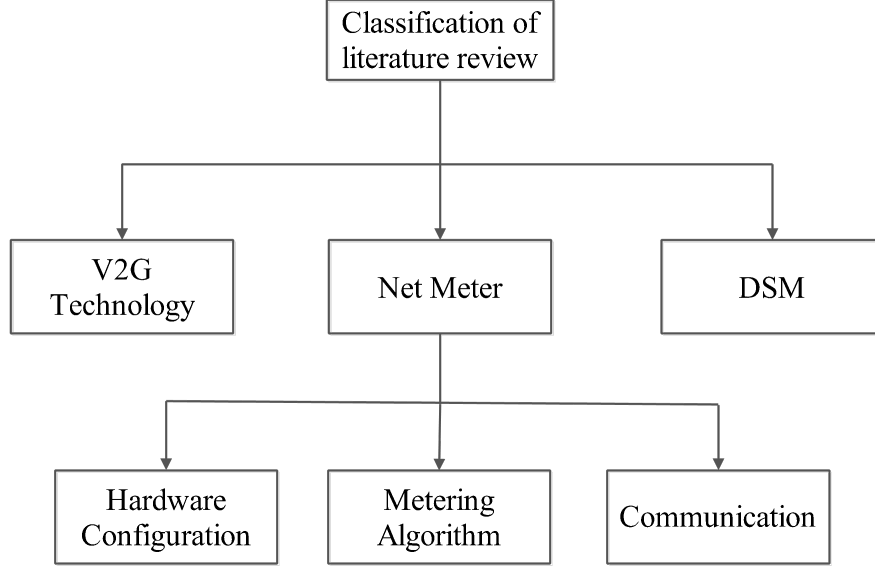


Figure 2.1: Classification of literature review.

2.1 Vehicle-to-Grid Technology

Development of the V2G concept depends upon the EVs as an energy source, bi-directional power flow with supportive converters, and intelligent on-board/off-board metering as shown in Fig. 2.2 [39]. V2G technology has received attention since EVs have gradually increased in the transportation market. The fluctuations in load demand and voltage and frequency regulation in the power grid result in high cost and energy wastage in the distribution system [40]. When the energy demand from the grid exceeds the power generation capacity of the system, the grid suffers from power outages and sometimes will participate in spinning reserves. In contrast, unused energy will be wasted in the distribution system when the load demand is lower than the power generation capability. Therefore, a power control system is required to balance the power generation and load demand. The regulation of voltage and frequency ensures the reliability of the power distribution system at increased grid operational cost. Here, V2G uses EVs as a buffer for the power grid; in high-demand hours, EVs feed the energy to the grid, and in low-demand hours, excess energy charges the EVs [41]. The V2G concept allows sharing the benefits among the grid operators and EV owners by reducing the operational utility cost and generating revenues, respectively [42]. V2G even accelerates the adoption of EVs in society, which helps to keep the environment pollu-

tion free.

More importantly, EV batteries have a finite period and charging-discharging cycles; thus, V2G can negatively impact battery longevity. However, there are studies [43,44] that support the V2G operation; accordingly, the worst-case scenario is the period when the battery is not in use or at rest. Therefore, intelligently optimizing the rest period of a battery via V2G technology may positively impact the health of an EV's battery. V2G demands an interactive, informative exchange over the AMI to enable smart charging-discharging in the infrastructure. The bi-directional communication must report the power utilization at EV prosumer end, exchange battery parameters, EV prosumer's priority and receive commands [45]. Net meters have been considered a better solution to support both the on-board and off-board metering in V2G technology [46,47]. It monitors and allows the exchange of information with the control centers through the distribution network [38]. Thus, EVs can support the grid as a controllable load and source when connected to the grid [48].

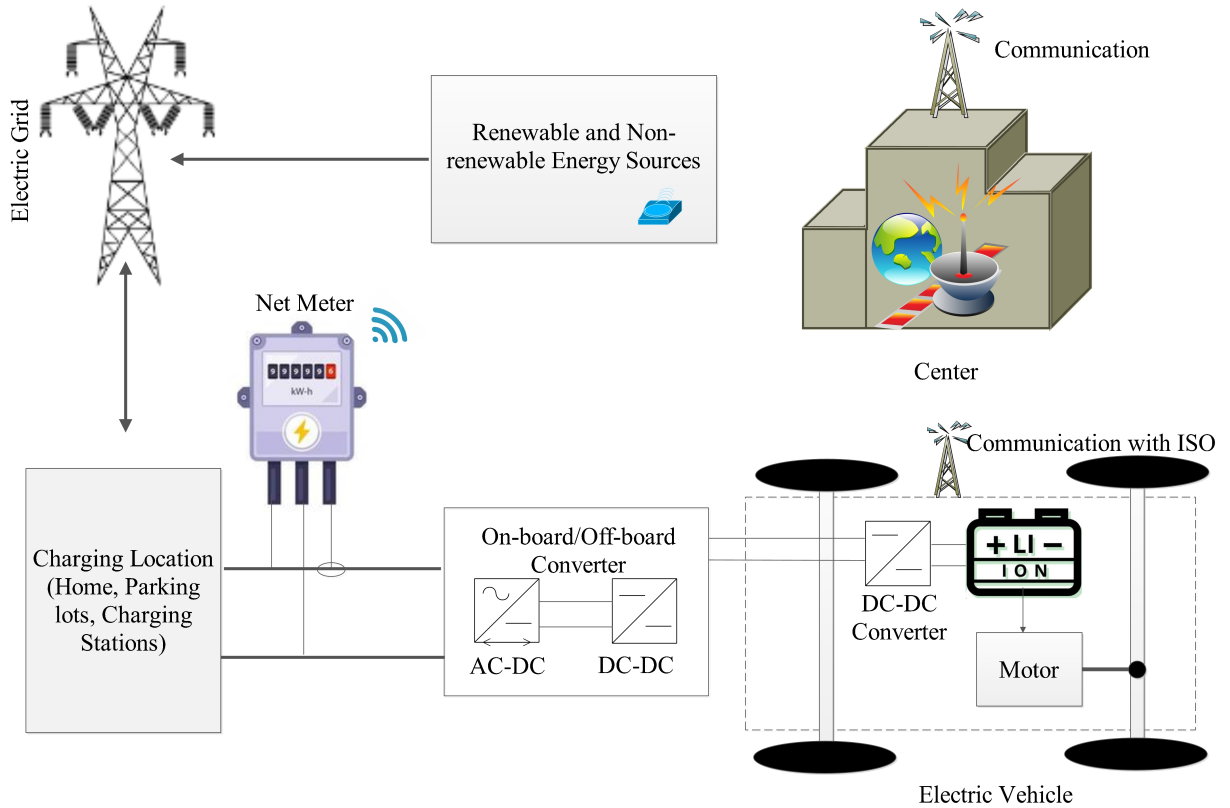


Figure 2.2: Power flow and components in V2G system.

The major challenge is found in intelligent metering that supports the feature of bi-directional monitoring and communication. The establishment of intelligent metering in V2G relies on electronic components such as Net Meters and sensors. In the V2G infrastructure, the chargers are employed with two-stage bi-directional converters: an ac-dc grid-connected converter that enforces power factor correction and a dc-dc converter to regulate the EV battery's charge-discharge rate. Researchers are investigating different techniques and have noticed that bi-directional converters with many switching devices have high losses and complicated control [49]. In contrast, the low switching condition adopted for bi-directional chargers makes operation difficult [50]. Therefore, chargers prefer high switching frequency environments that may induce noise and EMI. Hence, it may lead to inaccurate monitoring of energy transfer using Net Meters and affect the performance of the distribution network or may destroy the electronic devices. Another challenge is awareness of the connected EV and their respective battery capacity, SoC, and energy required or can be supplied based on requested operation [51, 52]. Thus, a communication link between the EVs and the monitoring device is demanded. To meet the above challenges, installing Net Meters adaptable to the varying operational scenario is a significant concern in successfully implementing the V2G application.

Besides, the bi-directional flow of power supply conceptualized net metering in V2G should benefit both the EV prosumers and service providers. However, individual EVs in V2G technology cannot contribute to stabilizing the grid. Therefore, aggregating EVs in the distribution network is essential in V2G to have a noticeable improvement. Overall, Net metering capabilities concerning EV users and service providers or compensation deter V2G applicability. Overall, various studies have focused on V2G development, though there are challenges in its adoption. The extra cost involved, issues in metering, noise, and policy concerns are considered for this study. The overall challenges that exist in V2G implementation are listed below:

1. The bi-directional energy flow and communication between the smart grid, EVSE, and EVs.
2. Energy losses and stress on the electronic devices due to the integration of bi-directional converters.

3. Suitable and accurate metering equipment and sensors that withstand the V2G environment.
4. Sustainable information exchange over the distribution network concerning EV battery parameters.
5. Extra cost and investment involved in V2G establishment.
6. Motivating the EV prosumers to participate in the V2G application.

2.2 Designing of Net Meter

A comprehensive solution for automation in the AMI of smart grid for the V2G concept is the integration of Net Meters. Net Meters are a bi-directional ICT tool that acts as a data logger system for various analytical and computational applications. The designing of Net Meter comprises integrating a hardware-software approach similar to the smart meters or bi-directional meters used in roof-top PV solar applications. Sun *et al.* [20] introduced different types of electric meters and emphasized smart meters as a fundamental part of AMI. Visalatchi *et al.* [29] and Bedi *et al.* [53] have fostered the installation of smart meters by introducing their benefits over conventional electro-mechanical meters in smart grid. Accordingly, the diverse functionalities of these meters allow for monitoring energy consumption and generation along with remotely controlling home appliances. Installing these meters at the consumer end primarily demands higher accuracy for accurate billing. The hardware and software configurations and the design's communication capability are described as follows.

2.2.1 Hardware Configuration

Loss *et al.* [54] implemented the energy meter using voltage and current sensing circuits and configured a peripheral interface controller (PIC) to evaluate the electrical quantities. The major drawback of the model was low accuracy due to electrical losses through the voltage divider and shunt resistors-based sensing circuits. Subsequently, voltage (VT) and current transducers (CT) replace

the sensing circuits for real-time sensing of instantaneous voltage and instantaneous current with negligible losses. In the design, the host processors perform software computation to measure energy usage and support other functionalities to meet the application's requirements. However, the software complexity and computational speed affect the system's performance. Zheng *et al.* [55] used ADE7758 application-specific integrated circuit (ASIC) for the computational task, reducing the software complexity at the manufacturing end. Li *et al.* [56] used ATT7022 while designing the bi-directional meter to measure the electrical quantities. The use of ASIC has improved the accuracy of the metering device with reduced software complexity. Nevertheless, the configuration of multiple measurement devices is required for the poly-phase concept, even increasing the hardware complexity and reducing the reliability of the meter. Benitez *et al.* [57] suggested the implementation of an energy meter using the ADE9000. The ADE9000 advantages allow the measurement of supply through a three-phase system. However, the device integrates a basic algorithm that limits the performance under varying AMI operational scenarios.

Labib *et al.* [58] designed a smart meter that extracts the sensor inputs through an analog-to-digital converter (ADC), excluding specific measurement devices. It computed the electrical parameters using ATmega2560 and reduced the development expense. However, the developed system attains low processing speed (maximum up to 20 MHz), limiting the performance in real-life applications that demand multiple operations in real-time. Also, FIR filter-based design restricted the harmonic analysis essential in the distribution network for V2G application. Morello *et al.* [24] designed a smart meter to monitor energy consumption with a fast-Fourier transform (FFT) algorithmic approach using a field programmable gate array (FPGA) board. The National Instruments single-board RIO 9626 FPGA used the LabVIEW platform for programming and targeted monitoring of several nodes in the distribution network. Arenas *et al.* [59] developed a smart meter over FPGA with the Institute of Electrical and Electronics Engineers (IEEE) 1459-2010 standard defined as a function of grid fundamental frequency. FPGA resolves the central concern of accurately measuring at multiple nodes with improved system throughput. However, Net Meter installed at a charger demands monitoring a single point, and thus, the use of FPGA is undesirable

as it may increase the product cost [60]. The above-discussed design schemes achieved class 1 accuracy by compromising the expense.

Net Meter in the V2G application demands a cost-effective solution for easy acceptance by EV prosumers. In addition, emerging fast-charging infrastructures require a highly flexible Net Meter over a broader range [32]. Nevertheless, the aforementioned research work is majorly designed to serve low-power applications, and thus, achieving higher flexibility will be a question. The static meters that are taken into consideration measure AC quantities while working on DC principal. The voltage fluctuation in the distribution network doesn't affect these devices. On the contrary, the infrastructure where the devices are placed may persuade the reading and their performance due to noise and EMI. Therefore, Net Meter designing must consider the IEC standards to withstand the automotive grade for V2G application. Concerning the IEC 62053-2x standard, metering chips STPM32 and CS5490 complied to support DC metering [61, 62]. These chips need to have reinforced fundamental energy monitoring from the grid to EVSE. Wu *et al.* [63] configured a metering device based on IEC 61000-4-30 for grid monitoring and DC metering. The inferiority of Fourier analysis lacked harmonic detection, which is essential to measure the system performance due to non-linear EV load. Also, the devices' processing speed at maximum is up to 16 MHz, precluding real-time performance.

Comparative analysis on the bases of designing the Net Meter considering the above-discussed survey is summarized with their advantages and disadvantages in Table 2.1.

2.2.2 Metering Algorithm

EVs are the non-linear loads that raised the efficient operational concerns of the distribution network due to increased electrical losses [20]. Due to the widespread integration of EVs with the smart grid, the current and voltage harmonic distortions increases. These current and voltage harmonics severely affect the power quality of the distribution network and may damage the equipment and EVs connected to it. The frequency measurement is essential for the smart grid's operational stability, safety, and efficiency. Fast and accurate frequency estimation leads to op-

Table 2.1: Comparative analysis on the bases of designing.

Schemes	Designing	Advantages	Limitation
Loss <i>et al.</i> [54]	Used voltage divider and shunt resistor circuit for voltage and current sensing	Simple and low cost	Low accuracy
Zheng <i>et al.</i> [55]	Used ADE7758 IC for evaluating electrical quantities	Reduce software complexity	Increases cost, low power applications
Li <i>et al.</i> [56]	Used two ATT7022 to measure electrical quantities	Reduce software complexity	Increases hardware complexity and cost of the product
Benitez <i>et al.</i> [57]	Used single ADE9000 for measurement	Reduces software complexity and can be used in poly-phase measurement	The device is expensive and on-chip basic algorithm limits under varying AMI operational scenarios.
Labib <i>et al.</i> [58]	Used ADC with ATmega2560	Low cost	Microcontroller limits the operational speed.
Morello <i>et al.</i> [24]	Used FPGA board	High accuracy	High product cost
Arenas <i>et al.</i> [59]	Used FPGA based designing	Class 1 accuracy	Increases cost of the system
STPM32 CS5490 [61, 62]	Designed concerning IEC 62053-2x	Reduce hardware complexity DC metering	Failed to perform fundamental grid monitoring Lack of communication modules
Wu <i>et al.</i> [63]	IEC 61000-4030 Maximum processing 16 MHz	Grid monitoring DC metering	Limited operation Lack of FFT analysis Low speed

timal power control and system protection in harmonics. Therefore, monitoring the frequency and harmonic components in the EV distribution network is essential. Several methods have been proposed for frequency measurement in past decades. The phase angle calculation using a zero-crossing detector (ZCD) is the simplest and most known method [64]. The technique requires ZCD circuitry, increasing the hardware size and reducing system reliability. Similarly, the filter-based algorithm accurately measures the power components using Finite Impulse Response (FIR) digital filters [58]. Both the estimation techniques followed time domain analysis that estimates the frequency of a certain signal by counting the time intervals. However, the time domain analysis fails

to understand whether the system is stable or not.

Besides, existing metering equipment employs frequency domain analysis to analyze harmonic contents in the signal using Fourier transform (FT). Among several mathematical transformations, the fast-Fourier transform (FFT) algorithmic approach is accepted as it attains low computational complexity [65, 66]. However, the frequency leakage problem may distort the actual spectrum of the signal and, thus, applies to only stationary signals. Hence, improving the metering approach for accurate billing under power quality disturbances or distortions is required. The swift advancement in signal processing techniques has facilitated different methods to measure the PQ events efficiently. Where short-time Fourier transform (STFT), and wavelet transform (WT) are employed with the drawbacks of fixed window length and redundant data, respectively [67, 68]. Krishnanand *et al.* [69] used Stockwell transform (ST), a hybrid of STFT and WT, for cross-differential protection on power lines. The scheme limits the performance compared to FFT regarding computational complexity and detection time. Jaiswal *et al.* [70] proposed a fast discrete Stockwell transform (FDST) based algorithm on FPGA using NI-LabVIEW that generates a highly accurate system. However, the approach compromised the computational efficiency of the system to respond in real-time. The summary of these techniques in terms of their advantages and disadvantages is given in Table 2.2.

Table 2.2: Frequency and harmonics measurement techniques.

Technique	Advantages	Disadvantages
ZCD [64]	Simple and well known method	Increases hardware complexity
Filter-based design [58]	High accuracy	Complexity depends on the order of filter
FFT [65]	Low computational complexity	Shortcoming in dealing with non-stationary signals
STFT [67]	Provides both time and frequency information	Fixed window length
WT [68]	Describes signal in both time and frequency domain simultaneously	Redundant data, heavy computation
ST [69]	Superior time–frequency	Computation complexity and detection time is greater
FDST [70]	Higher accuracy	Computational efficiency can be further improved for real-time implementation

2.2.3 Communication

Two-way communication is essential in the V2G application to monitor and control EV charging-discharging. Existing AMI offers diverse communication techniques, including wired and wireless channelization. IEC 61850 standard was primarily used for smart metering equipment as it addresses the aspect of communication in power systems and interoperability [71]. It was applied to the Local Area Network to exchange information between the substations. Further, the extension of IEC 61850 to fit the smart grid for WAN application came into existence. However, these standards need to consider EVs and the V2G concepts. In [72–74], authors have proposed the extension of IEC 61850-7-420 to incorporate the features regarding EV and V2G technology. Further, the drafting of IEC 62056 includes the electricity metering data exchange and is known as DLMS/COSEM, where DLMS stands for Device Language Message Specification, and COSEM is for Companion Specification for Energy Metering. The standards are working on the concept of the client-server protocol. Although the standard is widely accepted in Europe, many researchers are working on adding the missing options, such as security features.

The communication technology should be scalable in terms of capacity and coverage area. Besides, it also complies with a standardized approach to allow the diversity of meters and communication media. The Net Meter establishes communication while integrating EVs into the distribution network. In [75] research work, a secured framework for the smart Meter was suggested using a wireless environment for HAN that encompasses scalability, security, and massive data handling. Furthermore, article [76] presented an IoT-based platform that offered novelty in the architecture that included four design aspects at the customer end. Hlaing *et al.* [77] introduced a low-cost IoT-based meter for monitoring and data handling. However, implementing the V2G application has brought challenges, including data transfer, to ensure detailed EV operations and engagement. The V2G controlled infrastructure demands optimal energy dispatch about the EV status. Thus, the two major areas that need to be considered while establishing communication are connectivity and compatibility.

Following the above discussion, the lag in previous research are summarized as follows:

- Achieving class 1 accuracy using measurement ICs compromises the expense and reliability of the metering device.
- Most of the research covers low-power applications; thus, the performance of the devices in high-power applications over a more comprehensive range is a question.
- The above-discussed work needs to be revised in an explicit discussion concerning IEC standards to withstand the EV charging infrastructure.
- FFT analysis for non-stationary signals must catch up to present a computationally efficient solution.
- The existing Net Meters operate only on the client-server concept that is usually applied to the wireless connection and thus fail to establish communication with EVs.

2.3 Demand-Side Management

The integration of EVs with smart grid is in the preliminary stage, thus, requiring a lot of effort in the AMI that enables controlled electricity usage. AMI supports the change in incentives that can potentially promote the DSM with EVs. The price-based DSM schemes such as Critical-peak pricing, Real-time pricing, and Time-of-Use (ToU) alleviate the grid congestion problems and reinforce the power network [78, 79]. The techniques influence the consumer's behavior and mitigate unnecessary investment and change in the existing infrastructure [80]. DSM encourages EV prosumers to shift the EV charging time with the integration of V2G mode [81]. The ToU tariff is the most accepted scheme where the electricity rates over hours are predetermined, constant, and change based on the utilization curve of the grid. During the off-peak hours of the valley, the tariff rates reduce to motivate the consumers to shift their electricity consumption. In contrast, raised rates during peak hours help to reduce consumption from the consumer end voluntarily. However, the major obstacle in the technique is the quantification and determination of the tariff rates and ToU intervals. AMI in many developed countries has allowed the ToU scheme to be established.

The slight difference in the price between different time slots has resulted in a minute shift in the electricity consumption [82, 83]. Therefore, deriving the ToU tariff rates is a sensitive issue as it may motivate or demotivate EV prosumers.

In the case of DSM with EVs, individual EVs cannot rectify the power-related issues. Thus, establishing an aggregator (AG) allows the grouping of EVs as a whole to contribute to the power market. AG coordinates an area's EV charging and V2G activities based on the power grid situation [84]. EVs with distinct roles and geographic dispersion demand different historical and real-time information storage while accessing the power grids, [85]. Here, an area-wise grouping of EVs at AG helps to reduce the computational complexity and increases the flexibility and scalability for controlled EV charging [86]. A centralized approach to optimize the EV charging model was proposed based on ToU pricing by considering the SoC curve [87]. The technique involves complex computational tasks to avail the benefits of reducing costs and flattening the consumption curve. Dubey *et al.* [88] evaluated the aspects of EV charging under the ToU schedule with off-peak rates between 8 P.M and 3 A.M over a residential area. In the survey, they verified that 11 P.M to Midnight is the best time for EV charging. Also, they have determined the beginning of off-peak duration as detrimental to the distribution network. Enough EVs connected simultaneously to the grid may alter the demand curve and exacerbate the problem of stabilizing the distribution network.

Shinde *et al.* [89] suggested that EV charging scheduling helps overcome the issue of fixed tariffs over time. Accordingly, the EVs charged without proper ToU scheduling may jeopardize the sustainability of the grid even more than the situation of charging EVs without the ToU attribute. The efficient design for ToU tariff rates relies on determining the ToU intervals and calculating the peak/off-peak rates. Venizelou *et al.* [90] derived an optimum ToU tariff algorithm that re-evaluated the tariffs in every season using the electricity production cost. It reduces the peak hours consumption by a low value of 3.19 %, 1.03 %, and 1.40 % for every season. The technique focused on market-driven prices that may derive a narrow difference in the rates. Yu *et al.* [91] establishes a real-time price-based DR technique for optimal device control and energy manage-

ment. The method focused on the consumer benefits at residential places with EVs. However, the ToU's advanced fixing of price and intervals helps to schedule proper EV charging and global acceptance over real-time pricing. Li *et al.* [92] defined a methodology to set dynamic pricing for the overall load of the distributed network in real-time. In the techniques, higher prices are charged for the condition when the overall load demand exceeds the equivalent load of the isolated microgrid. Considering multi-stakeholder scenarios, the mechanism is defined only for coordinating scheduling between battery swapping stations and microgrids.

Further, Li *et al.* [93] configured an optimal dispatching model for community-integrated energy systems and EV charging stations. The mechanism supported dynamic pricing that combines the ToU and real-time pricing to explore the potential of DR. Although the defined method aimed to render DR at EV charging stations, it neglected the overall impact of EVs on the grid. Oprea *et al.* [94] proposed a methodology to set the ToU tariffs using big data technologies and machine learning. In the technique, consumers' contribution during peak and off-peak periods improved the efficiency to 5 %. The approach focused on consumers' contribution to power consumption, avoiding the risk of minute rate differences. However, the method did not focus on EV applications. It was restricted only for DR and undetermined the reverse tariff rates required in V2G while EV discharges to grid. Thus, modeling a pricing mechanism is necessary for DSM using EVs that even considers the various aspects of EVs. The technique demands a focus on negative impact due to simultaneous EV charging along with the V2G pricing targeting optimal DSM using EVs [95,96].

Table 2.3 summarizes the ToU strategies in the literature along with the proposed ToU pricing mechanism. The six main aspects include the EV applications to define the inclination of the method, DR and V2G mode, SoC inclusion, elasticity, and demand responsiveness as the result of charging price. Demand responsiveness further considers three sub-aspects of projecting aggregated and individual responses with ToU behavior.

Table 2.3: Methods regarding the ToU strategy.

	EV application	DR	V2G	SoC	Elasticity	Demand response		
						Aggregated response	Individual response	ToU behavior
[87]	✓	✓	-	✓	-	✓	-	-
[88]	✓	✓	-	-	-	✓	-	✓
[89]	✓	✓	-	-	-	✓	-	✓
[90]	-	✓	-	-	-	✓	-	✓
[91]	-	✓	-	-	-	-	-	✓
[92]	✓	✓	-	✓	-	-	✓	-
[93]	✓	✓	-	✓	-	-	-	-
[94]	-	✓	-	-	✓	✓	-	✓

2.4 Research Gap

The changing role of EVs in the smart grid demands that ICT tools be adaptable to varying scenarios. The significant contribution of Net Meter in the V2G application has opened the way to explore an accurate, reliable, and affordable solution for EV prosumers. The research in the area ensures the system should modulate to accommodate varying functionalities and attributes with the advancement in the smart grid. Therefore, it is crucial to consider the challenges involved in the development, data processing, and applicability of the Net Meter in the V2G application. The primary concern is the immense installation cost that does not allow the fast adoption of the Net Meters at consumer ends and limits the V2G operability. Based on the previous research work [24, 26, 55, 97], it is evident that most of the practical solutions are provided using high-end hardware and software solutions such as FPGA and LabVIEW. Also, ASIC designed to cater to highly accurate systems increases the expense and limits the functionality of the equipment.

Furthermore, the maintenance of electronic tools is a priority for the smooth conduction of the operation. However, EMI and noise-prone infrastructure may affect the performance and life of electronic devices. They may include hardware, software issues, and communication failure. Standardization ensures system reliability in different environmental conditions [19][23]. Besides, AMI is developing, and interoperability has become a significant issue due to different operating environmental conditions globally. The information accessible on the distributed network demands

the Net Meter be compatible with the existing AMI. The real-time functionality of V2G brings power quality measurement and time synchronization into concern. In addition, EVs are charged at a subsidized rate, making it an easily intended power theft. Thus, the system needs to trigger the security and privacy issues which should be incorporated into the architecture. Two-way communication between two ends over a vast network becomes a vulnerable target for hackers. They manipulate the cost of energy consumed by the customers and generate fake meter readings [29, 98, 99].

Besides, V2G is in the developing stage and incorporates DSM advantages. However, V2G demands to attract the EV owners' attention so that they participate in the application. Despite numerous studies and work on the metering part of AMI, from the above, it is clear that still a lot of work has to be initiated in the V2G application. The discrepancy in architecture and adoption of Net Meters and V2G, which can be taken for further research, are enlisted below:

1. The deployment of Net Meters in AMI comes at a massive cost, making adopting the V2G application inconvenient.
2. The Net Meters needs to be adaptable to the varying operational scenario of AMI due to EVs integration without risking the durability and accuracy of the product. Net metering is not much explored in the V2G application, and most existing research is inclined toward low-power applications.
3. A lot of scope of research exists for Net Meter integration in high-power applications with EMI filtering.
4. To ensure practical functionality, meters must be designed using regulatory standards to respond in real-time along with ToU feature for booming dynamic pricing policies.
5. Net Meters demands to interconnect the smart grid, EVSE, and EVs so that the controlled charging-discharging operations of EVs must be initiated.

6. Interoperability with the existing AMI is demanded, focusing on improved security and privacy features and solutions for massive data mining.

2.5 Objectives

The following objectives are set forth by analyzing the research gaps found in the related work.

1. To design a Three-Phase AC Net Meter for V2G to meet the regulatory standards.
2. To develop a Three-Phase AC Net Meter to ensure real-time performance with ToU capability.
3. To demonstrate the working of developed Three-Phase AC Net Meter in V2G environment as per the standards.

Chapter 3

Design and Development of A Three-Phase AC Net Meter for V2G Application

The notion of bi-directional metering inaugurates the implementation of an electronic device called Net Meter. The Net Meter generates bills and enables smart charging-discharging considering the EVs' requirement and grid condition [38]. The Net Meter in V2G application needs to be designed considering automotive-grade to sustain in the practical environment. The hardware-software configuration of the Net Meter needs to cover an extended range to attain higher flexibility between available charging levels in the V2G application [32]. Keeping this in mind, the chapter presents the detailed design and development of a cost-effective Three-Phase AC Net Meter for V2G enabled charging stations¹. The proposed prototype is developed concerning regulatory standards so that the device ensures performance in the real environment. The results obtained using two test benches ensured class 1 accuracy over a wider range with harmonic detection in real-time.

¹A. Kaur, M. Singh, Design and development of a three-phase Net Meter for V2G enabled charging stations of electric vehicles, *Sustain. Energy Grids Netw.* 30 (2022) 100598.

3.1 Contribution

The major contributions of this chapter are as follows:

- The primary focus of this chapter is to design a cost-effective Three-Phase AC Net Meter for V2G enabled level 1 and 2 charging stations at technology readiness level (TRL) 9.
- The chapter examines the Three-Phase AC Net Meter with Automotive Industry Standards (AIS) to verify compliance in automotive applications.
- The device is validated in a V2G application with a real-time charger to ensure performance in the practical environment.

3.2 System Framework

The proposed Three-Phase 4-wire Net Meter complied with IEC 61000/62052/62053 and comprised hardware-software integration. Table 3.1 enlist the specifications, and Fig. 3.1 shows the basic building blocks of the system with single-phase for better understanding. The hardware includes an analog and a digital card classified based on the circuits integrated into the board. Analog card comprises transducers followed by the signal conditioning circuit and ADC for data acquisition. Each phase consists of a VT and CT for sensing the instantaneous voltage and instantaneous current, respectively. Further, the digital card includes a C2000 Digital signal processor (DSP) core for the computational task. Other than the C2000 DSP core, communication modules such as universal asynchronous receiver-transmitter (UART), RS485, and Wi-Fi are adjoined to enable data transfer. A real-time clock (RTC) interfaced for the ToU feature is required for the dynamic pricing in V2G.

3.3 Component Selection

Enlist the components used in the design as it affects the device's cost and performance.

Table 3.1: Proposed Three-Phase AC Net Meter specifications.

Quantity	Value
Voltage range	3-Phase Supply
Standards applicable	IEC 61000-4, IEC 62052-11, IEC 62053-21
Current range	0.1-80 A
Accuracy	Class 1
Sampling frequency	1.6 kHz
Resolution	16-bit
Temperature operating range	- 40 to + 85°C
Dimension	20x17x7 cm
Supply voltage	5 V
Communication	RS485, Wi-Fi Module

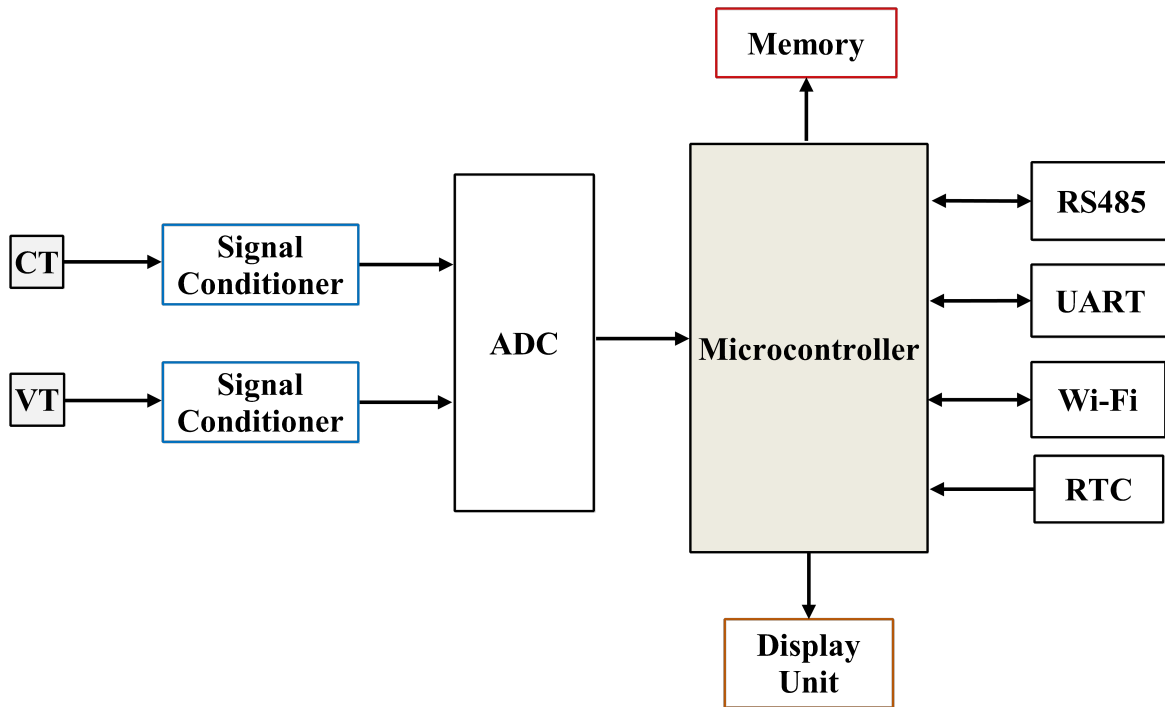


Figure 3.1: Basic building blocks of the proposed Three-Phase AC Net Meter.

1. **VT and CT Selection:** The prototype comprised isolated measurement transducers for detecting the current and voltage signals in the grid monitoring system. CT is one of the most crucial components used in bidirectional metering devices to sense the alternating current in either direction [100, 101]. 5A/10 mA rated CTs are used with the air isolation between the primary and secondary circuits. The load resistor of a lower value is selected to achieve high linearity over a wider bandwidth. VTs of 415V/2V rating with galvanic isolation are

interfaced to sense the three-phase supply to obtain a $\pm 0.5V$ voltage range. The signals obtained from VT and CT follow a few steps to obtain a DC-bias signal range within 0-5V.

2. **Processor:** C2000 DSP core TMS320F28069 is chosen for mathematical operations for supply monitoring, bill generation, and communication protocol implementation. It's a real-time controller of a 90 MHz CPU with much fewer effects of distortion and noise than an application-specific device. The sampling rate of the proposed model is in kHz, and the data rate is maximum up to 115,200 bps; thus, the DSP core provides a cost-effective solution over FPGA [60]. It is feasible to use FPGA only if the sampling and data rates are above a few MHz and 20-30 Mbps, respectively. Furthermore, DSP brings a computational performance that is a significant measure for any metering application. It is proven that the DSP cores perform better for FFT analysis than ARM core processors [102]. In addition, Texas DSP cores are highly portable, reducing the overhead of reprogramming the hardware to support future expansion as per requirement. Concerning all the benefits, the device suits the application in terms of cost without compromising performance.
3. **ADC:** The input analog signals must be converted into digital equivalent to do further computational processing. An external 16-bit AD7606 analog-to-digital converter (ADC) is selected over the on-chip 12-bit ADC of the microcontroller. 16-bit ADC renders $152.6 \mu V$ resolution, higher than any on-chip 12-bit ADC. This results in reduced quantization error and helps to improve the accuracy [103]. The selected device operates in the temperature range $-40^{\circ}C$ to $85^{\circ}C$ that best suits the automotive application. Its on-chip second-order anti-aliasing filter eliminates the aliasing effect. Moreover, the device supports the simultaneous sampling of eight channels with a throughput of 200 Ksps, which is needed in poly-phase supply monitoring.
4. **Communication Modules:** The hardware is configured with an ESP 12F Wi-Fi module to enable IEEE 802.11 technology for wireless connection over the field area network. It allows Internet access for IoT operation and enables a meter data management system (MDMS) for

the futuristic approach. Moreover, the study of V2G instigates the need to establish physical layer connectivity over a controller area network (CAN) bus with EV. The gateway analysis pushes to select a generic protocol for better data understanding. Thus, an interfaced RS485 module for communication with the MODBUS RTU protocol.

3.4 Hardware Modeling

The proposed Three-Phase AC Net Meter is a standalone device for real-time data acquisition, energy evaluation, and communication. Fig. 3.2 shows the developed prototype of Three-Phase AC Net Meter. The schematic of the proposed metering algorithm is shown with the help of Fig. 3.3, and the detailed description is given as follows.

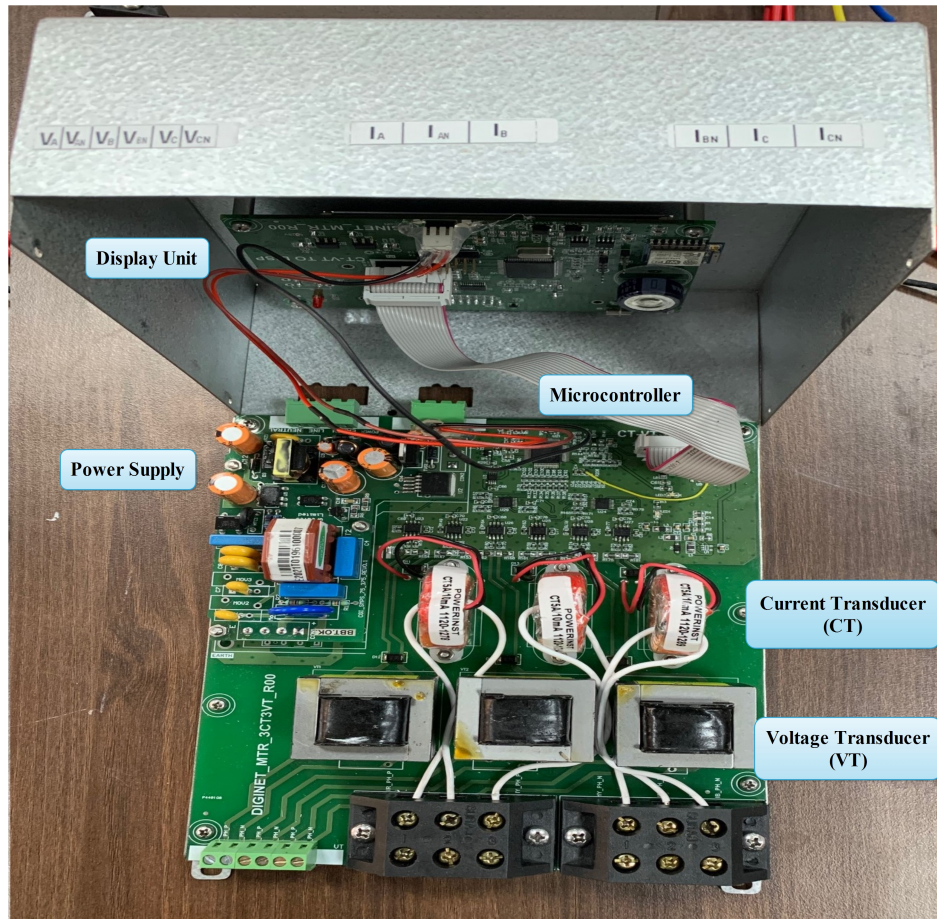


Figure 3.2: Prototype of the proposed Three-Phase AC Net Meter at TRL-9.

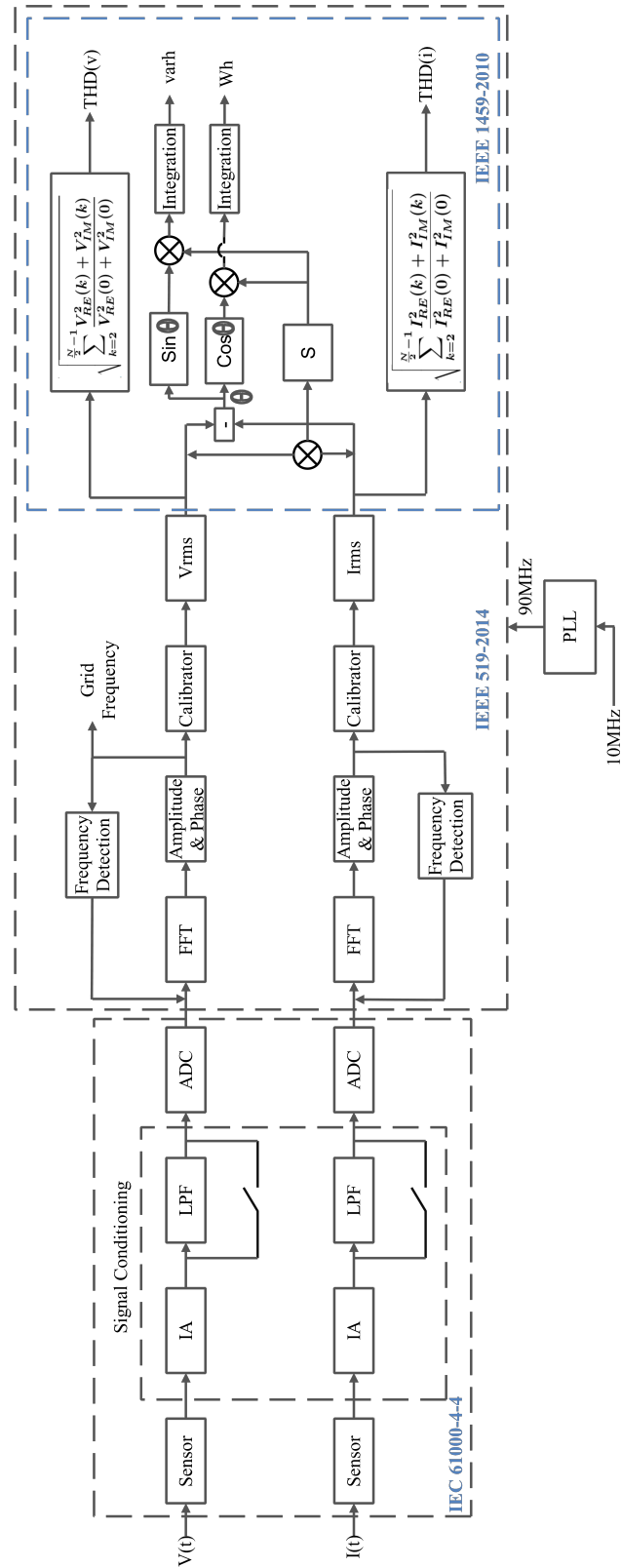


Figure 3.3: Schematic of the proposed Three-Phase AC Net Meter.

3.4.1 Analog Board

The design includes the IEC-based hardware-software integration ensuring class 1 accuracy [104]. The high-frequency switching techniques used in charging stations for power conversion demand EMI filtering. The basic steps involved in EMI filtering, followed by an amplifier and an offset circuit, are shown in Fig. 3.4. Concerning the analog board integrate input sensors and signal conditioning blocks to generate amplified and compatible signals for data acquisition. The signal conditioning circuit is implemented with highly accurate and sensitive operational amplifiers. IEC 61000-4-4 defines the provision of a power surge to deal with the power transient. It helps the meter to operate generally without changing its functionality under sudden variations. In detail, an instrumentation amplifier (IA) helps reduce the noise content in the input signal and provides only the signal output. It has further configured Low Pass Filters (LPF) to attenuate the signal above 1.5 kHz. Overall, the signal conditioning allows precise voltage and current measurements, which is essential for the metering application. Furthermore, the analog board acquires data using ADC for digital compatibility with the microcontroller for further signal processing. Here, AD7606 is used for conversion that samples the three-phase current and voltages through different channels with 16-bit resolution.

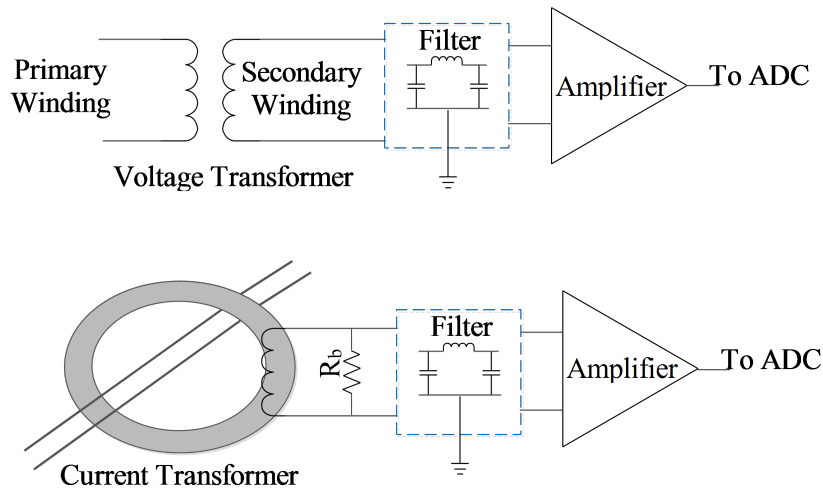


Figure 3.4: Conventional VT and CT equivalent circuit.

Fig. 3.5 depicts the developed analog board of the proposed Three-Phase AC Net Meter.

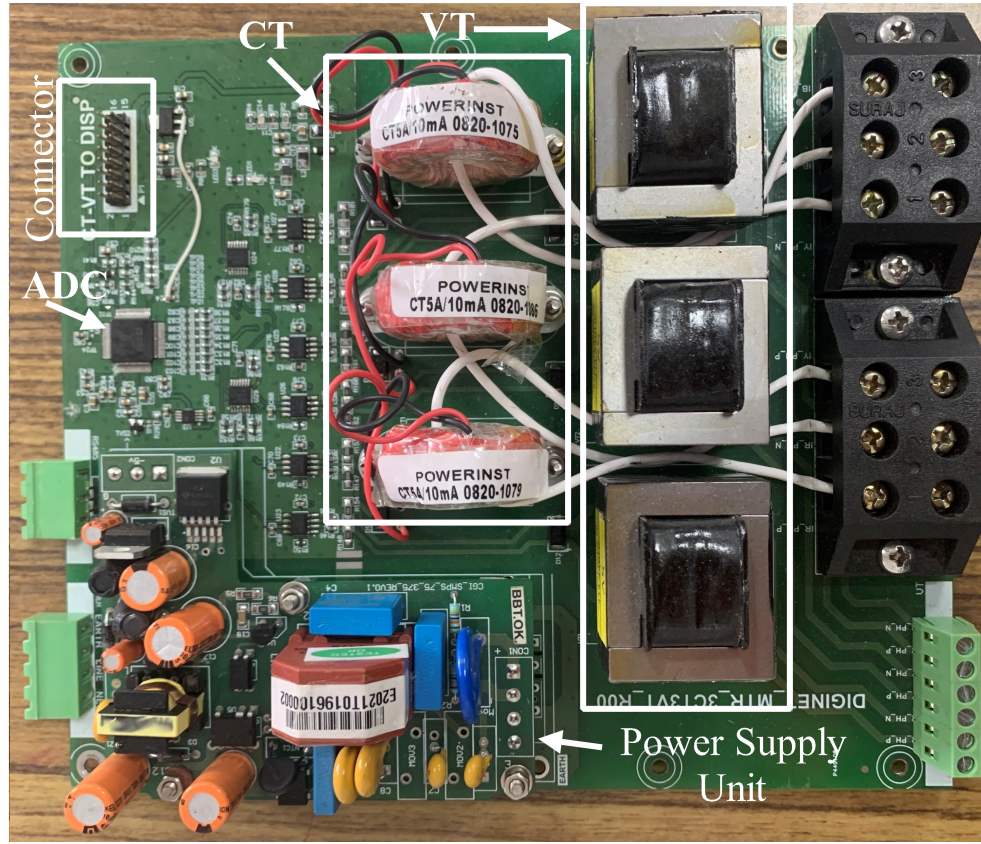


Figure 3.5: Analog board of the proposed Net Meter.

3.4.2 Digital Board

Signal processing is performed through the DSP core fabricated on a digital board with different peripherals. ADC samples the input voltage and current signals as $V[n]$ and $I[n]$ at approximately 1.6 kHz sampling rate based on the Nyquist theorem [63]. C2000 DSP core TMS320F28069 fetches the sampled inputs at 5 kbps using an on-chip serial peripheral interface (SPI) bus. DSP core performs energy estimation and real-time communication through different interfacing modules. ESP 12F Wi-Fi is integrated to render the Internet-of-Things (IoT) platform for data transfer and automation. RS 485 connectors are installed for external world communication. The device is embedded with an RTC to enable the time series data generation at different operations. External memory EEPROM is interfaced to store the evaluated time series data every 15 minutes.

Fig. 3.6 showcases the developed digital board of the proposed Three-Phase AC Net Meter.

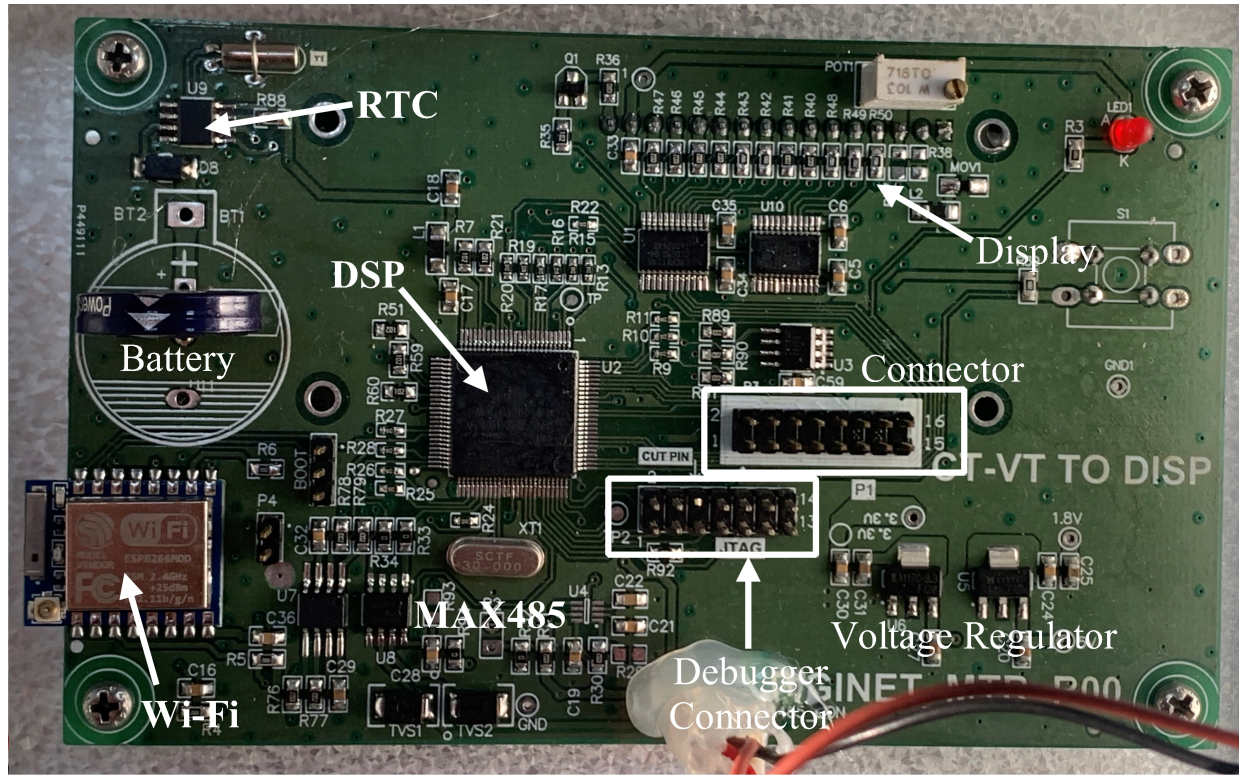


Figure 3.6: Digital board of the proposed Net Meter.

3.5 Software Implementation

The algorithmic software is implemented over C2000 DSP core TMS320F28069 using the code composer studio (CCS) platform. The prototype complies with the IEEE 519-2014 standard, explicitly highlighting the IEC 61000-4-7 and IEC 61000-4-30. In detail, the DSP core processes the sampled signal to evaluate the electrical quantities. The schematic diagram shown in Fig. 3.7 describes the process for computing the electrical parameters as follows:

1. Initially, assuming the line frequency of 50 Hz, instantaneous input voltage and current signals are sampled as $V[n]$ and $I[n]$ at approximately 1.6 kHz rate based on the Nyquist theorem. The desired number of samples taken per cycle is 32.
2. The DSP core processes the sampled signals to evaluate electrical parameters. Initially, it implements FFT with a window size of 200 msec, i.e., 10 cycles for 50 Hz and 12 cycles for 60 Hz. The FFT obtained from the digitally sampled data is as follows [105]:

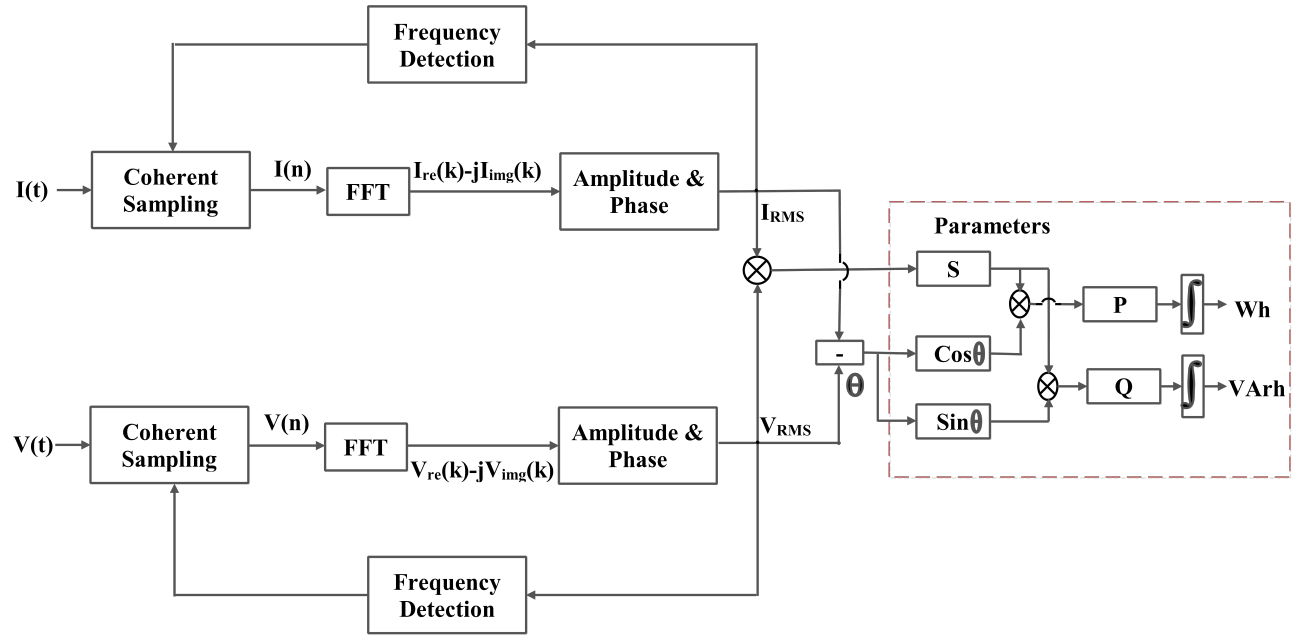


Figure 3.7: Schematic diagram of the metering algorithm.

$$V(k) = \sum_{n=0}^{N-1} V[n] e^{-j2\pi \frac{k}{N} n} \quad (3.1)$$

$$I(k) = \sum_{n=0}^{N-1} I[n] e^{j2\pi \frac{k}{N} n} \quad (3.2)$$

where $V(k)$ and $I(k)$ are complex numbers composed of real and imaginary parts as shown in Equations (3.3) and (3.4).

$$V(k) = V_{RE}(k) - jV_{IM}(k) \quad (3.3)$$

$$I[k] = I_{RE}(k) + jI_{IM}(k) \quad (3.4)$$

3. Calculated amplitude and phase of the voltage and current signals using the following equations:

$$V_{RMS} = \sqrt{re([X_v]_{max})^2 + im([X_v]_{max})^2} \quad (3.5)$$

$$I_{RMS} = \sqrt{re([X_i]_{max})^2 + im([X_i]_{max})^2} \quad (3.6)$$

$$\phi(v) = atan2\left(\frac{im[X_v]_{max}}{re[X_v]_{max}}\right) \quad (3.7)$$

$$\phi(i) = atan2\left(\frac{im[X_i]_{max}}{re[X_i]_{max}}\right) \quad (3.8)$$

where, V_{RMS} & I_{RMS} are the root-mean-square (RMS) voltage and current, $\phi(v)$ & $\phi(i)$ are the phase of voltage and current computed using X_v & X_i i.e the complex matrix for voltage and current signal.

The power factor is evaluated as follows:

$$\cos\theta = \cos(\phi(v) - \phi(i)) \quad (3.9)$$

4. DSP core accomplishes frequency measurement using the Hilbert transform (HT) technique that satisfies IEC 61000-4-30. It obtains the minimum-phase response from spectral analysis and is helpful in the frequency extraction of the instantaneous input signal. In contrast, the traditional frequency detection method employs zero-crossing detectors that increase the hardware size [58, 106]. The phasor measurement unit implemented with HT defined with the signum function $sgn(k)$ of the input signal with its FFT equivalent is as follows [107, 108]:

$$X_{HT}(k) = jsgn(k).X(k) \quad (3.10)$$

$$H(k) = jsgn(k) \begin{cases} -j, & k = 1, 2, \dots, \frac{N}{2} - 1 \\ 0, & k = 0; \frac{N}{2} \\ j, & k = \frac{N}{2} + 1, \frac{N}{2} + 2, \dots, N - 1 \end{cases} \quad (3.11)$$

Steps involved in estimating grid frequency are shown in Fig. 3.8 [107, 109, 110]. The rate of change of phasor derived through differentiation allows sampling frequency deviation

with the difference in the input signal frequency. However, the number of samples per cycle remains the same in the proposed technique. The frequency measurement provides a 10s integrated value to update the sampling frequency required for FFT analysis. Based on the IEC, tolerance for 50 Hz is kept as $\pm 7,5$ Hz and for 60 Hz is ± 9 Hz [110].

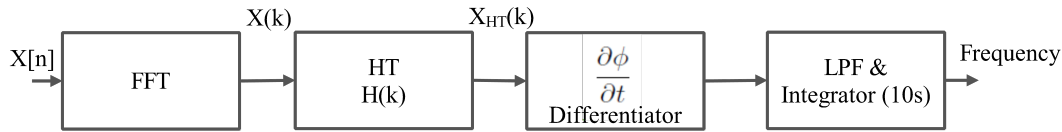


Figure 3.8: Steps involved in frequency measurement.

5. Furthermore, the prototype evaluates the electrical quantities of the supply as defined in IEEE 1459-2010 [24]. The device is programmed to perform an average of 10 cycles to nullify the transients due to sudden changes.

The coherent sampling technique is adopted to reduce the overhead in identifying the suitable window for FFT computation. In the proposed algorithm, the number of samples per frame remains constant to bring the advantage by always satisfying the following condition.

$$\frac{f_{IN}}{f_S} = \frac{M}{N} \quad (3.12)$$

where, f_{IN} is the input frequency, f_S is the sampling frequency, M is an integer number of cycles with the window, and N is the number of data points used to create FFT. The value of N must be a power of 2. It changes the sampling rate in real time with a change in the input frequency of the grid. The significant contribution of the technique is to improve the signal-to-noise ratio and Total-Harmonic distortion (THD) of the device [111, 112].

3.6 Experimental Validation and Results

The developed Three-Phase AC Net Meter is initially calibrated with the proposed mechanism using a standardized calibrator. Further, two test benches are configured to validate the prototype's

performance with four different test sets in the experimentation. A preliminary test set validates the measurement results obtained with CT and VT over the desired range. Further, the second test set validates the frequency measurement in reference to frequency fluctuations in the distribution network. Third, test the FFT algorithm for harmonic detection. Finally, the second test bench validates the operation of the proposed Three-Phase AC Net Meter in the V2G application using a real-time charger. In the test, experimentation measures the precision of different parameters and accuracy of the proposed Three-Phase AC Net Meter.

3.6.1 VT and CT Testing

The test bench configured in Fig. 3.9 analyzed the performance of VT and CT integrated on the proposed Three-Phase AC Net Meter. Applied different sinusoidal voltage and current waveforms with a step of 10 V and 1 A of RMS amplitude at 50 Hz using APS 5000 3-phase system spitzenberger spies (Grid simulator), respectively.



Figure 3.9: Test bench 1 configured for VT, CT and FFT testing is shown with the front and side view.

Fig. 3.10 and 3.11 show the comparative results obtained with the proposed Three-Phase AC Net Meter and FLUKE 434 series II power analyzer. The prototype is reported with a maximum percentage of voltage and current error is 0.0330 % and 0.0310 %, respectively. The proposed Three-Phase AC Net Meter has shown an acceptable performance over a wide range.

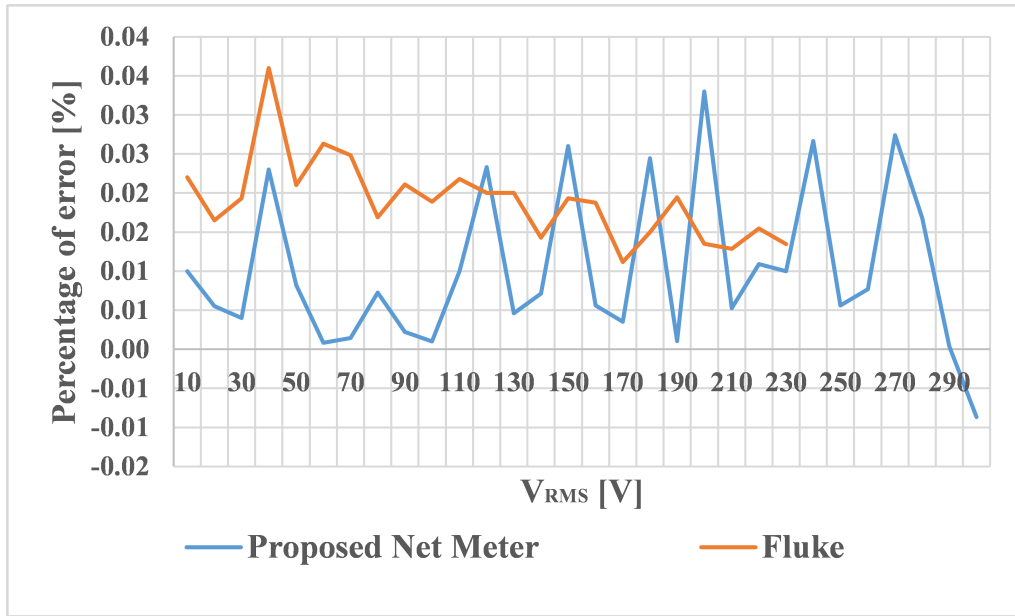


Figure 3.10: Percentage of error in V_{RMS} .

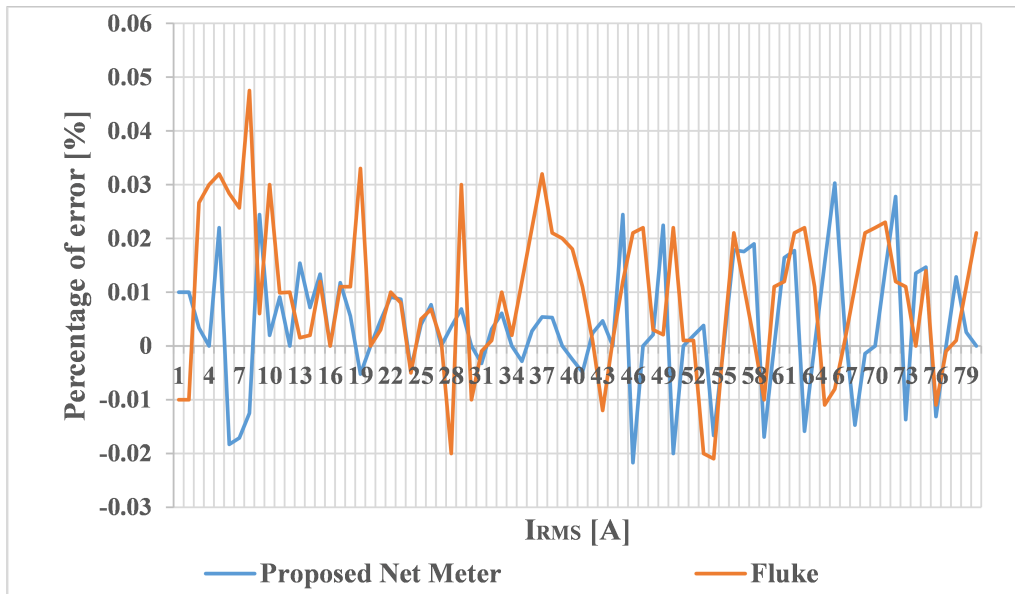


Figure 3.11: Percentage of error in I_{RMS} .

3.6.2 Frequency Measurement

The test bench 1 configured in Fig. 3.9 further used for the accuracy analysis in frequency measurement. A sinusoidal signal of constant amplitude at the varied fundamental frequency is connected to the load. The graph in Fig. 3.12 presents the proposed prototype's frequency measurement response compared to the Fluke 434 series II power analyzer. It is observed that the frequency measurement attained by the prototype is approximately equal to the response of the Fluke meter. Thus, the performance of the proposed Three-Phase AC Net Meter attains the maximum frequency measurement error of ± 0.01 HZ for the range 50 ± 7.5 Hz.

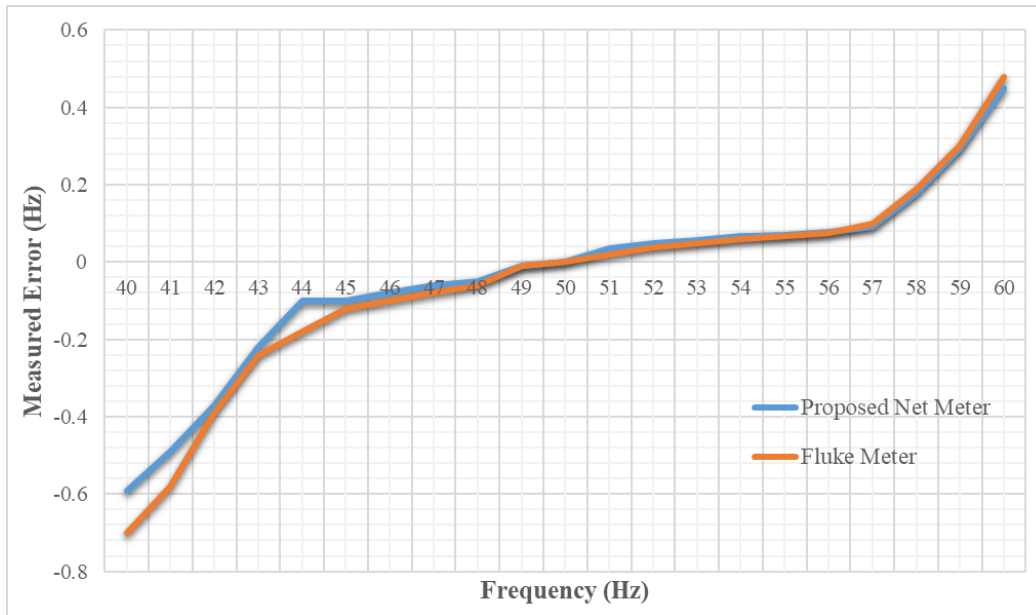


Figure 3.12: Frequency measurement error.

3.6.3 FFT Testing

The test bench configured in Fig. 3.9 was further used for accuracy testing of harmonics detection. A signal of 230 V at 50 Hz, injected with different harmonics through grid simulator at variable percentages. The bar graph shown in Fig. 3.13 presents the harmonic content of voltage in %, obtained using the proposed Three-Phase AC Net Meter with the reference value injected through the grid simulator individually. As a result, the maximum deviation observed for the single in-

jected harmonics is 0.07. Fig. 3.14 shows the THD measured with the proposed prototype and an RTH1004 digital oscilloscope 5 GSa/s. In the experimentation, 35 % voltage and 32 % current THDs are induced with the grid simulator. The proposed meter's voltage and current THD deviation are 11.3 % and 6.16 %, respectively. It is observed that less deviation is attained with the proposed algorithm. Therefore, the proposed prototype has shown an acceptable performance for the spectral response of FFT.

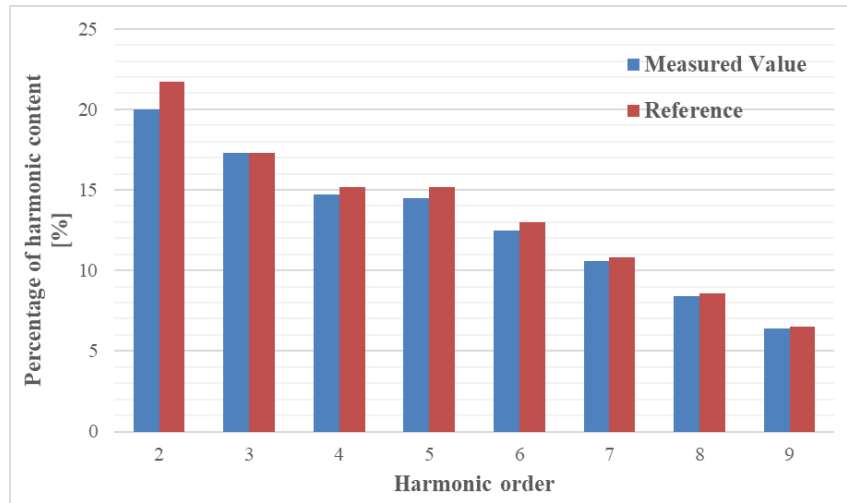
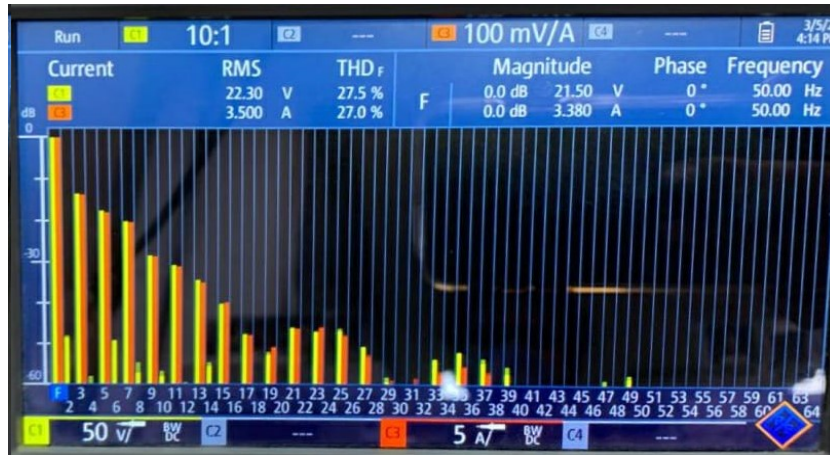


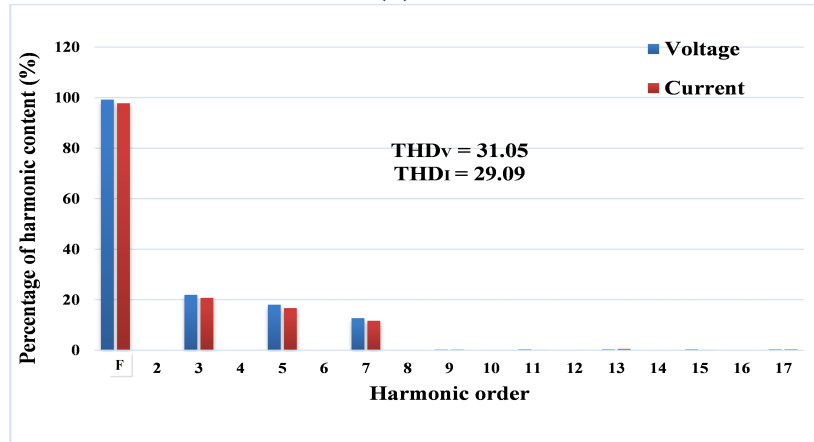
Figure 3.13: Percentage of individually induced harmonic component in voltage waveform with the proposed Net Meter and a reference value.

3.6.4 Experimental Results

Additionally, a test bench was configured considering the V2G application, as shown in Fig 3.15. A real-time bi-directional charger is used with a 48 Volts 30AH Li-ion battery at the load and a Three-Phase power supply as a source. The load is supplied with 230 V at 50 Hz frequency generated from the power source. The test injection facility of the laboratory injects up to 50 % harmonics in the supply. Fig. 3.16 shows the voltage and current waveforms. The proposed Three-Phase AC Net Meter performance is compared with a FLUKE 434 series II power analyzer. Table 3.2 shows observed results for the different parameters under test in each phase. The result shows distinct voltage and current values in each phase due to the unbalanced power supply connected at the input. The analysis does not allow us to compare the two measurement systems completely,



(a)



(b)

Figure 3.14: Measurement of THD in voltage and current waveform (a) Measured with the digital oscilloscope (b) Measured with the proposed Net Meter.

as the proposed Three-Phase AC Net Meter integrates more quantities. Considering the common measuring attributes, the proposed Three-Phase AC Net Meters achieve a high percentage of accuracy in most of the parameters under observation.

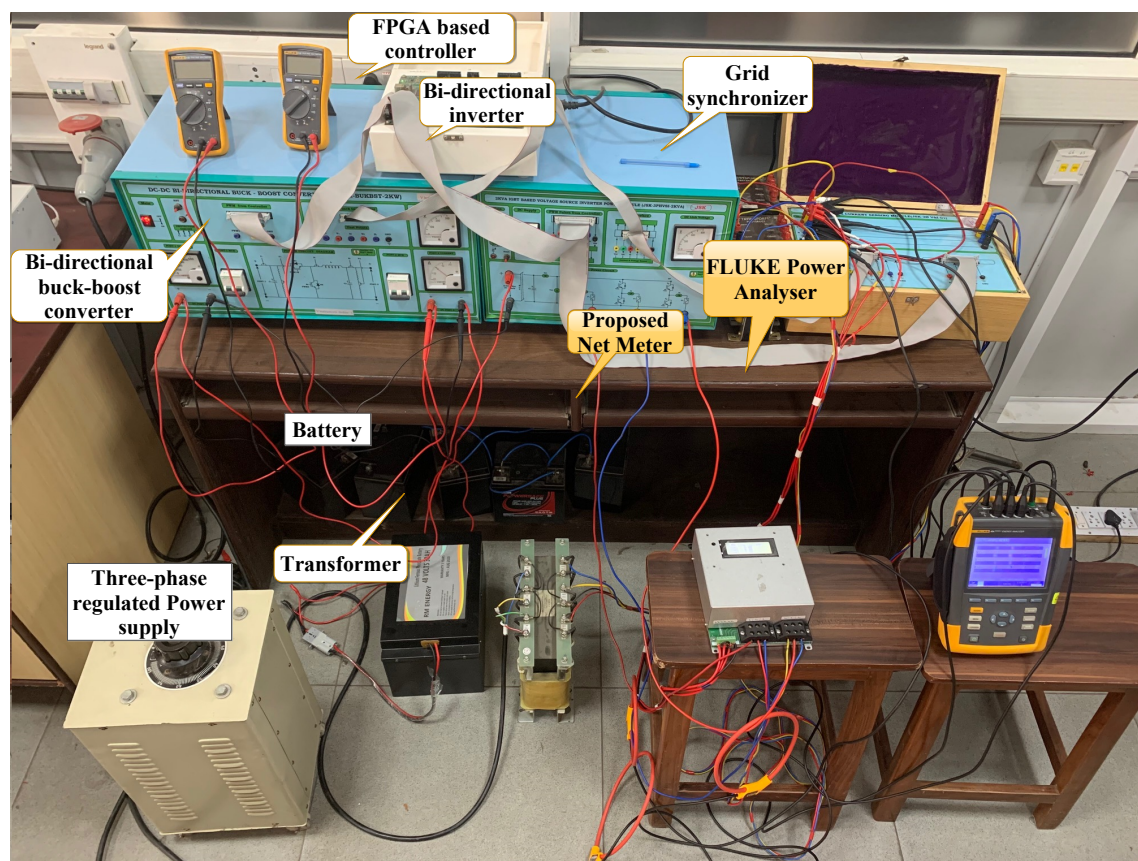


Figure 3.15: Test bench 2 configured to validate the performance of proposed Three-Phase AC Net Meter with a real-time charger.

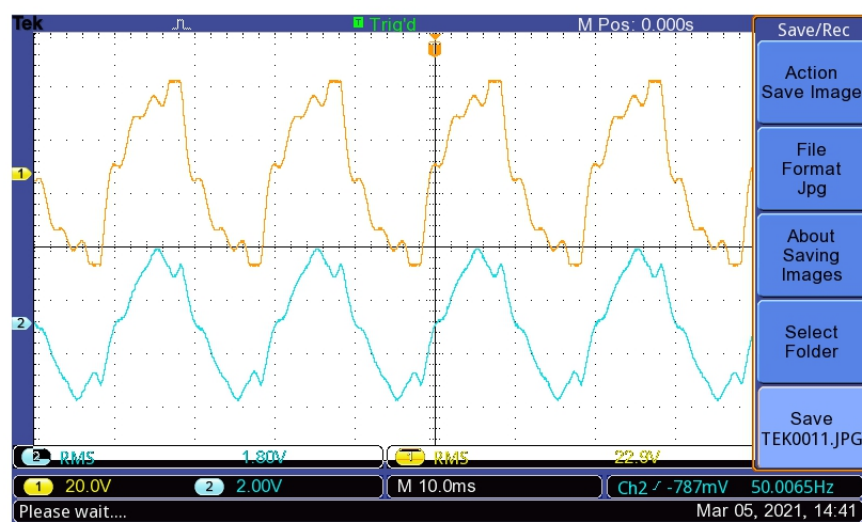


Figure 3.16: Voltage and current waveform.

Table 3.2: Experimental validation results of Three-Phase AC Net Meter.

Parameters	Reference Value	Measured Value	Percentage Deviation (%)
Phase 1			
V_{RMS}	228.4	228.437	0.016
I_{RMS}	6.320	6.3193	0.011
P [kW]	1.443	1.44	0.207
Q [kVAr]	0.069	0.07	0.09
S [kVA]	1.443	1.44	0.207
PF	1	1	0
Phase 2			
V_{RMS}	214.0	213.968	0.015
I_{RMS}	6.020	5.9673	0.875
P [kW]	1.288	1.28	0.621
Q [kVAr]	0.059	0.06	1.69
S [kVA]	1.288	1.28	0.621
PF	1	1	0
Phase 3			
V_{RMS}	229.3	229.295	0.002
I_{RMS}	6.390	6.3880	0.031
P [kW]	1.465	1.46	0.341
Q [kVAr]	0.061	0.06	1.639
S [kVA]	1.465	1.46	0.341
PF	1	1	0
3 Phase			
I_N [A]	0.34	0.3909	14.8
P [kW]	4.196	4.18	0.381
Q [kVAr]	0.189	0.19	0.529
S [kVA]	4.196	4.18	0.381
Freq [Hz]	50	50	0
THDi(1) [%]	52.6	59.02	12.2
THDi(2) [%]	56.4	62.55	10.9
THDi(3) [%]	51.5	56.45	9.6
THDv(1) [%]	51.7	58.37	12.9
THDv(2) [%]	52.8	60.02	13.6
THDv(3) [%]	51.6	59.33	14.9
Phase 1 [Wh]	NA	-	-
Phase 2 [Wh]	NA	-	-
Phase 3 [Wh]	NA	-	-
3-Phase [kWh]	NA	-	-

3.7 Summary

The chapter proposes a cost-effective Three-Phase AC Net Meter for the V2G-enabled charging station of EVs. The chapter outlines the hardware-software approach to designing the Three-Phase AC Net Meter at TRL-9. The Net Meter has complied with international standards to sustain in the practical environment. The data acquisition unit includes the VT and CT for a wide range to attain higher flexibility. Before measuring the billing quantities using IEEE 1459-2010 std, performs coherent sampling to compute FFT with C2000. The developed prototype is validated with two test benches to observe the performance in terms of real-time accuracy. The proposed Three-Phase AC Net Meter ensures class 1 accuracy complied with IEC 61000-4, 62052-11, 62053-21. Considering the automotive grade, the meter performance excelled in the AIS testing for electromagnetic compatibility (AIS-004 (Part 3)) and, thus, can be used for automotive applications in the field. Moreover, the same prototype can be used to measure single-phase and three-phase supplies to serve level 1 and 2 chargers. Besides, the algorithmic approach improved spectral resolution and THD detection in different conditions. In addition, coherent sampling reduces the stress of selecting an appropriate window for FFT analysis.

Chapter 4

IoT-Based Net Meter Integration in V2G Application

The rising density of EVs in society demands wireless solutions with reduced complexity to integrate the communication channel between the utility end and EV chargers. The chapter describes the system network applicable to the V2G application and the extension in the previously designed Net Meter to support the V2G application. Here, the IoT platform is enabled for wireless data transmission over the network through Net Meters. In the V2G application, bi-directional communication is needed between EV, EVSE, and grid operators for controlled operations. The information exchange includes the EV's battery parameters to eradicate over-charging or over-discharging and grid status to reduce stress. In the chapter, the IoT-based Net Meter is presented as a data source and recipient of information between the EVSE, EV, and grid operator for the V2G application¹. Besides, the chapter embedded ToU billing ability and tempering detection in the Net Meter for futuristic dynamic billing to support DSM and reduce electricity theft, respectively. In experimentation, the developed IoT-based Net Meter has shown an acceptable performance on a real-time 15 kW charger.

¹Amrit Pal Kaur and Mukesh Singh, "IoT-Based Net Meter for Vehicle-to-Grid Application with Time-of-Use," 2nd International Conference on Smart Technologies for Smart Nations, 18-19 August, 2023, Amity Global Institute, Singapore.

The major contribution of this chapter is summarized as follows:

- The chapter focuses on deploying an IoT-based Net Meter as a data source and recipient of information between the EVSE, EV, and grid operator for the V2G application.
- The chapter integrates the protection against physical tampering at EV prosumer end and facilitates ToU attribute for time series data generation and dynamic billing.
- A software calibration process is setup to re-scale the voltage and current sensors.

4.1 System Framework

The network clusters the EVs in an area using an AG to enable the net metering for efficient grid operation. In the V2G application, individual EVs cannot rectify the power-related issues while supplying electricity to the grid. Thus, establishing an AG allows EV grouping to overcome the load-shedding problem. Fig. 4.1 depicts the system distribution network for the V2G application. The smart grid is the central node that monitors the complete distribution network and interconnects all AGs. The AG collects data through multiple EVSEs in an area installed with a Net Meter and coordinates EV charging and V2G activities based on the grid situation [84]. Here, an area-wise grouping of EVs at AG helps to reduce the computational complexity and increases the flexibility and scalability for controlled EV charging-discharging [86]. Installing a Net Meter plays a significant role in the V2G infrastructure by acting as a data source and recipient of information necessary for the application. As discussed earlier, Net Meter recorded the electricity flow between EVSE and connected EVs to measure the energy exchange.

EVs with distinct roles and geographic dispersion demand different historical and real-time information access [85]. Net Meter collects the EV's parameters for prior energy transfer estimation, battery-safe operation, and the location at AG. The information leads to massive data generation that demands big data technology to analyze and access information for improved decision-making. Other than the computational speed, dedicated AGs provide easy data handling and system

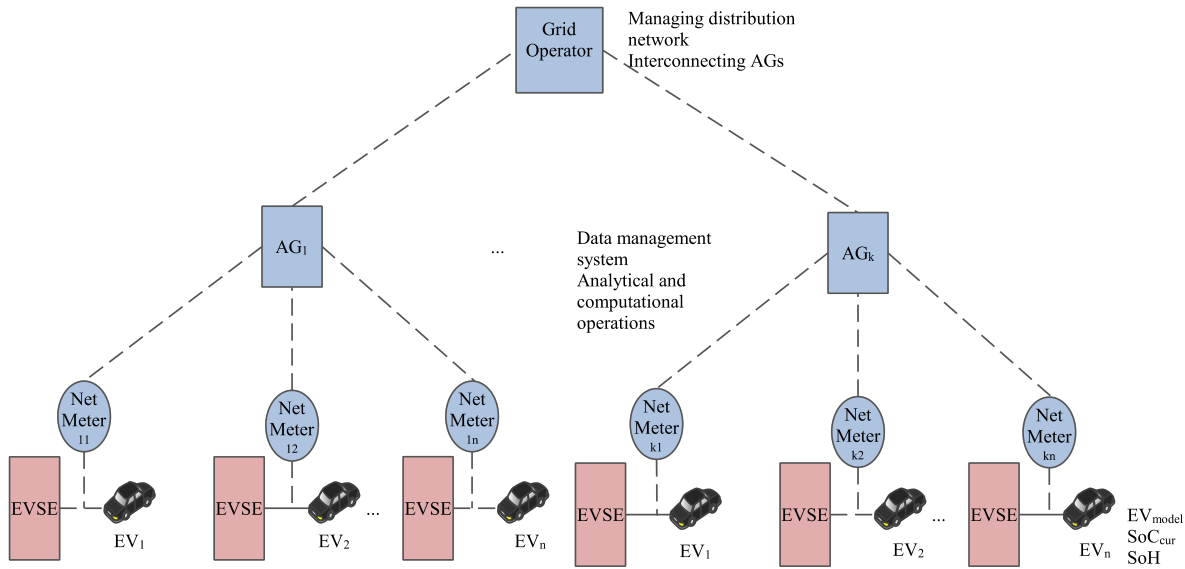


Figure 4.1: System network division.

robustness through the distributed approach [113, 114]. AGs in the system network are efficient for ample data storage and allow processing, querying, and tariff computation for efficient DSM with EVs. It helps to increase the data retrieval performance with distributed computational tasks and communication [115]. Thus, it reduces the central information processing to pursue the real-time control required in EV applications. AG receives and broadcasts data to multiple EVSEs in the area through an IoT platform integrated into the metering infrastructure. In addition, the IoT platform enables easy installation of new EVSEs, increasing with the acceptance of EVs in society [116].

In the system, the EV connects to the smart grid through an EVSE that associates only one EV at a time from the point. Multiple EVSEs in each area allow EV charging-discharging in a controlled manner based on the prosumer's request. Each EVSE is installed with an IoT-based Net Meter that becomes the primary data source in big data technology. IoT-based Net Meters measure and transfer data over the internet every 15 minutes to the AG. Other than electrical parameters, Net Meter associates communication with the BMS of the EV to access SoC, SoH, and other parameters. It helps establish the smart charging infrastructure and doesn't affect the battery performance by avoiding overcharging or discharging EV batteries. AG forms a cloud to collect all the information shared from multiple IoT-based Net Meters in the areas and broadcast the required

information based on application. Besides, EV mobility demands interconnecting the AGs for data sharing. Therefore, AGs are interconnected to each other and smart grid operators through data centers that are physically connected through optical-fiber cable in the proposed system [117].

4.2 IoT-based Net Meter

The metering equipment installed at the EV charging station must include more than just measuring the energy flow and evaluating the electrical parameters such as frequency, power factor, and harmonic distortions. It should enable the controlled charging-discharging infrastructure or smart charging through bi-directional communication between the smart grid, EVSE, and EV. Thus, the microcontroller's firmware, methods of communication, parameters, type of sensors, and other operational modules vary based on the application's requirements. The previously proposed Three-Phase AC Net Meter for the V2G application is extended to support IoT-based operations with ToU attribute. The integration of IoT enables automatic data collection and information exchange and plays a vital role in supporting different functionality in the AMI. The Net Meter has RS 485 module to set differential communication with the EV. The extended IoT-based Net Meter block diagram for EV applications is presented in Fig. 4.2.

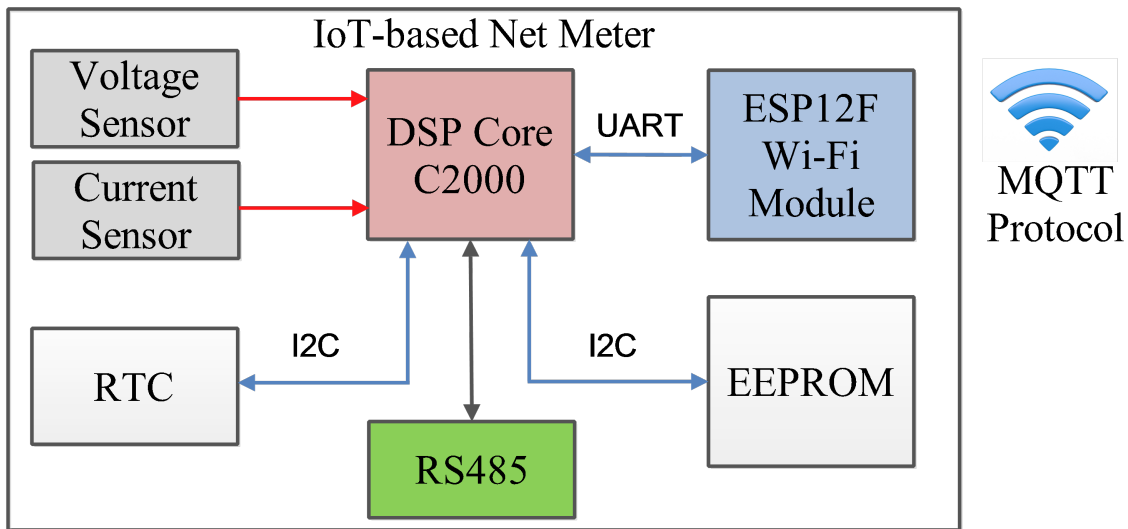


Figure 4.2: Block diagram of the proposed IoT-based Net Meter.

As explained in the previous chapter, the Net Meter comprises voltage and current sensors to monitor the respective physical quantities. TMS320F28069F DSP processor fetches the output of the sensors to compute the electrical parameters. RTC is interfaced for timely dynamic billing and data recording while charging-discharging the EVs. The DSP core stores the obtained and evaluated data values in EEPROM every 30 seconds with an interrupt action. Further, the DSP core transfers the data in Kbps through UART to Node MCU ESP12F. It is a Wi-Fi module programmed at 160 MHz to support data transfer at 54 Mbps to establish communication links through the IEEE 802.11 network. The device facilitates message queuing telemetry transport (MQTT) protocol for reliable communication through the internet with IoT middleware [118].

4.2.1 Data Processing

V2G application brings profound changes in the AMI that derive new information flow. The integration of EVs in the distribution network leads to an increase in data volume that demands a dedicated field for data processing, analysis, and collection. Big data can be considered an alternative to handle the bulk data and addresses distinct requirements of the emerging V2G application [119]. Big data combines unrelated and unstructured datasets and harvest the hidden information in real-time. The ease of integrating the new methodologies, computational and analytical techniques, and data management make it the best choice for the V2G application [120]. However, big data face data capturing, sharing, and storage difficulties. The ability to capture time data and transfer plays a crucial role in real-time applications [121]. Big data technology within the enterprise accumulates data through external sources such as sensors and actuators. The proposed IoT-based Net Meter installed at different charging points is a time series data source for big data technology.

The proposed device monitors the energy flow and connected EV battery status using the DSP core and further performs data transfer using the IoT platform. DSP core stores the time series data generated using an RTC to EEPROM every 30 seconds. It segregates the data before transmission into fields that include customer-id, ToU, operational mode, SoC, SoH, Ereq, energy consumption, and generation. Further, the stored data is fetched by the ESP 12F Wi-Fi module for transmission

over the internet. The data is transmitted to the server that acts as data storage for efficient input-output operation per second. It plays a significant role in data processing techniques, including SQL, NoSQL, artificial intelligence, and computational processing [122]. Before data processing, the data is converted into a globally accepted JSON format, and the reverse is performed while transferring the information back. The data accumulated from multiple meters are processed for V2G-related applications such as tariff rate evaluation, smart charging, and EV charge scheduling. Here, the JSON format selection enables a standard communication that most programming languages can handle. It leads to developing a scalable data storage mechanism to respond in real time for the V2G application.

4.2.2 MQTT Communication

The IoT platform establishes wireless connectivity between the server and Net Meter for data transfer. The IoT-based Net Meter facilitates MQTT messaging between the Net Meter, EVSE, and server. MQTT is a messaging protocol for IoT devices that works on the principle of a publish-subscribe communication model. Fig 4.3 illustrates the components present in the MQTT communication protocol.

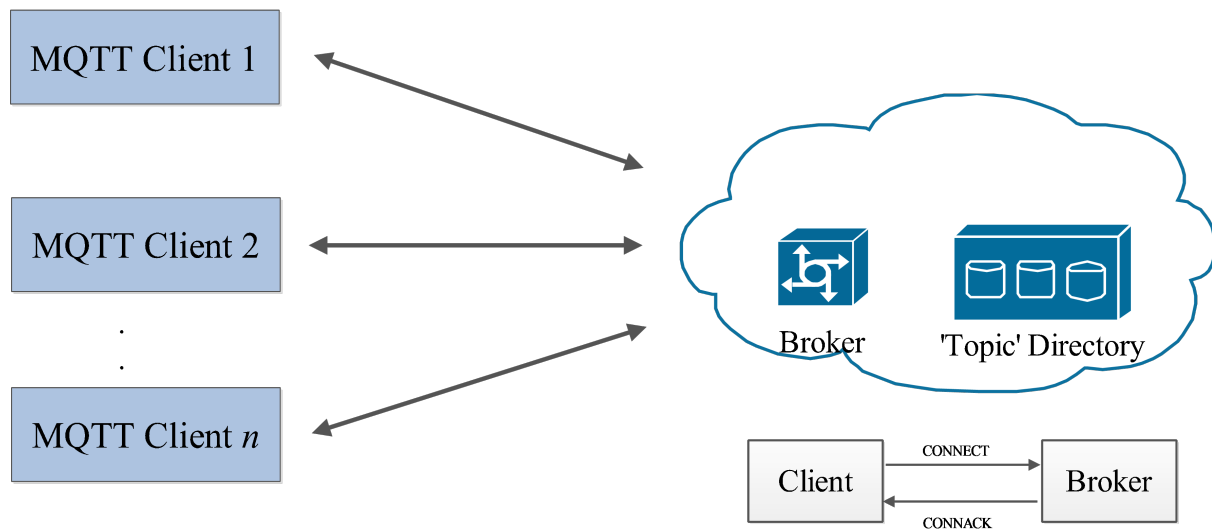


Figure 4.3: MQTT communication protocol.

MQTT supports data transfer between a client that is an IoT device and the server. It uses a publish-subscribe model different from a traditional communication model as it decouples the message publisher and subscriber. Instead, it uses a broker to handle the communication between the publisher and subscriber. If the client sends the message, it acts as a publisher, and if, in reverse, it receives a message, it acts as a subscriber. The broker segregates the incoming information based on topics and distributes them correctly to the respective subscribers. MQTT indirectly connects the publisher and subscriber concerning only the broker's hostname/IP and port to communicate with messages. The client initiates a connection with the broker by sending a CONNECT message, where in return, the broker acknowledges the connection using the CONNACK message. Any decent broker can easily connect around 1000 clients for data transfer. Once the connection is established, the clients either publish the message or receive the message or even do both. The broker forward the received message based on the topic to the interested subscriber. MQTT is advantageous for wireless communication as it reduces the time to reconnect the IoT device to the server.

4.3 BMS Interfacing

BMS of Li-ion batteries evaluates the battery status and control signals to manage the battery operations to ensure EV safety. Continues battery monitoring at EV prosumer end, and service providers benefit the application with efficient battery utilization with a minute effect on the life cycle. Here, Net Meters interconnect the EV and EVSE to fetch the status of the battery and enable the sourcing of data to the server for controlled charging-discharging or prioritization operations. Fig. 4.4 illustrates the BMS of EV establishes connectivity using CAN connector, and converter analysis pushes to choose a generic protocol at the application layer. The developed prototype configures RS 485 connector to establish a physical layer connectivity through pilot pins of charging connectors. RS485 is an industrial standard defined for serial communication between multiple points, and in the application, it connects the Net meter and BMS of a Li-ion battery mounted on

the EV.

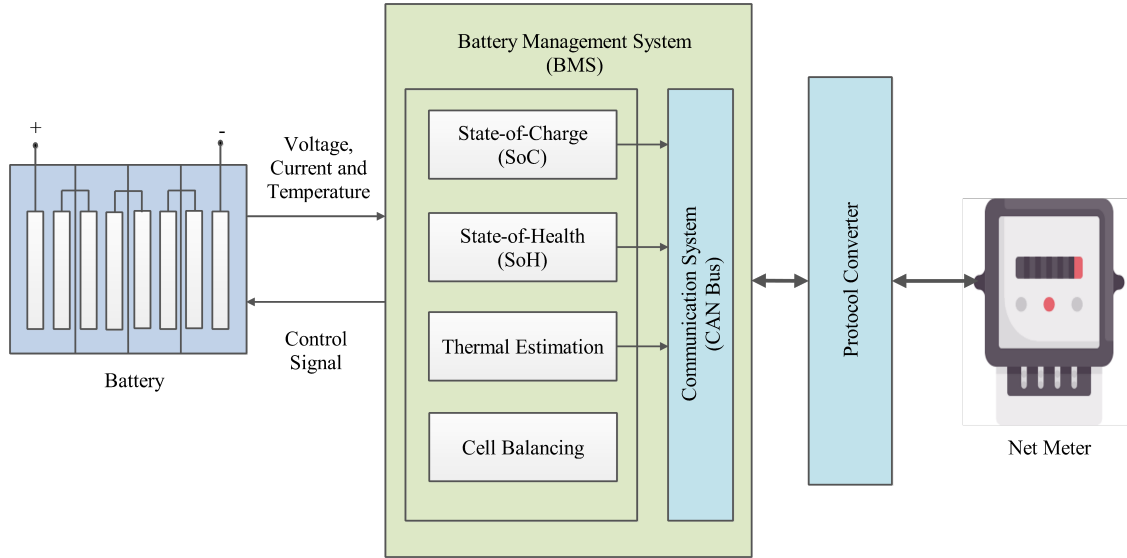


Figure 4.4: BMS connectivity with Net Meter.

In the implementation, MODBUS-Remote Terminal Unit (RTU) protocol is used on the top of the serial line with an RS485, as shown in Fig. 4.5. As it is an open protocol, it doesn't require to pay anything while embedding on equipment. MODBUS-RTU works on the concept of master and slave, where the master initiates the data transfer. The developed Net Meter is configured in both master-slave that embed the hardware with two RS485 connectors separately for each. Net Meter is a master while fetching the EV battery status through the BMS. The device is configurable based on the varying addresses, baud rate, and parity requirement. Data exchange is achieved using a request/response mechanism between the master-slave. The Net Meter is used to acquire EV battery parameters such as SoC, SoH, and temperature. The parameters are sources to the server using IoT interface, and even Net Meter accounts for the energy required or will be generated when EVs are connected to the grid. This helps draw a rough estimation billing amount and time needed for the requested operation to the EV prosumer.

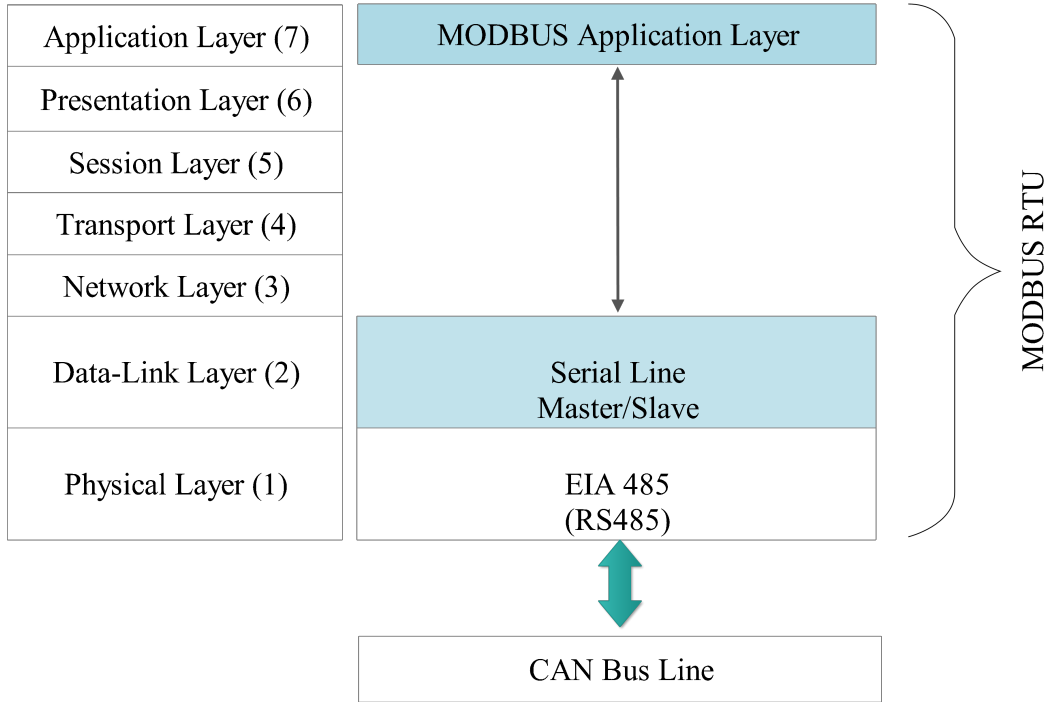


Figure 4.5: MODBUS RTU stack.

4.3.1 EV Battery Energy Estimation

In order to have a controlled charging-discharging environment, simultaneous monitoring of the EV parameters such as SoC and SoH are essential. EVSE set up communication with the BMS of the EV via charging connectors. EVSE shares the same communication channel with the Net Meter installed at EVSE to broadcast the energy demand at the market end for efficient energy utilization. The Net Meter fetches the SoC and SoH of the battery in real time and estimates energy based on the charging-discharging operation requested by EV at the EVSE end. The detailed description of the proposed mechanism to estimate the energy required is explained with the help of Fig. 4.6.

Initially, the Net Meter installed at EVSE establishes the communication link with the connected EV to read the prosumers' requested operation and the SoC. Based on the requested operation, Net Meter estimates the energy required as shown in Equations (4.1) and (4.2). This estimation helps smart charging and resolves the frequency fluctuation raised due to an imbalance between the electric load and generation [123].

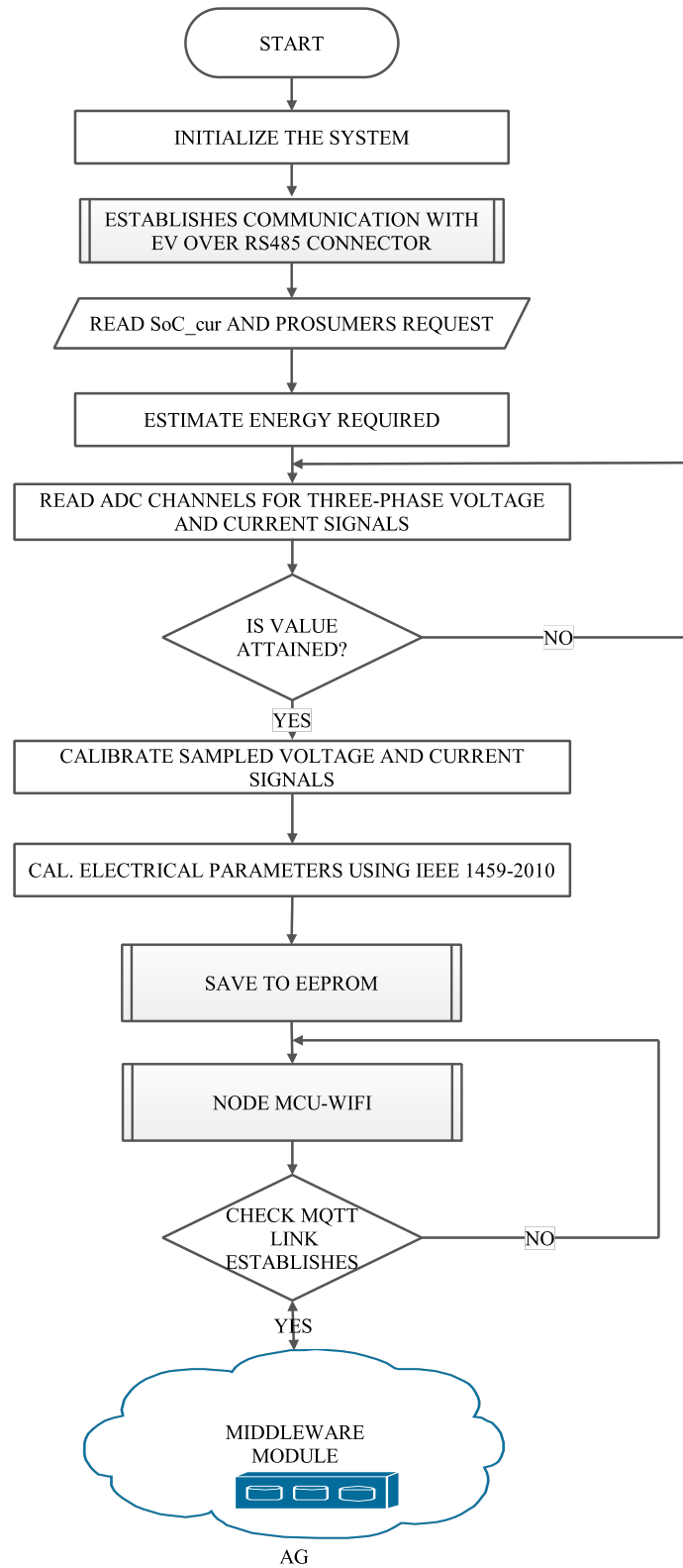


Figure 4.6: Flowchart of the proposed IoT-based Net Meter.

$$E_{char}^{req} = \frac{E_{rated}(100 - SoC_{cur})}{100} \quad (4.1)$$

$$E_{dis}^{req} = \frac{E_{rated}(SoC_{cur} - SoC_{limit})}{100} \quad (4.2)$$

where E_{char}^{req} and E_{dis}^{req} are the energy required in charging and V2G mode. SoC_{cur} is the current SoC of EV battery with E_{rated} rated voltage and SoC_{limit} nominal limit. However, the SoC is expressed with the percentage unit that reflects the level of charge of a battery relative to its capacity shown in Equation (5.10) [124].

$$SoC(t) = \frac{Q_{remain}(t)}{Q_n} \quad (4.3)$$

where $Q_{remain}(t)$ is the remaining charge in the battery at time t and Q_n is the battery's nominal capacity defined by the manufacturer, i.e., the maximum amount of charge a battery can store. DSP core calculates the electrical parameters using IEEE 1459-2010 standard to account for energy flow to generate billing quantities [104]. Node MCU ESP12F establishes the connection with the middle-ware module to exchange information.

4.4 ToU Enability

DSM demands dynamic billing to initiate the charging-discharging of EVs, focusing stabilized curve. The developed IoT-based Net Meter is configured to generate bills with variable tariff rates to support future demands. The device is embedded with an RTC and a Wi-Fi module in the hardware to receive tariff rates broadcasted by the AG. Algorithm 1 is implemented in the prototype to enable billing every hour of the day with variable tariffs.

In algorithm 1, the inputs r_{tm}^C and r_{tm}^S are the charging and discharging tariff rates per unit decided by the EV operators, respectively. E_{tm} is the amount of energy recorded by the meter at every hour to compute the final billing, i.e., $Bill$.

Algorithm 1 : Dynamic billing

Input: Tariff rates for each hour r_{tm}^C and r_{tm}^S

Output: Bill generation for charging and discharging of EV

```

1: Set  $Bill = 0$ ;  $E_{tm} = 0$ 
2: while EV=connected do
3:   Read the  $tm$  using RTC
4:   Compute  $E_{tm}$  over an hour
5:   if G2V then
6:     Compute  $Bill = Bill + E_{tm} \times r_{tm}^C$ 
7:   else
8:     Compute  $Bill = Bill + E_{tm} \times r_{tm}^S$ 
9:   end if
10: end while
11: Display the  $Bill$ 

```

4.5 Tampering Immunization

The proposed firmware integrates the hardware-software approach while installing the sensors for smart operations. It employs provisions to overcome the electricity theft or tampering that happens in the case of three-phase meters. The sensors are placed internal to the Net Meter to reduce the current tampering due to the placement of magnet or electromagnetic effects of EV charging infrastructure. The typical fraud in a three-phase meter is a skip of one-phase electric potential, i.e., voltage, to reduce the total power consumption. Fig. 4.7 shows the software approach that detects the missing voltage condition that persists for a certain period in any phase. In the process, the meter records the tamper event only if the current continues to flow for a duration in the absence of the respective voltage. The tampering is informed to the AG through a communication link to take necessary actions.

4.6 Software Calibration

EVSEs installed with the Net Meters need re-scaling of the input sensors to generate billing quantities. The automated calibration process sets up the prototype to correctly measure the input parameters without human intervention. In the design to calibrate the input sensors, ADC output

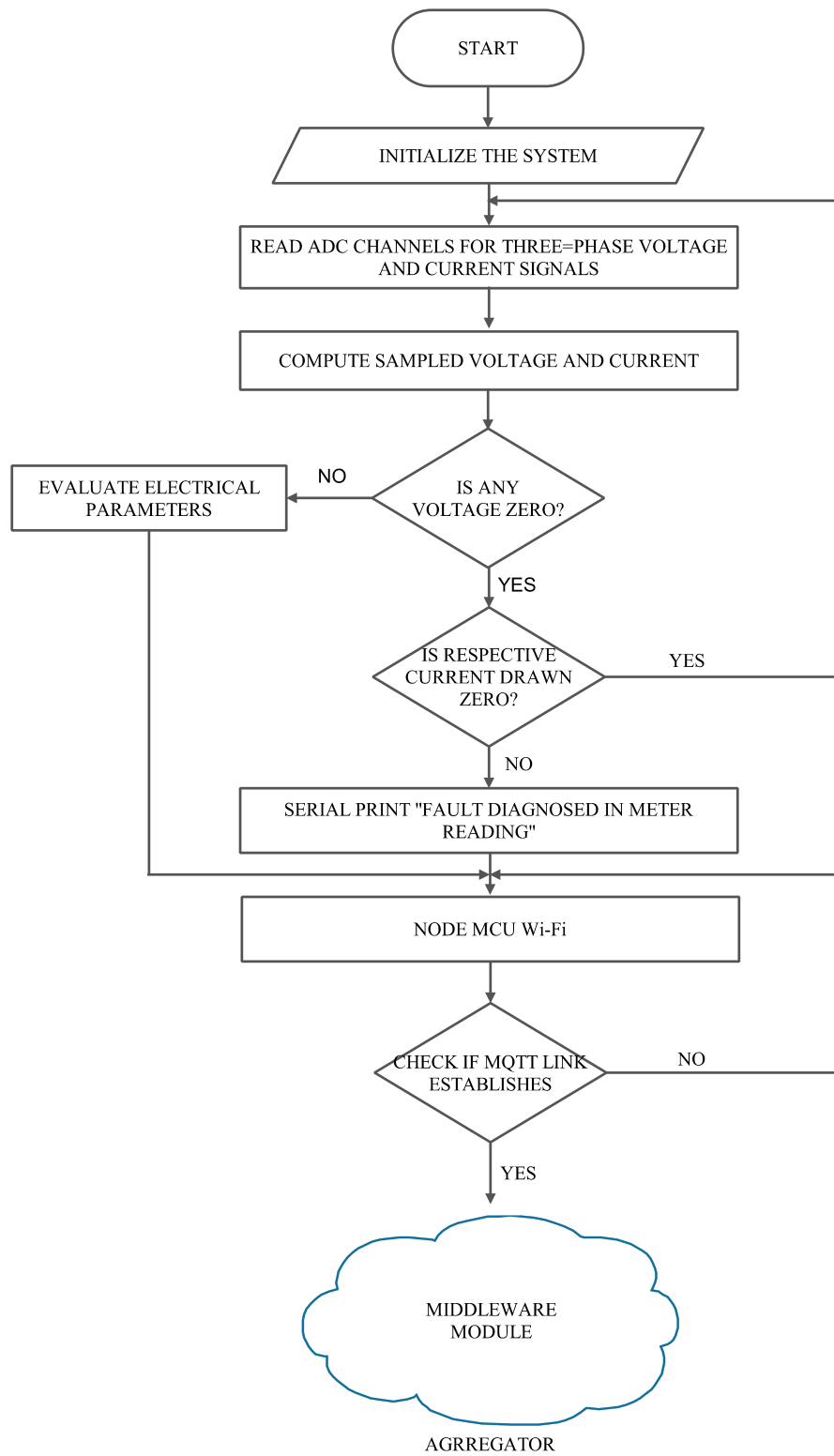


Figure 4.7: Flowchart for missing voltage detection.

is derived towards the correction mechanism to generate the desired output y as shown in Fig 4.8.

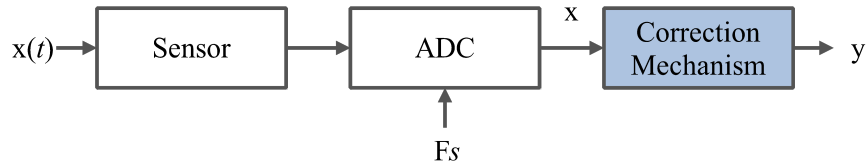


Figure 4.8: Steps in calibration process.

The correction mechanism is described as a function of a line as follow:

$$y = mx + c \quad (4.4)$$

where, y is the desired output, x is the ADC output, m is the line's multiplication factor or slope and c is the displacement constant.

The corrected output y should correspond to the actual input $x(t)$. In the process, low and high points are considered to calibrate the meter; therefore, it is called a 2-point calibration process [125]. The steps followed to calibrate each sensor in the process are as follows:

1. Connect a low input signal and a high input signal to the sensors.
2. Store the sampled outputs of the input actual signals in x_1 and x_2 .
3. Calculate the multiplying factor m as follows:

$$m = \frac{y_2 - y_1}{x_2 - x_1} \quad (4.5)$$

4. Estimate c using the following Equation.

$$c = y_1 - mx_1 \quad (4.6)$$

The above procedure computes the value of m and c based on the low and high voltage or current input signals applied at the input with the corresponding recorded samples as x_1 and x_2 . The

prototype's simplified software calibration is processed through the MODBUS RTU protocol. The communication uses the physical layer of the RS485, and a higher accuracy standardized calibrator is taken as a source in the calibration mode.

4.7 Demonstration and Validation

4.7.1 Experimental Calibration

The workbench to calibrate the proposed prototype is shown in Fig. 4.9. A ZM3 ϕ PEC 3-phase power energy meter calibrator with 0.1 % accuracy is used to scale the meter. Sine waves with minimum 1A, 40V, and maximum 5A, 230V are sourced through the calibrator. In Table 4.1, m and C obtained calibration constants while scaling the input sensors of the developed prototype.

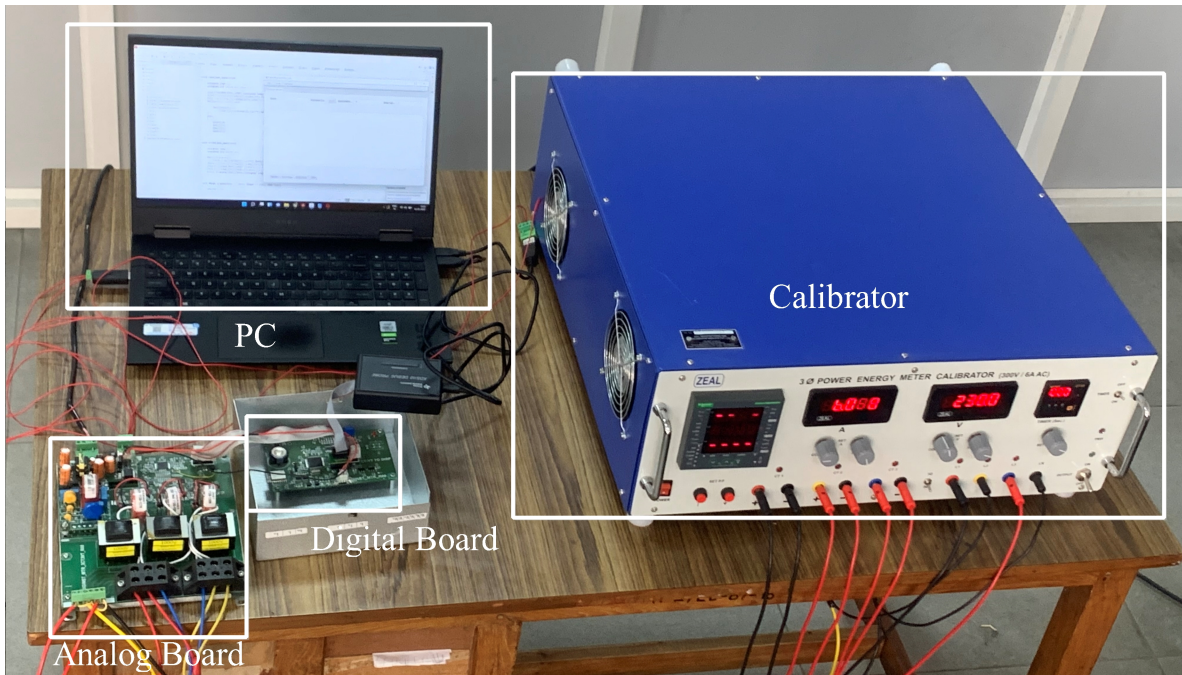


Figure 4.9: Workbench for calibration.

Table 4.1: Calibration variables.

Inputs	m	C
VT1	0.0000380	0.010
VT2	0.0000380	0.010
VT3	0.0000379	0.030
CT1	0.000036	0.011
CT2	0.000036	0.011
CT3	0.000035	0.012

4.7.2 Linearity Test

The test bench presented in Fig. 4.10 analyzed the prototype's performance through actual power calculation. An APS 5000 Spitzenberger Spies grid simulator generates signals at different power levels in the experimentation.

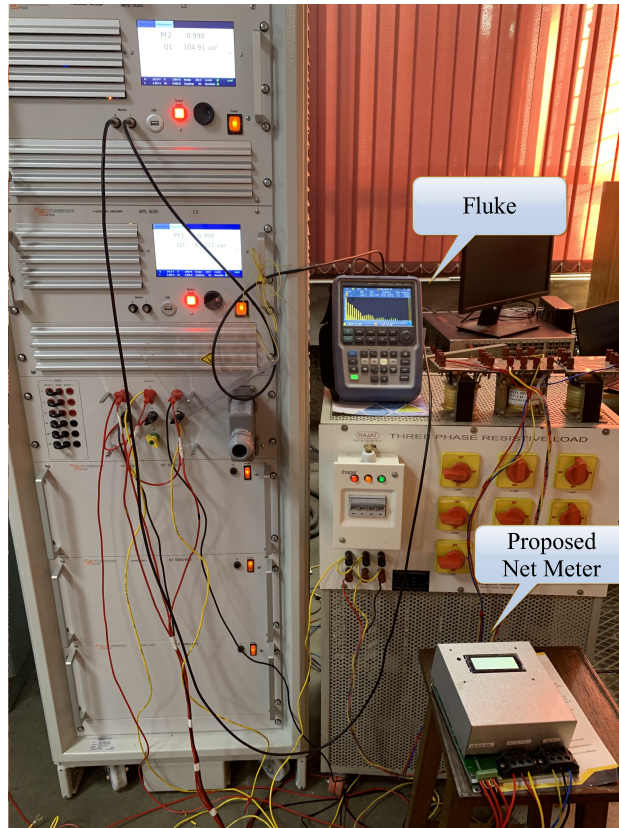


Figure 4.10: Test bench 2.

The experimentation obtained the power measurement accuracy of the prototype in reference to the Fluke 434 series II power analyzer. The comparative results are shown with the help of Fig.

3.12. The proposed Net Meter confirms class 1 accuracy with the maximum deviation of 0.05% concerning the IEC standards [126–128].

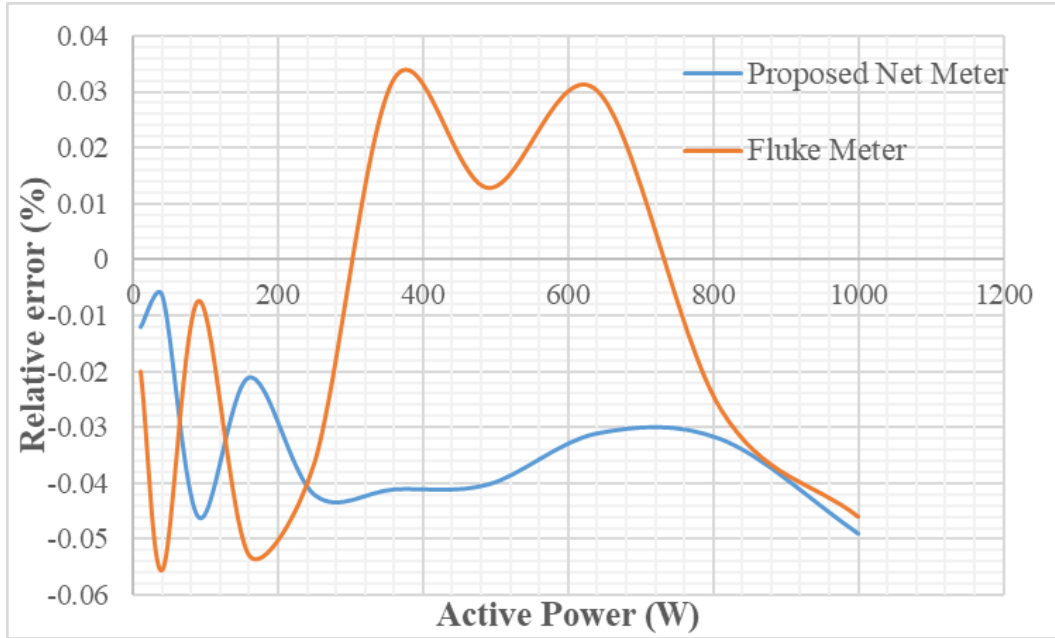


Figure 4.11: Percentage error in active power.

4.7.3 IoT-based Net Meter Laboratory Performance with a 15 kW Charger

The working of the proposed ToU-enabled IoT-based Net Meter is tested on a real-time 15 kW charger with a 17.28 kWh (720 V, 240 h) battery capacity. Fig. 4.12 shows the test bench used for the experimentation. The platform has an isolated transformer connecting the three-phase AC supply to the charger (EVSE). The charger obtains the DC supply at the output using AC-DC and DC-DC converters. The obtained DC supply is connected to the battery for charging. The periodically collected data from the proposed device is shown with the help of Fig. 4.13. It can be seen that SoC_{cur} and E_{char}^{req} are inversely proportional as SoC_{cur} increases, E_{char}^{req} evaluated with the Net Meter starts decreasing at the same rate in Fig. 4.13a and 4.13b. Fig. 4.13c and 4.13d shows the voltage and current in each phase drawn in the 3-hour duration. Power drawn in each phase and total power is shown with the help of Fig. 4.13e.

The setup charges the battery at different initial SoC with 0.33 C-rate in the experimentation.

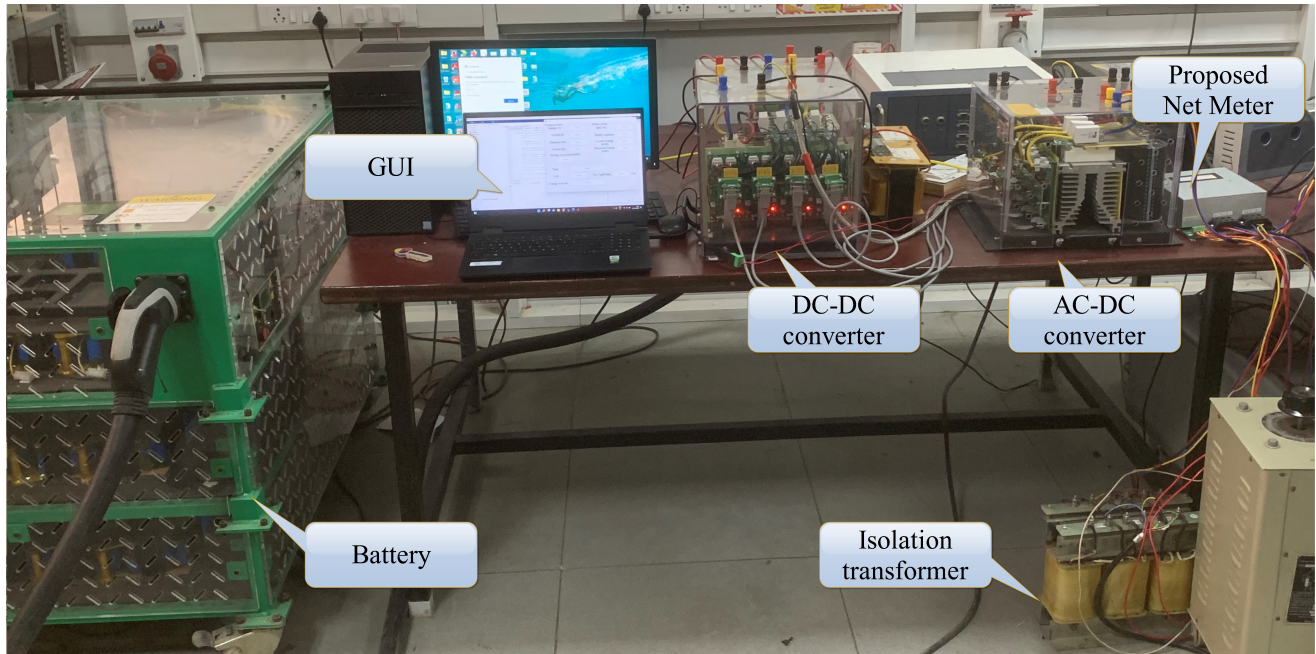


Figure 4.12: Test bench: 15 kW charger.

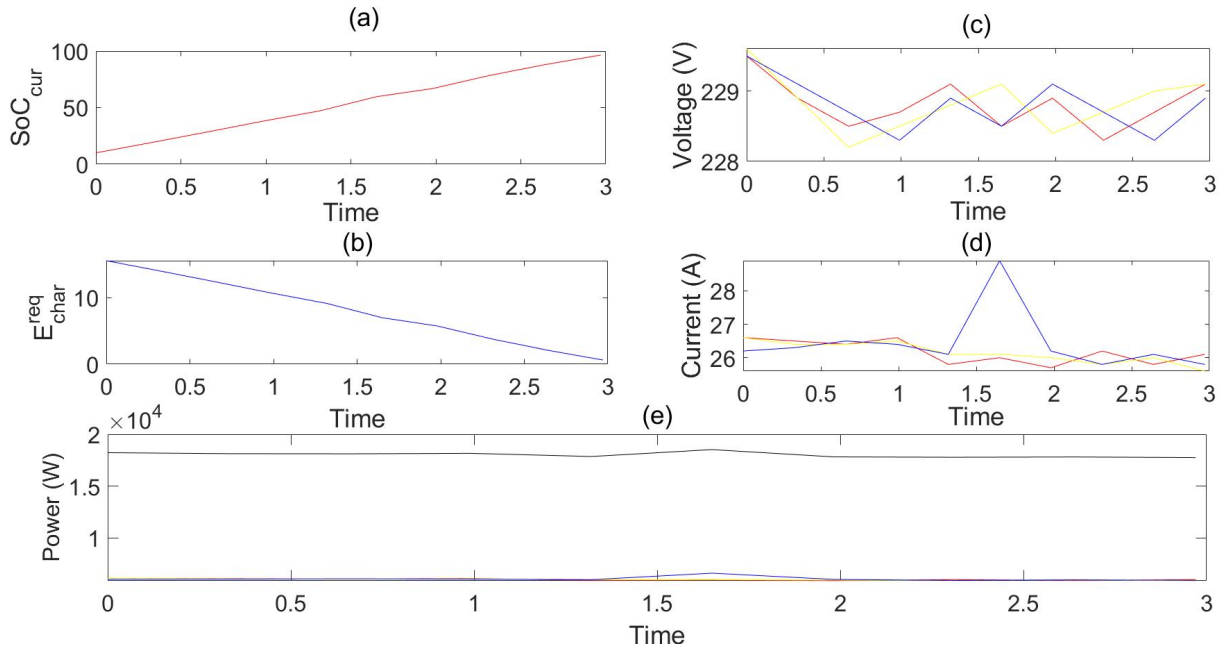


Figure 4.13: Laboratory test: IoT-based Net Meter performance with a 15 kW charger over 3 hour time interval. (a) SoC_{cur} of the battery in real-time. (b) E_{char}^{req} while charging the battery in real-time. (c) Measured voltages (V) in each phase. (d) Measured current (I) in each phase. (e) Power (W) in each phase and total power.

Table 4.2 presents the parameter readings and billing at variable tariff rates per hour using the proposed ToU-enabled IoT-based Net Meter.

Table 4.2: Proposed IoT-based Net Meter billing.

Connect Time	Initial SoC (%)	Required Energy (kWh)	Disconnect Time	Elapsed Time (h)	Energy Consumed (kWh)	ToU Tariff		Final Bill (\$)
						Interval	Rate (\$/kWh)	
23-02-2022 08:00	0	17.28	-	-	5.3	08:00-09:00	1	5.3
	30	11.98	-	-	5.5	09:00-10:00	2	11
	64	6.48	23-02-2022 11:00	-	5.3	10:00-11:00	3	15.9
23-02-2022 08:00			23-02-2022 11:00	03	16.1	-	-	32.2
26-02-2022 08:00	20	13.82	-	-	5.2	08:00-09:00	1	5.2
	50	8.62	-	-	5.3	09:00-10:00	2	10.6
	80	3.32	26-02-2022 11:00	-	3.3	10:00-11:00	3	9.9
26-02-2022 08:00			26-02-2022 11:00	2.30	13.8	-	-	25.7
01-03-2022 08:00	30	12.09	-	-	5.2	08:00-09:00	1	5.2
	61	6.89	-	-	4.9	09:00-10:00	2	9.8
	89	1.99	01-03-2022 11:00	-	1.9	10:00-11:00	3	5.7
01-03-2022 08:00			01-03-2022 11:00	2.20	12	-	-	20.7

4.8 Summary

The chapter described an IoT-based system network for the V2G application to enable net metering. An IoT-based Net Meter is presented as a data source and recipient of information between EV, EVSE, and server for the V2G application. The device enables real-time data accumulation that may be used to monitor the EV prosumers' behavior for DSM, load prediction, and booking charging slots. Net Meter establishes a connection with the BMS of the Li-ion battery using MODBUS-RTU protocol to read the battery parameters such as SoC and SoH. The developed prototype is configured as both master-slave; it operates in master mode while initiating communication with BMS. In addition, the prototype accounts for the energy required or will be generated by the EV when connected based on the requested operation. The EV parameters fetching and evaluation help to establish a coordinated charging-discharging environment without compromising the battery life. Besides, the chapter has embedded the device with a simplified software 2-point calibration process to accurately re-scale the input sensors. The results have shown that the prototype has attained class 1 accuracy with human intervention while scaling. In addition, the ToU attribute is enabled with the evolving techniques for dynamic billing and a protection mechanism against physical tampering is presented.

Chapter 5

Time-of-Use Tariff Rates Estimation for DSM using EVs

DSM with EVs is in the preliminary stage, relying on existing AMI to enable diverse motivational techniques. Amongst various schemes, ToU price-based mechanism is the most accepted, where tariff rates vary with the day timing. Determining tariff rates is significant to motivate EV prosumers for efficient DSM. In the V2G application, DSM encourages EV prosumers to shift the EV charging time with the integration of V2G mode [81]. The chapter proposes a methodology for ToU tariff estimation to provide an optimal DSM constituting DR and V2G using EVs¹. A novel mathematical model calculates the tariff rates using EVs' peak and off-peak contribution coefficients. Besides, conditional prioritization is presented based on EVs' SoC to mitigate the simultaneous charging of numerous EVs.

¹A. Kaur, M. Singh, Time-of-Use tariff rates estimation for optimal demand-side management using electric vehicles, *Energy* 273 (2023) 127243.

5.1 Contribution

The significant contribution of the chapter is estimating the ToU tariff rates for the V2G application are summarized as follows.

- The chapter presents a research methodology for setting the ToU tariff rates for optimal DSM using EVs through AG.
- A novel mathematical model for ToU tariff rates estimation is proposed considering the EVs' peak and off-peak contribution coefficients.
- The methodology integrates a priority determination algorithm to regulate the simultaneous charging of EVs based on the SoC of the EV's battery.

5.2 Research Methodology

The methodology for DSM using EVs by setting the ToU tariff rates consists of the steps illustrated in Fig. 5.1. Initially, the grid operator classifies the electricity consumption based on the area type in different categories, such as residential, industrial, and others. The classification is a prerequisite due to consumer behavior changes as per the area. Then, a 24-hour load profile is prepared for a week to determine the peak and off-peak ToU intervals. The power ratio of import-export capacity is the deciding factor in classifying the ToU intervals as peak and off-peak [129]. Here, the import power reflects the input power capacity of a voltage grid, and export is the consumers' demand from the grid. This complete procedure is repeated for each season as the electricity consumption varies between the seasons [130]. Further, the AG that coordinates the activities of EVs in an area prepares the 24-hour load profile of EV consumption. The obtained EVs load profile overlaps with the area's load profile broadcasted through the grid operator to determine the ToU intervals and allocate the ToU tariff rates. The tariff rates are evaluated at the AG, which reduces the computational complexity of the grid side. In the proposed methodology, the evaluation of tariff rates considers the peak and off-peak contribution coefficients of EVs in the area. Besides, conditional

execution to prioritize the EVs takes place to avoid the detrimental effect of simultaneous EV charging that may affect the consumption curve.

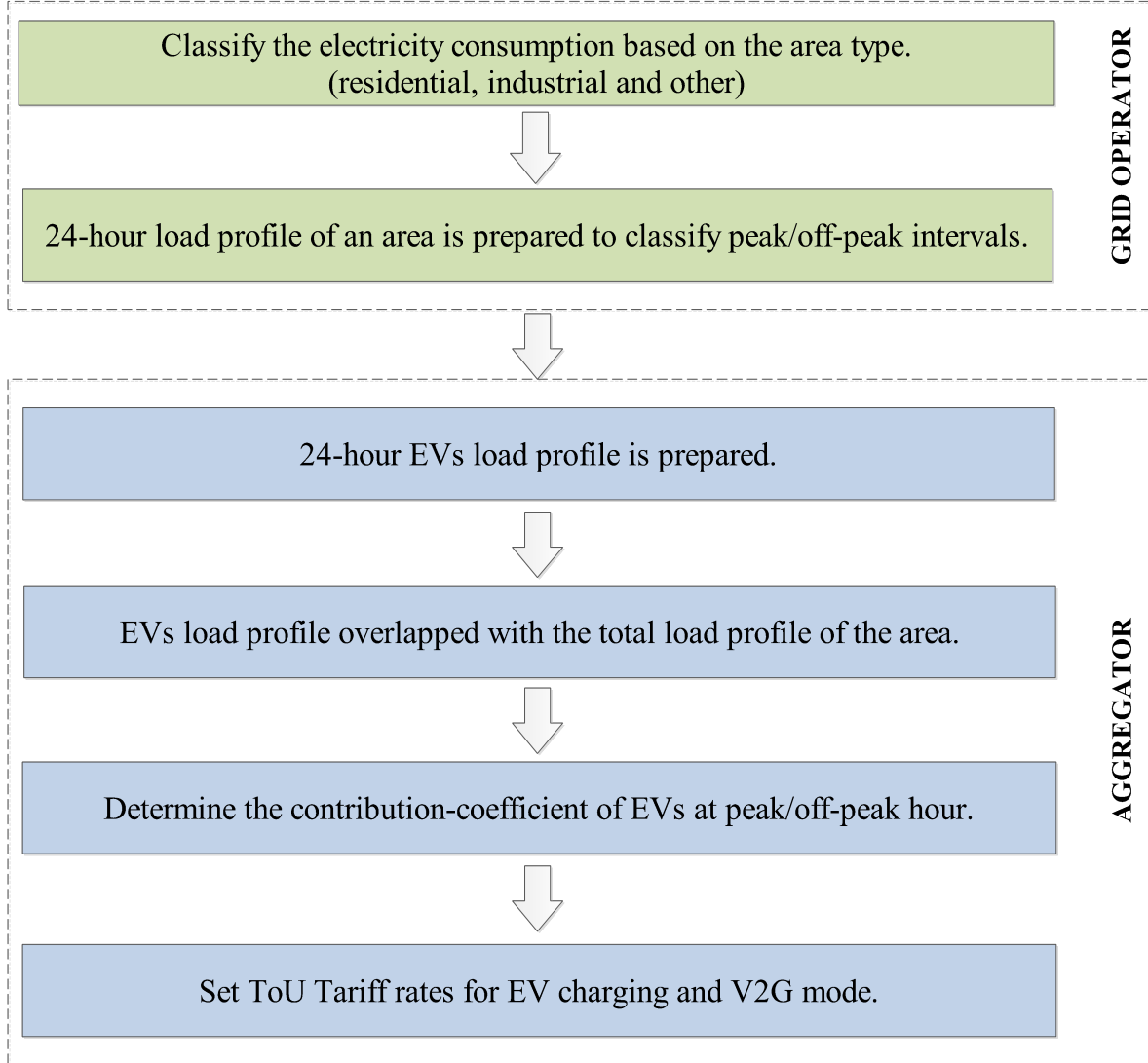


Figure 5.1: Methodology of setting ToU tariff for DSM using EVs.

5.3 Computational Facility at AG

5.3.1 Proposed Mathematical Model

The mathematical model for evaluating the tariff rates to generate the net bill is defined as follows. First, the flat electricity charges defined for EV charging and V2G mode are in Equations (5.1) and

(5.2).

$$P_{FT}^C = \sum_{h=1}^{24} r^C \times E_h \quad (5.1)$$

$$P_{FT}^S = \sum_{h=1}^{24} r^S \times E_h \quad (5.2)$$

where, P_{FT}^C and P_{FT}^S are the prices with flat rate implementation for EV charging and V2G mode, respectively. r^C/S are the unit flat rates and E_h is the amount of energy consumed or generated in an hour.

Second, the proposed ToU tariff rates calculation for EV charging and V2G mode are as follow:

$$P_{ToU}^C = \sum_{h=1}^{24} \alpha^{off/peak} \times r^C \times E_h \quad (5.3)$$

$$\alpha^{off/peak} = 1 \mp c^{off/peak} \quad (5.4)$$

P_{ToU}^C is the EV charging price with ToU; $\alpha^{off/peak}$ is the off-peak/peak multiplication factor for EV charging with ToU and $c^{off/peak}$ is the EVs' contribution-coefficient in off-peak/peak hours.

$$P_{ToU}^S = \sum_{h=1}^{24} \gamma^{off/peak} \times r^S \times E_h \quad (5.5)$$

$$\gamma^{off/peak} = 1 \pm c^{off/peak} \quad (5.6)$$

P_{ToU}^S is the price in V2G mode with ToU; $\gamma^{off/peak}$ is the off-peak/peak multiplication factor in V2G mode with ToU.

The off-peak/peak contribution coefficient ($c^{off/peak}$) of EVs is evaluated as follows:

$$c^{off/peak} = \frac{C^{off/peak}}{E_{total}} \quad (5.7)$$

Here, $C^{off/peak}$ is the EVs' consumption in off-peak/peak hours and E_{total} is the total energy consumption in the desired selected hour. The computational complexity involved to determine

the unit ToU tariff rate is defined using Big O notation with N number of inputs as follows:

$$Cost = Max(O(N), O(1), \Theta(\log(N))) \quad (5.8)$$

The EV prosumers' sensitivity to the tariff change is measured with the help of tariff elasticity [131]. The tariff elasticity (TE) is defined as the percentage change in the ratio of EVs consumption ($\Delta C \%$) in response to the change in tariff rates ($\Delta R \%$).

$$TE = \frac{\Delta C\%}{\Delta R\%} \quad (5.9)$$

5.3.2 Priority Determination

In the proposed scheme, AG regulates the C-rate, the speed at which the EV charges through the charging stations. It helps to mitigate the worst-case scenario of simultaneous EV charging. Here, EVs are prioritized based on the SoC of batteries at the time of the request while charging [132]. The SoC is expressed with the percentage unit that reflects the level of charge of a battery relative to its capacity as shown in Equation (5.10) [124].

$$SoC(t) = \frac{Q_{remain}(t)}{Q_{nom}} \quad (5.10)$$

where, $Q_{remain}(t)$ is the remaining charge in the battery at time t and Q_{nom} is the nominal capacity of the battery defined by the manufacturer, i.e., the maximum amount of charge a battery can store.

Further, conditional prioritization reduces the execution time involved in the scheme. Here, the smart charging infrastructure adjusts the C-rate based on the priority level allocated through AG. It involves the determination of the amount of charge required by each EV request for charging at time t as follows [123]:

$$SoC_n^{req}(t) = 100 - SoC_n^{cur}(t) \quad (5.11)$$

Here, $SoC_n^{req}(t)$ is the required SoC by n_{th} EV and $SoC_n^{cur}(t)$ is the current SoC of n_{th} EV at the time of request t for charging. Finally, estimating the total energy required in the respective hour for charging the vehicles connected to the charging stations of an area.

$$E_n^{req}(t) = \frac{E_{rated} SoC_n^{req}(t)}{100} \quad (5.12)$$

$$E_{total}^{req}(t) = \sum_{n=1}^N E_n^{req}(t) \quad (5.13)$$

where, E_n^{req} is the amount of energy required by n_{th} EV to charge, E_{rated} is the rated capacity of EV's battery and E_{total}^{req} is the total required energy to charge n number of EVs.

The proposed technique prioritizes the EVs in three different levels based on SoC provided by the battery management system of EV [133]. The mechanism has been elaborated in algorithm 2. Accordingly, prioritization of EVs occurs when n number of vehicles charging at the same interval requires the amount of energy that may alter the consumption curve. The technique prioritizes the EVs based on the required SoC for charging, and then the smart charging stations adjust the C-rate accordingly. The C-rate is high for high-priority vehicles and decreases for low-priority vehicles. The change in C-rate shifts the power consumption for the desired intervals. EVs with medium and low priority charges with a lower current value reduce the grid's stress and consequently increase EVs' charging duration.

However, as constrained, the battery charges or discharges no more than its maximum and minimum capacities as follows [134]:

$$SoC_{min} \leq SoC \leq SoC_{max} \quad (5.14)$$

where, SoC_{min} is the minimum limit of SoC and SoC_{max} is the maximum limit of SoC. The runtime involved for the execution is $O(N)$ and the final computational complexity of the proposed

Algorithm 2 : Priority determination of EVs

```

1: Read the value  $n$ 
2: Read  $SoC_n^{cur}(t)$ ,  $EV_n^{model}$ 
3: Compute  $SoC_n^{req}(t)$  using (5.11)
4: Compute  $E_n^{req}(t)$ ,  $E_{total}^{req}(t)$  using (5.12) and (5.13)
5: if  $E_{total}^{req} > E_{thd}$  then
6:   while ( $n > 0$ ) do
7:     if  $SoC_n^{req} \leq 20$  then
8:       Set  $pc_n = Low$ 
9:     else if  $20 < SoC_n^{req} < 80$  then
10:      Set  $pc_n = Medium$ 
11:    else if  $80 \leq SoC_n^{req}$  then
12:      Set  $pc_n = High$ 
13:    end if
14:    Update  $n = n - 1$ 
15:  end while
16: else
17:   Terminate the process
18: end if

```

method is $O(N)$ referring Equation 5.8.

The outcome of the proposed method consists of evaluating the peak and off-peak consumption and the change in EV consumers' behavior as a consequence. However, a catastrophic condition may occur when all EVs request to charge simultaneously with high priority. Besides, the frequent charging-discharging processes of EVs affect the battery life significantly. The proposed method focused only on estimating the tariff rates to reduce stress on the grid. Hence, it does not consider the battery life cycle at present. However, including SoH of EV batteries in the future may resolve battery-related issues to an extent.

5.3.3 Evaluation Criteria for Defining ToU Intervals

The import-export power ratio significantly influences the ToU intervals as peak, or off-peak [135].

The power ratio (G) of a grid is defined in Equation 5.15 [129].

$$G = \frac{p_o}{p_{in}} \quad (5.15)$$

The power grid transmits the electrical power from the power plants to the consumers, which must satisfy the import-export power ratio. Assuming the grid with a single voltage grade makes the consumers' demand equivalent to the grid's export power capacity. If the power ratio is higher than one, it reflects the consumers' demand is higher than the import power. On the contrary, a low load is on the grid if the power ratio is less than one. Table 5.1 presents the conditions of ToU intervals classification.

Table 5.1: Classification of ToU intervals

Interval	Condition
Peak	$G > 1$
Off-Peak	$G \leq 1$

5.4 Process Flow and Input Data

The technique aims to identify the EV consumers' behavior in the context of setting the ToU tariff rates for DSM with EVs. The secondary objective is to decide the ToU tariff to balance the consumption curve significantly. Hence, the assumption is verified considering a small area with a trial of 4 months period. The data with six fields include customer-id, date and time, EV battery status, consumption, and electricity generation every 15 minutes. Data storage is crucial in efficient input-output operation per second, from data collection to data analysis. This brings the need to develop a scalable storage mechanism that meets the big data requirements, the data type for data storage, and interoperability. Massive data collection from several IoT-based Net Meters leads to failed attempts to exploit several relational databases either in importing or updating. Thus, the NoSQL database model as an alternative is used for big data storage [94]. It allows both the accumulation of history and real-time data and the computational environment for electric power [31]. The research has selected the MongoDB database storage solution due to its fast reading speed and support for rapid growth in EV count [136].

The infrastructure of the proposed methodology to integrate the DSM with EVs is illustrated

in Fig. 5.2.

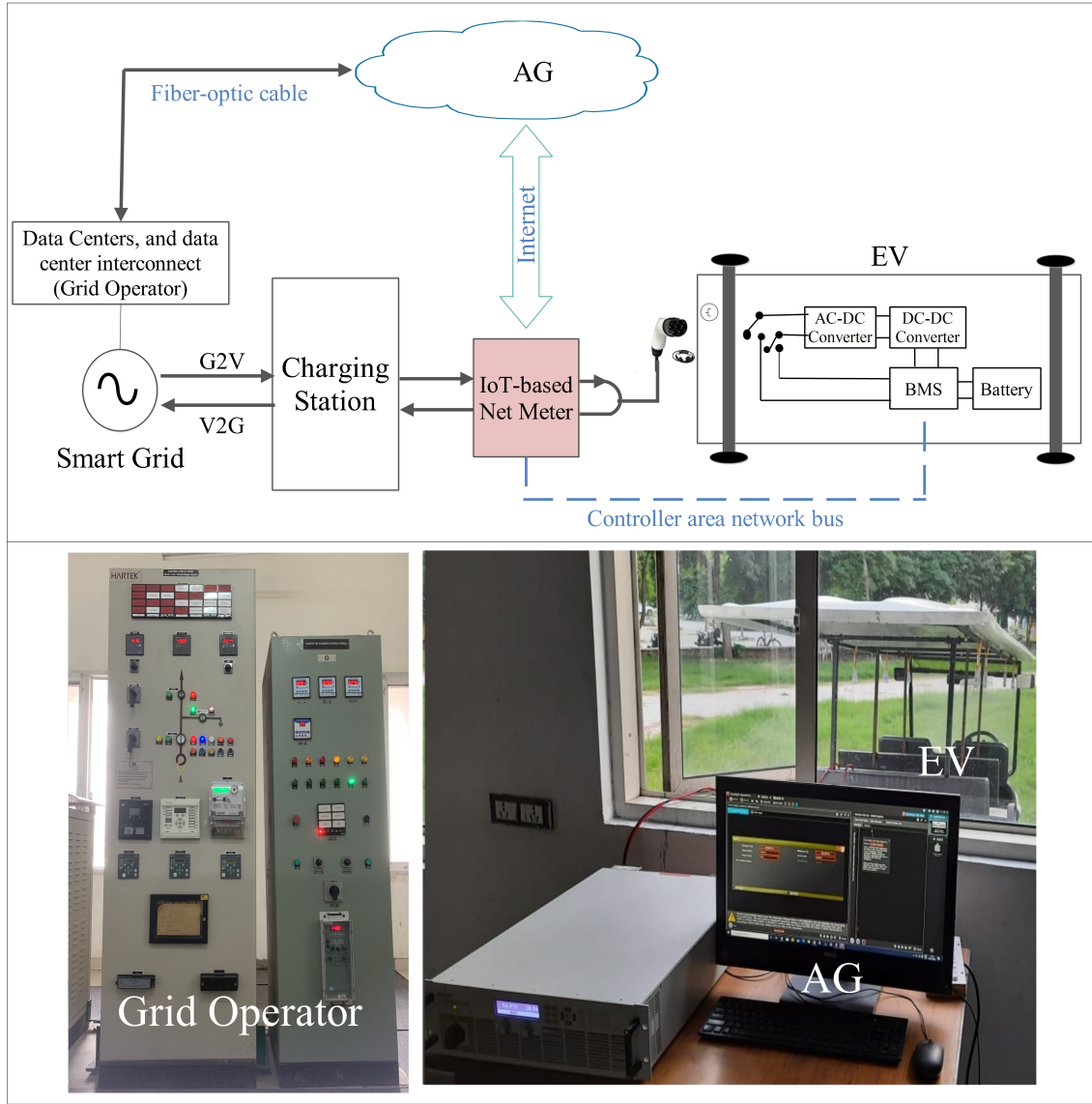


Figure 5.2: Infrastructure of the proposed methodology.

The EV connects to the grid through a constant-current and constant voltage type charger that associates only one EV at a time from the point. Multiple chargers in the area are installed with an IoT-based Net Meter to measure and initiate data transfer over the internet [104]. IoT platform sets cloud-based data management and computation service for a smart interactive environment. It reduces the operational cost with improved efficiency and adds scalability for easy integration of increasing EVs [137]. On the there hand, Net Meter retrieves EV's battery parameter from the

battery management system using a controller area network bus. AG forms a cloud that collects all the information shared from multiple meters in the areas and performs the computational task to derive the tariff rates. The mobility of EVs demands interconnecting the AGs for data sharing. Therefore, AGs are interconnected through the grid operator using the optical-fiber cable in the proposed system.

The battery temperature is monitored while charging the EVs to ensure a safe environment. Fig. 5.3 shows the observed temperature while charging EVs with different SoC at the time of the request.

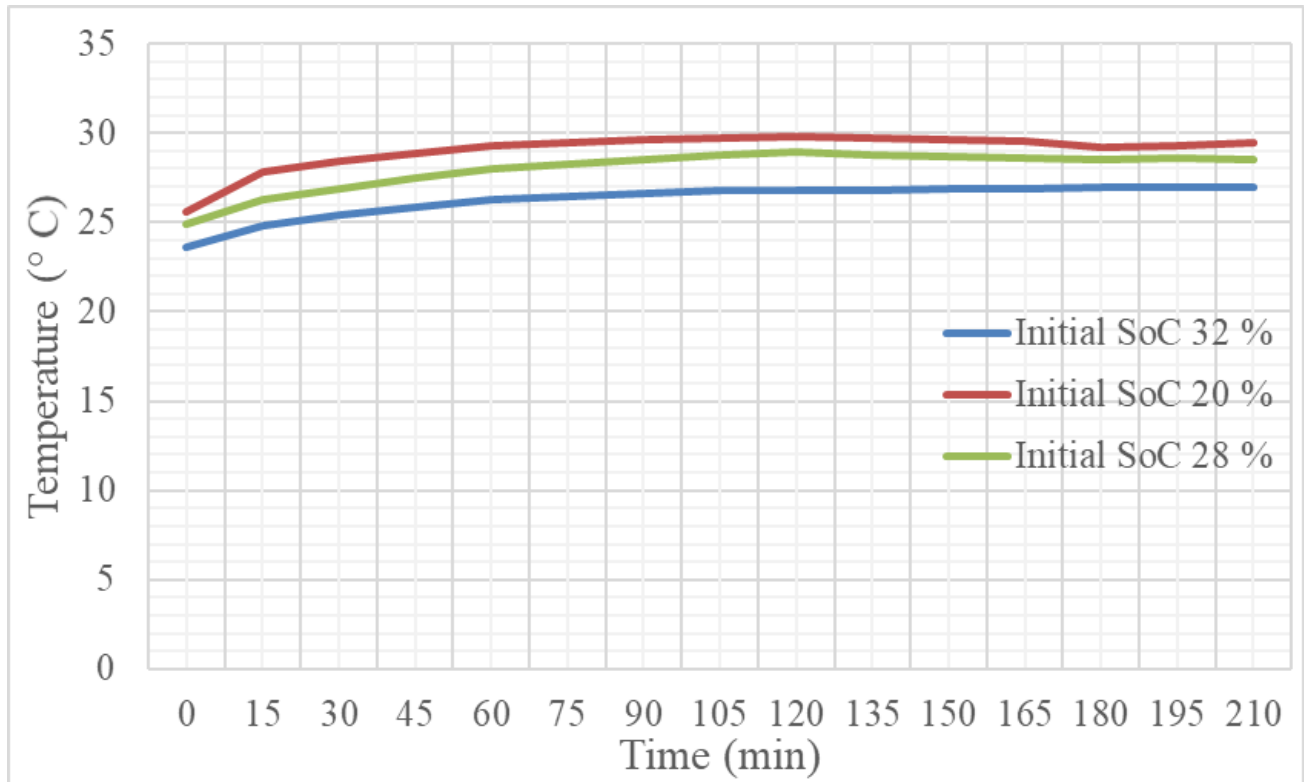


Figure 5.3: Battery temperature at different SoC levels.

The import input data of XLXS documents are transformed to JSON in the NoSQL database (MongoDB). The Python language has been selected for data handling, analysis, and mathematical computation for tariff rate calculation using Google Colaboratory. The full load profile of an area for a week has been depicted in Fig. 5.4. It is vivid that electricity consumption changes with the time of day and between days of the week. Hence, each day is classified in different intervals based

on the import-export ratio of the grid to identify the peak and off-peak intervals.

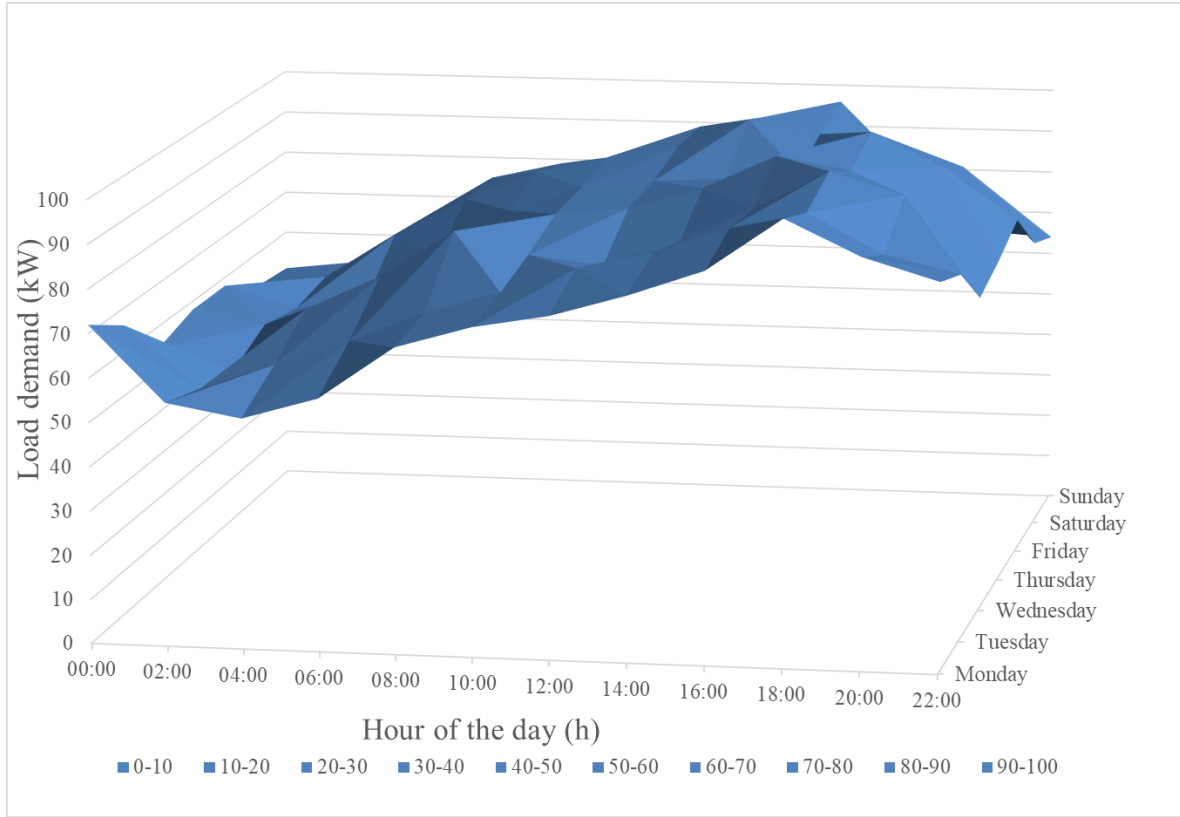


Figure 5.4: Load profile for a week.

5.5 Performance Evaluation

This section highlights the simulation results based on the proposed methodology. Real-time data is obtained with the 11 kV distribution line and an AG unit to validate the technique. The charging stations connect to the AG through the IoT platform using Net Meters. However, the scheme is extensible to a large area with a sufficient count of EVs. The results were simulated without considering the worst-case charging scenario and V2G operation due to the unavailability of smart-charging infrastructure.

5.5.1 ToU Tariff Rate Estimation

The proposed ToU tariff rate-setting methodology has been evaluated over a small area. The contribution coefficient of EVs in the considered area at peak and off-peak hours are as per Table 5.2. It can be seen that the consumption in peak and off-peak hours differ within weekdays. More importantly, the difference between tariff rates is slight, as the assumed area had a limited amount of EVs with a 2 kW charging capacity.

Table 5.2: Contribution-coefficient at peak and off-peak hours for a week.

Day	Peak hour (h)	Off-peak hour (h)	C^{peak} (%)	C^{off} (%)
Monday	H18	H3	14	4.0816
Tuesday	H17	H2	14	7.6923
Wednesday	H18	H2	16	8
Thursday	H16	H3	14.285	11.764
Friday	H18	H3	14.14	7.6923
Saturday	H14	H1	6.25	8
Sunday	H15	H1	14.583	8.1632

Suppose the flat rate for EV charging is assumed to be 1 \$/kWh. Accordingly, the peak and off-peak tariff rate calculation is shown in Table 5.3 based on the proposed mathematical model. Presently the deviation in tariff rates between peak and off-peak intervals is infinitesimal. The difference increases with the increased density of EVs, which can be considered the motivating element for consumers to support DSM.

Table 5.3: ToU tariff rates for a week.

Day	Peak rate (\$/kWh)	Off-peak rate (\$/kWh)
Monday	1.14	0.9592
Tuesday	1.14	0.9231
Wednesday	1.16	0.92
Thursday	1.1428	0.8824
Friday	1.1414	0.9230
Saturday	1.0625	0.92
Sunday	1.1458	0.9184

Fig. 5.5 illustrates the ToU intervals and tariff rates for the selected period in a week.

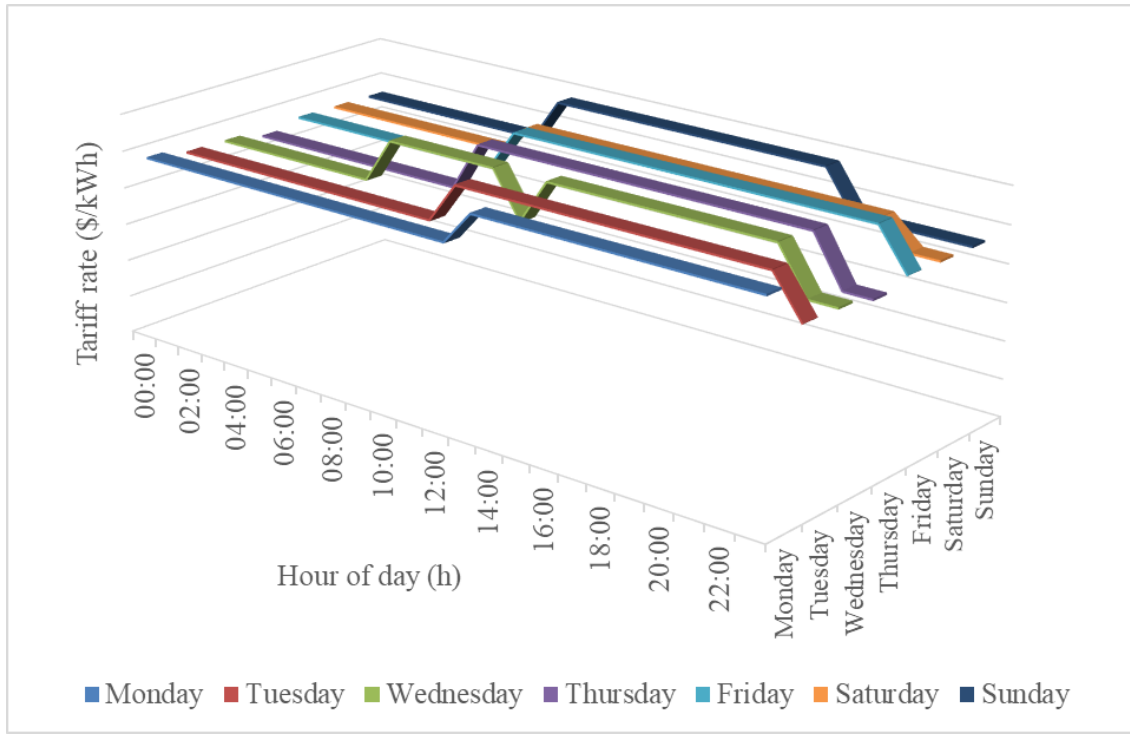


Figure 5.5: Tariff rates with intervals classification.

Equation 5.8 shows the time complexity of the proposed approach to determine the unit tariff rate. The best and worst case computational complexity is $O(N)$ due to the linear search to find the maximum energy consumption for contribution coefficient estimation.

Finally, with the help of Fig. 5.6 the relative change in the load profile of a day is shown. The proposed variation in tariff rates over the traditional method of constant flat rates has affected the consumption curve. This figure depicts that applying the proposed method has flattened the consumption curve to an extent compared to the traditional approach. The proposed scheme has compensated the excess consumption during peak hours with off-peak hours by shifting the EV charging time, as shown in Fig 5.7.

The bar chart in Fig. 5.8 shows the change in energy consumption at peak and off-peak hours by applying the proposed methodology against the traditional approach of flat rates. The consumption in peak hours is reduced by around 6-7 % (when TR is approximately 0.45) and shifted in off-peak hours by the same. Hence, the objective of smoothing the consumption curve and eliminating the negative impact of EVs due to charging at peak hours is achieved.

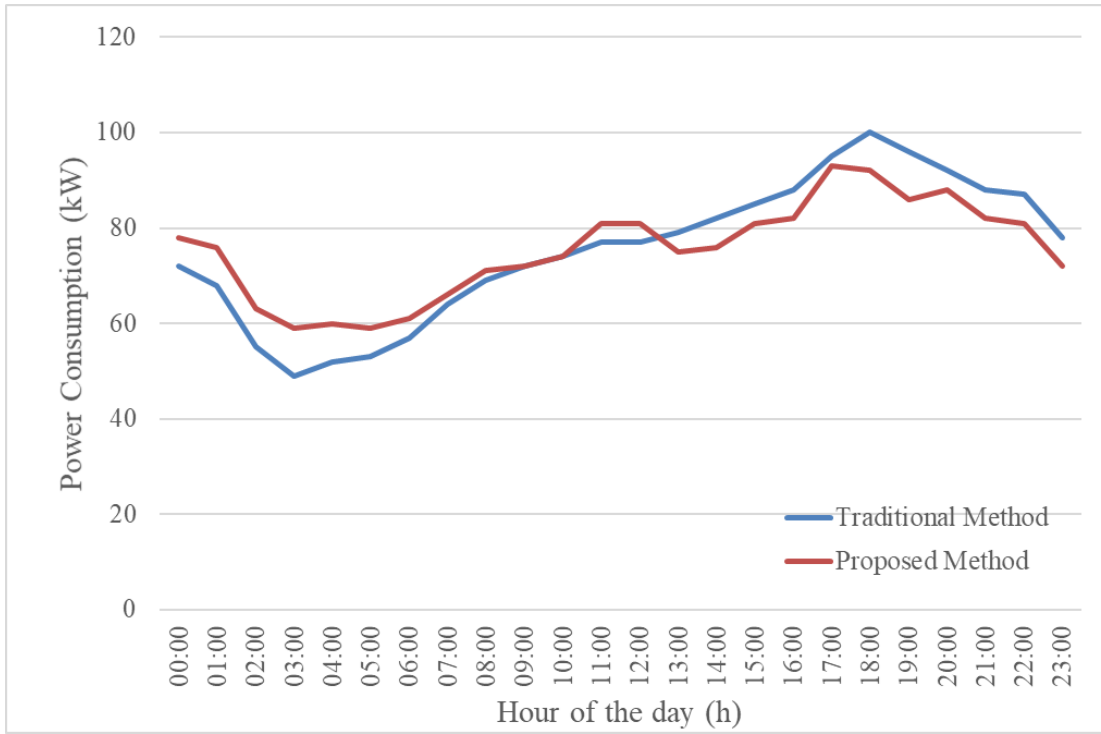


Figure 5.6: Load profile with traditional and proposed method.

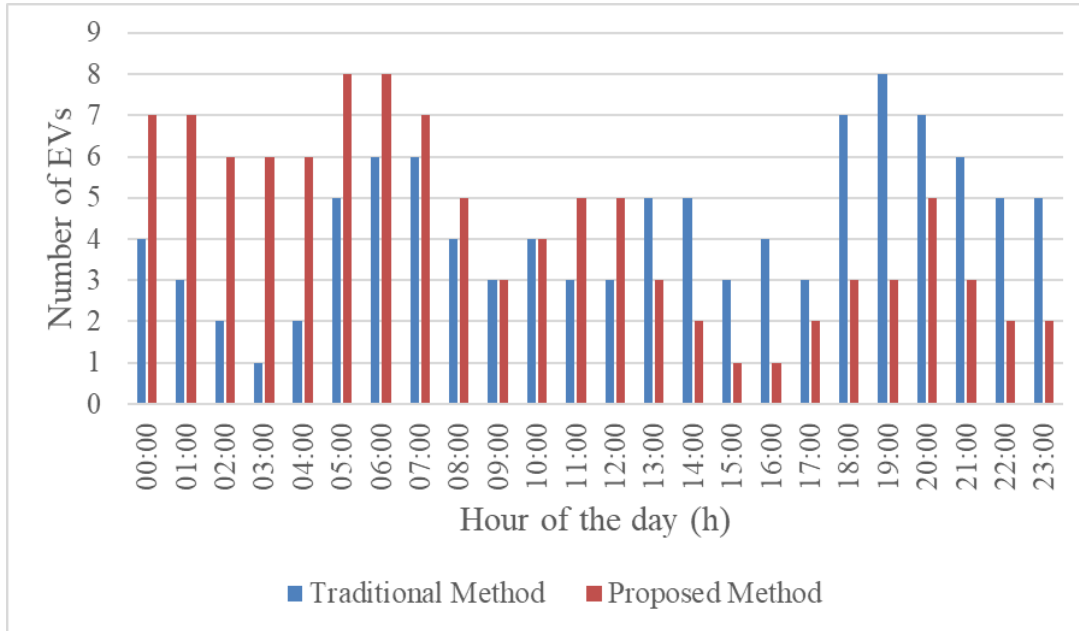


Figure 5.7: Number of EVs' charging in traditional and proposed method.

5.5.2 Priority Determination

Apart from setting the ToU tariff rates to shift EVs' charging time, the proposed scheme also prioritizes the EVs participating in the charging mechanism using algorithm 2. For this purpose,

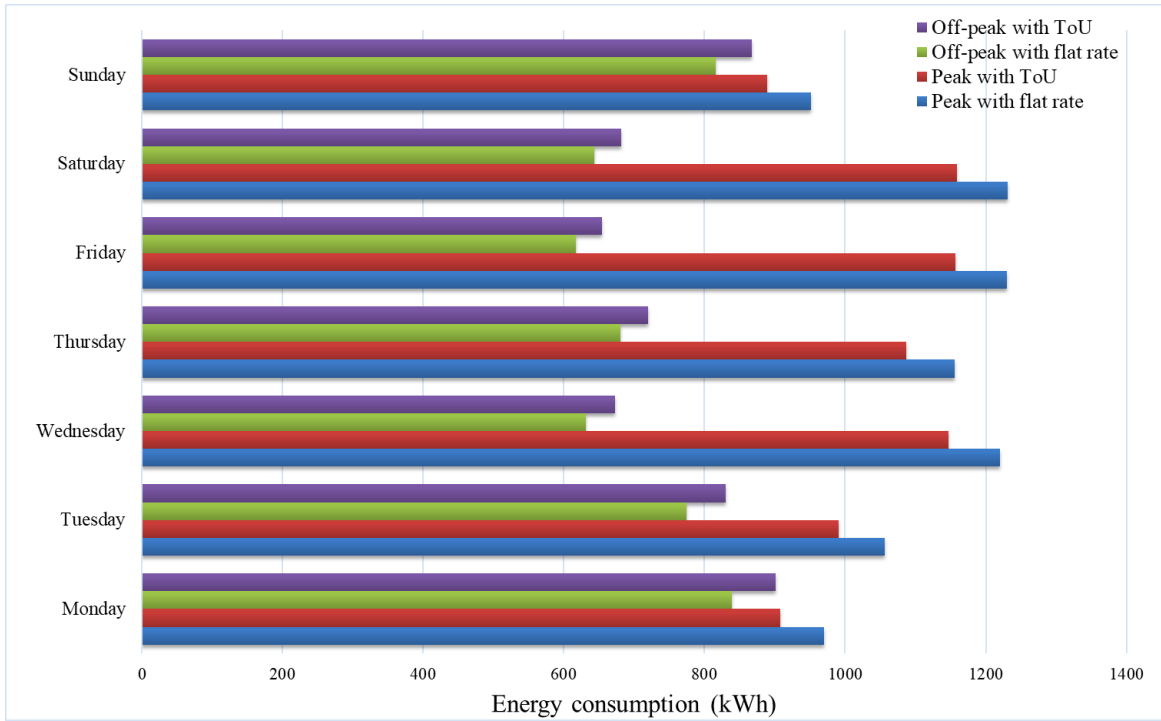


Figure 5.8: Energy consumed in peak and off-peak hours.

EVs of three types listed in Table 5.4 are considered with the 3.3 kW, 6.6 kW, and 7.2 kW chargers. The energy required by each EV that participates in charging and the needed total energy has been calculated using Equations (5.12) and (5.13). The simulation parameters assumed for the experimentation are presented in Table 5.5.

Table 5.4: Battery capacities.

Battery Type (kWh)	Nominal voltage (V)	Nominal capacity (Ah)	Temperature (° C)	Charging efficiency (%)
6	48	120	-20 to 60	99
16	96	170	-25 to 50	99
19.2	48	400	-25 to 50	99

Table 5.5: Simulation parameters.

Parameters	Values
E_{thd}	60 kWh
Default C-rate	1
SoC_{min}	10 %
SoC_{max}	90 %

The graph in Fig. 5.9 shows the total energy required by EVs in each interval that requests charging in the respective period. The slight variation in the color represents the demand from different vehicles in the hour. Further, Table 5.6 shows the hour-wise status of the prioritization execution based on algorithm 1. Accordingly, prioritization occurs if the requested energy exceeds the grid's threshold limit. On the contrary, it skips EVs' prioritization and helps reduce the associated execution time. The priority of EVs is decided based on the required SoC for charging that may help to control the C-rate in smart charging infrastructure.

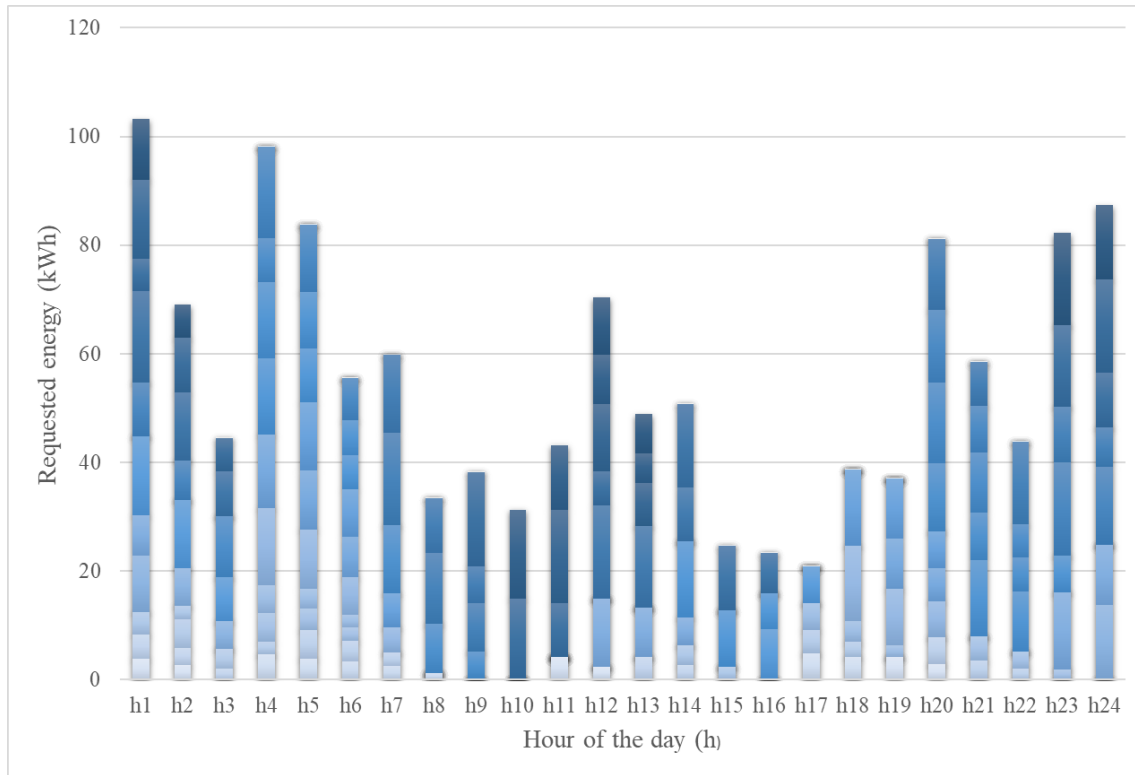


Figure 5.9: Requested energy for EVs charging.

5.6 Summary

The chapter proposes a methodology for setting the ToU tariff rates for EV prosumers to promote the DSM using EVs. Different tariff rates applied to peak and off-peak intervals significantly shave the peak consumption for a sustainable environment and power systems. The proposed methodol-

Table 5.6: Conditional execution for prioritization.

Time Interval (h)	h1	h2	h3	h4	h5	h6	h7	h8
E_{total}^{req} (kWh)	103	69.0	44.5	98.2	83.8	55.4	59.8	33.3
Execution	Yes	Yes	No	Yes	Yes	No	No	No

Time Interval (h)	h9	h10	h11	h12	h13	h14	h15	h16
E_{total}^{req} (kWh)	38.1	31.2	43.1	70.3	48.9	50.8	24.6	23.2
Execution	No	No	No	Yes	No	No	No	No

Time Interval (h)	h17	h18	h19	h20	h21	h22	h23	h24
E_{total}^{req} (kWh)	20.8	38.7	37.0	81.0	58.5	43.8	82.3	87.3
Execution	No	No	No	Yes	No	No	Yes	Yes

ogy considers two factors for effectively providing the DSM using EVs. Firstly, the rates are decided based on the area's peak and off-peak contribution coefficient of EV consumption. Further, conditional prioritization of EVs is performed based on the SoC of vehicles to avoid simultaneous EV charging. The advantage of the proposed method is the tariff evaluation at the AG reduces the computational complexity at the grid side. Also, conditional execution of worst-case scenarios reduces the computational speed in normal conditions and reduces the grid stress. The assumption is verified considering a small area due to the limited EVs with the IoT-based AMI. The data recorded through the local grid required big data solutions (NoSQL) as the application encounters rapidly growing extensive data with the increase in EVs. The peak/off-peak contribution coefficients are calculated and used for setting the tariff rates by assuming the flat rate as unity. The outcome has shifted the electricity consumption from peak hours to off-peak hours without affecting the other daily routines of the consumers. The consumption is reduced in peak hours by 6-7 % when the tariff elasticity is 0.45 and is shifted in off-peak hours by the same. However, the proposed study has not considered the battery life, which also plays a significant role in DSM by demotivating the EV prosumer.

Chapter 6

Conclusion and Future Scope

The chapter concludes the research work presented in the thesis and discusses the futuristic work which can be taken in the V2G domain.

6.1 Conclusion

The thesis introduces the basic concept related to V2G technology, the benefits, application in DSM, and challenges faced in intelligent metering. It shed light on Net Meter as a significant component in AMI and discussed its impact on the V2G application. Moreover, it highlights the challenges and constraints involved in the Net Meter deployment and support to DSM in the smart grid. In addition, a literature survey is performed, and a detailed comparative study is presented with the existing approaches in the area of Net Meter designing and DSM. The research aims to address the research questions by developing a prototype that sustains the actual V2G infrastructure and may support the futuristic demands of the application. To answer the questions, a Three-Phase AC Net Meter is developed concerning the regulatory standards, and the device is tested in the practical platform.

Chapter three develops a cost-effective Three-Phase AC Net Meter concerning IEC standards for the V2G enabled charging station. The chapter presents the hardware-software approach to designing the Net Meter at TRL-9. The data acquisition unit includes the VT and CT for a wide range

to attain higher flexibility, and coherent sampling is used to perform the FFT analysis. Considering the automotive grade, the meter performance excelled in the AIS testing for electromagnetic compatibility (AIS-004 (Part 3)) and assures class 1 accuracy. Besides, the algorithmic approach improved spectral resolution and THD detection in different conditions. Also, the choice of coherent sampling has reduced the stress of selecting an appropriate window for FFT analysis.

Chapter four discusses an IoT-based system network for the V2G application and presents an IoT-based Net Meter as a data source and recipient of the information in the network. The device enables real-time data accumulation that may be used to monitor the EV prosumers' behavior for DSM, load prediction, and booking charging slots. Net Meter establishes physical connectivity with the BMS of the Li-ion battery over RS485. It implements MODBUS-RTU protocol to fetch the battery parameters such as SoC and SoH. In addition, the prototype accounts for the energy required or will be generated by the EV when connected based on the requested operation. These EV parameters fetching and evaluation help to establish a coordinated charging-discharging environment without compromising the battery life. Besides, the prototype enables software calibration to reduce human error and supports ToU for dynamic billing. Moreover, the protection mechanism is enabled against physical tampering at EV prosumer end.

Chapter five proposes a research methodology for setting the ToU tariff rates for EV prosumers to promote the DSM using EVs. The proposed method considers two factors for effectively providing the DSM using EVs. Firstly, the rates are decided based on the area's peak and off-peak contribution coefficient of EV consumption. Further, conditional prioritization of EVs is performed based on the SoC of vehicles to avoid simultaneous EV charging. The advantage of the proposed method is the tariff evaluation at the AG reduces the computational complexity at the grid side. Also, conditional execution of worst-case scenarios reduces the computational speed in normal conditions and reduces the grid stress. The assumption is verified considering a small area due to the limited EVs and recorded 6-7 % shift in the consumption with 0.45 tariff elasticity. The technique keeps increasing the difference between peak and off-peak rates as the tariff is EV contribution coefficient dependent.

6.2 Future Scope

In the future, EV penetration will keep increasing in the smart grid, and the challenges may keep rising in the intelligent metering area of the V2G application. The contributions provided in the thesis are not enough to support the varying scenario of AMI due to the rising EV integration. The research directions in intelligent metering in the V2G application are as follows.

- The metering equipment must be adaptable to the fast-charging infrastructure for EVs.
- Protection against tampering from the service provider end is equally important to integrate into the mechanism.
- Focusing on the V2G schemes that must cover the cost of EV charging and battery to increase the participation of EV prosumers.
- Prediction of EV prosumers' behavior analysis may significantly improve the grid performance through various strategies such as advanced tariff rates forecasting.
- Focusing on the advanced charge-discharge booking mechanism helps to reduce the rush at charging stations.
- Tariff rates determination can consider the individual EV prosumer behavior and the battery life, as they may negatively impact the demand curve.

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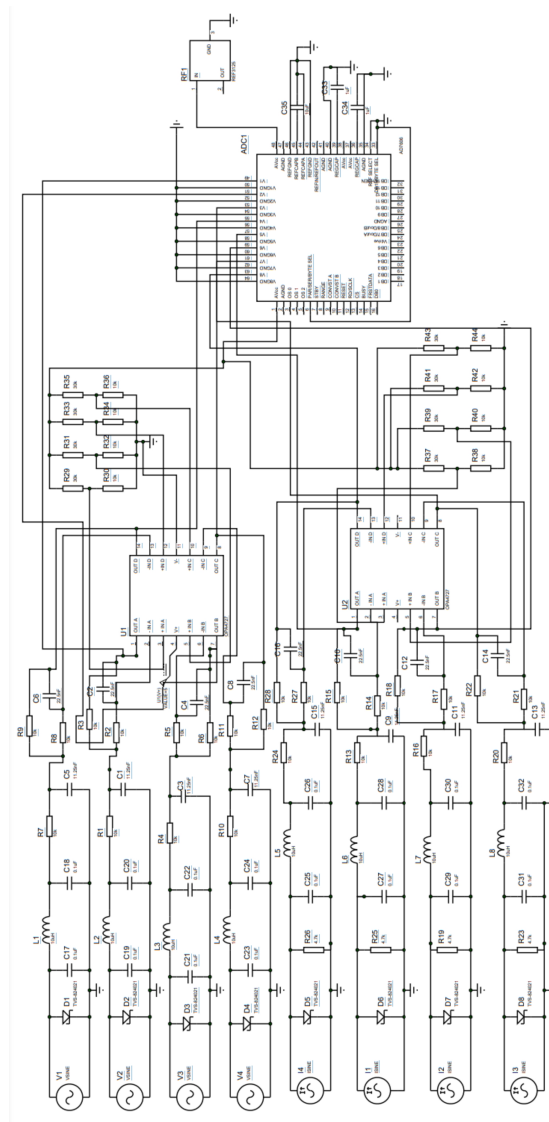
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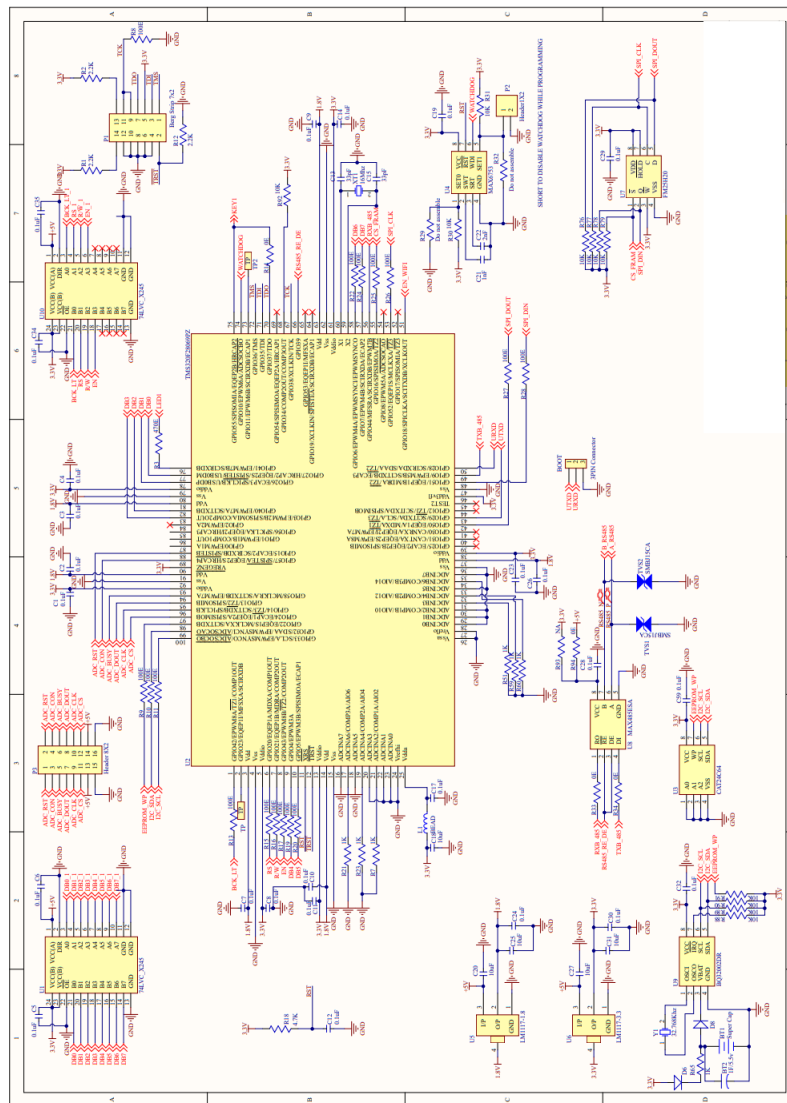
Appendix A

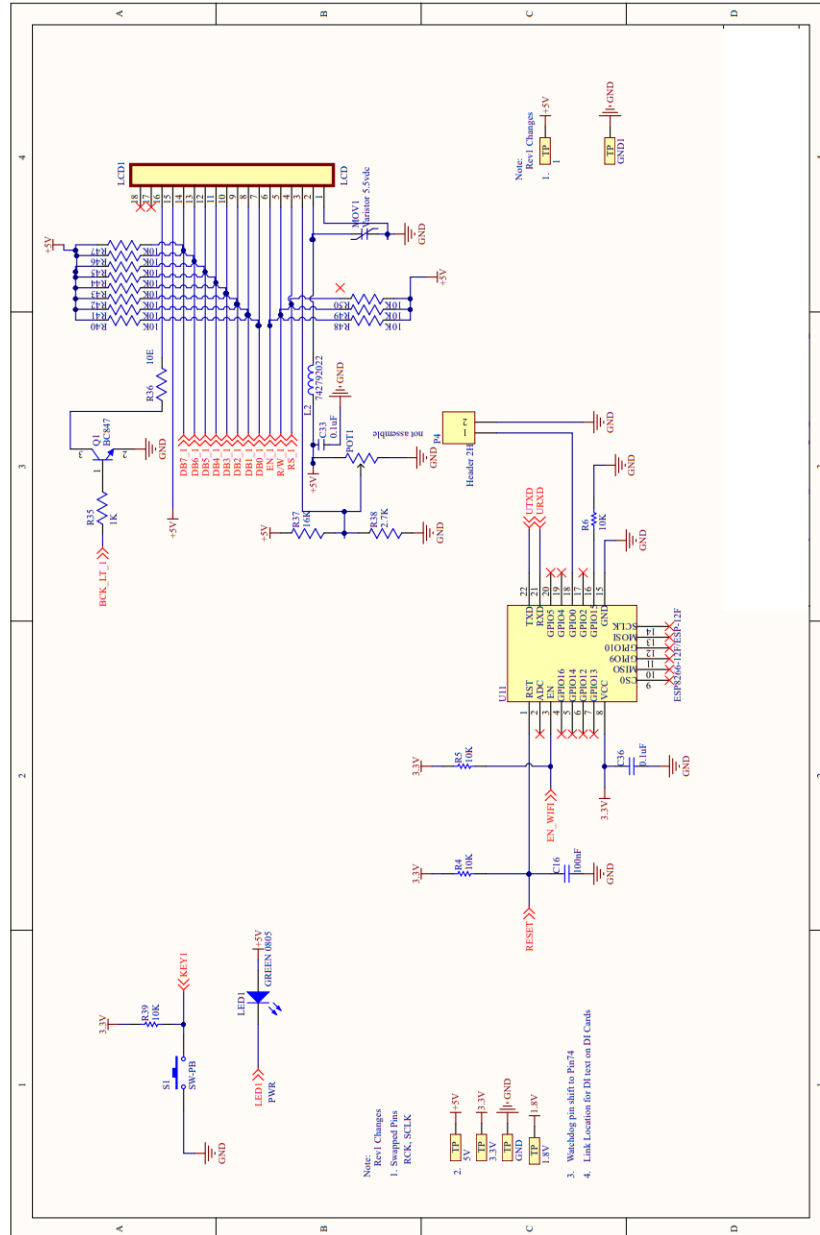
Analog Board

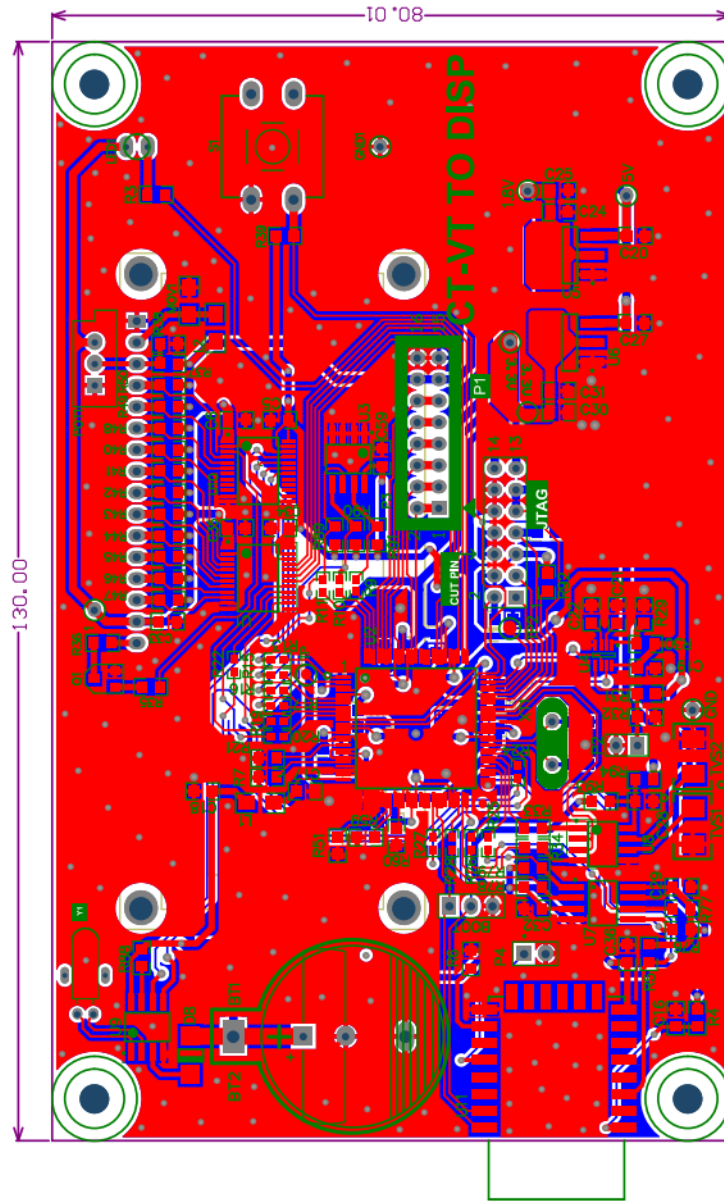


Appendix B

Digital Board







- | | |
|---------------------------------|-------------------------------|
| 1. PCB NAME | : uAegisNDRUT_Pro+6D0+4DI_R01 |
| 2. LAYERS | : Two |
| 3. MATERIAL | : FR-4, Cu |
| 4. PCB THICKNESS | : 1.6MM |
| 5. COPPER THICKNESS | : 35um |
| 6. PLATING | : HAL (Sn_Pb) |
| 7. PCB DIEMENSIONS | : 160mm X 148.7mm |
| 8. PCBs/PANEL & ANY | : NA |
| 9. TOP/BOTTOM SOLDER MASK COLOR | : GREEN |
| 10. TOP/BOTTOM SILKSCREEN COLOR | : WHITE |