OPTIMAL ASYNCHROPHASOR IN PMU USING SECOND ORDER KALMAN FILTER

by

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A dissertation submitted in partial fulfillment of the
requirements for the degree of

DOCTOR OF PHILOSOPHY IN ELECTRICAL AND COMPUTER ENGINEERING

2021

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To my mother and father
To my family

ACKNOWLEDGMENTS

I would like to extend my sincere thanks to everyone who had a great impact in supporting me during my PhD journey. Thanks especially to committee chair and advisor Dr. Mohamed Zohdy for his tremendous support and guidance to make this work happened, as well as the members of the committee, Dr. Subramaniam Ganesan Dr. Chris Kobus and Dr. Suzan Elsayed for their valuable inputs and support. This dissertation bears the first step towards a new beginning for a new stage to come. My extended thanks and appreciation to Dr. Qian Zou, Associate Dean of the School of Engineering and Computer Science, and Dr. Louay Chamra, Dean of the College of Engineering and Computer Science for their support during my journey at Oakland University. Gratitude is also owed to my family and friends who supported me along this journey.

Nayef Mohamed S Alqahtani

ABSTRACT

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Phasor Measurement Units (PMU) are very costly according to energy regulator and utility companies. Utility operators work on alternative solutions to reduce the error rate and operation costs of PMU. In this paper, we sought to optimize the PMU to reduce the level of error using Second-Order Kalman Filter (SOKF). Consequently, this optimization is based on minimizing the number of errors when receiving the signal from access points or from the main access point. We derived a simple mathematical model to estimate the phase coming from the PMU.

PMUs provide Global Positioning System (GPS) time stamped synchronized measurements of voltage and currents with the phase angle of the system at certain points along the grid system. Those synchronized data measurements were extracted in form of amplitude and phase from various locations of the power grid to monitor and control the power system conditions. A PMU device is a crucial part of the power equipment in terms of the cost and operative point of view. However, such ongoing development and improvement to PMUs' principal work is essential to the network operators to enhance the grid quality and the operating expenses.

A MATLAB model was created to implement the proposed method in the presence of Gaussian and non-Gaussian noise. It is based on an Asyncrhophasor technique resulting in a phase error minimization when receiving the signal from access point or from the main access point. The results show the proposed SOKF method outperforming the existing model as tested using Mean Square Error (MSE). The SOKF method was replaced with a synchronization unit into the PMU structure to clarify the significance of the proposed new PMU. This paper's proposed method leads to lower costs and less complex techniques to optimize the performance of PMU using SOKF.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF ABBREVIATIONS

PMU	Phasor Measurement Unit
SOKF	Second-Order Kalman Filter
GPS	Global Positioning System
MSE	Mean Square Error
DER	Distributed Energy Resources
DG	Distributed Generation
PV	Photovoltaics
LV	Low Voltage
POI	Point of Interconnection
DC	Direct Current
AC	Alterative Current
ANSI	American National Standards Institute
EPRI	Electric Power Research Institute
ESS	Energy Storage Systems
DFT	Discrete Fourier Transform
SDFT	Sliding Discrete Fourier Transform
PLO	Phase-Locked Oscillator
KF	Kalman Filter
LQE	Linear Quadratic Estimation
EKF	Extended Kalman Filter
MSE	Mean Square Error

SNR	Signal to Noise Ratio
PLL	Phase Locked-Loop
LKF	Linear Kalman Filter
LSE	Least Square Errors
EKF	Extended Kalman Filter
UKF	Unscented Kalman Filter

CHAPTER ONE

INTRODUCTION AND BACKGROUND

1.1 Smart Grid

Smart grid is an advanced electrical grid which enables the management of the grid operation. In addition, it remotely monitors the performance of the electrical grid by taking readings of its state and its components throughout devices, transformers, and feeder lines. To do this, it uses smart meters sent to the monitor and control room to ensure the reliability of the power flow as shown in Fig.1.1 . Therefore, it is an integrated and optimized electrical grid system that includes various power sources as well as control devices with wider accessibility and autonomous capabilities. Its working principle is based on automation techniques which require controls, computers, and sensors in a collaborative working environment using communication systems. The framework of the smart grid enables the grid to provide a unidirectional flow of the electricity as well as network status data through a digital communication system which allows the amount of change in the grid to be monitored. The change results from user behavior and equipment malfunction and interactions with such necessary procedures to ensure the reliability of the grid and the conductivity of the power system to operate smoothly and securely. Thereby, it has several capabilities; most notably, is the possibility of self-restoration and enabling consumers to become producers simultaneously. Additionally, it has the potential to rapidly restore and enable consumers to become producers simultaneously. It reinforces the idea of micro-grid with independent operating capabilities if required [1-2].

The smart grid originated in the power system's operating system through a mechanism which relies on remote control access for monitoring the grid. This system works based on a communication system to transmit the data about the state of the system to be informed and take the most appropriate decision according to the system's hosting capacity of the feeders along the network to ensure the reliability and quality of power delivery. Smart grid development has allowed the ability to deal with bidirectional power flow, enhancing the opportunities for distributed generation at the consumer site. Therefore, the network system has been dealing with increase of large amount of data with such sensitivity throughout Phasor Measurement Units (PMUs), Supervisory Control Systems And Data Acquisition (SCADA) and the like, which requires further development and improvement to ensure its protection and reliability [3].

A power systems' state estimation has become an essential and effective tool to monitor and control the power grid to ensure grid's reliability and safety for all stakeholders. Therefore, the PMU represents the most effective and substantial control device due to its capability. This is based on the synchronization of a GPS time stamped signal through a GPS signal receiver to determine time and location of a certain phase in real time. Such a real time system process is relied on by advanced communication system to ensure a speedy sampling rate. However, it is expensive and requires further development to reduce cost with high performance. In [4], the author discussed the optimal allocation of PMUs to cover the grid with a minimum number of PMUs for microgrids.

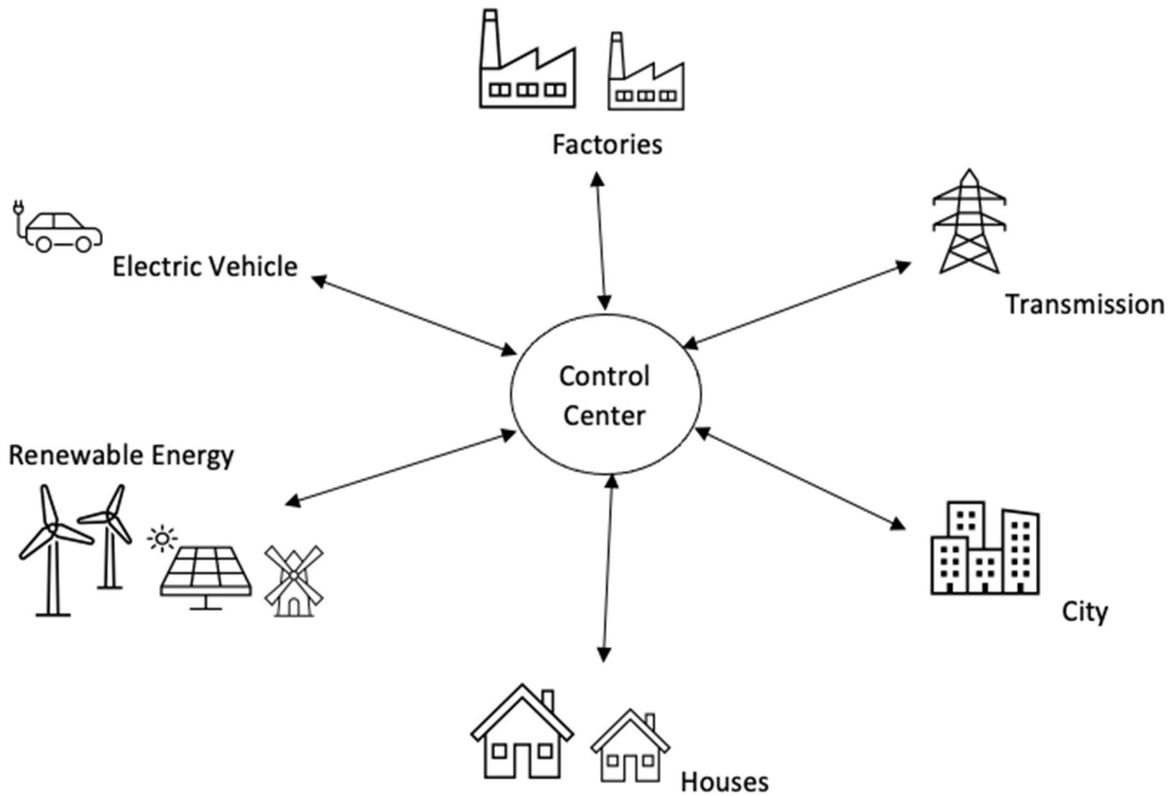

Figure 1.1: Elements of Smart Grid.

1.2 Microgrid

The development of the smart grid system and the introduction of Distributed Energy Resources (DERs) with a limited production capability has led to the formation of several micro-grids. These micro-grids are self sufficient in handling the required energy for consumption partially or completely. A microgrid is based on a decentralized set of small-scale Distributed Generation (DG) near the local loads, as illustrated in Fig. 1.2, which operates in grid-connected mode to the main grid with such formation creating the concept of a decentralized power system [5]. Its working principle is based on full operation separately from the main grid known as off-grid mode in the case of power or system failure. However, the high Photovoltaics (PV) penetration into the Low Voltage (LV) networks causes technical difficulties in network stability and power quality which could lead to electric outage and load increase in the local grid. Such a problem occurs due to overvoltage by DG. PV in the LV network has raised concern to overcome the problem. Therefore, the necessity for a developed control system masterly estimates the changes, and increases in voltage and the level of loads in the local low voltage network with the instant control feature that enables it to ensure the reliability of the network operation for the microgrid as well as the main grid as a whole [6].

1.3 Distributed Generation Systems

The rise in electricity prices along with the low cost of PV systems installation has led to high integration of PV into the LV networks. This type of increase in integration of PV causes technical problems related to network stability, power quality, electric outage, and load increase in the local electricity grid. The most prominent of these problems is overvoltage. This paper [6] investigates overvoltage problem caused by the increase of DG

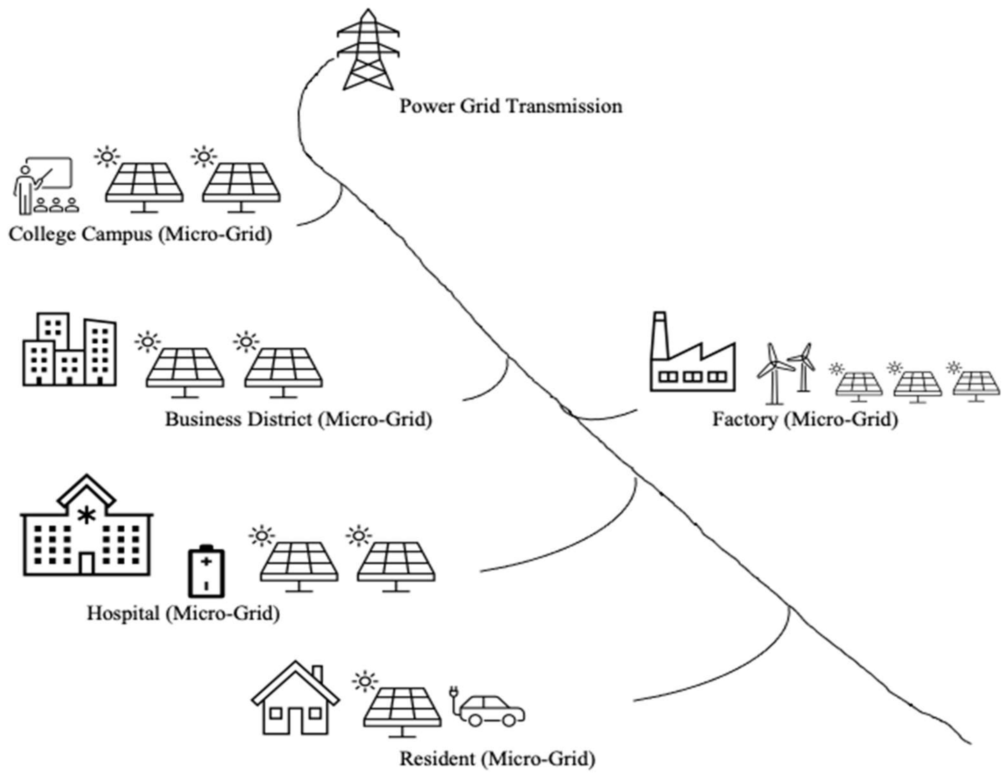

Figure 1.2: Micro-Gird Diagram.

in LV distribution networks, mainly PV generation. A Case study was developed using the OpenDSS simulation tool [7] to overcome the overvoltage problem due to high penetration of the PV systems in the LV distribution network. This study indicates several scenarios to specify the extent of this negative impact presented with graphs of this study. A proposed solution is introduced in this paper to deal with this type of voltage changes caused by DG sources in the LV network. The suggested solution to overcome this problem is based on an advanced inverter to handle such differences in voltage patterns in the network due to DG integration with the existing power grid. Such advanced inverter would be able to deal with the overvoltage issues at the point of interconnection (POI) by different types of modes according to the situation of the feeder.

1.3.1 Introduction of Distribution Generation Integration

Integration of DG is increasing rapidly at low voltage (LV) due to the fact that electrical price has increased. The increasing demand for photovoltaic installation is due to billing increase, government incentives, PV efficiency improvement and climate conditions enhancement in several locations around the world. One of the most sophisticated challenges faced by the electricity networks operators is the integration of Distributed Energy Resources (DER) at low voltage distribution network where the network originally intended to supply the electricity in one direction. It creates bidirectional power flow that is against the original unidirectional power flow [8].

The exiting electrical network system has been designed on a regular basis with a traditional one-way pattern (unidirectional), so that the electric power is produced from the electric power generation planet and sent through high voltage transmission network grid to be delivered to the low voltage distribution networks. On this basis, technical challenges are compounded by the integration of Distributed Energy Resources (DER) at the points of interconnection (POI) in feeder at distribution network level, thus becoming a bidirectional operation. Bidirectional power flow at LV distribution networks may cause overvoltage and overload problems due to high PV penetration with present of high R/X ratio which normally sets high at LV distribution level. Substantial amount of voltage caused by High PV penetration introduced into the feeder with High line impedance [9].

The traditional electricity system works based on three main stages. First, the electricity is generated from the power generation. Then, Transmitting the generated electricity through transmission grid to distribution network as last stage to deliver the electricity to the consumer. This traditional built-on design that is exists today are changing due to the integration of DG sources to the distribution network creating two-way directions.

This paper [9], study the integration of DG penetration impacts in distribution network and recommended the solutions to reduce the negative impact. Due to the local DERs within a certain range of the network, DERs can contribute to form a local network which may stand alone from the main network, if necessary, to operate in a separate mode known as a micro grid. Therefore, the protection coordination in such system that contains DG systems with Direct Current (DC) to Alternative Current (AC) inverter creates difficult in islanding mode. So, the author addressed this paper to evaluate the challenges facing the existing.

High PV penetration may occur occasionally in a large and surprising manner depending on the solar radiation, which may lead to over voltage in the circuit at low voltage network level. This high increase in the voltage causes excessive load, electrical equipment damages, and power outages [10]. Integration of PV production into existing conventional electrical networks could impact on the system reliability, voltage stability and power quality.

In this paper [10], the authors propose high speed control and radio communications to reduce total PV sources production to get along with the local loads and limit reverse power flow toward the substation using curtailment algorithm to minimize the impacts of PV penetration. The author proposed the solution by considering one source of PV at one POI, so the solution aimed to mitigate the effect of PV penetration by offering two modes of operations which can be used with respect to the local demand of the network.

In [11], the paper discusses power losses and voltage profile stability due to DG integration in LV distribution network. The purpose of this paper is to study DG impact on distribution network to reduce power losses and increase voltage stability based on the location and size of DG using ETAP 6.0 program, Manokwari in Indonesia electricity distribution system used as case study. The author presents the technical losses resulted by electricity transmission. The severity impact on the low voltage network depends on the location of the DG. Conceptually, Distributed generation defined as small scale electric generation with 15 to 100 MW generation capacity that is interconnect to the distribution network at the consumer site.

PV production is considered high when the PV production is higher than the consumption at the DG source location. The feeder will consequently experience reverse power flow. Thus, the reverse power flow could cause power quality problems due to excessive voltage that exceed ANSI limits [12]. The consumers produce electricity from PV systems more than their actual consumption and therefore there is over voltage in the circuit.

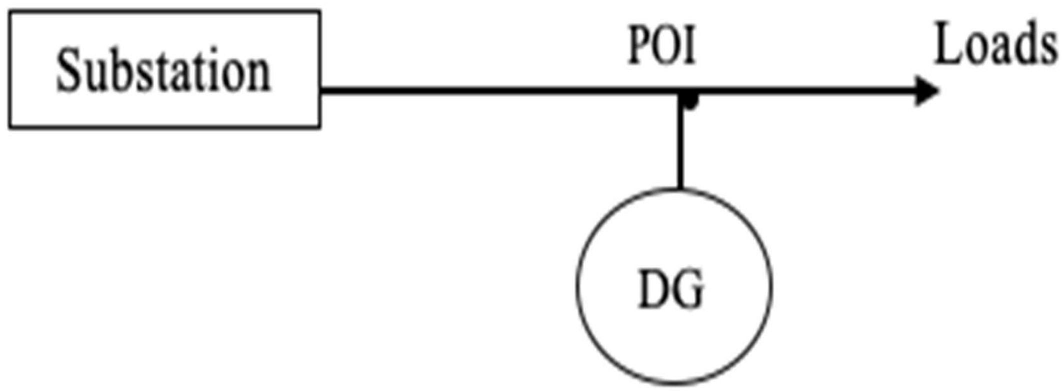

Figure 1.3: Low Voltage Feeder Circuit.

The typical distribution feeders are designed to deliver unidirectional power flow. Thus, reverse power flow due to overvoltage may cause different issues along the line up to the substation as shown in Fig. 1.3. Basically, Reverse power flow may occur when the PV penetration is higher than the demand limit and losses on that feeder. Overvoltage occurs in the feeder during the periods of high PV generation and low load [12]

In [13] discussed the voltage violation due to the PV penetration excess the permissible limits in LV networks where the voltage production of the PV systems reaches 2.5% at single point of grid connected DG. The hosting capacity of LV network could be extended to 110% of PV penetration level as long as the DG locations are properly distributed along the feeder to ensure power quality of service especially for short feeders. High PV penetration in LV networks is evident compared to medium voltage networks. Thence, high PV penetration into LV networks creates significant difficulties in the hosting capacity of feeder.

Note, that voltage rise due to high PV penetration appear at peak period where there's low load or no load at all in certain feeder, such case causes reverse power flow and VArs issues.

1.3.2 Overvoltage Mitigation

Integrated PV systems as DERs have a significant negative impact on the nature of the traditional working principle of the grid on which it was designed. Therefore, the most significant negative impact is load increase, excessive voltage, and network malfunctions. In this paper, the study is to highlight on the increase in voltage at low voltage distribution network due to High PV penetration into LV network feeder. The effect of the over voltage extends along the main feeder line, whose range of effect can be described over three levels. These levels are the node level, circuit/feeder level and substation level. When solar radiation increases, there is a high PV penetration from PV systems that cause overvoltage and voltage instability into the feeder.

Network operators consider five percent allowed voltage rise above the normal voltage level. Thus, an overvoltage is considered a violation when the voltage exceeds the 5% allowed limit [14]. Overvoltage problems occur due to high PV production compared to low consumed load.

This research presents over voltage mitigation in distributed network caused by the integration of PV system using OpenDSS simulation tools. The purpose of this paper is to present a case study on the problem of overvoltage caused by the integration of the consumers' PV systems to the low voltage distribution network.

The proposed solution in this paper is to solve overvoltage produced by PV system into LV distributed network. As a result, the solution is based on mitigating overvoltage due to High PV penetration by controlling the voltage in such a way to emphasize the maximum use of renewable energy resources and avoid the waste of it to ensure the ultimate use of DER. Accordingly, the goal is to reduce cost and improve operational efficiency. Overvoltage impact on distribution system directly, this impact could extend to transmission grid [15]. Distribution residential system is a radial system that every circuit is supplied by one source. Consumers located far from the substation could face more frequent interruptions than those who are located near the substation. Typically, small scale PV system is framed to supply real power whereas no reactive power is supplied [14]. In the other hand, large scale PV systems supply real power with respect to VAr limits. High PV penetration increases the voltage in the main feeder due to excessive PV systems production. The high increase of the voltage in the feeder occurs during noon to afternoon time in the fall and spring seasons causing high PV production.

High PV penetration integrated into the LV feeder can negatively affect the voltage profile due to low load and high PV penetration. It's illustrated by the formula (1) below. So, the PV penetration is the ratio of the total PV production to the total generation supplied by the substation [15].

1.3.2.1 Photovoltaics Penetration

As seen in equation (1.1) below the total PV production represents the entire PV systems production that are connected to the feeder, whereas the total generation represents what so called gross load that are supply by the substation from the utility side without DG contribution.

$$\text{PV Penetration } (\%) = \frac{\text{Total PV production (W)}}{\text{Total generation (W)}} \qquad (1.1)$$

At some point total PV system production can called PV name plate as shown in the equation (2) that is revise the equation (1).

$$\text{PV Penetration } (\%) = \frac{\text{PV name plate}}{\text{Gross load}} \qquad (1.2)$$

Studying PV penetration consider essentially the calculation of PV penetration at minimum load along the feeder at the peak hour of the year. Basically, network operators concern to keep the voltage within ANSI limits as shown in Fig. 1.4 where both of the red lines are representing the ANSI range limits [16]. When the voltage raises due to grid connected DG to a part of the network through the feeder, this would change significantly both forms of active and reactive power and voltage drop profile [17] as shown in Fig.1.4. The notable voltage increase appears due to the low demand and high PV penetration at a time, leading by the large amount of energy flows along lines with high resistance. This phenomenon causes voltage violation at end of the feeder which excesses the upper ANSI limits.

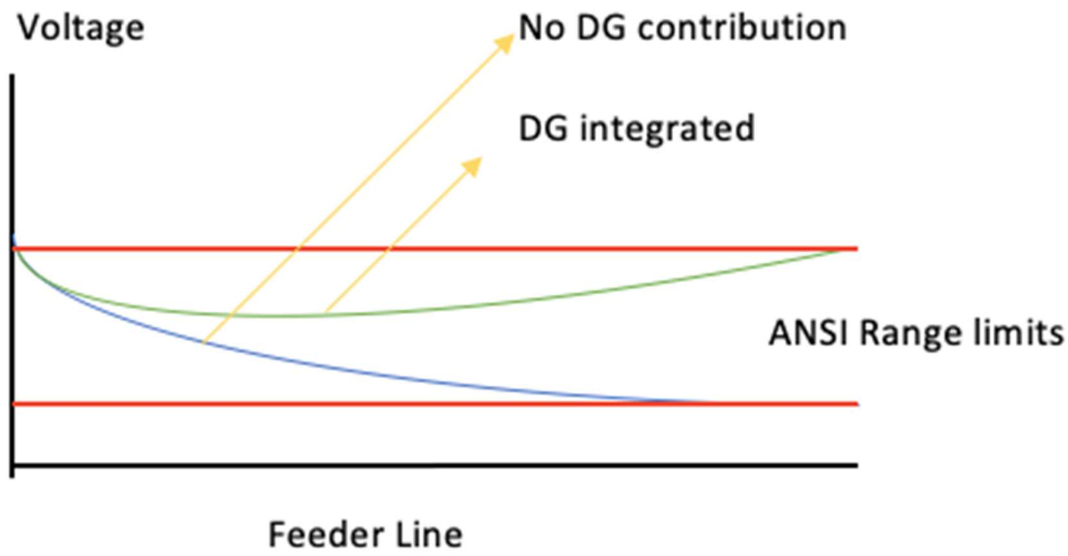

Figure 1.4: The Limits of Voltage Profile in The Feeder Circuit

1.3.2.2 Voltage Profile

The voltage profile gives an idea of voltage drops along the feeder. It takes the voltage at every node which is the voltage over the distance. Voltage regulation is to control and mitigate the overvoltage. Therefore, the feeder voltage is regulated to stay in the desired level. However, in the case of high PV penetration the feeder would experience overvoltage that is above the upper ANSI limit creating problems. Anti-islanding is considered to avoid any power supplied by PV during power outage from the substation. Thus, operators monitor the power status, once the circuit breaker become on, it sends signal to the Point of interconnection (POI) at the consumer's meter to break PV production into the network [10].

1.3.3 Case Study

In this paper, a case study was conducted for overvoltage problem in four different scenarios to highlight the negative impact of overvoltage that's harmful to distribution system feeder due to high PV penetration. These four scenarios are depicted into two main phases: the first is during periods of peak electrical loads whereas the second is during the minimum periods of electrical loads, taking into account whether there is a photovoltaics output or not, as well as the amount of PV production by the time period of the year. This indicates the negative impact on the feeder due to the high penetration of PV systems, which may cause the failure of the power system, power outage, equipment damage and impact on the protection systems associated with the substation. The tested system feeder was IEEE 123 bus feeder in a residential system. The load system power factor is 0.93 whereas the PV systems power factor is set on unity factor (1.0) with 60 Hz base system frequency. PV nameplate is 5 kW/system. The voltage base is 0.24 kV. Overvoltage case due to high PV penetration was done by using a distribution system simulator. The simulation tool used for this case study is called OpenDSS which is provided by the Electric Power Research Institute (EPRI). The designed circuit is as shown below in Fig. 1.5 where the substation is represented as red tringle.

In the first phase, the first and second scenarios test cases were conducted on "Tuesday", July 11th, 2017 at 7 pm with peak (high) load around 7 MW and the weather temperature is at 37 C. Therefore, there is a high load and low or no PV production that wouldn't compensation the actual consumed power from the utility line.

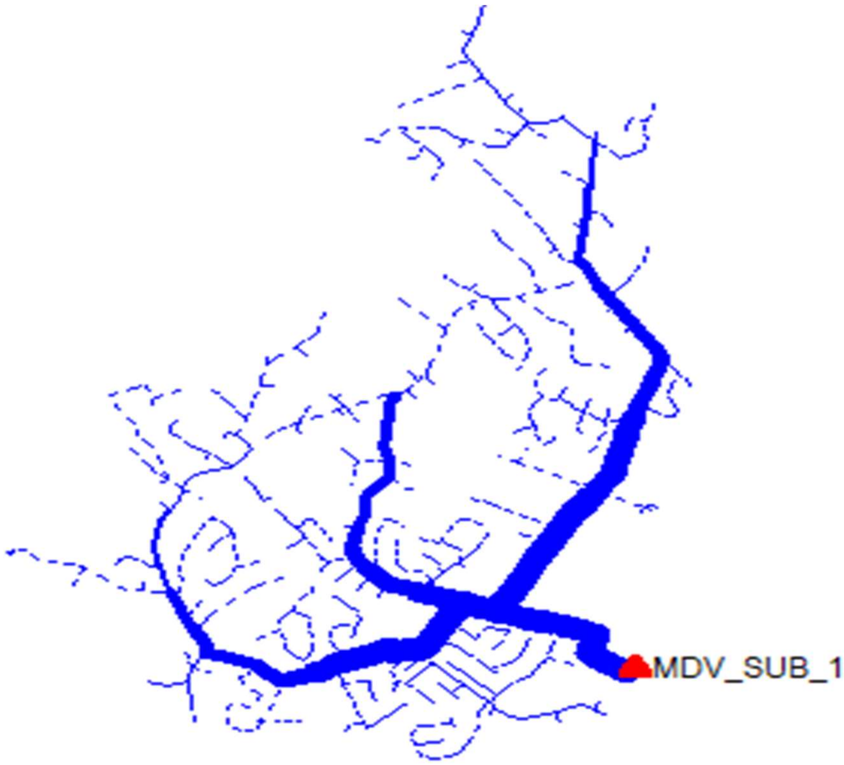

Figure 1.5: IEEE 123 Bus Test Feeder

1.3.3.1 First Scenario

In this scenario, the feeder line starting from the substation to the consumers considers no PV integration to visualize the actual peak load status on the entire circuit and the system voltage profile. As shown in the Fig. 1.6 below that the voltage level along the feeder line is within the upper and lower ANSI limits, therefore it turns out that there is no negative impact by the DG due to the absence of a photovoltaic systems into the circuit feeder. The actual meter reading at the substation shows the power flow of the load where the real consumed power and the reactive power was 7.35 MW – j 0.378 MVar respectively with total losses of 2.449 kW + j 8.478 kVAr.

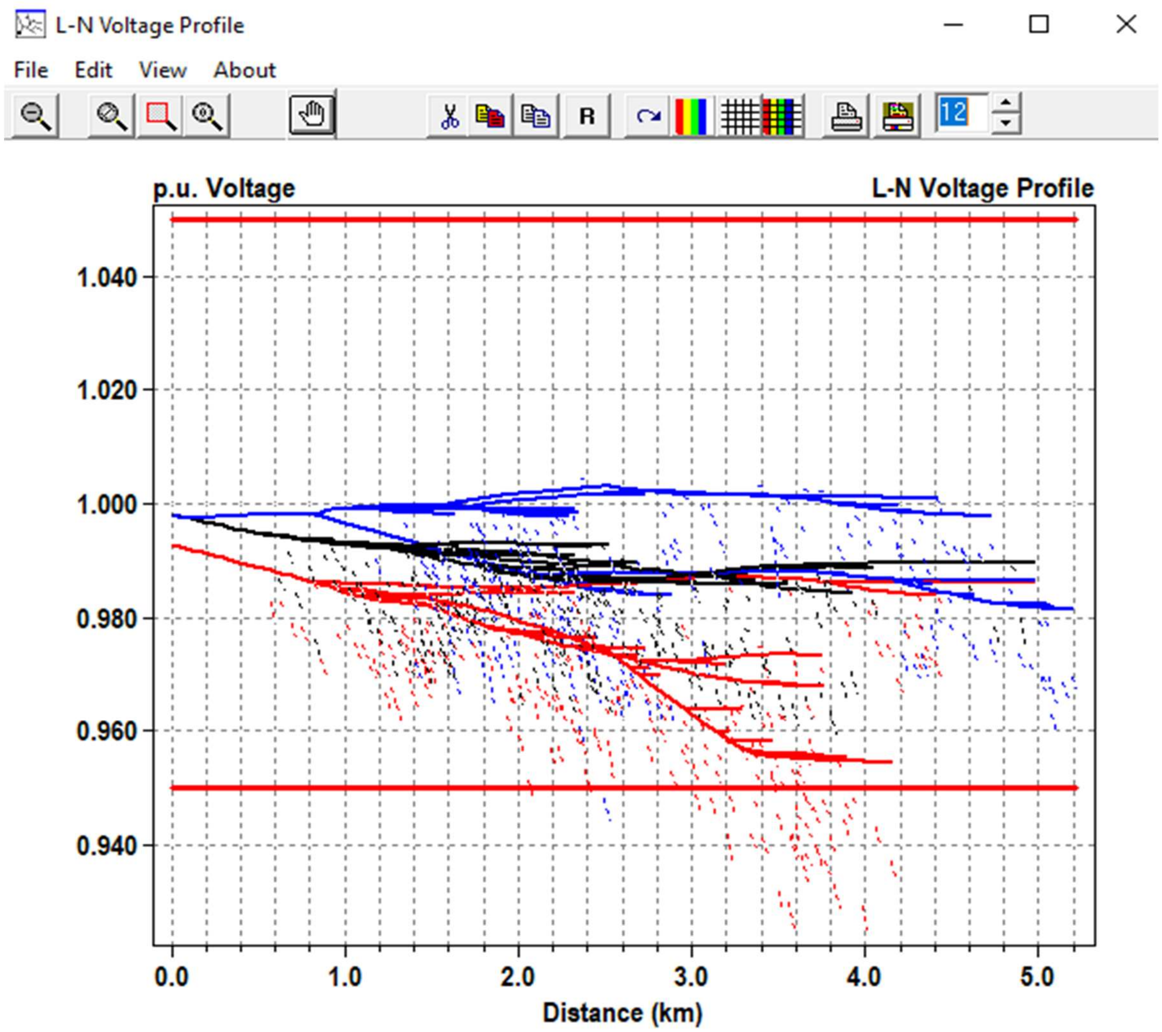

Figure 1.6: No PV & Peak load

1.3.3.2 Second Scenario

In this second scenario for the same peak load period, the PV systems were integrated within the feeder line starting from the substation to the consumers to monitor the changes on the peak electrical loads along the circuit feeder and the voltage profile of the system. This case considers peak load with low PV penetration. As shown in the voltage profile Fig. 1.7 below, there is slightly changes on the voltage level along the feeder line which still stays within both upper and lower limits. So, there is no negative effect by presence of DG source due to the fact that higher electricity consumption versus lower PV systems production along the feeder. It is clearly explicated by the meter reading of the load which is 5.93 MW –j0.51 MVAr where the total losses were decreased to 1.593 kW +j 5.5 kVAr.

For the third and fourth scenarios, the two simulations were performed on "Tuesday", March 6th, 2018 at 1 pm afternoon in Phoenix, AZ with minimum load around 1.75 MW, and the weather temperature is optimal temperature at 25 C. The data were assembled to present an overvoltage case on impacted feeder similar to the reality. In order to highlight the extent of affected part of the circuit due to high PV penetration to investigate the problem and make the most of the DER. It is a sunny day as usual. Therefore, there is a low load and high PV production up to peak PV production due to high solar radiation emitted on the solar panels.

1.3.3.3 Third Scenario

For the third scenario, the case was conducted during the daytime where the load at minimum with the absence of PV systems. So, the feeder line along the line starting from the substation to the consumers considers no PV system production to visualize the

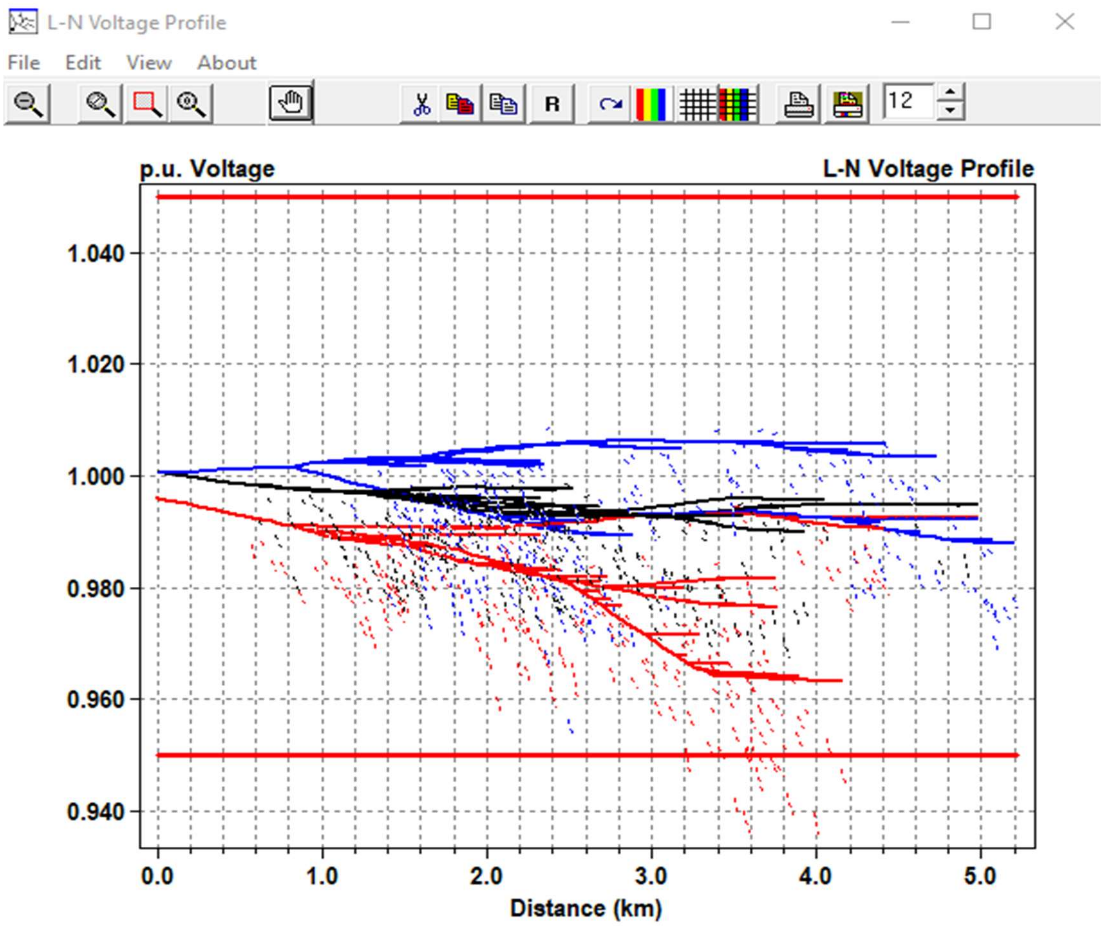

Figure 1.7: PV & Peak load

actual minimum load on the circuit and the system voltage profile before applying PV penetration into the system. In the voltage profile Fig. 1.8 as shown below, the voltage level along the feeder line is within the upper and lower limits with high increase toward the upper limit due to minimum load with no PV system integrated to the line from the consumer during this specific period. Therefore, it turns out that there is no negative impact by the DG yet due to the absence of a photovoltaic system into the circuit feeder. Note that the meter readings at the substation shows the power flow of the load where the real consumed power and the reactive power was 1.867 MW – j3.655 mVAr where the totel losses decreased to 0.7 kW +j 2.424 kVAr respectively.

1.3.3.4 Fourth Scenario

This scenario considers the minimum load with high PV production integrated. PV systems were integrated within the electrical network during the noon time in which the PV systems production are very high, corresponding to the minimum actual consumption of consumers. Therefore, the feeder line presently experiences a high PV systems penetration along the line from consumer's side all the way to the substation as a result of the high PV systems production to conceive the effect of integrated high PV production at the minimum load on the circuit during the same period. Thus, it manifests the negative impact on the voltage profile performance due to the increase in voltage above the upper limit creating overvoltage problems as shown in Fig.1.9 below. This is conspicuous from the actual power surplus of the power flow loads as -4.938 MW – j3.667 MVAr with total losses of 1.572 kW +j5.448 kVAr.

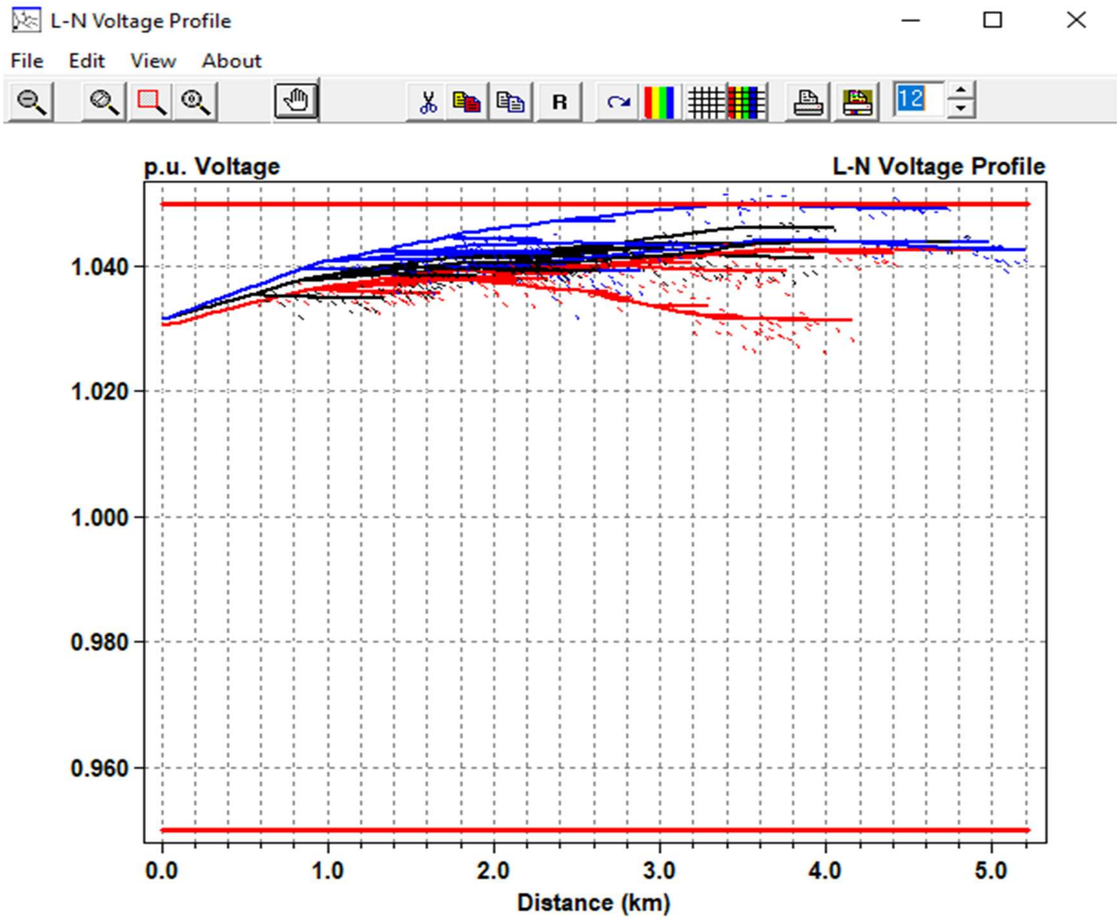

Figure 1.8: No PV & low load

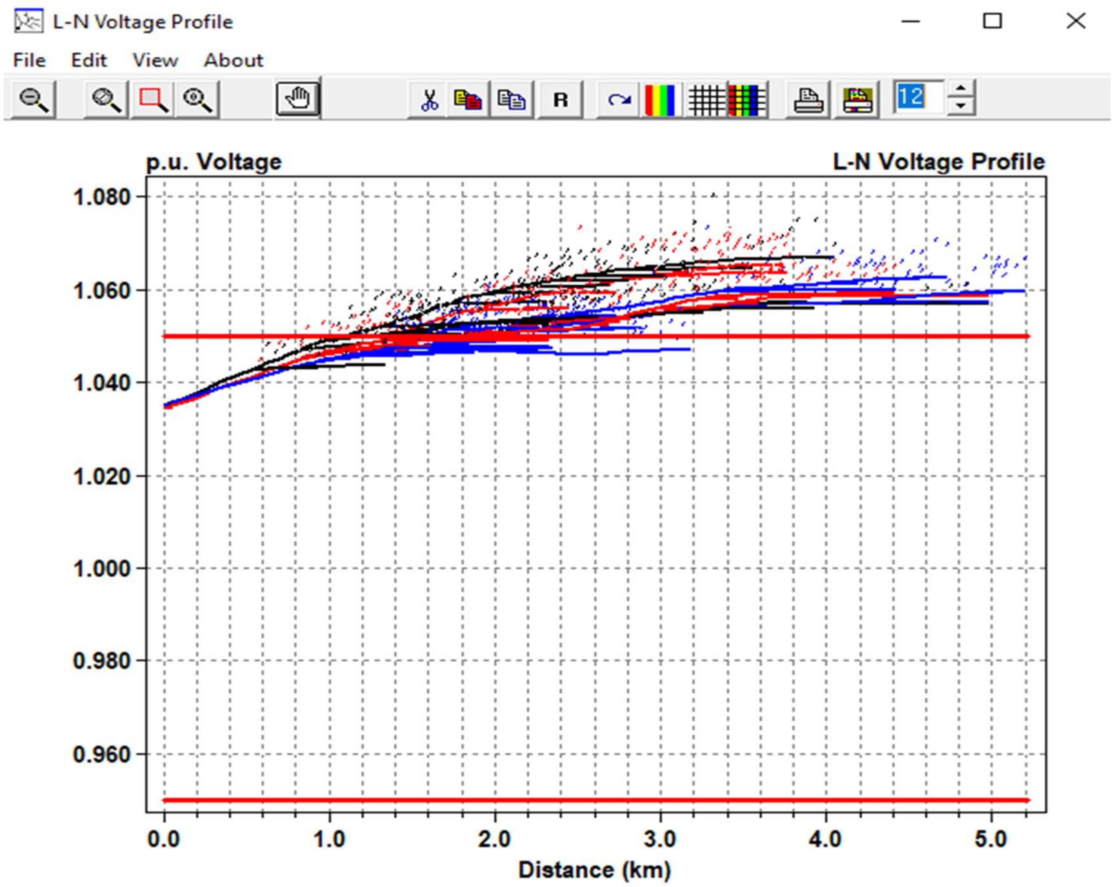

Figure 1.9: PV & low load

1.3.4 Proposed Solution of The Case Study

As a result of this study, one of the most appropriate solutions for the existing feeder is the inclusion of advanced inverter which would be capable to deal with the overvoltage issues at the POI by different types of modes according to the situation of the feeder. Since PV system produce power in form of DC then the inverter is required to converter DC to AC power form in order to integrate the PV production into the LV distributed network. However, the existing inverters are not capable to mitigate the overvoltage by absorbing or injecting VArs due to the transient of PV system as a result of the clouds effects [18].

Typically, the standard inverter is used to converts the power pattern supplied to the feeder regardless the state of the feeder and its hosting capacity for the additional voltage, this behavior poses a clear and explicit threat to the utility feeder. Therefore, an advanced inverter that works on the principle of sensing the line's ability to host extra effort by absorbing or supplying the VArs to ensure the grid from collapsing or overloading, by monitoring the voltage profile for the desired line. The advanced inverters are characterized by rapid response and thus fast inject or absorb unnecessary VArs, which helps to maintain voltage stability and avoid harmful impact, interruptions, faults, and equipment damages resulting from such increase.

1.3.5 Energy Storage Systems

In addition, Energy Storage Systems (ESS) units are one of the most prominent solutions that could come in parallel with advanced inverter which is responsive to the status of the feeder and the extent of their need for VArs or overloading to provide more stability for the circuit. However, ESS requires optimal size, location, and the type of technology used.

1.3.6 Conclusion of The Case Study

Overvoltage problems from DER is increasing rapidly and significantly as result of the change in the consumers' behaviour. Therefore, mitigating the overvoltage due to high PV penetration should be performed by testing several realistic and effective solutions to ensure the optimal and maximum utilization of DER mainly PV systems. Taking into account, the operational condition, and PV maximum production rates to the loads at a certain period to ensure the highest level of LV network reliability performance and lower operation cost to compile with market regulations. Hence, a case study was conducted over four different scenarios to illustrate the degree of difference and impact due to the overvoltage resulting from the integration of PV systems, noting that this case considered the time, maximum PV production and the peak and minimum load at different time of the year. This case study was developed using the OpenDSS simulation tool [1] to visualize the problem resulting from the high penetration of PV systems in low voltage distribution network. Most states interconnection PV system requirement does not exceed consumers' loads.

The proposed solution in this paper is introduced to handle such type of voltage issues caused by DG sources in the LV network which is based on applying advanced inverter to mitigate overvoltage and the changes in patterns through the network due to the voltage behaviour in the existing power grid. Advanced inverter can simply be described as smart inverter which is different from the conventional inverter by using a rapid response technique. Such device relies on the fast injection or absorption of unnecessary VArs based on the voltage profile of the feeder, which greatly helps to contain the overvoltage problem and its consequences. Thus, it is necessary to accommodate the research on the applications of such advanced inverter, which help to reduce the dependence on the expensive ESS units or the loss of the utilization of DER to reduce electrical loads in general for both utility provider and the consumer along the feeder.

1.4 Phasor Measurement Unit

A Phasor Measurement Unit (PMU) is a device used to estimate the magnitude and phase angle of an electrical phasor quantity (such as voltage or current) in the electricity grid using a common time source for synchronization. The values of voltage and current signal at various places in a power network are measured by PMU. Therefore, a Phasor estimation process has a lot of importance in design of control mechanism and various protection systems to be implemented. Cost of the power plant operation is proportional to the phase error.

The author in [19] discussed the PMU estimation techniques where Discrete Fourier Transform (DFT), Sliding Discrete Fourier Transform (SDFT), zero crossing are some type of estimations techniques to measure the magnitude and phase difference of the system's input. The PMU provide stamped GPS time data with the ability to monitor the large power network to determine the voltage and current at any certain time and location [20,21]. PMU was initiated throughout DFT estimation technique based on the Symmetrical Component Distance Relay technology. These units provide wide monitoring of the electrical network, which allows to avoid interruption and ensure the conductivity of the network. Therefore, the principal operation of such unit enhances the integration of the smart grid, so that the network is controlled by analyzing, and monitoring the data of network to ensure both the protection and conductivity of the network. Clock Synchronization Unit, Measurement Unit, and Data Transmission Unit are the main type of PMU.

The PMU obtains data from dispersed locations along the grid which is time stamped GPS data [19-20]. Thus, it is a real-time data collected from dispersed locations along the grid. The PMUs measure the voltage and current with the respect to phasor and time stamped which shapes a Synchrophasor. The Synchrophasor is based on the complex value of the sinusoidal signal wave of the magnitude and phase. The significant impact of PMU is to extract phasor which contains an important inform about the voltage and current by 1μs. Synchrophasor is known as synchronized phase measurement to observe a certain gird condition. Therefore, the network operators would be able to collect the required data for power system monitoring and prevent unacceptable activity. Accordingly, the PMUs take the measurements from several locations along the gird to cover the entire grid condition. It is based on the magnitude and phase angle of the frequency as indicated by the cosine signal.

This paper [21] introduces PMU technology to measure the system phasors across the gird, through a time synchronous measurement technique using a Kalman filter to visualize the desired accuracy for the better monitoring of the network. PMU determine the phasor measurements of both voltage and current at up to 50 samples per second. These measurements are based on synchronization and Global Positioning System (GPS) time stamped. In addition, the PMU able to analyze the frequency operation and its deviation. PMU enables to estimate the state of the system by indicating the phasor of both voltage and current at every bus along the grid.

When two power plants are operating out of phase, the least powerful power plant is acting as a resistance to the other, and the fight occurs within grid transmission lines and transformer stations where huge amounts of energy are being absorbed. Left undetected, this can cause a transformer station to overheat and catch fire. It is one of many examples of how a better monitoring system can help grid engineers visualize the health of their power grid and make better-informed decisions.

The PMU is a measuring device for the phasor of the system to ensure the grid stability by measuring the system's phasor for both voltage and current simultaneously with GPS time stamped. Analog input is the instantaneous phasor information of voltage and current. These units are placed at different location such as near to the transformers along the network to ensure the safety and quality of the grid.

The PMUs have become significant devices that enhance the smart grid systems to measure the system phasors around the grid. It offers the ability to measure the system phasor of both voltage and current at the certain time and location using GPS systems [22]. Therefore, it is significant to work on the development of the existing PMU to provide a less complexity and cost savings which helps the existing grid to handle the penetration of Distributed PV sources. The integration of DG requires faster response, less cost, and reduced of complexity. In this paper, a simplified mathematical model is introduced to improve the accuracy with regards to lower the cost and reduce the complexity of the PMU. So, the proposed model develops the ability to deal with PV penetration of distributed generation sources which may support working on PV penetration challenges supplied by distributed energy resources in the low voltage networks.

PMU is a measuring device which is based on synchronization and time stamped using GPS [20]. PMU is used for the phasor measurement of the power system to ensure the operation of the grid reliability. It plays a significant role to control, monitor and protect the state of the power system. It is a state estimation application to estimate the phasor for every bus in the system. The input is an instantaneous phasor information of voltage and current of the grid at a certain location. The PMUs are placed at different locations such as near to the transformers along the network to ensure the safety and quality of the grid. The phasor estimation process has a significant importance in the design of the control mechanism and various protection systems to be implemented through the grid. The cost of the power plant operation is proportional to the phase error. It is essential to work on the introduction of enhanced phasor estimation technique in which to outperform the system's reliability as it has been introduced in this paper which is Second-Order Kalman Filter (SOKF). The PMU conceptual work is based on collecting real-time data from widespread locations along the grid. These data represent the voltage and current phase measurements which enveloped in time stamped GPS signals to form Synchrophasor where is formed in a complex value of the sinusoidal waveform for amplitude and phase to identify the state of the power system. This unit has helped the network operator to keep up with real-time state of the system, but it requires the development and operation cost. The PMU produces the state phasor of the power system at the desired site to control the power system and take the appropriate action for such conditions of the dynamic system.

1.4.1 PMU Structure

The PMU Structure consists of three main units, these units are synchronization unit, measurement unit, and data unit as shown in Fig. 1.10 below. Synchronization unit provides the synchronized phasor to measurement unit. Where the measurement unit ensures the bandwidth of the signal is to be sampled within the limit of the desired frequency range. So that the data unit transmits the processed signal throughout the transmission system.

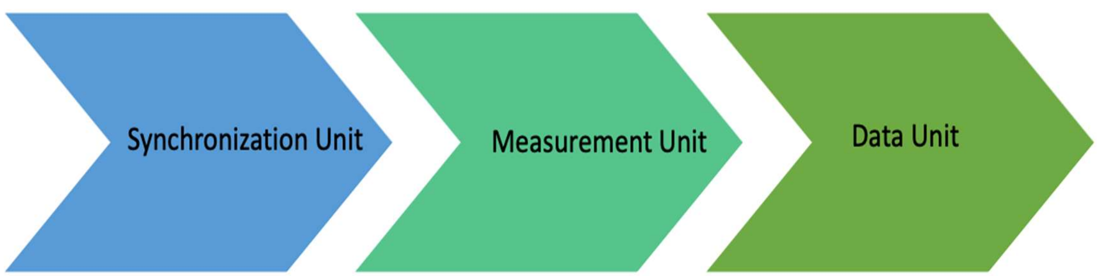

Figure 1.10: PMU Structure

1.4.2 THE PMU PRINCIPALS' WORK

The PMU is the phasor of the system measurement device which is used for monitoring and control of the power grid to certify the power connection reliability. It takes the phasor of the system for the voltage and current with GPS time stamped for validity and allocation. The PMU principals' work as shown in Fig.1.11 takes place with the synchronization

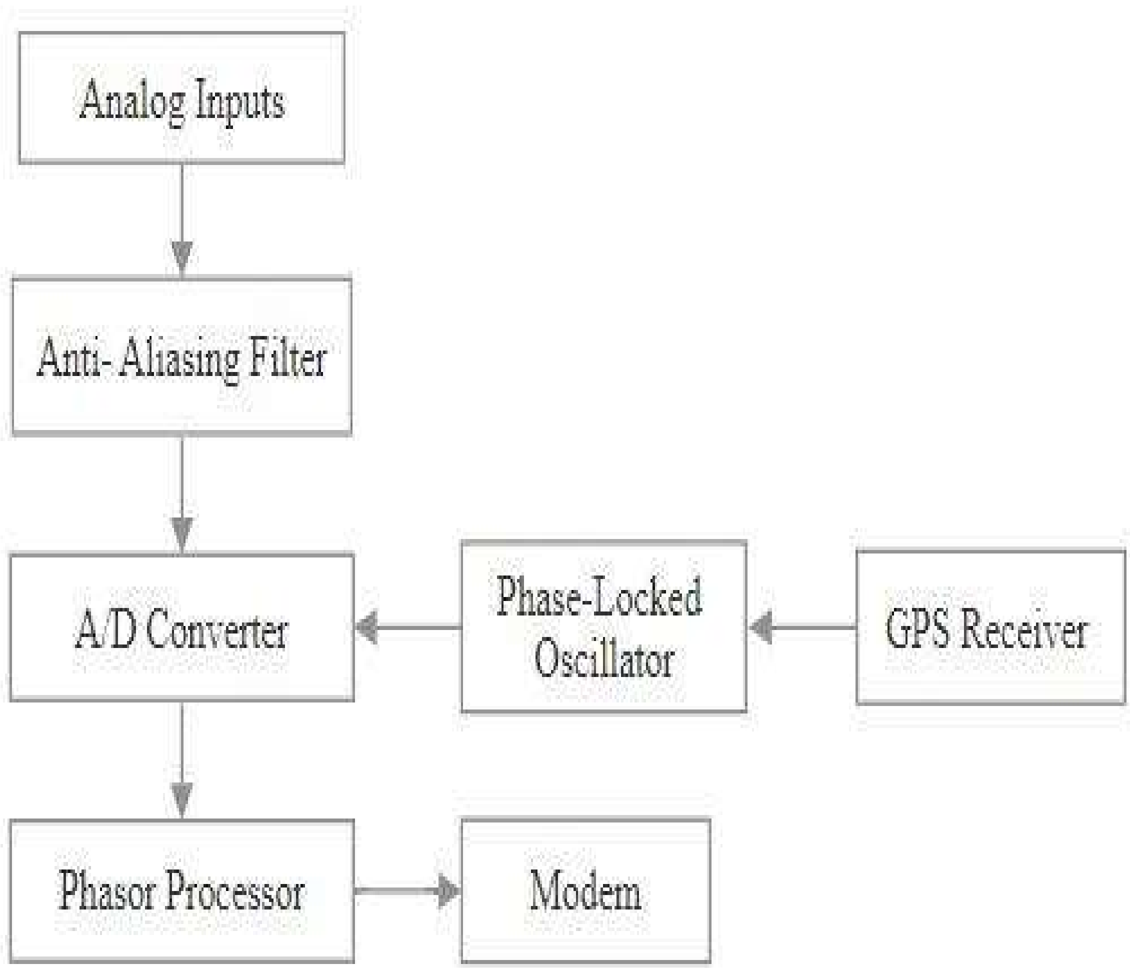

Figure 1.11: PMU Principals' Work

unit which contains GPS receiver and Phase-Locked Oscillator (PLO) to provide the sample clock for the measurement unit. The GPS receiver is a sinusoidal signal which carries the amplitude and frequency. PLL/PLO is to aliens the reference phase with transmitter phase. The measurement unit has the anti-aliasing filter to ensure the bandwidth of the signal to be sampled is limited to the desired frequency range, analog to digital converter and phasor processor. The data transmission unit which receives the data from the measurement unit to be transmitted through the Modem [23-24].

In Fig.1.11, the synchronization unit contains GPS receiver and phase-locked oscillator to provide the sample clock for the measurement unit where the measurement unit has the anti-aliasing filter to ensure the bandwidth of the signal to be sampled is limited to the desired frequency range, analog to digital converter and phasor processor. The last unit of the PMU is the data unit which receives the data from the measurement unit.

The existing PMU has demonstrated technical challenges due to the rapid development and changing patterns of smart grid operation with integration of DGs. Therefore, Synchrophasor may present tremendous error due to the traditional synchronization required process where the traditional technique is based on a synchronization circuit unit [25].

1.5 KALMAN FILTER

Kalman Filter (KF) is an estimation approach that was introduced by Dr. Rudolf E. Kalman in his 1960 publication. It is a set of mathematical estimation processes based on prediction and updating the state measurement using a mathematical model to provide the best solution out of the system. KF's application is vastly known in signal processing and control systems applications. It stands out as one of the most sensing and highly accurate Linear Quadratic Estimation (LQE) algorithms for predicting data today. This is due to its low cost and the redundancy characteristic, which is based on updating the state of measurement to correct the previous estimation state. KF capabilities reach far and beyond many kinds of noises including Gaussian and Non-Gaussian noise. KF estimation process is widely considered to filter the signal from noise and distortion. It relies on updating the filtered system state by knowing the dynamic of system behavior in advance, and the updating the prediction of the next state and then correcting the prediction result [25].

Kalman Filter is a recursive estimation process as shown in Fig. 1.12 below. It begins with an initial estimate to predict the projection of the next state, and error covariance, and then computes the Kalman gain, and updates the measurement estimation and error covariance. So, it's simply predicting the next state through the mathematical model and then updating the state estimation measurement. It works through predicting the next state using a mathematical model and then updating the state estimation measurement with feedback gain.

1.5.1 Extended Kalman Filter

Extended Kalman Filter (EKF) is a linearization process for non-linear system which enables to linearize the state space of every step to the updated state estimation using Taylor approximation or Jacobian approach for non-linear system. The existing applications mostly involve a non-linear differential equation whether it is the system or the state measurement [25-26].

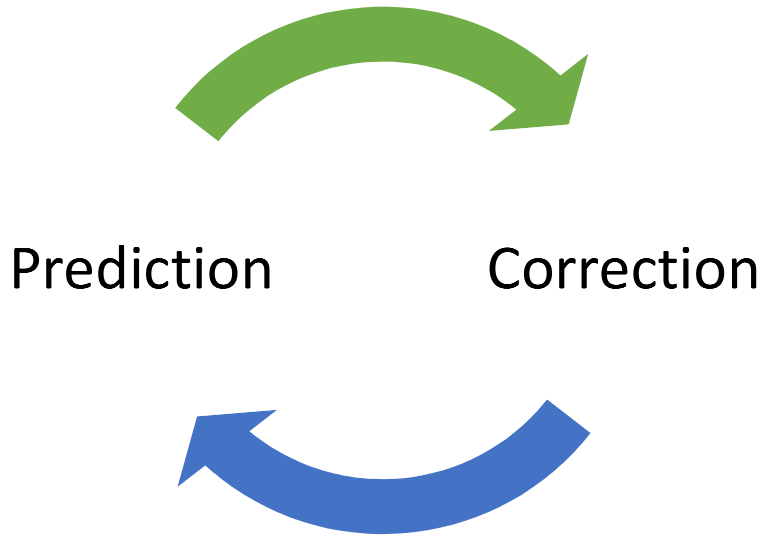

Figure 1.12: Kalman Filter Process

State estimation enables to control the online network due the sensitivity of the state of network to ensure the efficiency operation particularly for microgrid which may relies on DG at certain conditions.

1.6 Signal Noise

Signal systems are exposed to many phenomena that affect their performance and cause signal weakness due to several factors which could be resulting from communication, device, and equipment condition, as well as external interference to the signal as result from natural surrounding conditions.

1.6.1 Gaussian Noise

Gaussian noise is a normal distribution which helps to figure out the noise effectiveness applied to the signal of the system to validate the quality of the signal throughout the noise. The Additive White Gaussian Noise (AWGN) represents most common type of Gaussian noise in a signal channel. In fact, AWGNs occur due to the high load on the electronic devices in which cause such noise, transmission environments or communication interference. It allows to identify the effected signal considering the disturbance and noise along the transmitted signal as shown in Fig. 1.13 below [27].

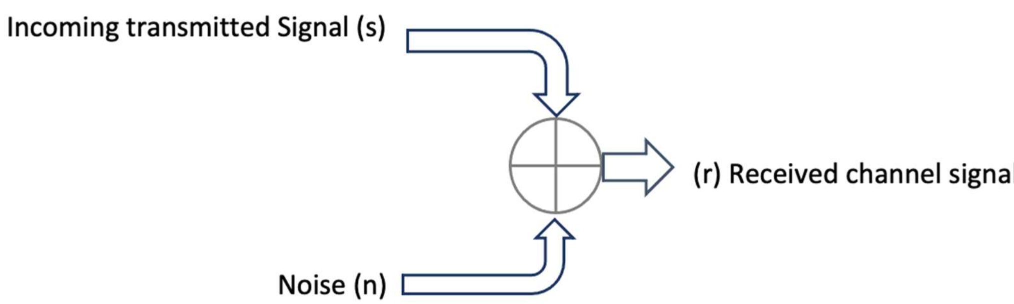

Figure 1.13: Additive White Gaussian Noise Channel

1.6.2 Non-Gaussian noise

Since communication and signal systems are exposed to numerous various types of noises which may be different from Gaussian noise, it is essential to frame a highly disruptive environment. Therefore, non-Gaussian noise has been included to validate the system's signal robustness to tackle the system's signal in such severe environment conditions. Non-Gaussian noise is basically a mixture of multiple of Gaussian noise forming a severe noise environment as shown in Fig. 1.14 below. In this paper, the proposed method considered under different environments to test the system robustness [27].

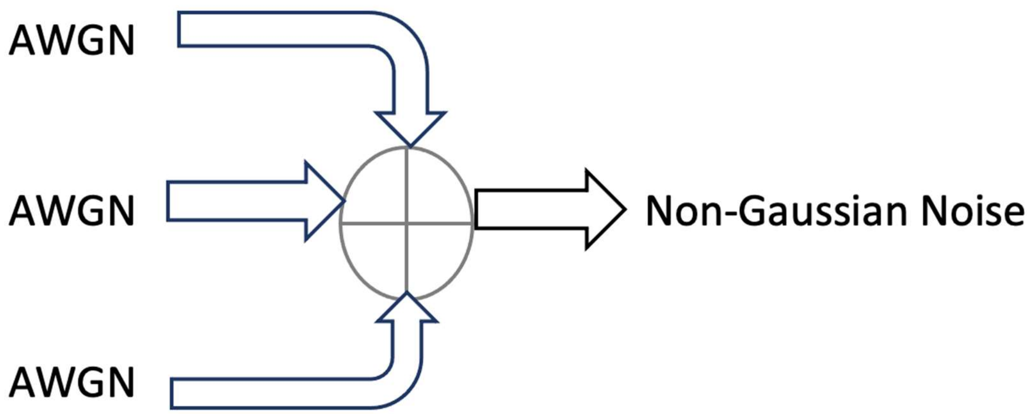

Figure 1.14: Non-Gaussian Noise

CHAPTER TWO

RELATED WORK

2.1 Related work

The rapid increase of the data rate in the PMUs has required an extreme development. Yet, the higher data collection rate has allowed better situational awareness along the development of better tools. However, it has created a significant concern to handle these data efficiently with less cost consumption and lower error rates. Thus, there is an imperative need for highly efficient mathematical tools that ensure a lower error rate with less operation costs and complexity [28-29].

In [30], the research proposes an improved method for dealing with bad data in power systems via the PMU while the high PMU rate measurement. This proposed method introduces an algorithm which checks the measured data to identify the bad data. It detects the wrong measurement condition and its location to enhance the accuracy of the measurement. Moreover, the performance of the proposed model was verified by testing it under several environments to ensure the robustness of the model in different operational conditions.

This paper [22] discussed the raising challenges of the integration of Distributed Generation (DG) in the micro-grid. The authors addressed a proposed model considering Weighted Least Squares (WLS) process to handle the penetration of DG sources mainly PVs to the low voltage distributed networks with the respect to the PMU position along the network.

In [21], the author addressed Kalman Filter (KF) to estimate the synchronized phasor of the system through the distributed PMUs along the power grid for monitoring and control. The author addressed a KF for simultaneous phase estimation of the system through phase measurement units spread across the power grid to monitor and control performance reliability. Such measurements required linearization step process and synchronization clock units for the Synchrophasor.

This paper [31] presented the application of KF for phase tracking in Binary Phase Shift Keying (BPSK) in ZigBee system to optimize the phase changes with consideration of the presence of the Additive White Gaussian Noise (AWGN). The outcome of the proposed method was promising due to its high accuracy to track the phase changes in the presence of AWGN which encourage to expand the research work on the phase optimization process.

In this paper [32], the authors investigated the effective of Extended Kalman Filter (EKF) to track the phase changes mainly Binary Phase Shift Keying (BPSK) using ZigBee receivers. The proposed method was applied for the optimization of the phase changes to minimize the phase error under different types of environments.

In this paper [33], the authors deal with the method of using the KF residuals to expose the transient state in the PMU by recognizing the differences between the measurement and estimate values. Note that the difference is close to zero at the steady state, which is exactly the opposite when the unforeseen shifts present a greater raise to show the extent of the unalike between the measurement and estimated values. Therefore, the authors resorted to studying the performance to discover the magnitude and phasor of the system and the power quality of the system including the frequency shifts and the grid state of power transient.

The proposed method in this paper [34] used multiple of Linear Kalman Filters (LKF) connected to each other to form a new form of phase tracking with enhanced priori knowledge about the phase. The method considered the KF to be tested under different type of noises to validate the robustness of the proposed solution to system's phase tracking. The system's novelty was verified by considering Mean Square Error (MSE) in consideration of Signal to Noise Ratio (SNR).

The PMU measures the amplitude and phase of the voltage and current along various locations along the electrical grid. Its primary work is based on the value of the phase for the collected data using an optimal estimation process. The enormous role of the PMU consists of controlling and protecting the grid systems in various circumstances and locations, it is significant for the development for the phasor estimation technique to contribute on raising the level of accuracy at a lower cost and with higher efficiency. This paper [19] illustrated numerous approaches to estimate the system's phase includes KFs as well as the PMU framework which identifies the synchronization, measurement, and data units.

The authors [35] discussed two types of nonlinear Kalman Filters for estimating battery system state behavior. One of which is the Extend Kalman Filter (EKF) which requires a linearization step process to its state space equation. In contrast, the Unscented Kalman Filter (UKF) relies on unscented transformation [36-37]

The purpose of this paper [38] was to examine the replacement of the Phase Locked-Loop (PLL) with the LKF for phase changes optimization process within ZigBee receiver through different operation condition. The implication of LKF revealed accurate estimation for the phase changes with respect to different type of noises. Such application outcomes encourage the development of an optimization to a similar system's condition.

PMU stands out as one of the most useful tools for monitoring and controlling the smart grid. It forms a significant functionality in control and supervision of the smart grid systems by taking the system's phasor in different parts of the network to ensure the reliability of operation. The ultimate use of PMU is to detect the measurement of the magnitude and phase for the voltage or current at certain time and location synchronized with time stamped GPS clock. Therefore, the existing PMU highlights the importance of optimization to save the cost with less complexity to handle the existing network deals with the penetration of distributed PVs.

In this paper [39], the H∞ filter has been introduced referring to EKF. The proposed model formed a so-called H∞ Extended Kalman Filter (HEKF) to enables the dynamic control system to face the operation challenges for various power system conditions. Therefore, it requires a solid control system that is capable of bypassing these variables steadily and ensuring the network conductivity is safe. The proposed model was tested using IEEE 39-bus system for the effectiveness verification. The paper considered EKF and UKF for comparison with HEKF which outperformed them in two different cases. Note that, the proposed model requires a linearization step using Jacobian matrix.

The authors [40] discussed the parametric variables on the dynamic state estimates for Phasor Measurement Units of the synchronous power generation systems employing Monte Carlo method. Both EKF with unknown inputs and UKF were investigated to recognize the out of which these filter fits effectively on the estimation process due to parametric variabilities using the IEEE 39 bus system. The authors concluded this paper by assuring that the selection of the type of Kalman filter would not impact the estimation process looking at the deviation of the parametric variation where the UKF was lower MSE while the EKF has showed the opposite.

This paper [41] discussed several models for the state estimation process for the PMU associated with the generation side, where the focus was on the Least Square Errors (LSE), EKF, and UKF for each of the parameters and states.

In [42], a study has been conducted to illustrate the differences among several methodological tools within the Bayesian framework for dynamic system estimation for the PMUs outcome data. This study includes EKF, UKF, Ensemble Kalman filter (EnKF), and the Particle Filter (PF); each method has been gone through robustness validation work including different types of noise. The studies show how the EnKF outperformed the other methods in terms of accuracy to estimate the PMUs data while PF requires high number of samples among the other methods for better accuracy. The performance of both EKF and UKF methods have demonstrated a greater robustness with lower sensitivity while EnKF required more time to present better accuracy tracking data.

In [43] there were two types of KF estimation process applied to this paper to track the system's phase using high-speed data across PMUs of the power system grid which are EKF and the UKF. It was found throughout this research using MATLAB simulation tools that UKF could evaluate the mean and covariance to third degree and EKF able to the first degree. However, EKF performed better with real-time implementations.

An investigation has been conducted to determine the optimal estimation approach among Least Square estimator and Kalman Filter (KF) for the voltage sag within the power grid by estimating the systems' power phasors. A comparison-based assessment of the capabilities of Least Square and KF designed to better estimate the phasor where the results showed the of the Least Square to excelled for less than one cycle compared to the KF process [44] .

The research in [45] introduced a Second-Order Kalman Filter (SOKF) to minimize the phase error as a new optimization method to reduce the phase signal error received from an access point based on a less complicated mathematical model of phase estimation process for the PMU. However, instead of applying the Extend Kalman Filter to enhance the estimation of the result, the SOKF indicates that the optimization of the result resulted in less system complexity and a result closer to the reference.

In this paper, the robustness of the new optimal method proposed in [45] has been analyzed; the system performance has been extensively tested using MSE with respect to SNR values. It shows more robustness with no linearization techniques implemented. The simplified mathematical approach excludes the circuit to detect the system phase which is known as the Asynchrophasor technique. The Asynchrophasor technique is less expensive than the Synchrophasor technique. The proposed method has been tested in the presence of different nominal propagation where the solution results in a phase error minimization.

CHAPTER THREE

METHODOLOGY

3.1 SECOND ORDER KALMAN FILTER FOR PMU PHASE SIGNAL DETECTOR

The Asynchrophasor technology has been formulated to overcome many challenges and is centered on eliminating the need for synchronous process. The introduction of the Asynchrophasor has helped to ensure low costs and reduce complexity resulting in less error of the outputs of the PMU. The Asynchrophasor estimation technique relies on a SOKF to reduce errors and complexity associated with the synchronization process. The working principle of this introduced technique does not require a synchronization process as shown in Fig. 3.1, which helps to reduce the cost. The synchronization process is an old technique to detect the Synchrophasor; in this proposed method it was replaced by an efficient algorithm that is based on SOKF to detect phase changes as shown in Fig. 3.1 below. This new method will help to optimize the device and reduce and narrow down the cost with less error.

The optimized Asynchrophasor approach presented in this paper has been modeled using SOKF to minimize the phasor error of the PMU. The intention of the proposed solution is to optimize the PMU to lower the cost and complexity which replaces the synchronization circuit through the Asynchrophasor approach in the PMU layout. This proposed method includes a minimization process of phasor error based on MSE with no linearization techniques needed. Such an intended method has shown how costless and robustness the system is by considering the system outcome to be tested in the presence of Gaussian and non-Gaussian.

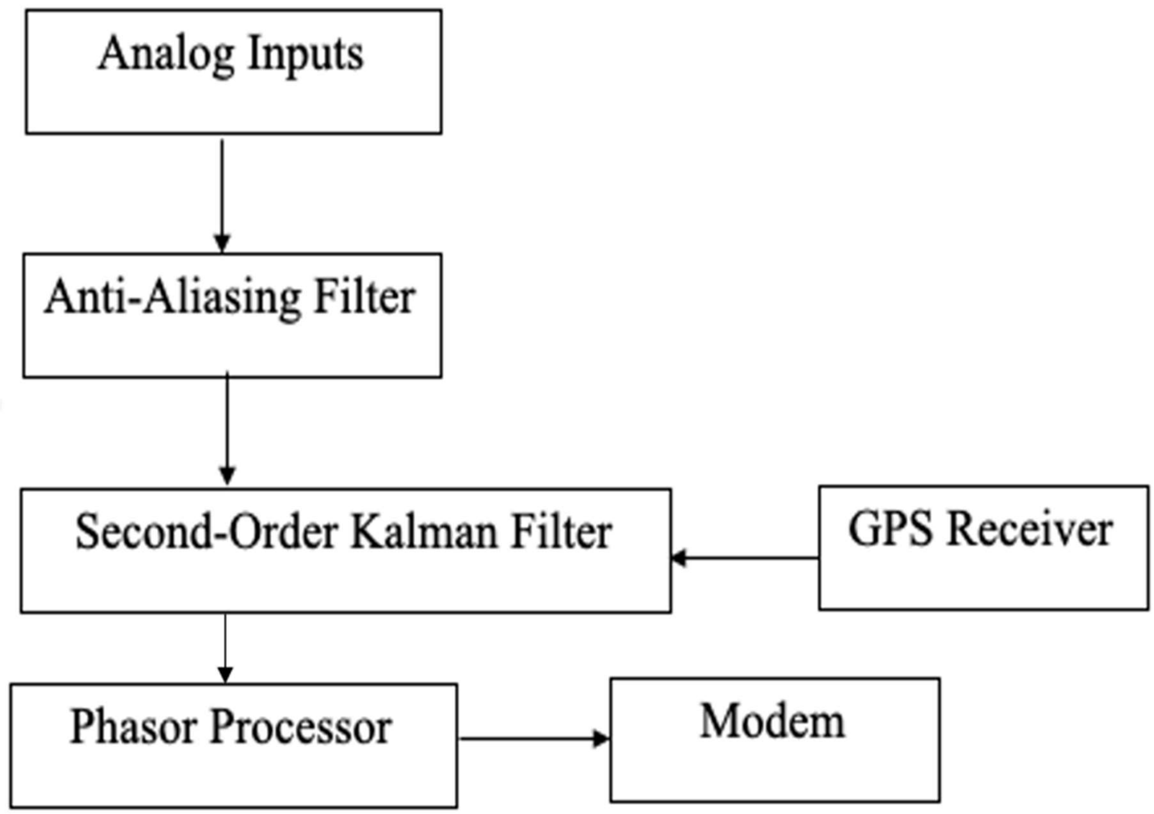

Figure 3.1: Asynchrophasor PMU Structure

Instead of Synchrophasor for the synchronous phase technique, the developed technique of the proposed solution within the PMU relies on an asynchronous phase technique which is known as an Asynchrophasor.

3. 2 Optimization of PMU

The results covered in this work are based on optimizing the PMU to reduce the cost through the application of SOKF. This Asynchrophasor estimation technique reduces the complexity and costs compared to the Synchrophasor; however, the Asynchrophasor does not use synchronization clock unit.

3.2.1 PMU Signal

The PMU signal is a sinusoidal function. The mathematical model of the PMU signal can be expressed in the following equation (3.1) as follows:

$$x(t) = M\cos(\omega t + \theta) \tag{3.1}$$

Note that M is the amplitude of the sinusoidal function, where ω represents the angular frequency, and θ forms the variant of phase angle of the wave signal.

3.2.2 PMU's State Space Model

The state space model of the PMU is given below (3.2) for the implementation of SOKF. It is represented below for the state variables of the PMU to estimate the system phasor. The implementation of the SOKF indicates mathematical model for the system's phase in the state space variables where the time update equation includes the transition matrix with the consideration of the noise in (3.2). Where $x(k+1)$ is the time update equation, F is the transition matrix, x(k) is the general plant dynamical solution of the PMU, and w(k) represents the Gaussian noise.

$$x(k+1) = F\,x(k) + w(k) \tag{3.2}$$

The effectiveness of a SOKF is clearly demonstrated by its application to the mathematical equations of the system phase by expressing the state of the variables of the space state in the time update equation via the transition matrix in (3.3).

$$F = \begin{bmatrix} 0 & 1 \\ -w^2 & 0 \end{bmatrix} \begin{bmatrix} -w\sin wt \\ -w^2\cos wt \end{bmatrix} \tag{3.3}$$

The measurement equation is expressed by z(k) in equation (3.4), where the observation matrix is represented by H, and the measurement noise is stated as $v(k)$. The general dynamical solution of the PMU plays a major role in time updating equations as well as the measurement equation (3.4) towards more accurate results and less cost. This module replaces the phase locked oscillator device to reduce cost and improve the results.

$$z(k) = H\,x(k) + v(k) \tag{3.4}$$

$$H = \begin{bmatrix} 1 \\ 0 \end{bmatrix} \tag{3.5}$$

The PMU's general plant dynamical solution takes its place in both of the time update equation and the measurement equation to update the estimation process to the phase error minimization. Such asynchronous phasor process supersedes the existing synchronization process.

3.3 Kalman Filter Algorithm

In this section, we summon Kalman Filter (KF) Algorithm to predicts and updates the state space of the filter for the state of the phase accordingly [46]. The estimation process of Kalman Filter begins the predication for the system's phase with the initial estimate X_0 along with update error matrix P_0. Then, the Kalman Filter Gain G is calculated for predication correction. The error constraints are considered to update the estimation according with and without the consideration of the deviation.

Since KF is a recursive process, the predication and correction process are implemented according to each time step n [36-38].

First step starts where the initial values are being calculated X_0 and P_0. Second, KF Gain G is calculated for the predication correction with priori knowledge of the covariance process as follow:

$$G(n) = P(n \mid n-1)\ \ C\text{^}T\ \ [H\, P(n \mid n-1)\ \ C\text{^}T + R]^{-1} \tag{3.6}$$

Third, the posteriori covariance $P(n)$ is being calculated indicating the covariance update for the process with priori covariance $P(n \mid n-1)$ and Kalman Gain G where we calculate the posteriori covariance:

$$P(n|n) = [I - G(n)\, C\ \ [\, P(n \mid n-1)] \tag{3.7}$$

Then, the predicated process covariance is calculated. However, $P(n+1)$ will be considered for the previous estimation for the coming step n. So that, we calculate the predicted process covariance as follow:

$$P(n+1) = A\, P(n|n)\, A^T + Q \tag{3.8}$$

The current estimation can be described as the follows:

$$\hat{x}(n|n) = \hat{x}(n|n-1) + G(n)[y(n) - C\, \hat{x}(n|n-1)] \tag{3.9}$$

Note, that $\hat{x}$ (n | n-1) is the previous estimate which can be expressed as follow:

$$\hat{x}(n|n\ -\ 1) = F\, \hat{x}(n-1|n-1) + \Delta \cdot \mathcal{U}(n-1) \tag{3.10}$$

In order to update the phase estimate, it should be picked by the minimum error value among the error equations below:

$$e_1 = y(n) - C\ x(n|n-1)] \tag{3.11}$$

$$e_2 = y(n) + C\ x(n|n-1)] \tag{3.12}$$

CHAPTER FOUR

SIMULATION AND RESULTS

In this section, the results of the presented model are a result of implementing the optimal mathematical model using MATLAB simulation software are discussed to demonstrate the capabilities of the optimized Asynchrophasor technique. It relies on the SOKF to track the system's signal phasor across the PMUs throughout the grid.

4.1 Simulation

The simulations of the proposed method include testing through different environments to demonstrate the robustness of the proposed model. The solution results in reduced phase error. The results show the superior performance of the Asynchrophasor as applied in the PMU compared to the existing working principle which depends on the synchronous circuit in the distributed PMUs along the grid. The results below show the outperformance of the Asynchrophasor in PMU compared to Synchrophasor in PMU.

4.2 Results

Note that the Fig. 4.1 below considers the phase in radians versus the number of samples. Noting that, the Asynchrophasor technique picks up the value very rapidly as it takes more samples closer to the reference line. However, the blue stars of Synchrophasor shows jumps in the samples toward 200 samples. This model indicates its validity by getting very close to the real measured value as represented by black line. The results show the high accuracy of the estimation done by second Kalman filter

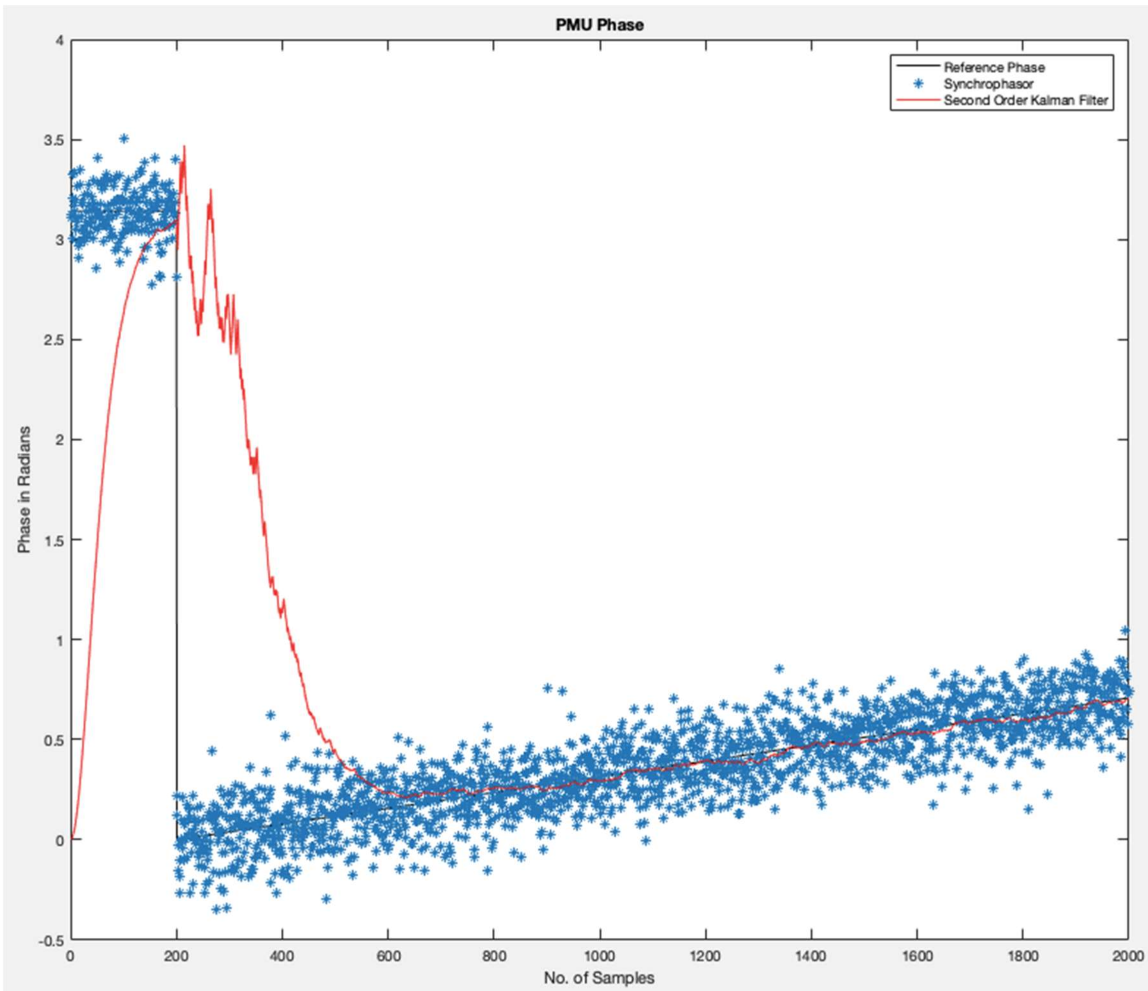

Figure 4.1: PMU Phase

which proves the validity of the model towards the reference phase. This model is effective in reducing the cost of grid operation.

4.2.1 The MSE in Presence of Gaussian Noise

In Fig. 4.2, the proposed method in the PMU has been considered in the presence of Gaussian noise with the application of MSE with respect to SNR as shown below. As a result of the application of SOKF, the results have picked up the values of the Asynchrophasor as it takes a larger number of samples with closer outcomes to the reference phase. The reflection of the Asynchrophasor results in a better and closer outcome than the Synchrophasor under Gaussian noise. The proposed model excels in the presence of Gaussian noise by using MSE to measure the effectiveness of the proposed technique based on SOKF, as it was shown that was able to better track the phase of the system in the presence of Gaussian noise. Notice that at the rate of 5 dB it shows the improvement where by 21.45% under Gaussian noise.

4.2.2 The MSE in Presence of Non-Gaussian Noise

In Fig. 4.3 the simulation results were considered in the presence of non-Gaussian noise. The Asynchrophasor approach in the PMU has performed better than Syncrhophasor under severe environment conditions that shows the robustness and effectiveness of the optimal method SOKF. Apparently the SOKF approach has worked much better than the existing model in the presence of non-Gaussian noise as evaluated by MSE. Therefore, it is crucial to have SOKF in the presence of non-Gaussian noise. It should be noted the improvement at the rate at 5 dB by 16.2% for the presence of non-Gaussian.

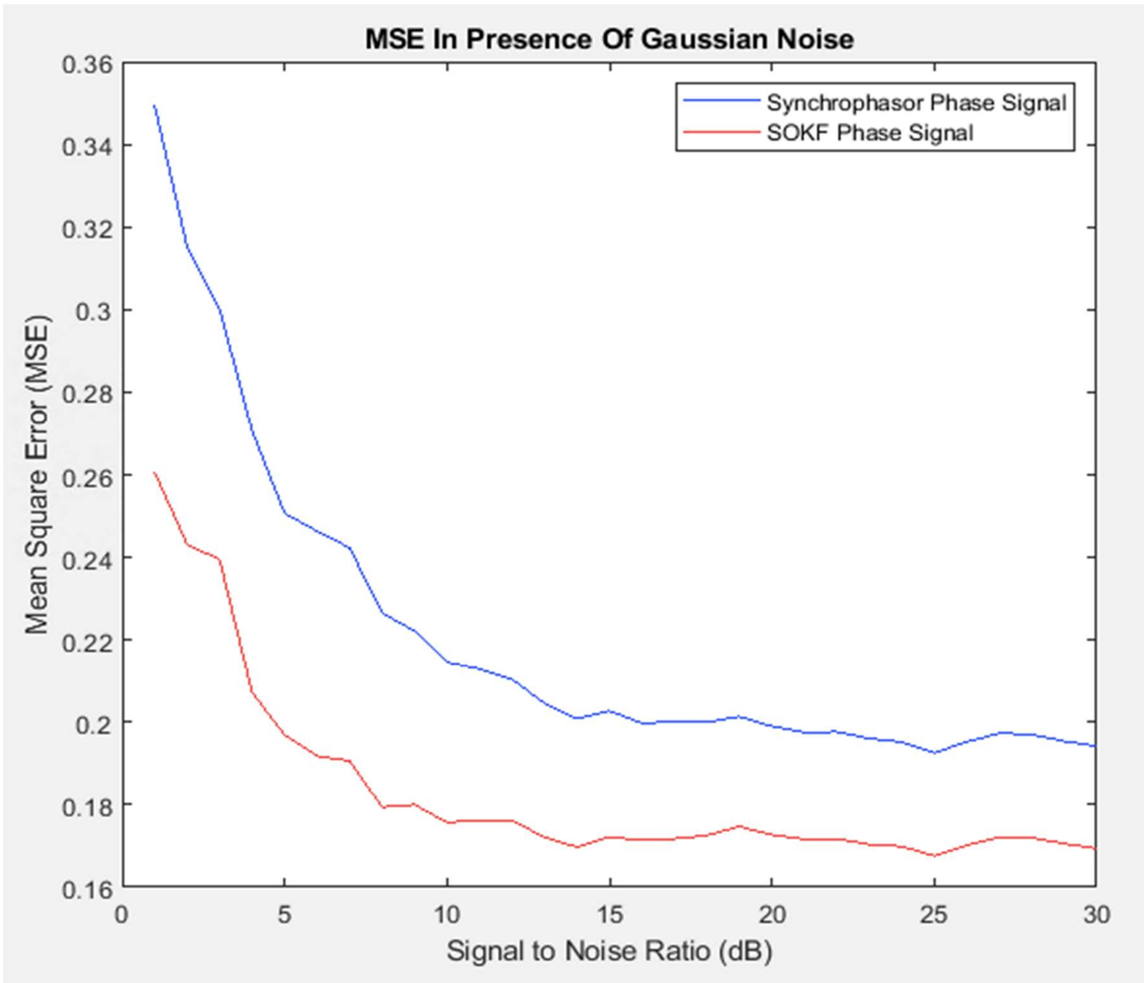

Figure 4.2: MSE In Presence of Gaussian Noise

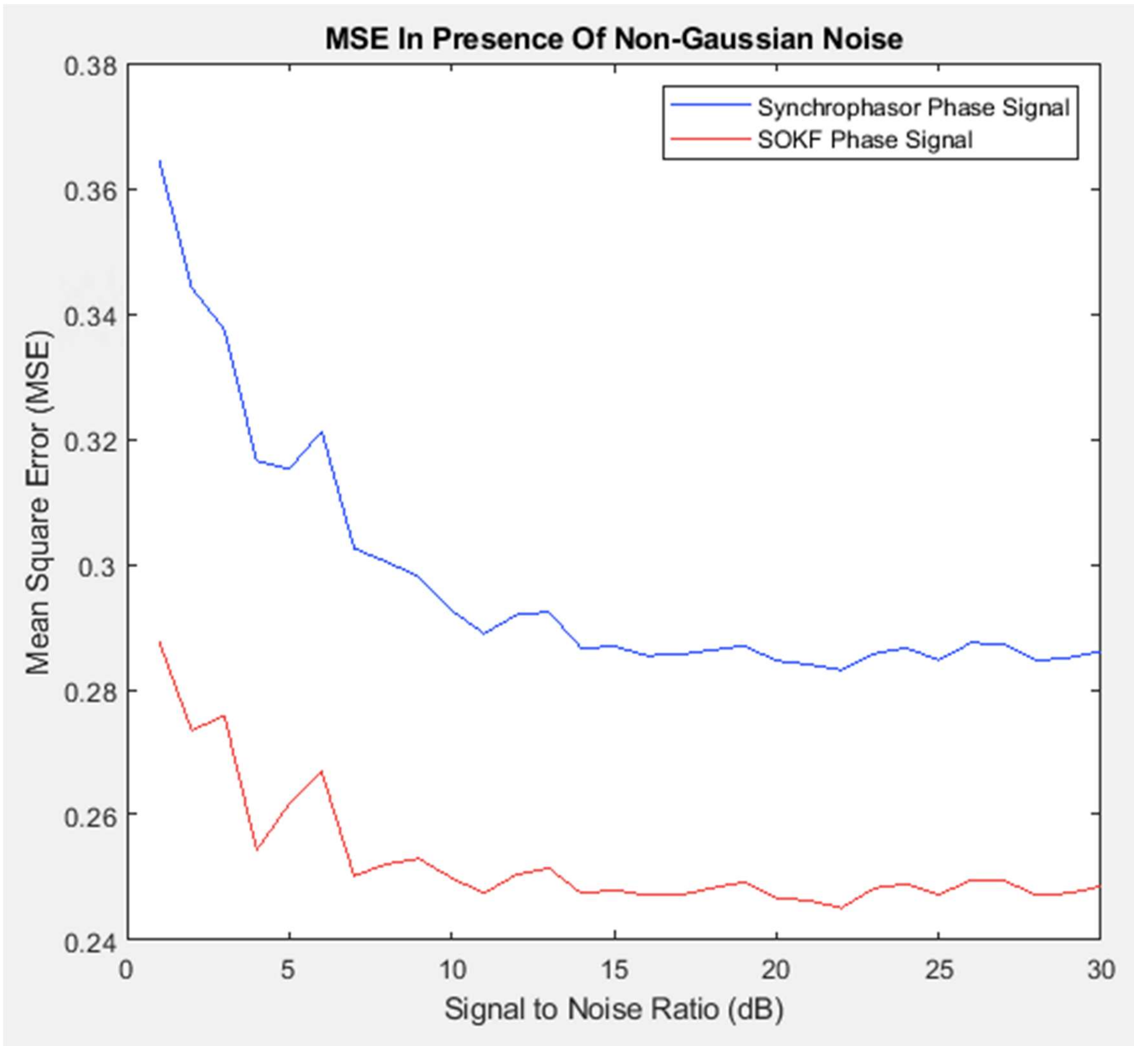

Figure 4.3: MSE In Presence of Non-Gaussian Noise

CHAPTER FIVE

CONCLUSION AND FUTURE WORK

5.1 Conclusion

This research generated a mathematical model using the Second-Order Kalman Filter (SOKF) method to optimize the Phasor Measurement Units (PMU). The model considered an asynchronous technique in the PMU for phase error minimization and cost reduction. It is a simplified model based on replacing the Asynchrophasor technique which outperforms the Synchrophasor device by eliminating the need of the existing synchronization process. The outcomes of this optimization technique were verified by taking the MSE with respect to SNR values to measure the phase error deviation of the signal. The proposed method includes the minimization of the phasor error that is based on MSE; no linearization technique was needed. The optimal solution of the proposed method has obtained an effective and significant role to be used in place of the existing technique. This research demonstrates the significance of such estimation methods to the economic burden as a result of operating the network. The estimated result using SOKF provided enhanced results of the Synchrophasor PMU at a lower cost which helps network operators maintain network reliability and sustainability in the presence of different environments, including in the presence of Gaussian noise and non-Gaussian noise.

5.2 FUTURE WORK

The proposed work in this thesis focused on cost reduction and phase error minimization considering a simplified approach. Therefore, Second-Order Kalman Filter (SOKF) has been used, which is based on simplified mathematical model. It outperformed the existing Synchrophasor PMU. This model has been tested, which has proven its effectiveness in terms of simplicity with low cost, robustness in different conditions, and optimality of the results with less phase errors. The simulated results using MATLAB have shown that how much development on the PMUs have been done using such an effective model, SOKF, as addressed in this dissertation. Such proposed model has showed promising future through different models based on Asynchrophasor approach as follows:

⇒ Unscented Kalman Filter (UKF) can be useful implementation to overcome the challenges in PMUs.

⇒ An Artificial Neural Network could be used in place of the existing Synchrophasor of the PMU for phase tracer enhancement.

⇒ The proposed method could be considered for evaluation in terms of stability, protection, and voltage conditions.

⇒ Applying the proposed method in this research, Asynchronous phasor technique, may include multiple nodes.

APPENDIX
KALMAN FILTER

The model whose value is to be estimated is assumed as follows:

$$x_{k+1} = F_k x_k + w_{k\ \mathrm{a}} \tag{A.1}$$

So that;

$x_{(k+1)}$ is the time update equation

x_k is the state vector of the time $t = k$

F_k is the state transition matrix at time $t = k$

w_k is the Gaussian noise at time $t = k$

Where the observation measurement equation is addressed at time t = k is as follow:

$$z_k = H x_k + v_k \tag{A.2}$$

Where;

z_k represents the measurement equation

H represents the observation matrix

$v(k)$ is the measurement noise

with $N\,(0, {\sigma_w}^2)$ at time $t = k$

Establishing an initial estimate $x\hat{}_0^+$ according to prior knowledge for the process prior to time $t = k$ for to initiate Kalman Filter process. Such start is needed to get the current observation where it is denoted by $x\hat{}^-_k$ as follows:

$$x\hat{}^-_k = F_{k-1} + x\hat{}^+_{k-1} \quad \text{(A.3)}$$

Where initial error covariance P^+_0 take place as shown below.

$$P^-_k = F_{k-1} P^+_{k\text{-}1} F^T_{k\text{-}1} + Q_k \quad \text{(A.4)}$$

Then, the Kalman Gain is being calculated considering the calculated priori process covariance P^-_k above.

$$K_k = P^-_k H^T_k (H_k P^-_k H^T_k + R_k)^{-1} \quad \text{(A.5)}$$

After that, the priori estimate $x\hat{}^+_k$ can be calculated considering z_k as follow:

$$x\hat{}^+_k = x\hat{}^-_k + K_k (z_k - H_k\, x\hat{}^-_k)$$

So, the posteriori covariance is being computed which includes the known priori process covariance as shown below:

$$P^+_k = P^-_k (I - K_k H_k) \quad \text{(A.6)}$$

The general dynamical solution of the PMU plays a major role in time updating equations as well as the measurement equation (3.4) towards more accurate results and less cost.

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