Three Phase State Estimation in Power Distribution Networks by Integrating IEEE-1588 with Smart Meters

Maman Ahmad Khan
Department of Electrical and Electronic Engineering
National University of Ireland, Galway (NUIG)
Galway, Ireland
m.khan7@nuigalway.ie

Barry Hayes [1, 2]
Department of Electrical and Electronic Engineering
[1]University College Cork (UCC), Cork, Ireland
[2]National University of Ireland, Galway (NUIG), Galway, Ireland
barry.hayes@ucc.ie

***Abstract*—This paper proposes a novel design for distribution system monitoring using a Modified Smart Meter (MSM) to enable accurate, time-synchronised measurements. The detailed design and the operation of the MSM are explained in this paper. The Precision Time Protocol (PTP), IEEE 1588, provides the main feature of time synchronisation in the MSM. The MSM uses the existing smart meter sensor hardware for collecting data measurements. This technique is expected to reduce the overall cost of MSM based distribution network monitoring implementation compared to the system based on Phasor Measurement Unit (PMUs). Some applications of the proposed MSM are outlined, and the applicability of the MSM is tested by simulating three-phase state estimation using standard IEEE networks and comparing its performance to standard PMU devices. The results indicate that the MSM could represent a viable monitoring solution for MV and LV distribution networks, providing an acceptable trade-off between performance and cost.**

***Index Terms*—Distribution system state estimation, modified smart meter, phasor measurement unit, precision time protocol, three phase unbalanced networks.**

I. INTRODUCTION

Distribution System Operators (DSOs) are in charge of the reliable performance and maintenance of the distribution network. Techniques for the monitoring of the high voltage transmission grid are very well established [1-3]. However, the monitoring approach and the equipment used in the transmission network cannot be applied directly to distribution systems. The primary reason behind this is a large number of nodes as well as the total length of the lines in the distribution network [4]. The integration of Distributed Energy Resources (DERs) such as electric vehicles, heat pumps, solar and wind power brings a considerable amount of uncertainty in the distribution system. These changes in the distribution network create the need for extensive real-time monitoring at the distribution level [5]. In recent years, a growing significance of the application of PMU (Phasor Measurement Unit) for the monitoring distribution systems has been reported [6, 7]. Recently Von Meier *et al.* [8] designed a μ-PMU (micro-Phasor Measurement Unit) for the real-time monitoring of the power distribution network. However, the placement of μ-PMUs in that paper is only at primary nodes, i.e. substation, feeder and at distribution transformer level. It is considered economically unfeasible to connect PMUs at most or all distribution buses, due to the very large number of nodes and components in the distribution network. A low-cost PMU is designed in [9], using a Rogowski coil as a current sensor. However, the data is collected from this device at 6-minute intervals, making it too slow for real-time monitoring. Some more recent work has been focused on either reducing the installation cost or using low-cost hardware while designing and implementing PMUs in the distribution network [10-12].

The applications that are conceptually mature at transmission network still have significant challenges at the distribution level. This is entirely due to the lack of real-time measurements in the distribution network [13]. A wide range of application of μ-PMUs in the distribution network is described in [14-16]. However, this paper focuses only on diagnostic applications, which help the DSO to better understand the past and present condition of the distribution system. Power system applications such as Distribution System State Estimation (DSSE) can play a significant role in the monitoring and control of the distribution grid [17]. Although, most distribution networks have insufficient measurement data, which affects the performance of DSSE. In previous work, various DSSE algorithms which use pseudo measurements and SCADA measurements in order to make the system observable have been investigated [18]. However, these type of measurements contains a high level of uncertainty, which leads to poor estimates. Some other work [19] performs single phase state estimation by assuming the distribution system to be symmetrical, which is practically not applicable as the distribution networks are mostly unbalanced. Thereupon, this paper will demonstrate case studies related to three-phase state estimation on the unbalanced network after proposing a low-cost PMU equipment designed to deliver better accuracy as compared to the conventional measurements in state estimation.

The key innovation of this work is the development of a Low-Cost PMU (LCPMU) based on PTP (Precision Time Protocol) integrated with the existing smart meter. The proposed PTP-based Modified Smart Meter (MSM) solution provides real-time measurements at a data rate of 10 frames/second in the distribution system, which allows the topology and steady-state behaviour of the network to be determined. This paper aims to validate the performance of the PTP-based MSM in DSSE using Weight Least Square (WLS) estimation technique. The reason for choosing this technique lies in [20] which states that the WLS estimation is the best-suited DSSE technique for the low redundancy levels typical in distribution networks.

This paper is structured into six sections. Section II outlines the proposed architecture and discusses the main functionality of the Modified Smart Meter (MSM) and its applications. Section III describes the methodology and explains the operation of each part of the MSM along with the communication technique adopted. Section IV presents the algorithms used for three-phase WLS state estimation. In Section V, the results and discussion for the two different case studies three-phase state estimation and a comparison is made between the estimated error of a PMU-based monitoring system and an MSM-based monitoring system. Lastly, conclusions are presented in Section VI.

II. PROPOSED ARCHITECTURE

A. Main Functionality

The concept of the PTP, also known as IEEE 1588, standard-based synchronisation was proposed in [21]. However, the concept was limited only to the substation end where the series of IEC61850 standards have been introduced. The primary motive of this paper is to facilitate real-time monitoring in the distribution network. For that, a novel architecture based on smart meter unbundling concept [22] consists of PTP based PMU is designed.

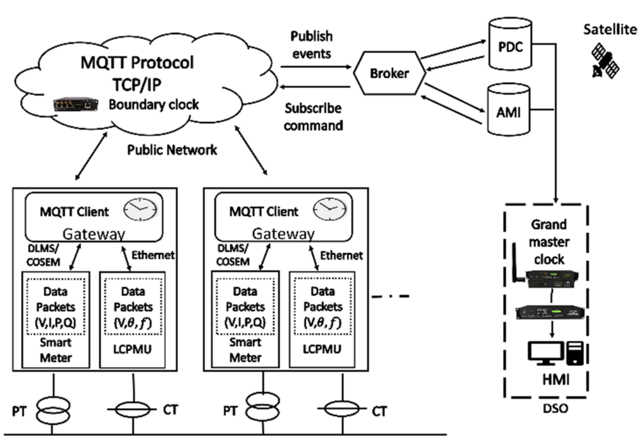

Fig. 1. Block Diagram of Modified Smart Meter

The architecture of the proposed Modified Smart Meter (MSM), Fig. 1. is subdivided into three different fundamental elements. The first sub model is the existing smart meter, which is assumed to be already implemented at the consumer end for billing purposes. This uses the smart meter sensors, including the current transformer (CT) and Potential Transformer (PT) for reading the data. This portion of the MSM applies the smart meter unbundling concept [22], and can function with any existing smart meter in the market.

The second sub-model in the MSM is the novel approach for the low-cost PMU based on PTP. The primary functionality of the PTP is the inbuilt feature of Pulse per Second (PPS). It helps to trigger the acquisition and provides the support in maintaining the real-time operation without the need of extra hardware components such as the Digital Signal Processor (DSP) or micro-controller for its operation. [23, 24]. Traditionally, PMU uses GPS for the time synchronization, which requires the GPS module to be installed at a place where the sky should be visible clearly. However, the low-cost PMU is integrated with the existing smart meter in the MSM design, which may not be installed in an open area. A PTP-based design allows the MSM to function, without the need for open space. The fundamental concept of PTP is similar to NTP (Network Time Protocol) in which a time is distributed from top to bottom. However, the requirement for time synchronisation in MSM case needed to be within 50-100 microseconds and NTP have the synchronisation capacity in milliseconds. Hence, to achieve a better synchronisation, PTP is considered. This MSM-based low-cost PMU design uses the existing smart meter's CT and PT to provide synchronised, real-time measurements at the data rate of 10 frames/second.

The Modified Smart Meter Gateway (MSMG) is the most critical subsystem of the architecture. The primary objective of this gateway is to provide the communication for the two meters, ie. Smart meter and LCPMU available in the MSM with the external world for monitoring and control purposes. It collects smart meter and PMU data with the access of their specific protocol at a synchronisation speed between 50-100 microseconds and stores it in a real-time database with the help of the public network. The required interfaces are defined in the gateway which provides firewalls for the protection of different type of data transferring to different external bodies.

B. Communication Infrastructure

In Modified Smart Meter (MSM) design, the gateway is connected with both the smart meter and LCPMU and serves as the only interface for the DSO, Fig. 1. The connection takes place with the help of public network already present in the located area to process, store and transfer the measurements at the control centre. As seen in Fig. 1, the smart meter is connected with the gateway through a serial Ethernet connection based on the existing standard protocols like DLMS and COSEM (Device Language Message Specification/ Companion Specification for Energy Metering). The low-cost PMU (LCPMU) is connected with the gateway via the IEC61850 protocol. The gateway will help in converting the standard PMU protocol (like std. C37) to a protocol-specific in DSO which is IEC61850 that also serves for the smart grid SCADA [25]. The advantage of standardizing the MSM with IEC61850 is that it provides a way of exchanging the synchrophasor data with PMU, Phasor

Data Concentrator (PDC) and Wide Area Monitoring, Protection and Control (WAMPAC) in a way that is compliant with the substation automation standards.

The MSM located at various locations will be connected with the DSO with the help of MQTT (Message Queuing Telemetry Transport) protocol [26]. It is a publish-subscribe lightweight protocol. The most significant requirement for an MSM is to deliver the real-time data without any data loss. It can be seen from Fig. 2 that the real-time data from MSM is transferred based on the subscription made with the Mosquitto Broker in the MQTT protocol. The broker receives and publishes the data in real time. The MQTT publisher clients, i.e. MSM do not require any separate configuration and can be installed in the software established with the meter. The data type for the transmission will be in XML format.

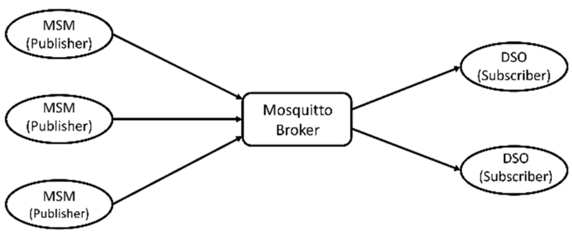

Fig. 2. MQTT Block Diagram proposed for MSM

The communication technology used for transferring smart meter data in Europe and other countries worldwide is not uniform, and different countries have installed different communication technologies. Another benefit of the proposed MSM design is that it does not require a separate communication technique, instead, it works using the available, established techniques of existing smart meters. Table I shows for the communication techniques which can be used for MSM communication.

TABLE I: COMMUNICATION TECHNIQUES USED FOR SMART METER [5]

Technology	Frequency Band	Data Rate	Country
NB-PLC	3-490 kHz	~200Kbps	Italy, Spain, France
3G/LTE	450MHz,1.9GHz/ 700-2500MHz.	0.2-14Mbps/100-~320Mbps	UK
GPRS	900MHz,1.8GHz	56-114Kbps	Germany, Sweden, Greece
GSM	900MHz,1.8GHz	14.4Kbps	Sweden, Greece

The primary communication requirement for the MSM is to transfer the data at 10 frames/second rate. Since this data rate is not very high, TCP/IP connection can be used as it provides assurance of making a contact and guaranteed response with the configuration message. Hence, all the above techniques are fulfilling the requirements for the transfer of MSM data. Therefore, MSM can be utilized with any of the communication techniques as mentioned in Table I, taking the MQTT protocol over TCP/IP layer under consideration as shown in Table II. The main benefit of this MSM design is that each component can be modified as well as tested separately based on the requirements.

TABLE II: DATA FLOW SPECIFICATION FOR MSM

Data Flow	Protocol	Connection	Data type
Real time data	MQTT	TCP/IP	XML

C. *Application of MSM*

The application of the proposed MSM is directly related to the constraints of the meter like sampling rate, reporting rate, angular resolution and communication latency [8]. MSM can help in determining the distribution system topology as its only requirement is to differentiate between zero and non-zero power flow on a particular branch. The other and the primary requirement is to analyse the steady state of the system. The main application for steady-state monitoring is through state estimation and fault detection. In the distribution network, information has to be collected from a large number of nodes. Thus, the data rate of 10 frames/second reduces the computational burden and can be easily applied in the network for the application related to the topology and steady state of the system. The knowledge of steady state operating condition in real time is a precondition for interpreting specific information about particular devices or particular incidents [27]. For this, state estimation will be the foundation for most of the other applications of LCPMU data.

Other application of MSM includes, the topology detection, high impedance fault detection with improved sensitivity and selectivity using voltage phasor values. The reverse power flow detection can be done with the help of MSM at the locations which are not directly monitored in the distribution network.

III. METHODOLOGY

A. *IEEE 1588 principle*

PTP, also known as IEEE 1588 defines the reference clock as the grandmaster clock and then develops a master-slave relationship among all of the other clocks in the whole network. The master provides a time reference, and the slaves synchronise with the master. A grandmaster clock in this work is synchronised to a time reference of the GPS present in the PMU attached anywhere in the power network. These time stamping provided by the master clock is used to determine the latency which is needed to synchronise the slave to the master. As shown in Fig. 3, the time stamps are used to define the delay and the offset of the clock as per (1)-(4) :

$$\text{Delay} + \text{Offset} = t_2 - t_1 \quad (1)$$

$$\text{Delay} - \text{Offset} = t_4 - t_3 \quad (2)$$

$$\text{Delay} = \frac{((t_2-t_1)+(t_4-t_3))}{2} \quad (3)$$

$$\text{Offset} = \frac{((t_2-t_1)-(t_4-t_3))}{2} \quad (4)$$

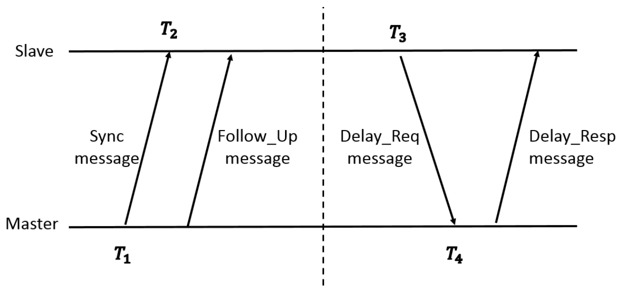

Fig. 3. Structure for PTP communication

In Fig. 3, the adjacent master and slave clocks exchange information which helps the slave clock to estimate the offset compared with the master clock, (1)-(4). T_1 is the time stamping of transmission by master clock. The slave clock recieves the message at time T_2. Then, the slave clock sends the delay request message back to the master at T_3 and finally, the master clock records the recieving time of the delay request at T_4, [28].

As seen from Fig. 1, this paper contains one grandmaster clock which is provided by the GPS of the PMU that is already installed at any particular location in the whole power network, one boundary clock available as a switch or a router, and the slave clock available in different gateways. The need of the boundary clock here is to reduce the effect of jitter. A switch serving as the boundary clock runs the PTP protocol, which is synchronised with the grandmaster clock. Along with this, the boundary clock acts as the master clock for all the slave clocks attached to it. With this procedure, all the latencies and jitter are compensated and do not affect the synchronisation accuracy.

B. Operation of the Modified Smart Meter (MSM)

The primary application of the smart meter is to perform the main function of handling power measurements for billing purposes. This billing data is highly-sensitive and is related to the customer's security, and care needs to be taken so that this data is secure from any outside intervention. This sensitive, smart meter data is transferred to the DSO via MSM gateway. Voltage and frequency measurements from the smart meter, are considered non-sensitive data and can be used for monitoring purposes.

The second sub-model used in the MSM design is the low-cost PMU. The PTP module port installed in the MSM gateway helps to provide a time reference for the time stamping of the calculated phasor. The PTP inbuilt PPS feature supports the synchronisation of the data acquisition. As shown in Fig. 4, the data acquisition board is triggered with the assistance of the PPS signal, and the acquisition of the data starts when the pulse is received. The samples are then recorded at the overall data rate of 10 frames/second. This MSM data obtained from different locations in the form of LCPMU data are transfered to the PDC (Phasor Data Concentrator) as shown in the Fig.1, before being transfered to the DSO for further processing and monitoring purpose.

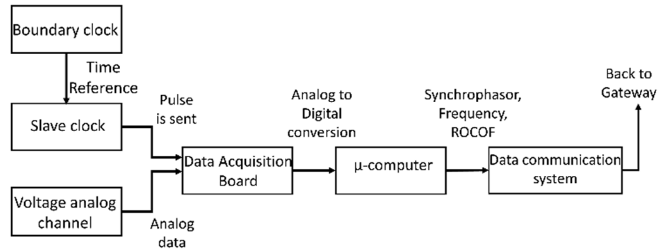

Fig. 4. Block diagram of LCPMU

The Discrete Fourier Transform (DFT) is used on the data obtained by the LCPMU to get the amplitude and the phase angles of the achieved signal. Upon receiving the voltage and voltage angles, a zero crossing algorithm will be applied for calculating the frequency of each period as per [29]. In this technique, the obtained signal is scanned for each sample, and it distinguishes the zero crossing events when the signal moves from positive to negative. The time (t_1) at which this event occurred is calculated by interpolating the two samples. This step repeats when the signal again crosses the zero crossing and the value of it is stored as (t_2). Hence, the difference between these two stored data calculates the time period of the acquired cycle which helps in calculating the frequency (f) as the inverse of this difference.

The time period of the acquired cycle:

$$Tp = t_2 - t_1 \quad (5)$$

Calculated frequency:

$$\text{f} = \frac{1}{N_C}\sum_{i=1}^{N_C}\frac{1}{T_p} \quad (6)$$

Finally, Rate of Change of Frequency (ROCOF) is calculated as the difference between the inverse of the time for the first period and that obtained for the last period.

$$\text{ROCOF} = \frac{1}{t_1} - \frac{1}{t_n} \quad (7)$$

This technique is able to uphold a suitable frequency and ROCOF for the non-periodic signal in the presence of noise and harmonics. The obtained results will then published following the IEC61850 protocol in the substation PDC which typically monitor a few tens of PMU. The function of the PDC in the substation is to aggregate and time align the PMU data and feed it to the upper-level PDC.

C. Standard network configuration and network data

For the application of MSM, this paper considers a highly unbalanced network with unsymmetrical network components which makes it essential to include an exact three-phase model of the network components. The whole network consists of line resistances, reactances, transformers, unbalanced loads and switches.

i. Line model: In the distribution network, the overhead and underground lines are either single phase, two phase or three phase. Therefore, it is essential to measure the impedance of these lines taking care of self and mutual impedance values.

A modified Carson's equation is applied in the model as:

$$Z_{ii} = r_i + 0.095 + 0.121 \times \left(Ln\frac{1}{GMR} + 7.934\right)\Omega/mile \quad (8)$$

$$Z_{ij} = 0.095 + 0.121 \times \left(Ln\frac{1}{D_{ij}} + 7.934\right)\Omega/mile \quad (9)$$

Where, Z_{ii} is the self impedance of conductor i, Z_{ij} is the mutual impedance between conductors i and j, r_i is the resistance of conductor, GMR is the geometric mean radius of the conductor i and distance between conductor i and j is referred as D_{ij}. Kron reduction technique is used to convert all the line model into specifix (3×3) phase impedance matrix assuming single and double phase element as zero.

$$Z_i = \begin{bmatrix} Z_{aa} & Z_{ab} & Z_{ac} \\ Z_{ab} & Z_{bb} & Z_{bc} \\ Z_{ac} & Z_{bc} & Z_{cc} \end{bmatrix} \quad (10)$$

ii. Loads Model: The loads in the distribution network in this paper are considered to be a combination of constant current, constant power and constant admittance models. The load values in the distribution network are mostly given as power delivered to the load and are typically converted into an appropriate constant model parameters.

iii. Transformer model: The three-phase transformer is modelled by the admittance matrix. Depending upon the connection type it is taken as either Y-Y, Y-Δ, Δ-Δ in the paper. The full explanation of the transformer connection is taken from [30], and switches are considered as branches with zero impedance.

IV. WLS BASED THREE PHASE STATE ESTIMATION

In this paper, the Weight Least Square (WLS) based state estimation algorithm is applied to the three-phase unbalanced distribution network to minimise the following objective function (*J*):

$$J = [z_1 - h(x)]^T W^{-1}[z_1 - h(x)] \quad (11)$$

The nonlinear measurement function is given by

$$z_1 = h(x) + r \quad (12)$$

With error vector

$$r_1 = \begin{bmatrix} z_{1,s} - h_{1,s}(x^{(1)}) \\ z_{1,sm} - h_{1,sm}(x^{(1)}) \\ z_{1,p} - h_{1,p}(x^{(1)}) \\ z_{1,v} - h_{1,v}(x^{(1)}) \end{bmatrix} \quad (13)$$

$$W_1^{-1} = \begin{bmatrix} W_{1,s}^{-1} & 0 & 0 & 0 \\ 0 & W_{1,sm}^{-1} & 0 & 0 \\ 0 & 0 & W_{1,p}^{-1} & 0 \\ 0 & 0 & 0 & W_{1,v}^{-1} \end{bmatrix} \quad (14)$$

Where z stands for the measurement vector, x is the system state vector, h(x) is the measurement state variable which generally is a non-linear function and r is the vector of the measurement errors. W stands for the covariance matrix of the measurement errors. In (14), the subscript 's' stands for the substation data, 'sm' is used for smart meter data and 'p', 'v' are used for pseudo measurements and virtual measurement data.

In this paper, different types of measurements have been taken such as substation measurement, pseudo-measurement and phasor obtained first from the existed micro-PMU and then with the MSM placed at the specific buses in the distribution network. Applying the iterative weighted least square (WLS) [31], the state variable can be estimated as:

$$\hat{x}_{k+1}^{(1)} = \hat{x}_k^{(1)} + G_1(\hat{x}_k^{(1)})\, [H_1^T\, (\hat{x}_k^{(1)})\, W_1^{-1}] \times [z_1 - h_1(\hat{x}_k^{(1)})] \quad (15)$$

Where $\hat{x}_k^{(1)}$ is the state vector which is estimated for kth iteration of $x^{(1)}$. After solving the partial derivative for h_1 ,the algorithm achieve jacobian matrix H_1. The gain matrix, G_1, in (15) is defined as:

$$G_1(\hat{x}_k^{(1)}) = [\, H_1^T\, (\hat{x}_k^{(1)}) W_1^{-1} H_1\, \hat{x}_k^{(1)}]^{-1} \quad (16)$$

The reason for selecting the post processing method is that, it does not change the existing configuration of Energy Management System (EMS) software. Hence, more appropriate in practise [32]. In the first step of estimation, the measurement vector consists of substation measurements along with the smart-meter and pseudo measurements. These comprise of branch power flow, whereas, the active and reactive power injection measurements are assumed to be available from the smart meters. In the post processing step, the traditional PMU with 1% uncertainty has been compared with the novel MSM with 3% uncertainty. The benifit of post processing is that, the comparison has been made simpler without any major changes in the MATLAB program and just by running the state estimation with different uncertainties in the data one after the other to obtain the two different estimation results for comparison. For the WLS estimation technique, the measurement data generated for state estimation has added measurement uncertainties of 1% for the substation measurements, 10% for the smart meter data, 50% for the pseudo measurements and then using post-processing method adding 3% uncertainty for the MSM implementation [33].

For this method, the voltage phasor measurement of MSM which consists of voltage magnitude and voltage angle is incorporated with the first step estimated state vector $\hat{x}_k^{(1)}$ to update the state estimates.

$$z_2 = \begin{bmatrix} \hat{x}^{(1)} \\ \hat{x}_{MSM} \end{bmatrix} + r_2 \tag{17}$$

where $\hat{x}^{(1)}$ is the estimated first step state vector before the post processing method and $\hat{x}_{MSM}$ is the estimated state when MSM is been implemented on the bus network. r_2 denotes the measurement error which consists of a Gaussian random variable with the covariance matrix W_2.

$$W_2 = \begin{bmatrix} W_{\hat{x}^{(1)}} & 0 \\ 0 & W_{MSM} \end{bmatrix} \tag{18}$$

In (18), $W_{\hat{x}^{(1)}}$ represents the weighted matrix of the first step estimation, while W_{MSM} indicates the weighted matrix of MSM which comprises of voltage magnitude and phase angle. With the help of this post-processing algorithm, the state vectors are compared by running the state estimation first with conventional measurements including PMU, and then by replacing the voltage and voltage angle data from MSM.

The performance of the two devices when applied to state estimation in the distribution networks is analysed in Section V, comparing them according to their error difference [17], by comparing the error histograms. The error histogram for the worst cases of the unbalanced three phase is calculated from the state estimates.

V. RESULTS AND DISCUSSION

A. Test and Simulation

In this paper, the following test for the comparison of the novel designed MSM and the existed PMU is performed. In the testing phase, the three-phase state estimation is implemented on highly unbalanced standard IEEE 13 and IEEE 123 bus network. The WLS technique explained in the previous section is adopted for the state estimation process. The measurement data is generated using the backward-forward load flow technique, and the measurement uncertainties are added as explained in the previous section. For the comparison, 1% error in the PMU is added following with 3% in the MSM using the post-processing method [33]. In this work, the MSM provides only the bus voltage phasor as the real-time measurement, while the slack bus and the pseudo measurements provide the active and reactive power injections. Since, the number of nodes to be monitor are very high in distribution network as compared to the transmission network. The number of MSM required will be high. Hence, to cut down the cost of the MSM, only the voltage measurements are sufficient for monitoring distribution network and micro-grid functionality. The convergence criteria is taken as 10^{-5} for state variable updates for both the networks.

The three-phase power flow algorithm is run in MATLAB using the backward-forward sweep technique to provide the measurement data set. This load flow code is generated with the help of network information and standard load data [34]. Due to the fact that the three-phase case study networks have a high level of unbalance. Hence, solving large, poorly-conditioned matrices was a significant challenge in this work. In order to resolve these problems, the standard WLS technique was modified as follows. A subdivision of the network was carried out, dividing the network into feeders and laterals. The 13 bus network is divided into 6 different topology matrices, and 123 bus is divided into 48 partitions. Afterwards, the state estimation takes place on each row separately. Each partition takes a maximum of 5 iterations in order to converge. This approach significantly reduced the complexity and computation time required.

B. Case Study Networks

The IEEE 13 and IEEE 123-bus networks [30] consist of overhead as well as underground lines which are modelled using modified Carson's equations. These distribution test feeders include star and delta loads which are both single phase and three phases, and loads are represented using the ZIP model as explained in the previous section. The proposed MSM design was implemented on these test feeders, and the three-phase state estimation performance using MSM devices is compared to the state estimation performance using existing PMU devices.

i. IEEE 13 Bus Network Results

The standard IEEE 13 bus network is a small network with relatively highly loaded 4.16 KV feeder. The switch between 671 and 692 in IEEE 13 bus is assumed to be closed, and zero injection is considered across the switch. These zero injection voltage magnitude and angles along with voltage at the regulator are considered as equality constraints. Unbalanced spot load and the distributed load is present in the network. There is one transformer with grounded Y- grounded Y connection in the network.

The power flow results were used in place of flat start conditions in order to gain a faster solution. The standard IEEE 13 data is taken to carry out the power flow solution. The main motive of selecting the power flow solution over the flat start is to gain faster convergence in less number of iteration. The inverse square of the measurement uncertainty helps in calculating the measurement weighting constant 'W' in the WLS estimation with the assumption that a normal distribution is one-third of the given maximum error percentage about the mean value for a 99.7% coverage factor [32].

The WLS algorithm is coded in MATLAB using standard IEEE 13 bus system, running on Core i7 at 3.4GHz with 16GB RAM. The error difference is plotted for PMU and MSM in Fig.5, which shows the frequency of the occurrence of magnitude error for PMU and MSM, and Fig. 6, shows the frequency of error in the angles for PMU and MSM.

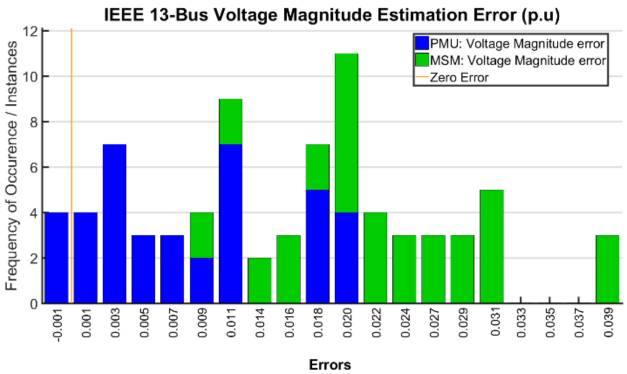

Fig 5: IEEE 13 Bus Voltage Magnitude Error histogram

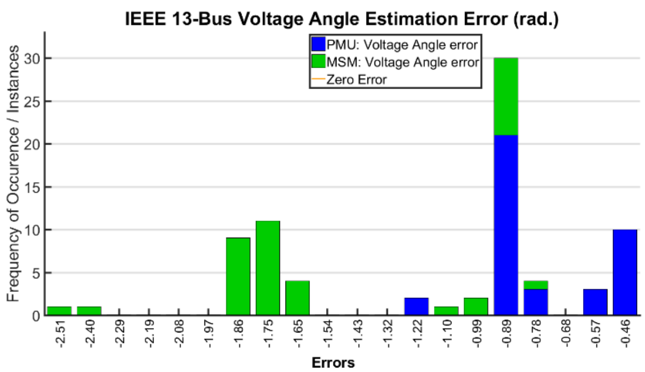

Fig 6: IEEE 13 Bus Voltage Angle Error histogram

The performances of the PMU and MSM are compared in detail using error histograms. In Figs. 5-6, the green bars represent the frequency of occurrence of each error for the MSM, whereas the blue bars show the PMU frequency of error. The x-axis denotes the errors, and the y-axis shows the frequency of error on corresponding buses. It can be clearly seen that the blue bars in the histogram, which indicate the PMU frequency of error is closer to the zero mean in the magnitude as well as the angle, while the green bars denoting the MSM have a larger spread. This indicates that the MSM frequency of the error is higher than the PMU, as expected. However, the MSM errors do not deviate from the PMU errors by a very large degree, and these MSM errors are considered to be within an acceptable range for steady-state applications.

ii. IEEE 123 Bus Network Results

The highly unbalanced IEEE 123 bus network is taken as the second test case for the comparison of PMU and MSM. The nominal voltage level for this test feeder is 4.16KV. The nodes connected to a switch is considered as one node. All of these switches are assumed to be open while only the switch between 121 and 123 is kept closed. The errors histogram for PMU and MSM are plotted in Figures 7 and 8.

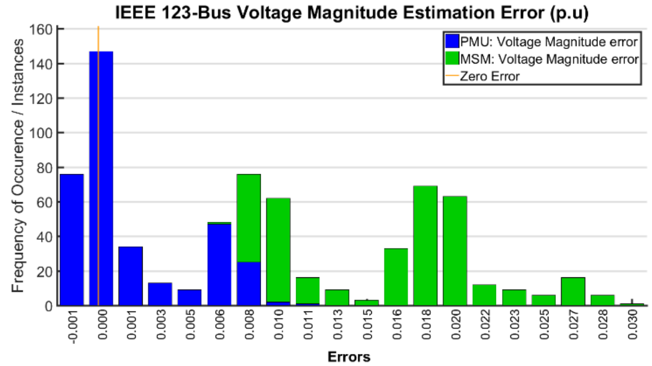

Fig 7: IEEE 123 Bus Voltage Magnitude Error histogram

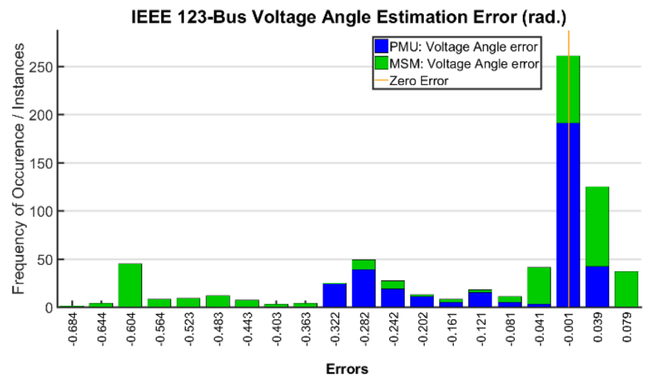

Fig 8: IEEE 123 Bus Voltage Angle Error histogram

These two plots show that even in large IEEE 123 bus network, the uncertainty is somewhat higher in the case of the MSM, represented by the green bars. The MSM has larger errors and a greater spread of errors compared to the PMU, denoted by the blue bars. However, the MSM green bars are within the permissible limit. This shows that the acquired histogram results for the novel design MSM are found to be satisfactory within the allowable error range.

VI. CONCLUSIONS

This paper addresses the need for improved monitoring and situational awareness in MV and LV distribution networks. Existing PMU techniques, adopted from transmission networks may not be feasible for distribution network monitoring due to the high cost of implementation. The proposed MSM design is more appropriate for distribution networks, which typically have a very large number of nodes. One of the benefits of the MSM is that it can be integrated with the existing smart meter using the unbundling concept and it can also utilise available sensor hardware to collect the data for measurements. The PTP technique is the main concept used in the MSM for data synchronisation at a rate of 10 frames/second.

Moreover, the paper highlights a number of applications of the proposed MSM device. In Section V of the paper, the state estimation formulation is presented for the unbalanced three-phase case, and the comparison is made between PMU and MSM. The resultant plots, Figs. 5-8, illustrate that the low-cost MSM could be applied for distribution network state estimation in place of PMUs, at the expense of reduced estimation accuracy. This represents a trade-off between the cost of implementation of the monitoring system and its accuracy. However, the level of accuracy provided by MSM devices in this analysis is deemed acceptable for most steady-state distribution network monitoring applications. Future work will analyse more comparisons of the device performance, and a detailed study of the costs of implementing an MSM-based monitoring system in large-scale distribution networks will be carried out.

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