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PTP-based time synchronisation of smart meter data for state estimation in power distribution networks

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Abstract: This paper develops a novel approach for distribution system monitoring and state estimation, where time synchronisation of smart-meter measurements is carried out via the Precision Time Protocol (PTP). The approach is based on the concept of a Modified Smart Meter (MSM), a distribution system monitoring instrument that enables accurate time synchronisation of smart meter data. The design, application, communication technique and protocols of the MSM are described in detail. The proposed MSM device features PTP-based time synchronisation of smart meter measurements, and the concept of unbundling is applied to collect measurements utilising the existing smart meter sensors. This is expected to reduce the overall implementation cost of an MSM-based distribution network monitoring system compared to a system based on Phasor Measurement Units (PMUs). The problem of requiring open sky access for GPS links can potentially be solved by means of PTP synchronisation. Three-phase state estimation simulations using the IEEE-13 and 123 bus unbalanced test networks are employed to demonstrate the applicability of the MSM, and its performance is compared to standard PMU devices. The results indicate that the MSM may represent a workable monitoring solution for MV and LV distribution networks, with an acceptable trade-off between cost and performance.

1 Introduction

Distribution system operators are in charge of the network, which is mostly of radial topology with a one-way power flow. However, with the development of distributed energy resources, the introduction of variability and uncertainty in the grid arises [1–3]. Some advanced modifications in the distribution system such as distributed generation, more customer-initiated demand response, electric vehicles and other changing customer-load characteristics require the need of better situational awareness and monitoring of the distribution network. To acquire this, the DSOs are more dependent on the measurements available from supervisory control and data acquisition (SCADA) systems, which typically provides data at several second intervals [4]. However, with the transition of distribution networks into active distribution networks (ADNs), there is a growing interest in using a precise observation tool for the network that provides a high level of time granularity and fast communication [5]. There has been substantial growth in the application of PMUs (phase measurement units) for monitoring the distribution system recently [6, 7]. Lately, the advanced research projects agency-energy micro-synchrophasor project in [8] developed a low-cost PMU which connects at the primary and secondary level distribution network for monitoring single or three-phase voltages. The advantage of this PMU design is that it facilitates a millidegree level of phase resolution, however, the demerits of this device are that the cost remains high and it is not deemed economically feasible to connect it throughout the whole distribution network for complete monitoring and network control [9]. Wang *et al.* [10] have proposed a low-cost PMU device which uses a Rogowski coil as a current sensor. However, the data collected is at 6-minute intervals, making it too slow for real-time monitoring. There are several other authors who have recently proposed their current work on low-cost PMU either by reducing the installation cost or by using low-cost hardware along with open-source software [11, 12].

These recent efforts are being implemented to make the distribution system more visible and improve network situational awareness for DSOs. Many research projects have focused on the application of PMU at the transmission level. However, these applications are still under development in the distribution network because of the lack of real-time measurements and network observability [13].

It is vital to address all the medium voltage (MV) and low voltage (LV) level challenges to achieve situational awareness. A wide range of applications of distribution level PMUs are described in [14–16]. Distribution system state estimation (DSSE) plays an important role in the distribution network as it provides the initial condition for many distribution management system applications [17, 18]. However, very few monitoring devices are available at the distribution side, making the network unobservable. Many utility companies use pseudo measurements and SCADA measurements to make the system observable [19]. However, the poor level of accuracy of these measurements makes the state estimation at the distribution network very unreliable. Alternative approaches [20, 21], include assuming the distribution network to be symmetrical to perform DSSE. Nonetheless, such approaches cannot provide accurate situational awareness at the power distribution level, as the distribution network is typically an unbalanced network. Hence, this paper considers all of these constraints and performs three-phase state estimation on an unbalanced IEEE standard network.

To deliver better accuracy as compared to conventional measurements in DSSE; this paper proposes a low-cost modified smart meter (MSM) design, primarily focused on developing a real-time low-cost monitoring device, which can be implemented in the distribution network economically. Generally, at the LV side of the distribution network, smart meters are installed for customer billing, and do not typically contribute to real-time grid operation. Henceforth, the key innovation of this work is to better utilise these already implemented smart meters, and for that, a novel low-cost PMU (LCPMU) is designed based on precision time protocol (PTP) integrated with regular utility-grade smart meters. The same PTP technique has been used in [22] but for traditional PMU synchronisation. However, the LCPMU is integrated with the smart meter, which receives inputs from the sensors of the smart meter and provides with an output data rate of ten frames for each second.

The proposed MSM design is intended to be used for distribution network applications such as topology detection and steady-state monitoring. In this paper, this novel design is compared with already existing PMU solutions by testing it on the distribution network using three-phase DSSE. The reason for choosing the WLS for state estimation is that it is the best-suited DSSE technique in low-redundancy systems such as distribution networks [23].

The paper is structured as follows: Section 2 provides the background for all existing low-cost PMU solutions and discusses the novel proposed architecture of the proposed MSM, along with its functionality. Section 3 describes the operation of the hardware, network and database. Section 4 describes the problem formulation by deriving the WLS method for three-phase state estimation. In Section 5 results are presented; first, for PTP testing, and later comparison of the SE performance using the MSM device and the existing PMU is shown. Section 6 concludes the paper.

2 Proposed architecture

2.1 Overview of existing PMU modules

The PMU was originally developed for the transmission network applications. The estimated cost of the PMU installation was ∼ $40,000 to 180,000 [24].

Primarily, these PMUs were designed for transmission network applications like wide area monitoring, protection and control. However, with the introduction of ADNs, implementation of PMUs in the distribution system has become crucial. The design and operation of distribution networks are significantly different from transmission networks. Hence, the transmission level PMUs, which are expensive are not economically feasible to be used at the distribution network. The first effort to deploy PMUs in the distribution level was made at Baltimore University, which was named as Gridtrak PMU [25].

Other efforts are being made by different power system labs as shown in Table 1, [7, 8, 11, 25–27] to design a low-cost PMU. However, the use of specific hardware and licensed software have made these modules expensive [28, 29]. The other aspect which differentiates MSM from these existing PMUs in is its novel design. The MSM uses an unbundled technique, which enables the LCPMU hardware to be integrated with the existing utility smart meters at the LV level [30]. It also uses the IEEE-1588 PTP for the time synchronisation purpose in the place of GPS (Global Positioning System). This makes the proposed MSM module stand out from the existing low-cost PMUs such as those described in Table 1.

2.2 MSM architecture

The main objective of this paper is to enable real-time monitoring in the ADNs. The primary focus is to create visibility in ADNs by installing a network of devices for monitoring the LV and MV side of the network. Accurate fault location and better monitoring of the secondary distribution level voltage behaviour becomes achievable with a high level of penetration of measurement devices. Recently, the number of installed measurement devices in the distribution network has increased significantly. At the LV side, smart meters have been installed in large numbers in many countries. In some cases, other low-cost devices such as fault current detectors are employed at specific points in the distribution network. These devices can provide certain measurements to the utility for the monitoring of the distribution network. However, these measurements are typically only available with some delay, and therefore cannot be applied in real-time monitoring of the network. This leads to the requirement of a time-synchronised device, which can provide real-time data.

A preliminary concept of MSM was presented by the authors in [30]. In this paper, full details of the proposed MSM implementation, including the IEEE-1588 PTP time synchronisation testing is presented.

Furthermore, a precise comparison has also been done between the novel designed MSM with the existing PMU by measuring their relative deviation index [31].

The architecture of the proposed MSM, Fig. 1, is subdivided into three different fundamental elements which are smart meter, LCPMU and the gateway. The smart meter is assumed to be already installed at the consumer end. The sensors, i.e. current transformer (CT) and potential transformer (PT) used in the smart meters for billing data are also used for obtaining the input for the LCPMU. The MSM concept is designed in such a way that it can be implemented using any regular utility smart meter available on the market. This reduces the effort of installing a new, separate device for monitoring purposes.

The other sub-model apart from the existing smart meter is the novel design of the low-cost PMU (LCPMU). It takes the input from the existing smart meter sensors, i.e. CT and PT and synchronises it using the IEEE-1588 protocol. The LCPMU only measures the voltage of the network, as many distribution networks and microgrid functionalities can be monitored by tracing the network voltage. The IEEE-1588 protocol is expected to synchronise the data at 10 μs intervals via ethernet cables. Furthermore, PTP-based LCPMU has an inbuilt feature of pulse per second (PPS). It provides the triggering of the analogue to digital converters (ADCs) which helps 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 [32, 33].

Table 1 Existing Low-cost PMU

PMU name	DTUPMU	GridTrak	IDE4L-LOCOPMU	OpenPMU-v1	OpenPMU-v2	FNET/Grid-Eye	μPMU/ PQube3
Institution	Technical University of Denmark	Baltimore University, Maryland	RWTH University Aachen, Germany	Queen's University Belfast	KTH, Royal Institute of Technology, Sweden	University of Tennessee	UC Berkeley
Hardware	PC-units (not disclosed)	dsPIC30F30-13 micro controller & NI-DAQ	MCC USB 201, the Raspberry PI (RPI) 3	NI-DAQ Module	BeagleBone Black	Micro-controller	Micro-controller
Software	MS-DOS, LabVIEW	Python	Raspbian Open source libraries libiec6850	LabVIEW	Linux, Python	Not known	Personal designed software (BtrDB)
Methodology	Goertzel Algorithm for phase estimation	Zero crossing Algorithm	Zero crossing Algorithm	Fast Fourier Transform & Modified iterative curve fitting algorithm	Least squares estimation technique	Least squares estimation technique	Method not disclosed
Time synchronisation	GPS	GPS	GPS	GPS	GPS	GPS	GPS

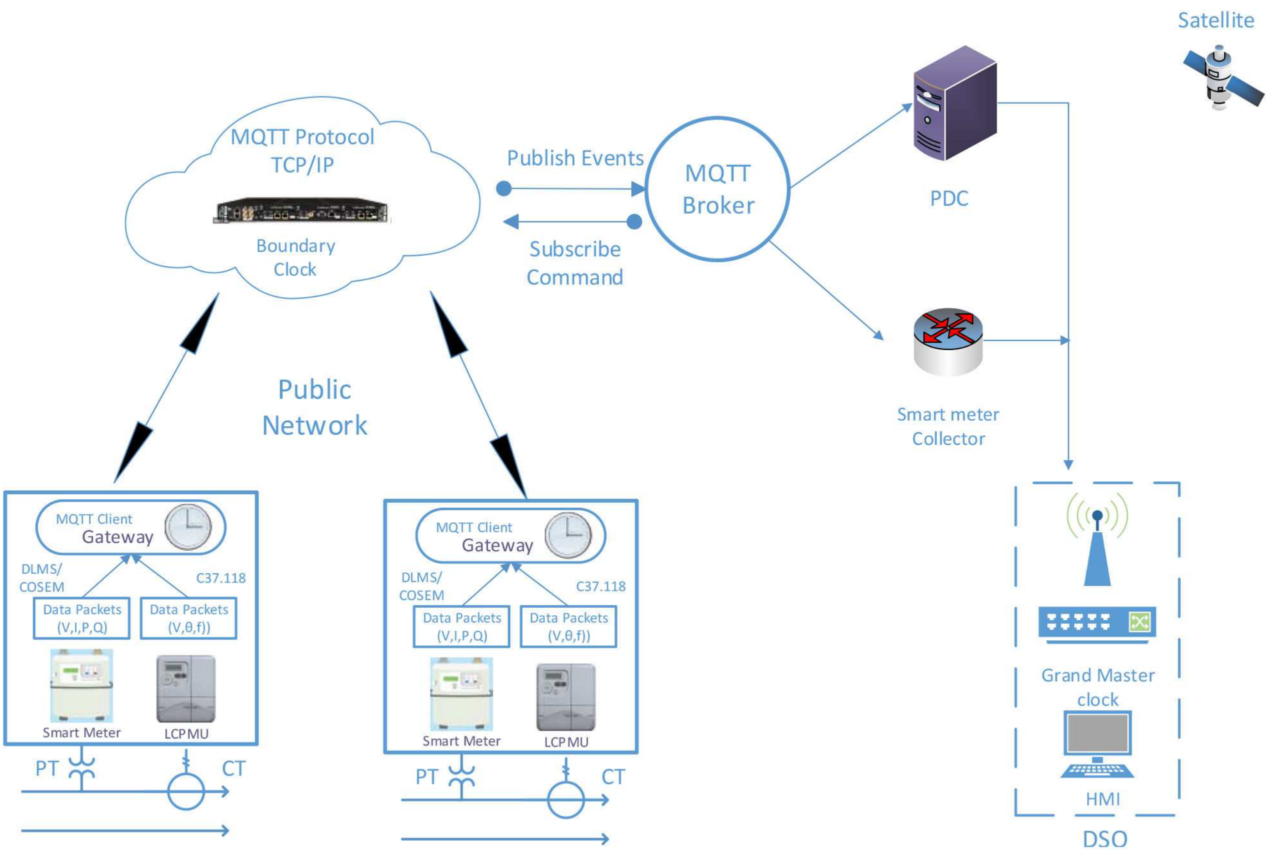

Fig. 1 *MSM architecture*

Table 2 Communication techniques used for smart meters

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

The MSM gateway is the most important subsystem of the MSM. Its primary objective is to collect the smart meter and LCPMU data. It is connected with these two separate devices via ethernet connection following the existing protocols such as DLMS and COSEM (Device Language Message Specification/ COmpanion Specification for Energy Metering) for the smart meter and the C37.118 protocol for the LCPMU. The other main objective of the MSM gateway is to convert the PMU C37.118 protocol to a protocol specific to substations (e.g. IEC61850) for transferring the real-time data from the MSM to the DSO for monitoring purposes [34]. This protocol conversion is required to make the data compliant with substation automation standards.

The smart meter and LCPMU data are sent to the real-time base with the help of an MQTT (Message Queuing Telemetry Transport) interface [35]. It is a publish–subscribe lightweight protocol. The data is transferred from the LCPMU, which acts as the MQTT client, to the DSO, which is the subscriber using the MQTT broker as an interface. The benefit of using the MQTT protocol is that it does not require any separate configuration; rather it can be installed in the software already established in the meters.

This paper considers two measuring meters as shown in Fig. 1. One is the existing smart meter, and the other is the newly designed low-cost PMU. For the establishment of the database for these two separate meters, a new mechanism is adopted which is known as role-based access control (RBAC). Since there are two separate data streams coming from two separate meters at different data rates, it is important for the gateway to generate separate databases for separate meters using RBAC. The role of the smart meter gateway is to generate the separate databases with the data acquired by smart meter and the LCPMU, process it and transfer it to the external entities. The MQTT protocol as explained above is responsible for providing an interface for the different databases with the external network. The MQTT protocol incorporates the RBAC method, where the role of the MQTT protocol is to encrypt the databases to make it secure and protected from any external attack.

As can be seen from Fig. 1, two different databases are formed for smart meter and LCPMU in the gateway. The MQTT protocol makes different profiles of the databases and these databases are published in the phasor data concentrator (PDC) and smart meter collector (SMC) based on the subscription made via MQTT Broker. The DSO collects the database from the SMC for billing purposes, whereas all the PDC databases are forwarded into the regional PDC before being stored by the DSO for monitoring and control.

Different communication technologies have been adopted in Europe and outside Europe at the LV side of the distribution network to process and forward smart meter data [30]. For the LCPMU data transfer, the already established communication techniques of the smart meter (described in Table 2) can be used. Thus, unlike traditional PMU, the novel MSM integrated LCPMU does not require to establish a separate communication setup for its operation. The LCPMU of the MSM is expected to transfer the data at 10 frames per second data rate. The complete MSM design requirement and implementation are given in Table 3. The reason for choosing the TCP/IP layer connection is the guaranteed response of message along with the assured connection.

2.3 Economic feasibility of the novel MSM design over existing PMUs

To achieve maximum observability in the distribution network, the LCPMU will be interconnected with the utility smart meters which are already installed on the LV side of the distribution network. Since they are not connected at high voltage substations or at the feeder ends, costly high-performance CT and PT sensors are not required and the installation cost can be reduced to approximately one-tenth of the cost of the typical PMU installation, as explained in [11]. In addition, the hardware of the LCPMU is not using a separate DSP or micro controller for the triggering of the ADC, which removes the cost of this extra hardware. The LCPMU utilises the PTP for time synchronisation, therefore the high-cost GPS installation on each PMU is also removed. The biggest hindrance in using GPS on a large scale is its communication requirements, as it needs a dedicated communication infrastructure to ensure accuracy with at least four satellites visible all the time.

As stated in [24], communication system costs can be very high, exceeding $15 million in several projects, excluding the cost of PMUs and PDCs. Therefore, using PTP for time synchronisation (which uses the already existing communication infrastructure instead of relying on a new, dedicated one) cuts down costs to a large extent. As compared to the existing PMU, the total hardware cost of the novel LCPMU design including the CT and PT sensors and installation cost will be comparatively much lower. The total cost of the novel designed LCPMU is estimated to be around one-tenth of the existing PMU.

3 Methodology

3.1 IEEE-1588 principle and time synchronisation mechanism

The PTP was introduced by the IEEE-1588 standard [36]. The main aim of PTP is to provide a hardware level time accuracy using a standard local area network with ethernet cables. To the best of authors' knowledge, this PTP technique has never been used to synchronise PMUs integrated with the smart meters for the distribution network. The intention of this work is to design an LCPMU using the PTP that provides the time accuracy of 1 µs. It is measured as the deviation of each node with the Coordinated Universal Time.

The PTP adopts the master–slave clock technique for synchronisation. As seen in Fig. 2, the time t_1 denoted the time needed to send the sync message to the slave clock which is received by the slave clock at time t_2. The exact same process is used by the slave clock to send a message to the master at time t_3, which is received by the master clock at time t_4. Hence, with the help of these four given time stamps, the one-way delay and the offset is calculated.

For testing the PTP time stamp as explained above, PTP daemon (PTPd) is applied for time synchronisation of the MSM. PTPd is an open-source software for defining the IEEE-1588 standards [36]. It runs on the Linux machine for synchronisation on the hardware, in which the open-source software is installed to calculate the offset and delay in the network. The PTPd carries out time synchronisation within microseconds. The open-source PTPd is suitable for testing and analysis of the delay and offset of the network before implementing the MSM in the real network.

In Fig. 2, the adjacent master and slave clocks exchange information which helps the slave clock to estimate the offset compared with the master clock using delay and offset equation as in [37]. Single-board computers are used to implement the master clock and the slave clock. The testing platform also serves as the grandmaster clock, as it is synchronised with GPS. An ethernet switch connects the grandmaster with the master and the slave clock. PTPd is installed on the single board computers (SBCs) and the simulation takes place on the testing platform. This allows the delay and offset between the master and the slave to be calculated and compared to the grandmaster clock.

As seen in Fig. 1 for the MSM communication infrastructure, the design proposed in this paper comprises one grandmaster clock provided by the GPS from a PMU located at any location in the wider power network. For instance, a transmission network PMU can serve as the grandmaster clock reference. The second hardware in the communication infrastructure is a switch also called as boundary clock, which serves as the master clock, synchronised with the grandmaster clock to run the PTP protocol. The last clock in the network is the slave clock available at various gateways for synchronising the MSMs. A multiport device known as Transparent Clock can also be used in place of boundary clock depending upon the number of slave clocks to be synchronised with one master clock. This procedure compensates all the latencies and, jitter is compensated without affecting the synchronisation accuracy.

Table 3 MSM design requirement

Requirement	Implementation
Communication protocol	MQTT
Connection	TCP/IP
Data type	XML
Input power	step down the 230 V input to 3.3 V (acceptable range of ADC).
Timing synchronisation	precision time protocol (PTP)
Phase estimation	ipDFT
Target cost	$500–700 (approx.)

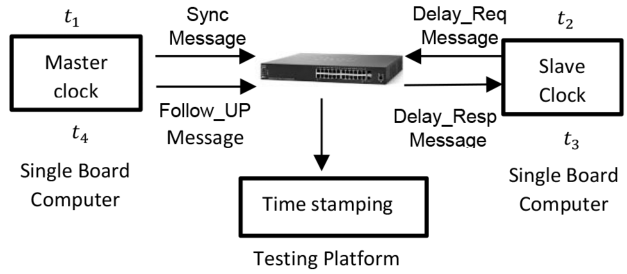

Fig. 2 *Testing of PTP communication*

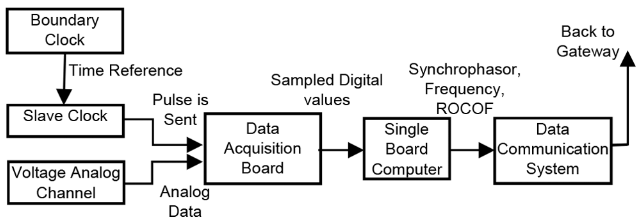

Fig. 3 *Block diagram of LCPMU*

3.2 MSM functionality

This paper describes a novel approach method in which two measuring meters (Smart Meters and LCPMU) are considered. To transfer data from these two meters at different data rates, a gateway is implemented, which serves as the interface, this has been explained in the previous section. The main function of the existing smart meter is to transfer the data to the DSO for billing purposes. The smart meter does not transfer all the data at the same time because of the limited available bandwidth. The sampling time of the billing data is also typically within a few seconds. Since smart meter data is sensitive and has privacy issues, it is simply transferred to the DSO through the MSM gateway for billing purpose only.

The main sub-model of the MSM device is the LCPMU, which is responsible for providing the time synchronised data for real-time monitoring. This paper has considered that since the voltage and frequency measurements are considered non-sensitive data, they can be used for monitoring purposes with the help of smart meter sensors (i.e. CT and PT). The MSM gateway installed the IEEE-1588 module port which helps in providing the time reference for the time stamping of the calculated phasor.

The complete layout description of the LCPMU is shown in Fig. 3. The voltage analogue data is available with the help of smart meter sensors. These analogue data are transferred to the Data Acquisition Board (DAB) where the PTP module via the slave clock provides the inbuilt PPS signal. This PPS signal provides a synchronisation trigger source for the DAB. Hence, when the pulse is received, the acquisition of the samples starts at the required sampling rate. The samples are recorded at a data rate of 10 frames per second. The sampled digital value is been transferred to the SBC where the main computational activity takes place to get the synchronised data outputs.

The sampled data are fed to the SBC as shown in Fig. 3 for the frequency and phasor calculation. The synchrophasor estimation (SE) algorithm used for the transmission network cannot be adopted at the distribution level [38]. This paper deals with the PTP-based PMU installed at the LV side of the network where the requirements of harmonic and inter-harmonic rejection are more demanding.

For the distribution network, mHz resolution is required but using the conventional discrete Fourier transform (DFT) gives very poor frequency resolution, in the range of ∼10 Hz order of magnitude. The accuracy of the conventional DFT algorithm can be improved either by decreasing the sampling frequency or by increasing the window length. However, these modifications can result in aliasing errors and long DFT computation time. It is not practical to use very long windows to reach a high level of accuracy, as this increases the response time of the LCPMU. Hence, in this LCPMU, the SE algorithm adopts a classical interpolated-DFT (ipDFT) technique based on the Hanning window. This outperforms other SE techniques due to its high accuracy and low computational complexity. The reason for selecting the Hanning window is that it performs well in relation to attenuation of the spectral leakage. The ipDFT technique interpolates the spectrum and is expected to give sub-mHz resolution.

The signal parameters for calculating frequency, phasor amplitude and phasor angle, using a Hanning window are [39]:

$$\hat{f}_0 = \left(k_m + \hat{\delta}\right)\Delta f_0 \tag{1}$$

$$\hat{A}_0 = |X(k_m)|\left|\frac{\pi\,\hat{\delta}}{\sin\pi\hat{\delta}}\right|\left|\hat{\delta}^2 - 1\right| \tag{2}$$

$$\hat{\varphi}_0 = \angle X(k_m) - \pi\hat{\delta} \tag{3}$$

where $\hat{f}_0$ stands for estimated fundamental frequency, k_m is the index of the the DFT bin characterised by the highest amplitude and $-0.5 \le \delta \le 0.5$ a fractional correction term. $\hat{\delta}$ is the estimated fractional corrected term between the highest bin and the second highest bin as shown in [38]. $\hat{A}_0$ is the estimated amplitude, $|X(k_m)|$ is the modular highest bin of the DFT spectrum. $\hat{\varphi}_0$ is the estimated phase and $\angle X(k_m)$ is the argument of k_m. This algorithm provides high accuracy even with a time-limited window. Also, it shows good performance in the steady-state condition; especially in the presence of harmonics and inter-harmonics, which serves the purpose of this paper.

In a typical arrangement, a few tens of LCPMUs are monitored by a PDC in the substation which follows the IEC61850 protocol. Hence, the same protocol will be followed for frequency and phasor calculations which are transferred from the MSMs to the PDC.

4 Problem formulation

In this paper, for comparing the DSSE performance of novel MSM device with the existing PMU, the weighted least square (WLS) state estimation is used as a test algorithm. The WLS-based state estimation technique is applied to the three-phase unbalanced distribution network as can be seen in [31]. The measurement error for the different measurement types, such as smart meter, substation and pseudo-measurements have been considered. Accordingly, different weights for each of these measurements are assigned in Section 5 below.

A hybrid calculation model is established by incorporating a post-processing estimator where the WLS state estimation is run with PMU and traditional measurement input. In the next step, the PMU measurement is replaced by an MSM measurement with uncertainty to compare the accuracy between PMU and MSM cases. This technique greatly reduces the number of iterations and the processing time per iteration when comparing different measurement sets in state estimation. The phasor measurements are obtained first from the existing micro-PMU for the first step of the post-processing algorithm and then in the following step, it is replaced by the MSM's phasor measurements. The micro-PMUs are located at optimal locations and these micro-PMUs are then replaced by the MSMs on the same locations in the distribution network.

Thus, by applying the iterative WLS technique as given in [31], the state variable can be estimated. As described before, in the first step of the post-processing method the measurement vector consists of substation measurements which provide branch power flow, the smart meter measurement which provides active and reactive power injections; and the pseudo-measurements, along with the micro-PMUs measurements placed at optimal locations. 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 and 50% for the pseudo measurements. (These two give active and reactive measurements) The accurate micro-PMUs' measurements (giving voltage magnitude and voltage angle) consider 1% uncertainty in the first step of post-processing method and 3% uncertainty in the MSMs' measurement which are implemented in the following step. It is assumed that the previous three measurement types give the measurement of active and reactive power injections, while the PMU and MSM provide voltage magnitudes and phase angles.

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

$$z_2 = \begin{bmatrix} \widehat{\boldsymbol{x}}^{(1)} \\ \widehat{\boldsymbol{x}}_{\text{MSM}} \end{bmatrix} + r_2 \tag{4}$$

where $\widehat{\boldsymbol{x}}^{(1)}$ is the estimated first step state vector of the post processing method which comprises the micro-PMU measurements and then $\hat{x}_{\text{MSM}}$ is the estimated state when MSM measurements is being implemented on the bus network. In the same equation, r_2 denotes the measurement error which consists of a Gaussian random variable with the covariance matrix $\boldsymbol{W}_2$

$$\boldsymbol{W}_2 = \begin{bmatrix} \boldsymbol{W}_{\widehat{\boldsymbol{x}}^{(1)}} & 0 \\ 0 & \boldsymbol{W}_{\text{MSM}} \end{bmatrix} \tag{5}$$

In (5), $\boldsymbol{W}_{\widehat{\boldsymbol{x}}^{(1)}}$ represents the weighted matrix of the first step in estimation. $\boldsymbol{W}_{\text{MSM}}$ indicates the weighted matrix of MSM measurements 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 micro-PMU measurements; second, by replacing the voltage and voltage angle data of micro-PMU with the MSM data.

The performance of the two devices when applied to the state estimation in distribution networks is analysed in Section 5, where the comparison of both devices is carried out according to the performance indices and error histograms, as outlined in [31].

In this algorithm, for a better comparison of the MSM with the existing MSM device, a more precise method applying the following two synthetic indices are used.

Maximum Voltage amplitude relative deviation index:

$$\text{MRVD} = \max_i \left| \frac{\left|\hat{E}_i\right| - |E_i|}{|E_i|} \right| \tag{6}$$

Here $i = 1 \ldots N$, where N stands for the total number of buses. $|E_i|$ and $\left|\hat{E}_i\right|$ are the true bus voltage amplitude at node i and the estimation for it.

Maximum phase angle deviation index:

$$\mathrm{MPD} = \max_i |\hat{\varphi}_i - \varphi_i| \tag{7}$$

for $i = 2, \ldots N$, where φ_i and $\hat{\varphi}_i$ are the true and estimated bus voltage angles at node i, respectively. The estimated amplitude and angle errors are expressed relative to the absolute values of the true voltage and angle.

5 Test results

5.1 PTP-based synchronisation

PTP synchronisation has been tested using SBCs. This simulation has been carried out to test the level of accuracy by analysing the delay and offset between the master clock and the slave clock, as explained in Section 3. Time synchronisation is required before sampling the input signal for comparison in the LCPMU. The grandmaster clock is based on the GPS clock showing delay and offset between the master and the slave clocks.

The one-way delay is shown in Fig. 4, explaining the link delay between the slave and the master clock computed and filtered by the PTPd software. The only one-way delay has been measured, since the link delay for both the sides as seen in Fig. 2, tends to be the same because the path has a symmetrical latency. As shown in Fig. 5, the offset from the master clock defines how far the slave clock is from the master clock. This is the time shift which the PTPd is attempting to correct by applying a frequency shift to the local clock.

5.2 Test and simulation

The following test comparing the two devices for power system application is done by optimising both devices one after the other at particular locations, and solving the three-phase unbalanced DSSE. Two IEEE standard distribution feeders have been considered for state estimation. The measurement data are derived from the slack bus, smart meters, PMU and MSM. For the state variable update the convergence criteria is taken as 10^{-5}. These measurement data are taken to solve the three-phase power flow by using backward–forward sweep technique [40]. The input measurement data for the load flow code are generated using the network information and the standard load data from the IEEE standard bus network. The three phase case study IEEE standard networks have a high level of unbalance. Therefore, solving the large poorly conditioned matrices was a major challenge in this work. Hence, the first step to make the solution faster was to use the load flow output as the measurement data set instead of the flat start condition.

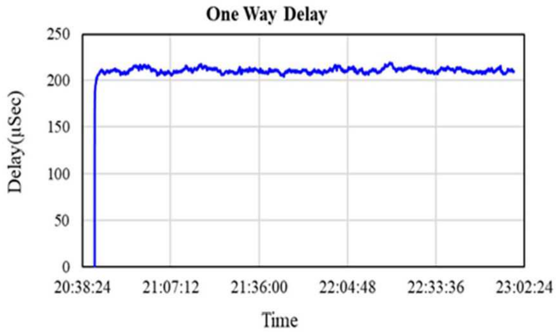

Fig. 4 *One way delay between master and slave clock*

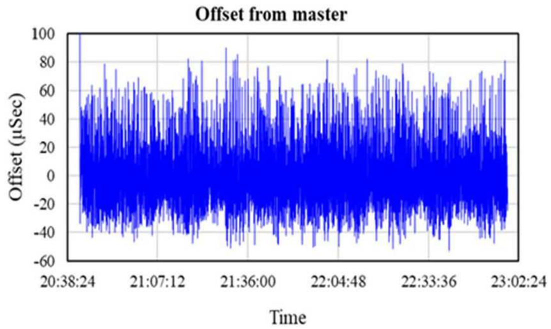

Fig. 5 *Offset from master in IEEE-1588 testing*

Another modification is done in the standard WLS technique to resolve the challenge mentioned above. A subdivision of the network was carried out, in which the network was divided into feeders and laterals. The standard IEEE 13-bus network was divided into six different topology matrices whereas the IEEE 123 distribution bus network was divided into 48 partitions. After the sub-division of the bus network, the state estimation takes place on each row separately. Each partition takes a maximum of five iterations to converge. This subdivision state estimation approach helps in reducing the complexity along with the computation time required.

5.2.1 Case study networks: The standard IEEE 13 and IEEE 123-bus networks [41] were used as the case study networks. Both of these networks operate at 4.16 kV nominal voltage. These test networks were chosen for their high level of unbalanced loading, which resembles the real distribution network. The post-processing distribution state estimation is run on these networks. The measurement data is generated with the help of load flow technique. The measurement uncertainty is taken into consideration, as explained in Section 4. The measurement weight (W) is calculated as the inverse square of the standard deviation of maximum uncertainty which is assumed to be a normal distribution. The maximum error percentage is chosen to represent measurement uncertainty. The three-phase state estimation is run for two different cases first, considering PMU in the network and the second case is replacing the PMUs with the MSMs on the same location. The performance indices (6) and (7) are plotted for PMU and MSM for IEEE 13 and IEEE 123-bus network in Figs. 6–9. These figures depict the worst-case scenario, i.e. the largest error in the three phases at each bus, shows the maximum voltage amplitude relative deviation across the three phases, with maximum phase angle deviation. The red dotted line plots the performance of MSM-based DSSE while the blue line shows the performance of the PMU-based DSSE.

As expected, PMUs are more accurate with a maximum deviation of ∼1% in magnitude and 1.5% in angle in IEEE 13-bus network and, 1% in magnitude and 0.4% in angle for IEEE 123-bus. The deviation indices for the MSM are larger than the PMU in both networks, but it is still within an acceptable range of ∼2% in magnitude and 3% in angle for IEEE 13 network and the magnitude deviation reaching ∼2% and angle deviation up to ∼1% for IEEE 123-bus network.

The performances of the existing PMU and the novel designed MSM is compared in more detail above using the error histogram for the voltage magnitude and the voltage angle deviation index. The error histograms provide insight into how the errors are spread. Figs. 10–13 demonstrate the error performance in the IEEE 13 and IEEE 123-bus networks. 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 number of times the given error is occurring on each particular bus. A comparison of the error histograms for the two different monitoring devices reveals that the PMU error is closer to zero error compared to the MSM error. However, there is no large degree of deviation in the MSM errors and the small deviations seen are within an acceptable range for steady-state applications. This shows that the acquired histogram results for the novel design MSM are satisfactory within the allowable error range. This post-processing WLS algorithm is run on Intel Core i7-2600, 3.40 GHz with 16 GB RAM.

Since voltage phases are most important in assessing the distribution network, the LCPMU gives only voltage magnitude and voltage angle as its output however, the traditional PMU can provide voltage as well as current phasors. As seen Figs. 6–9; although, the voltage phasor is not as accurate as in the traditional PMU given the cost efficiency of this novel design LCPMU, the trade-off between the cost and accuracy can be acceptable. Based on the available network connection of existing smart meter, the

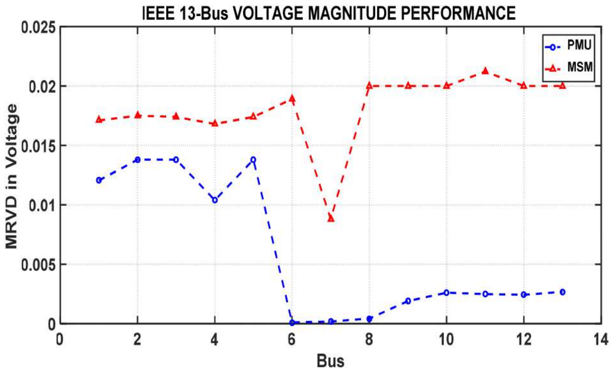

Fig. 6 *Maximum voltage amplitude relative deviation index for IEEE 13 Bus*

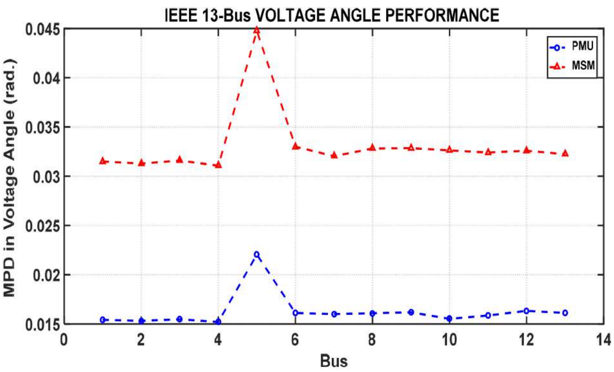

Fig. 7 *Maximum phase angle deviation index for IEEE 13 Bus*

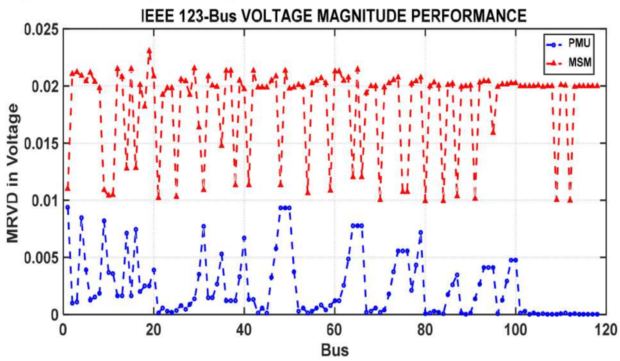

Fig. 8 *Maximum voltage amplitude relative deviation index for IEEE 123 Bus*

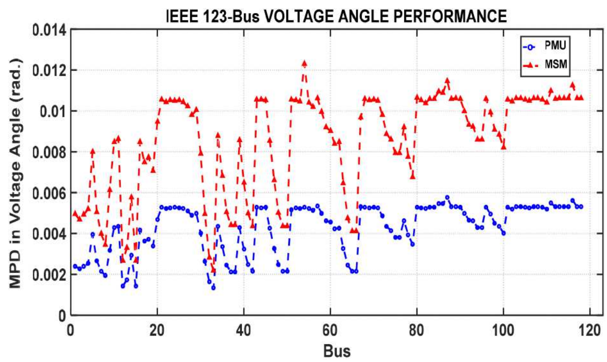

Fig. 9 *Maximum phase angle deviation index for IEEE 123 Bus*

synchronisation of 10 μs can be taken into consideration in LCPMU via ethernet connection. Whereas, the traditional PMUs have the advantage of using GPS for time synchronisation which has a precision of <1 μs. The LCPMU deals only with voltage phasors which is considered as non-sensitive data, therefore, it does not disturb the privacy of the customers. Also, the MQTT protocol

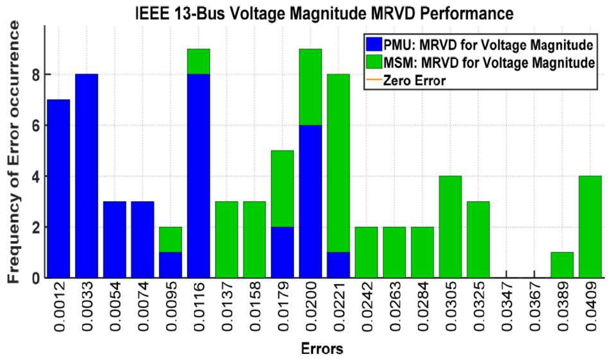

Fig. 10 *MRVD error histogram for PMU and MSM in IEEE 13 Bus*

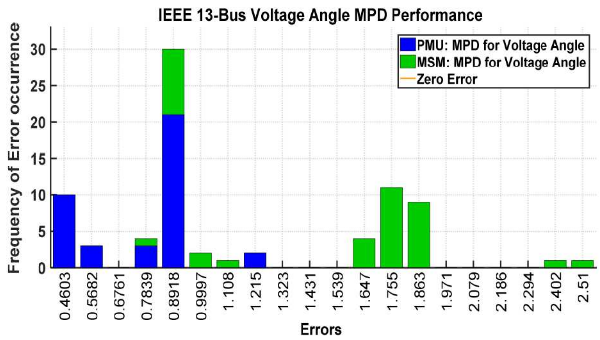

Fig. 11 *MPD error histogram for PMU and MSM in IEEE 13 Bus*

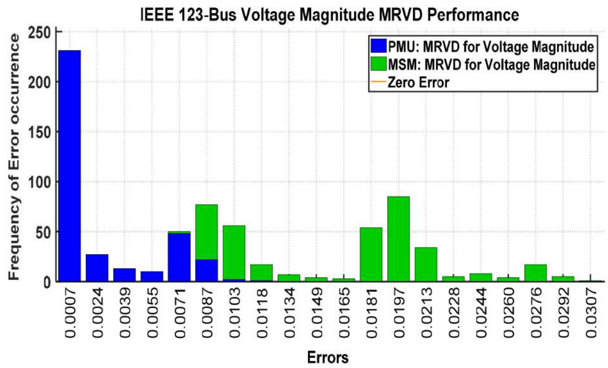

Fig. 12 *MRVD error histogram for PMU and MSM in IEEE 123 Bus*

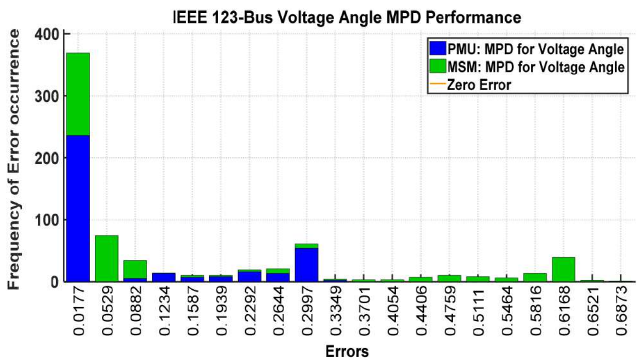

Fig. 13 *MPD error histogram for PMU and MSM in IEEE 123 Bus*

encrypts the smart meter and LCPMU data separately using RBAC which protects the customers' data.

6 Conclusion and discussion

Due to the complexity and very large number of nodes in MV and LV distribution networks, the costs of implementing a PMU-based monitoring system may be prohibitive. Accordingly, this paper proposes a low-cost MSM based on PTP synchronisation, designed for MV and LV distribution network monitoring and control applications. One of the main benefits of the MSM is that it utilises the existing sensor hardware of smart meters. The MSM can be integrated with existing smart meters using the smart meter unbundling concept. The PTP and MQTT techniques are used to provide a low-cost PMU alternative, with synchronised data at a rate of 10 frames per second. The test results of this paper demonstrate that the proposed low-cost MSM design can potentially be a viable alternative to expensive PMUs for the distribution network monitoring. While the MSM does not achieve the same level of DSSE accuracy as a high-cost PMU solution, it has the potential to achieve an acceptable level of DSSE accuracy with low-cost hardware. The trade-off between cost and accuracy demonstrated in Section 5 is appropriate for MV and LV monitoring, and at 10 frames per second data rate, the MSM can be used for most steady-state applications.

Future work will analyse the technical requirements and costs of implementing an MSM-based monitoring system on various SBCs to improve the data rate for large-scale implementation. This will allow the MSM technique to be used for certain dynamic applications. A Monte Carlo simulation is intended to be performed in future for testing the MSM measurement dataset to analyse the full range of loading conditions. A detailed cost analysis will be performed for the proposed new MSM design, comparing its cost and accuracy to existing micro-PMU solutions for a range of power network monitoring and control applications.

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