Enhancing the State Estimation for Low Voltage Distribution Grids

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Abstract—The increasing integration of distributed energy resources (DERs) in distribution grids imposes an imperative need for reliable and accurate monitoring of the grids' operating condition. Consequently, electric utilities have recently started considering the deployment of Phasor Measurement Units (PMUs) in Medium Voltage Distribution Grids (MVDGs) in order to enhance and improve the monitoring capabilities of the operator. In this paper, a fast reporting measurement device is considered at a MV-LV transformer substation for enhancing the monitoring of the MVDG. A monitoring scheme is then proposed that utilizes the capabilities of this device not only for enhancing the monitoring of the MVDG, but also to simultaneously improve the monitoring of the Low Voltage Distribution Grid (LVDG). The results of the numerical simulations indicate that the proposed scheme exhibits good performance in all the considered scenarios.

Keywords— Low voltage distribution grid, monitoring, phasor measurement unit, smart meters, state estimation

I. INTRODUCTION

Low voltage distribution grids have an integral role in the smart grid concept. The increasing energy demand, the electrification of the heating/cooling and transportation sectors as well as the need for a more sustainable future are pushing the contemporary distribution grids, and especially the LVDG, to their operational limits [1]-[2]. Under the framework of the smart grid, LVDGs are expected to completely transform from traditional passive grids into highly complex active systems. To mitigate the detrimental impacts that the high penetration of DERs can have on the operation of the LVDG, the deployment of an advanced distribution management system (DMS) is required. Demand response, voltage and frequency support, detection and localization of energy theft and protection against cyber-attacks are a few of the grid support functionalities that such a DMS should provide [3].

This kind of grid support functionalities most often require some level of information about the system's state. This information is used for deciding what kind of corrective actions should be taken, according to the considered control scheme. The Distribution System State Estimation (DSSE) provides this information to the decision-making control and automation schemes. In this direction, distribution system operators are currently investing substantial amount of resources [3]-[4] in the deployment of smart meters and to the implementation of advanced metering infrastructures. This infrastructure can improve the system awareness and enable the accurate monitoring of LVDGs [5]-[6]. In recent works,

PMUs in the MVDG, known also as micro-PMUs (μPMU), have been considered in an effort to facilitate their real-time monitoring [7]-[8]. In [9], an analysis is conducted on the estimation error of a branch current state estimator when it is used for monitoring a generic MVDG. The results indicate that there is a major improvement in the estimation results when PMUs are deployed in MVDGs. An actual application of PMUs in an MVDG is presented in [10]. In this work, the monitoring system consists of only PMUs and the timing latency and accuracy of a real time application of a three-phase state estimator based on the discrete Kalman filter is experimentally validated for distribution networks. The utilization of PMUs in MVDGs has enhanced considerably their real-time monitoring and the fast refreshing rate of the state has enabled the development of proper control and automation schemes. In contrast, the monitoring of LVDGs is vastly limited by the reporting rate of smart meters. Due to the sheer size of LVDGs (up to thousands of nodes) and the significant cost of having dedicated communication infrastructure for the smart meters, their reporting rate is rarely below 10 minutes [9], [11]. In the envisioned smart grid, such a low reporting rate will not suffice as several functionalities will require a reliable real-time monitoring system for the LVDG.

The aim of this paper is to develop a new monitoring methodology for LVDGs that considerably enhances the update rate of the system's state. The proposed monitoring scheme assumes that a PMU, or a fast reporting smart meter (with reporting period in the range of second), is installed at the MV-LV transformer (to monitor the MVDG). This fast reporting device is utilized in the proposed scheme for not only monitoring the MVDG but to also enhance the DSSE application of the LVDG. In cases where the MV-LV transformer supplies more than one feeder, then a fast reporting device should be installed at the beginning of each feeder or, the PMU/smart meter should measure also the current from the LV side of each feeder. The contributions of this paper are: 1) a hybrid DSSE scheme that combines both slow and fast reporting measurements, 2) a cost effective solution to increase the situational awareness in LVDGs with a higher resolution of the state estimator, 3) an investigation of the proposed DSSE accuracy using different reporting rates for the smart meters.

The remainder of this paper is organized as follows. In Section II the weighted least squares state estimation (WLS SE) that is used in this paper is presented. The proposed monitoring scheme is presented and described in Section III while in Section IV information regarding the test system is provided. Section V contains the case studies that are used to evaluate the proposed scheme and the paper concludes in Section VI.

II. WEIGHTED LEAST SQUARES STATE ESTIMATION

Numerous methodologies have been proposed over the years for the monitoring of power systems [6], with the most widely used being the WLS SE. In this paper, the proposed monitoring scheme is also based on this methodology. Due to the unbalanced nature of the LVDGs however, a three phase approach is required so that the uneven coupling effect between the phases as well as the unbalanced loading of each phase is accounted properly [5], [12]. In the formulation of the WLS SE, the state variables, which for this paper will be the nodal voltages in polar form without losing generality, are related to the available measurements as,

$$z = h(x) + e \qquad (1)$$

where z is a vector containing all available measurements, $h(x)$ is a vector containing nonlinear functions that relate mathematically the state variables with the measurements, x is the state vector and e represents the Gaussian noise (measurement error) that affects the measurements. The state vector is obtained under the framework of the WLS SE by minimizing $J(x)$,

$$\min_{x} J(x) = \sum_{i=1}^{n} \frac{[z_i - h_i(x)]^2}{\sigma_i^2} = [z - h(x)]^T R^{-1}[z - h(x)] \qquad (2)$$

where n is the total number of measurements, σ_i is the standard deviation associated with the ith measurement, and R is the measurement error covariance matrix which is used for measurement weighting.

III. PROPOSED DSSE SCHEME

In Fig. 1, the proposed real time monitoring scheme for LVDGs is presented. The idea behind this scheme is that the high reporting rate of a PMU or a smart meter that is installed at the MV-LV substation can be exploited for monitoring the load variation inside the LVDG between two execution times of the WLS SE, which is once every minute ($T_{SE} = 1$ min). This allows to gain information about the state of the LVDG in a very short timeframe despite not having any fast reporting measuring device installed inside the LVDG. The detected load variation of the whole feeder is allocated to the various consumers and using the previously estimated voltage, the WLS SE is executed every minute. In order to account for the increase of uncertainty of the measurements used in the WLS SE of the LVDG, a weight scheme is used which increases the uncertainty of a measurement based on the time that has passed since it was last updated. More specifically, the main steps of the proposed scheme are as follows:

1) Initialization: Initially it is assumed that all measurements from all the devices are available at $t = 0$ s [13]. Then, each smart meter follows the update pattern that is illustrated in Fig. 2. The way of this update pattern construction is discussed in Section IV. Having all necessary measurements, the WLS SE is executed for the first time, providing the system's state. The estimated voltage states of the LVDG are then temporarily stored so that they can be used in the next WLS SE as virtual measurements for the smart meters that have not updated their measurements. Moreover, the power measurements from all smart meters and the fast reporting device at the MV-LV transformer are stored for calculating the feeder's load deviation at a later stage.

2) Consider latest measurements: In each iteration of the proposed DSSE scheme, the latest measurements from the
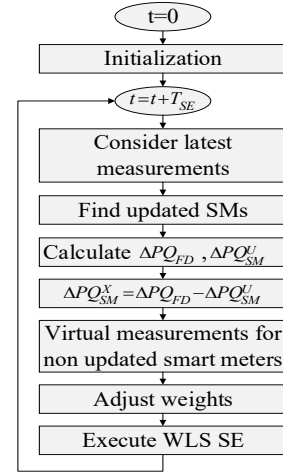

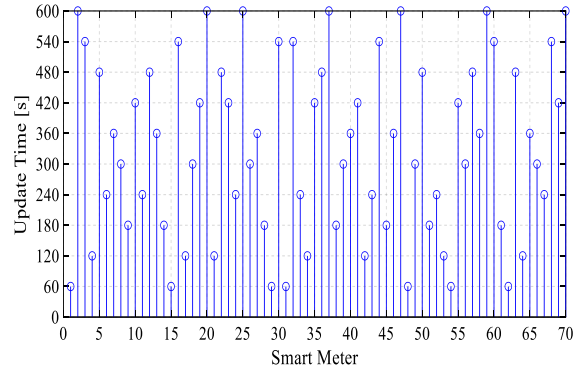Fig. 1. Proposed DSSE scheme

Fig. 2. Update pattern of smart meters

fast reporting device are considered in order to calculate the feeder's load variation in relation with the previous execution point of the proposed DSSE scheme ($t - T_{SE}$).

3) Find updated smart meters: After the first execution of the WLS SE, the smart meters follow the update pattern that is illustrated in Fig. 2. In this step, all smart meters that have updated their measurements within the last T_{SE} are identified and are included in the subset U of N ($U \subset N$) for this time instance, where N is the set containing all smart meters. The remaining smart meters that have not updated their measurements within the last T_{SE} are included in the subset X.

4) Calculate feeder's load deviation: At each time instance that the WLS SE is to be executed after $t = 0$, first the load variation of the feeder is calculated. Using the measurements from the fast reporting device the feeder's load variation within the last T_{SE} interval is calculated as,

$$\Delta PQ_{LVDG}^{t} = PQ_{FD}^{t} - PQ_{FD}^{t-T_{SE}} \qquad (3)$$

where ΔPQ_{LVDG}^{t} is the load variation of the feeder at time instance t, PQ_{FD}^{t} and $PQ_{FD}^{t-T_{SE}}$ are the power measurements of the fast reporting device at time instance t and at $t - T_{SE}$ respectively ($PQ_{FD}^{t} = [P_{FD}^{t}, Q_{FD}^{t}]^T$ are the active and reactive power measurements). In the case that some smart meters have updated their measurements (subset U is not empty), then the load deviation of these smart meters is calculated as,

$$\Delta PQ_{SM_U}^{t} = \sum_{i=U} PQ_{SM_i}^{t} - PQ_{SM_i}^{t-T_{SE}} \qquad (4)$$

where $\Delta PQ^t_{SM_U}$ is the overall load variation at time instance t from the smart meters that have updated measurements, $PQ^t_{SM_i}$ and $PQ^{t-T_{SE}}_{SM_i}$ are the power measurements of the ith updated smart meter at time instance t and at $t - T_{SE}$ respectively. Having the load variation as seen by the feeder and by the updated smart meters, the load variation corresponding only to the smart meters that have not been updated (belonging to the subset X) at the current time instance can be calculated as,

$$\Delta PQ^t_{SM_X} = \Delta PQ^t_{LVDG} - \Delta PQ^t_{SM_U} \qquad (5)$$

5) Virtual measurements for non-updated smart meters: During the execution of the proposed DSSE, the power measurements from smart meters that have not been updated within the last T_{SE} are adjusted according to the calculated $\Delta PQ^t_{SM_X}$. In this paper, this allocation is done equally amongst the smart meters that have not been updated,

$$PQ^t_{SM_{X_i}} = PQ^{t-T_{SE}}_{SM_{X_i}} + \frac{\Delta PQ^t_{SM_X}}{N_X} \qquad (6)$$

where $PQ^t_{SM_{X_i}}$ are the adjusted power measurements of the ith smart meter that has not been updated and are going to be used in the next execution of the WLS SE, $PQ^{t-T_{SE}}_{SM_{X_i}}$ are the power measurements of this smart meter from the previous execution of the proposed DSSE and N_X is the total number of smart meters that have not updated during the last T_{SE} interval. Regarding their voltage measurements, within one reporting cycle from the smart meters, the state of the LVDG can change considerably. To allow the proposed DSSE to track as accurate as possible the voltage variation of the feeder, the voltage measurements that are used in the WLS SE are updated based on the previous estimated results,

$$|V|^t_{SM_{X_i}} = |V|^{t-T_{SE}}_{SE_{X_i}} \qquad (7)$$

where $|V|^t_{SM_{X_i}}$ are the voltage measurements of the ith smart meter that has not been updated and are going to be used in the next execution of the WLS SE and $|V|^{t-T_{SE}}_{SE_{X_i}}$ are the estimated voltage states corresponding to this smart meter from this previous execution of the proposed scheme. For the smart meters that have been updated during the last T_{SE} interval, their latest measurements (power and voltage) are used in the execution of the WLS SE.

6) Adjust weights: Due to the small time skewness of the measurements in the transmission system, the measurement weights of the traditional WLS SE are defined by the inverse of the variance that characterizes each measuring device [5], [12]. In the case of the LVDG however, since the smart meters have a slow reporting rate and they report measurements at significantly different time instances, the measurement set that is used in the WLS SE cannot be treated as synchronized. As time passes since a smart meter reported its last measurements, the uncertainty of these measurements increases as the consumers' behaviour in LVDGs is highly dynamic and unpredictable. This implies that during the time period between updating instances of a smart meter, the measurements of a smart meter can change significantly in a very short time span. Consequently, for the real time monitoring of LVDGs the asynchronicity of the smart meters must be properly considered. For this purpose, in [14] a

method for adjusting the variance of each measured signal is proposed as a means to incorporate this asynchronicity in the WLS SE procedure,

$$\sigma^i_{new} = \sigma^i_{device}(1 + kT_i)^a \qquad (8)$$

where σ^i_{device} is the intrinsic uncertainty of the measuring device associated with the ith measurement, σ^i_{new} is the adjusted standard deviation, T_i is the time duration since the ith measurement was last reported and parameters k and a are used as tuning parameters. In this paper, two set of tuning parameters are used according to the type of measurement. In particular, a set of parameters (k_P and a_P) is used for the adjustment of the power. measurements' uncertainty while a different set of parameters (k_V and a_V) is used for the voltage measurements. It should be noted that the choice of the values for these parameters is discussed in Section IV.

7) Execute WLS SE: In this stage, the concatenation of the two types of measurements, i.e., the ones that are updated and the ones that are calculated through (6) and (7) is first performed. The full measurement vector is then utilized in the WLS SE scheme. The estimated voltage states of the LVDG as well as the power measurements from the measurement vector are temporarily stored so than they can be used in the calculations of the next iteration of the proposed DSSE.

IV. SYSTEM INFORMATION

In this paper, it is considered that a fast reporting device is placed at the MV-LV substation and its advanced features are utilized to enhance the monitoring of the LVDG. The test system that is illustrated in Fig. 3, is used for evaluating the proposed method. This system is based on the topology of the IEEE European Low Voltage test feeder, which was slightly modified to include some three phase loads as well. A phasor simulation model has been developed in MATLAB/Simulink to test the effectiveness of the proposed technique. To enable the WLS SE it is assumed that all consumers in this test system are equipped with a smart meter.

A. Smart meters

In the system illustrated in Fig. 3, there are 70 consumers whose consumption is monitored through smart meters. It is assumed that each smart meter can provide active and reactive power measurements, as well as voltage magnitude measurements at the consumers' premises (all in per phase). In Table I the measurement error as a percentage of the full-
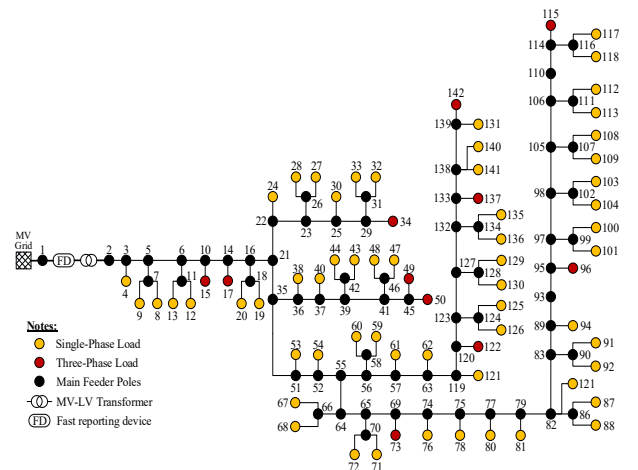

Fig. 3. IEEE European low voltage test feeder

scale meter reading is provided for various accuracy classes of smart meters as a function of its nominal current (I_n). The measurements used in the following case studies are created by superimposing to the actual value of a measurement, derived by the simulated system, a Gaussian measurement noise $N(0, \sigma)$ as,

$$z_{meas} = z_{true} + FS \cdot N(0, \sigma_{P,Q,|V|}) \qquad (9)$$

where z_{true} is the true value of a measurement, FS is the full scale meter reading for each type of measurement (9.2 kVA and 300 V) and $\sigma_{P,Q,|V|}$ is the standard deviation of each measurement type, according to the considered accuracy class for the smart meters.

In the base case study, it is assumed that the smart meters update their measurements once every 10 minutes ($T_{SM} = 10$ min) in an asynchronous manner. In Fig. 2 the update pattern of the smart meters is illustrated for a single 10-minute time interval. This pattern was created by randomly assigning to each smart meter an integer multiple of T_{SE}; this number represents the time instance in which a smart meter will report its measurements in the 10-minute time interval [13]. After the end of each cycle, T_{SM} is added to the update pattern in order to get the updating time instances of the smart meters for the following cycle.

TABLE I
PERCENTAGE MAXIMUM ERROR LIMITS OF SMART METERS

Accuracy Class	$\cos(\theta) = 0.5$ lagging		$\cos(\theta) = 1$	
	$0.1I_n \leq I \leq 0.2I_n$	$0.2I_n \leq I \leq I_{max}$	$0.1I_n \leq I \leq 0.2I_n$	$0.2I_n \leq I \leq I_{max}$
0.2s	±0.5%	±0.3%	±0.4%	±0.2%
0.5s	±1.0%	±0.6%	±1.0%	±0.5%
0.5	±1.3%	±0.8%	±1.0%	±0.5%
1	±1.5%	±1.0%	±1.5%	±1.0%
2	±2.5%	±2.0%	±2.5%	±2.0%

V. CASE STUDIES

In order to evaluate the performance of the proposed DSSE scheme, the operation of the LVDG that is illustrated in Fig. 3 is simulated for 2 hours. A conventional DSSE scheme is also implemented for comparison and validation of the proposed scheme. In this conventional scheme, the WLS SE is executed only at the end of the smart meters' reporting cycles, considering the smart meter measurement set from each corresponding reporting cycle. For the load profiles of each of the consumers, real data from a measurement campaign are used. These data were provided by the Cyprus DSO (EAC) and it consists of the recorded consumption pattern (through smart meters) of over 60 consumers in Cyprus. Due to the low measurement resolution (30 minutes), the time between measurements is reduced from 30 minutes to 20 seconds to replicate more realistic conditions to test the proposed DSSE. The accuracy class of the considered smart meters is 0.5 and 1 (see Table I) for active and reactive power measurements and 0.5% of the full scale meter reading for voltage measurements.

A. Offline tuning of weight parameters

In Section III it was mentioned that two pairs of tuning parameters are used in order to adjust the weights of the smart meter measurements based on the time that has passed since they were last reported. The choice of these parameters can have a significant effect on the proposed DSSE. In Fig. 4 the average 2-norm and average max-norm estimation errors are presented for different unique combinations of the tuning parameters. This figure shows that with a correct choice for
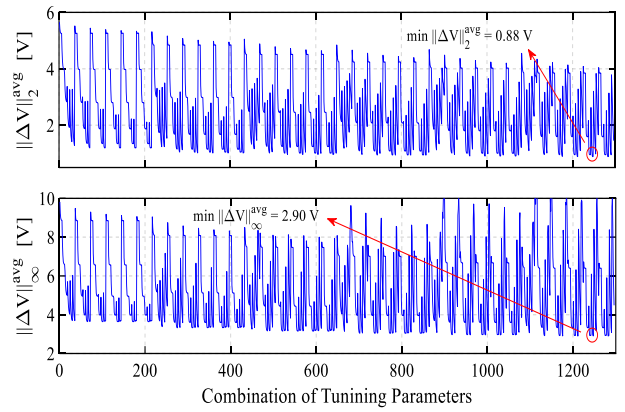

Fig. 4. Effect of the weight tuning parameters

the tuning parameters, the performance of the proposed DSSE can increase considerably. From this investigation, it is found that the 1247th combination yields the lowest estimation errors. This combination corresponds to $k_P = 3$, $k_V = 2.5$, $a_P = 2$ and $a_V = 2.5$. These tuning parameters are used in following case studies.

B. Case Study I: 10-minute reporting rate (base case)

In Fig. 5 the 2-norm and max-norm of the estimation error are presented for the proposed and conventional DSSE schemes. These errors are calculated based on the true state of the LVDG at the time instances that the WLS SE is executed (every 1 minute for the proposed DSSE scheme and every 10 minutes for the conventional). As expected, since the conventional DSSE scheme updates its state once every 10 minutes it has a considerable higher estimation error when compared to the proposed DSSE scheme. The proposed scheme not only is able to run at much faster rate (despite that in both schemes the smart meters update their measurements once every 10 minutes) but is also highly accurate. In Fig. 6, the estimated voltage profile of the three-phase system node 142 is presented for both schemes. The time instances that the proposed DSSE and conventional schemes are executed are marked with a red and blue X respectively on this figure. Since the time resolution of the Simulink model is 20 seconds and $T_{SE} = 1\ min$, in between executions of the proposed DSSE scheme the system's true state is updated three times (according to the load profiles). Despite this blind interval, when the proposed DSSE scheme is executed, the estimated states can still track accurately the true state of the system. Comparing the estimated voltage profile of both schemes, the contribution of this work is highlighted. Despite considering smart meters with a reporting rate of 10 minutes, the proposed DSSE scheme can accurately track the system's state with a 1-minute resolution.
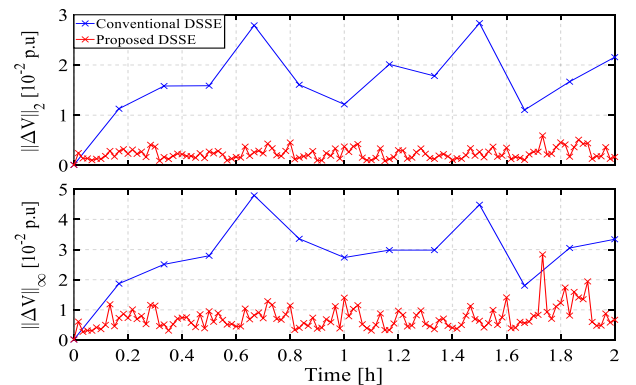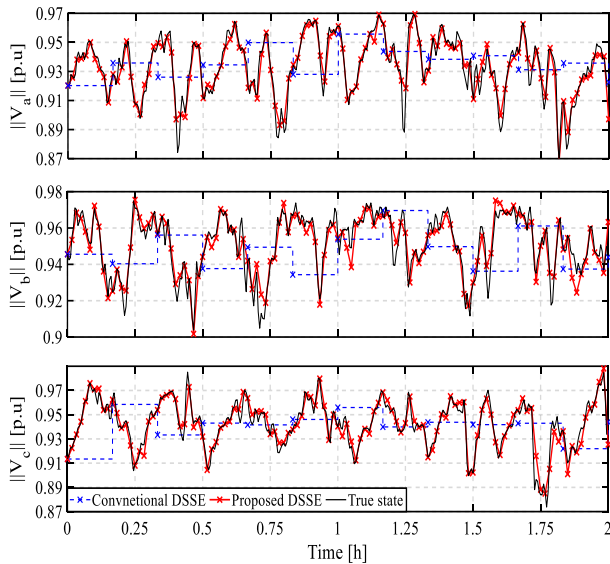

Fig. 5. Estimation errors

Fig. 6. Voltage profile of system node 142

As it is evident in Fig. 5, in some instances the estimation error of the proposed DSSE scheme is higher than the median. This is mainly due to the blind time interval in which in some occasions the system's state changes considerably. As a result, the last known values for the system's voltage (from the previous WLS SE) are significantly different than the actual current state of the system. In the proposed DSSE, the estimated voltages from the previous WLS SE are used as measurements in the current iteration. Therefore, in instances that the state of the system changes considerably during the blind time intervals, the accuracy of the proposed DSSE decreases. However, it should be highlighted that the load profiles used in the Simulink model with a 20 s resolution were constructed from real measurements with a 30 min resolution. Such variations of the system's state within the timeframe of seconds may not be that common.

C. Case study II: Different reporting rates

To generalize the results, the proposed DSSE scheme is implemented for several different smart meter reporting rates (from 5 to 30 minutes). In Fig. 7 the average 2-norm and average max-norm error from all system nodes within the simulated 2-hour period is presented for the different reporting rates. As it could be expected, the performance of the proposed DSSE scheme is greatly affected by the reporting rates of the smart meters, almost linearly. From this figure, it can be concluded that the proposed DSSE scheme maintains a satisfactory performance for up to a 20-minute reporting rate from the smart meters. For slower reporting rates, the proposed scheme can still operate but with a reduced
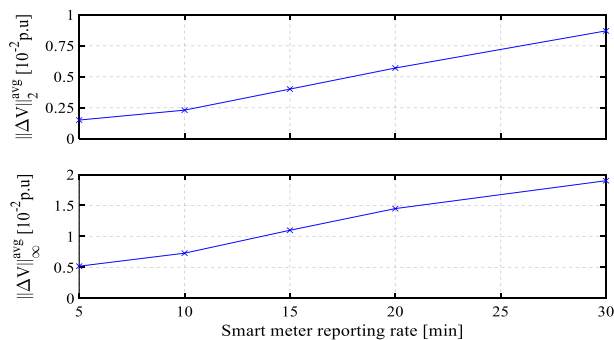

Fig. 7. Estimation errors for different smart meter reporting rates

performance. Considering that the output of the proposed DSSE scheme is to be used in several DMS applications, the requirements for its accuracy (i.e. smart meter reporting rate) can set by the operational requirements of these applications.

VI. CONCLUSIONS

As more DERs are integrated to the LVDGs, their accurate real-time monitoring will be a necessity. Under the smart grid concept, it is expected that LVDGs must be able to offer several grid support functionalities. To enable the applications of an advanced DMS, a reliable monitoring scheme is required. In this paper an innovative DSSE scheme has been proposed that fully exploits the installation of a fast reporting device at the MV-LV transformer substation of LVDG, as well as the smart meters at the consumers' premises. By utilizing this fast reporting device, the proposed scheme can run once every minute regardless of the reporting rate of the smart meters. Numerical simulations using the IEEE European low voltage test feeder have shown that the proposed DSSE can offer accurate information about the system's state in a per minute resolution despite considering smart meters with relative slow reporting rates (from 5 up to 30 minutes).

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