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Experimental Validation of a Steady State Model Synthesis Method for a Three-Phase Unbalanced Active Distribution Network Feeder

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ABSTRACT This paper presents the field validation of a method that performs steady-state model synthesis (SSMS) of active distribution networks using synchrophasor measurements. The validation is performed by applying the SSMS method on a real active distribution feeder network by utilizing the measurements from real phasor measurement units (PMUs) installed at the EPFL campus. An extended version of total vector error and a power flow comparison at the PMU buses are used as performance assessment metrics. A real-time hardware-in-the-loop simulations set up at the Distributed Energy System Laboratory is used for further performance assessment of the SSMS application. The effectiveness of the SSMS application is demonstrated by testing it extensively for several different case studies.

INDEX TERMS Active distribution network, experimental validation, model synthesis and phasor measurement unit.

I. INTRODUCTION

The amount of renewable generation sources connected to distribution networks have increased dramatically in the last decade [1]. According to [2], a substantial amount of renewable generation (especially from solar and wind technologies) has been installed in the last few years at the distribution level, and it is expected to grow in the near future. This has transformed power distribution networks from passive to active grids. Active distribution networks (ADNs) require improved frameworks for operational interactions between Transmission System Operators (TSOs) and Distribution System Operators (DSOs) [3]. A better interaction can help in reducing, enable TSOs to have a better situational awareness of their connected distribution networks, and lead to a better management of Distribution System Resources (DSRs) [4], [5]. In this perspective, one possible way to improve the interactions between TSOs and DSOs is to have accurate steady state models of ADNs and a framework to exchange these models to TSOs.

A. MOTIVATION AND PREVIOUS WORKS

With the increased penetration of renewable generation in the distribution networks, the requirement of developing and maintaining models of these networks is becoming compelling. Presently, most TSOs are only able to determine reduced models of limited portions of distribution networks with aggregated models [6]. This is due to the limited network observability at the distribution level, insufficient modeling information, and challenges with information collection, aggregation and management when handling larger scale grids. There is therefore an unmet demand for equivalent models of ADNs so that the impact of distribution networks could be estimated on the overall power system behavior without modeling individual elements [7].

Existing methods used by TSOs to determine reduced equivalent models require a detailed model of the network to be reduced [8] and often make assumptions, such as “pure load”, that are no longer valid for ADNs. Occasionally, detailed modeling of a few portions of distribution networks

is performed (e.g. for voltage instabilities studies). However, the models are updated yearly and cannot be updated automatically [9]. This motivates the need for methods that can synthesize reduced models in real-time for multiple sections of unbalanced and generic distribution networks.

In this context, a steady state model synthesis (SSMS) method has been proposed in [10], where measurements from Phasor Measurement Units (PMUs) from multiple locations in a distribution network were exploited for synthesizing a three-phase steady state equivalent model of the observed network. Synthesized PMU measurements were used in [10], using a hardware-in-the-loop (HIL) simulation setup at KTH SmarTSLab. Moreover, in [11], a detailed sensitivity analysis of the SSMS method was presented in order to investigate how sensitive the output of the method is to changes in its inputs. Although [10], and [11] presented the theoretical background of the method and carried out performance validation in a laboratory environment, there is a need to test the validity of the SSMS method using the data from real PMUs installed on real ADNs.

B. PAPER CONTRIBUTIONS

The contributions in this paper are summarized as follows:

- An HIL experimental validation of the PMU-based SSMS application.
- A performance assessment of the SSMS application using “real” PMU data from a distribution feeder.
- A detailed analysis of the parametrization of the SSMS application w.r.t. model parameter estimation update rate.

The contributions summarized are further explained in the sequel. In this paper, an extensive experimental validation of the SSMS method is performed. The synchrophasor measurements were acquired from the real PMUs installed at an actual active distribution feeder at EPFL’s campus, Lausanne, Switzerland [12]. The extended version of the Total Vector Error (TVE) concept (first introduced in [11]) and power flow comparisons at the PMU buses were used as performance evaluation metrics.

In this paper, a detailed performance assessment of the method is conducted by testing the method extensively under different conditions. The method was tested by utilizing the PMU data for the days of the year when the targeted distribution feeder at EPFL campus was mostly active (i.e. with a surplus of PV generation) and for the time when it was mostly passive (i.e. with minimal PV generation). Moreover, the partial solar eclipse event of 2015 that occurred in Switzerland [13] was analyzed in order to investigate its impact on the performance of the SSMS method.

Additionally, a comprehensive analysis is presented in Section V, which might help power system operators to configure a target application based on the SSMS method. It is shown how the performance of the SSMS method, and hence the estimation error, varies by varying the update rate of the

target application. The tradeoff between estimation accuracy (tracking) and update rate (speed) is determined.

The paper starts by summarizing the concept of steady-state model synthesis in Section II. Section III presents the data acquisition & validation methodology. Section IV presents the experimental validation results. A discussion is presented in Section V, analyzing how the performance of the SSMS application is affected by varying the update rate of the SSMS application. The conclusions and the future work are presented in Section VI.

II. THE STEADY STATE MODEL SYNTHESIS METHOD

Assuming that PMU measurements are available at the boundary buses of a generic 3-ph unbalanced distribution network; a three-phase steady state equivalent model can be synthesized for the part of the distribution network that is located between the installed PMUs. As the operating conditions of the system changes, the parameters of the equivalent model may be updated in real-time.

Fig. 1 shows an arbitrary section of a distribution network, bounded by multiple PMUs. As the figure shows, the bounded section may include any kind of feeder structure with an arbitrary combination of local loads and generation. The three-phase voltage and line current synchrophasor measurements, provided by the PMUs, can be utilized to derive the reduced steady state model. As Fig. 1 depicts, the model consists of a parallel branch, including an impedance in series with a voltage source to represent the net balance of generation/load in the selected section, and multiple

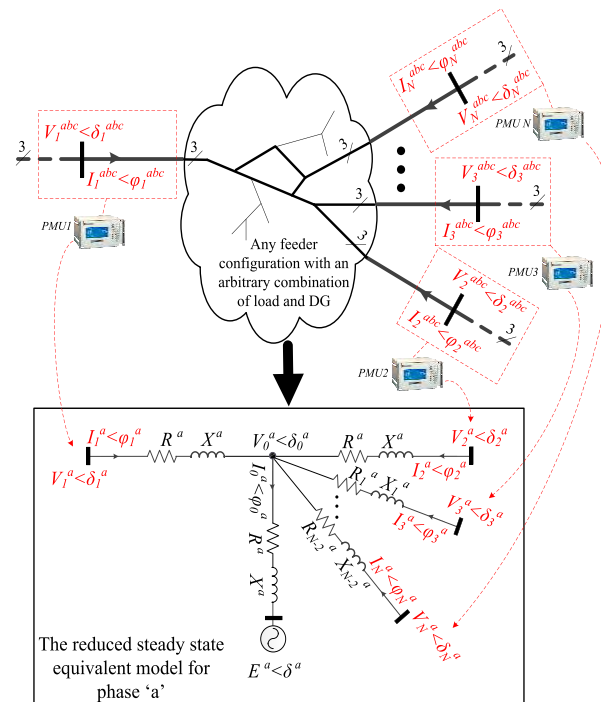


FIGURE 1. Synthesized model based on PMU measurements located at the boundaries of the observed power network.

series-connected impedances to represent the feeders of the selected sections. The synthesized model is a three-phase model that captures the imbalances between the three phases of the distribution network. The reader is referred to [10] for the detailed theoretical background of the SSMS method.

It was shown in [10] that the SSMS method can produce accurate models for any feeder configuration located between the installed PMUs. If the system configuration is changed, the parameters of the synthesized model will be updated automatically in real-time. The reduced models of distribution networks can then be sent to Transmission System Operators (TSOs) in real-time to be utilized in their energy management functions. This could provide TSOs, a capability to analyze changes in distribution networks and to take preventive or corrective actions, which in turn may increase the overall reliability of the electric grid.

III. DATA ACQUISITION AND VALIDATION METHODOLOGY

A. THE EPFL CAMPUS ACTIVE DISTRIBUTION NETWORK

As shown in Fig. 2, the power distribution network of EPFL campus [12] includes all the components of an ADN. The lines are short, and the load demand is variable as a function of the time of the day and weather conditions. Moreover, active power injections are present as 2 MWp of photovoltaic (PV) generation together with 6 MW of combined heat and power generation units. Due to the variable demand and the extensive use of power electronics, the voltage and current profiles contain the typical dynamics of ADNs, which make the EPFL campus network an ideal testing venue to validate the SSMS application.

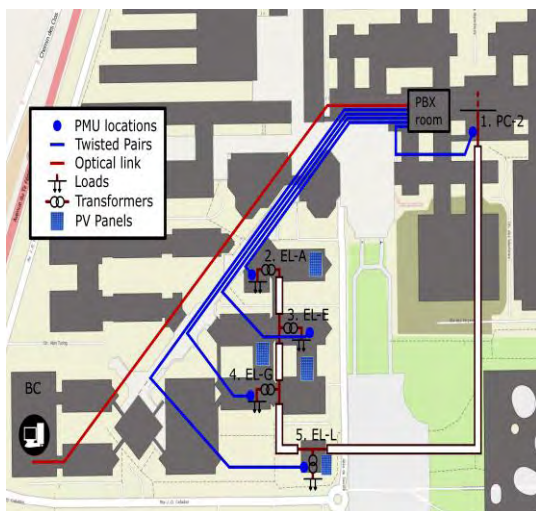


FIGURE 2. Network topology of the power distribution feeder overlaid on top of a map of the EPFL campus.

The monitored network is composed of 5 electrical substations i.e. EL-A, EL-E, EL-G, EL-L and PC-2 as shown in Fig. 2. PV panels inject active power at EL-A, EL-E, EL-G and EL-L. The lines in the network are underground

cables with parameters as reported in the Appendix. A class-P PMU prototype [14] based on the NI cRIO 9068 hardware is installed in each substation to estimate voltage and current synchrophasors. A stationary GPS unit (NI-9467) is used for the synchronization to the UTC-time.

B. DATA ACQUISITION

The PMU measurements were acquired from specified locations as shown in Fig. 2. A single line diagram of the active distribution feeder network at the EPFL campus is shown in Fig. 3. The purpose of Fig. 2 and Fig. 3 is to show how to obtain a reduced equivalent model of the detailed EPFL campus network. The reduced model is shown in Fig. 4.

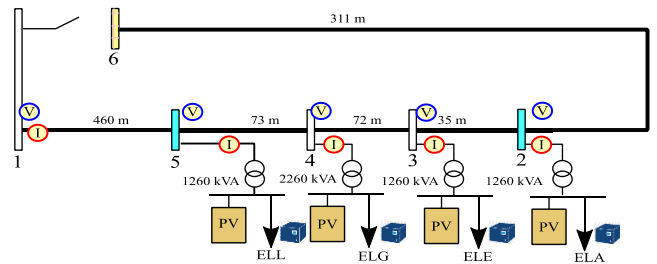
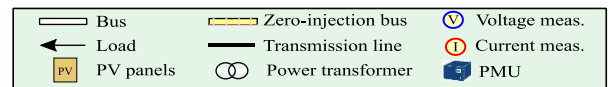


FIGURE 3. Targeted EPFL Campus active distribution feeder.

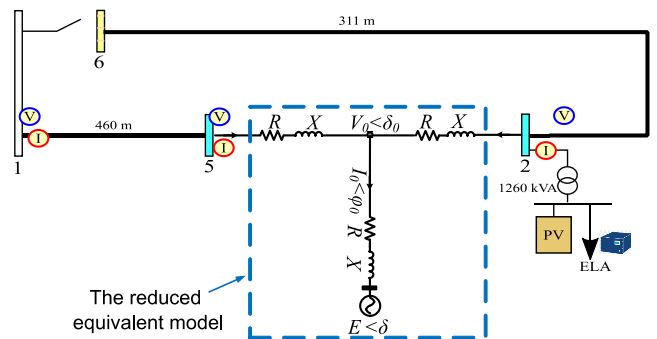


FIGURE 4. Reduced equivalent network of the targeted EPFL campus feeder.

C. DETAILED VALIDATION MODEL

Procedure 1:

- The acquired PMU data is replayed in a Real Time Simulator (RTS) as shown in Fig. 5.
- Active power (P) and reactive power (Q) are calculated based on the acquired PMU data and given to the RTS load models.
- A simulated EPFL PMU model estimates the phasors at bus 5 and 2, i.e., \tilde{V}_T, \tilde{I}_T . The simulated PMU is based on a synchrophasor extraction (SE) algorithm presented in [14], which is both compliant with the accuracy requirements of the IEEE Std. C37.118 [15] and deployable into a RTS platform [16]. The PMUs

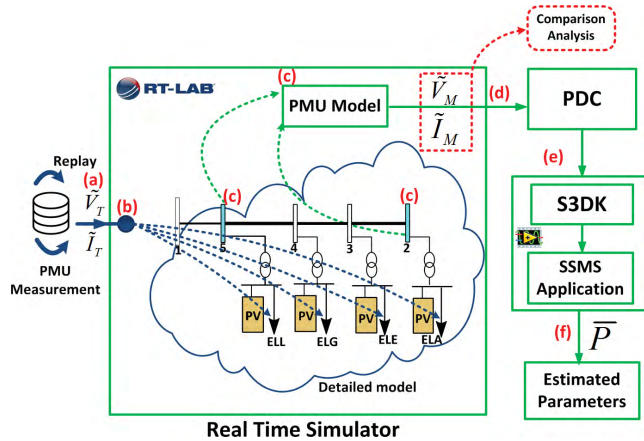


FIGURE 5. Detailed validation model.

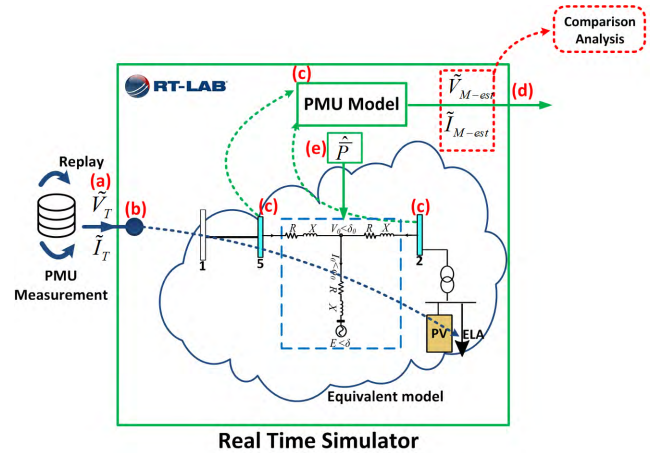


FIGURE 6. Equivalent model.

installed at the EPFL network, and the simulated PMUs in the RTS, use the same SE algorithm. The SE algorithm, its implementation and validation in real have been described in details in [14]. Moreover, integration of the simulated PMU into OPAL-RT eMEGASIM RTS has been experimentally validated in [16].

- (d) \tilde{V}_M, \tilde{I}_M are sent to a Phasor Data Concentrator (PDC), i.e. SEL-PDC-5073.
- (e) PDC streams the data over TCP/IP to a workstation computer holding SmartGrid’s Synchrophasor Development Kit (S3DK) [17], which provides a real-time data mediator that parses the PDC data stream and makes it available to the SSMS application in LabVIEW environment.
- (f) A LabVIEW SSMS application estimates the parameters \hat{P} of the reduced equivalent model of the detailed EPFL network.

D. EQUIVALENT MODEL

Procedure 2:

- > (a) - (c) are the same as in procedure 1.
- (d) $\tilde{V}_{M-est}, \tilde{I}_{M-est}$ are the synchrophasor estimated by the simulated PMU for the reduced equivalent model as shown in Fig. 6.
- (e) The pre-processed parameters \hat{P} (explained in Section III.E), obtained from (\bar{P}) in procedure 1 are replayed in the reduced model.

The synchrophasors $\tilde{V}_M, \tilde{I}_M, \tilde{V}_{M-est}$ and \tilde{I}_{M-est} as shown in Fig. 5 and 6 are used for the performance analysis.

E. PRE-PROCESSING OF \bar{P} FOR USE IN THE RTS

For validation purposes, the estimated parameters require some pre-processing as shown in Fig 7.

- (a) The raw estimated parameters i.e. \bar{P} have an update rate of 0.5 sec. A sample-and-hold functionality is applied to \bar{P} , i.e. the output holds its sampled value until a new estimate is produced.
- (b) PMU measurements have a refresh rate of 20 m sec, whereas, the LabVIEW SSMS application estimates the parameters with an inherent update rate of 2

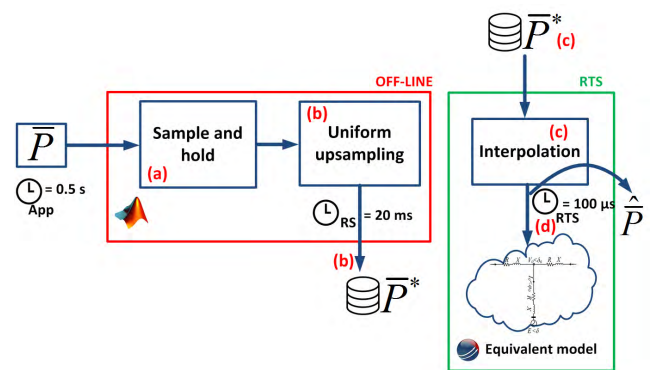


FIGURE 7. Pre-processing of the estimated parameters.

estimates / second (i.e., every 0.5 sec). Therefore, a uniform up-sampling is performed on the estimated parameters \bar{P} to get \bar{P}^* , to synchronize the sampling rate of the PMU measurements to the estimated parameters.

- (c) As the P and Q of loads in the detailed network (Fig. 5) and in the equivalent network (Fig. 6) were interpolated to simulate both networks in the RTS at a relatively small time-step, (i.e. 100 μ sec), the up sampled parameters were interpolated.
- (d) The pre-processed parameters \hat{P} are replayed in the equivalent model.

IV. EXPERIMENTAL VALIDATION RESULTS

A. PERFORMANCE EVALUATION METRICS

1) END-TO-END TOTAL VECTOR ERROR (TVE)

In this paper, end-to-end TVE is used as one of the performance evaluation metrics for the SSMS application. The end-to-end TVE, initially introduced in [11], is defined as the difference between the actual phasor value of the signal being measured and the reproduced version of the same phasor, as shown in (1).

$$TVE_{end-to-end}(n) = \sqrt{\frac{(\tilde{V}_r(n) - V_r(n))^2 + (\tilde{V}_i(n) - V_i(n))^2}{V_r(n)^2 + V_i(n)^2}} \tag{1}$$

Where

- $\tilde{V}_r(n)$ = Real part of the reproduced voltage
- $V_r(n)$ = Real part of the measured (actual) voltage
- $\tilde{V}_i(n)$ = Imaginary part of the reproduced voltage
- $V_i(n)$ = Imaginary part of the measured (actual) voltage

2) POWER FLOW COMPARISON

The other metric used for the performance evaluation of the SSMS application is the comparison of power flow for the active power P and the reactive power Q at the PMU buses for both the actual and the reduced equivalent network, defined as

$$\begin{aligned} \Delta P_{ij}^{kl} &= P_{ij}^k - P_{ij}^l \\ \Delta Q_{ij}^{kl} &= Q_{ij}^k - Q_{ij}^l \end{aligned} \quad (2)$$

where ‘ k ’ is the true value and ‘ l ’ the reproduced values of P and Q in the line between nodes ‘ i ’ and ‘ j ’.

B. CASE STUDIES AND RESULTS

In this section, PMU data from the EPFL campus feeder network is used to perform experimental validation of the SSMS application using several case studies. Following the methodology described in Section III, the metrics defined by (1) and (2) are analyzed.

1) CASE STUDY 1 (A TYPICAL LOAD PROFILE)

In this case study, a typical load profile from the installed PMUs at the EPFL campus feeder is considered. PMU data for 1st of September 2014 between 13:00-13:01 is fed to the SSMS application. The equivalent model parameters for phases a , b and c estimated by the SSMS application, are shown in Fig. 8. The figure shows that the parameters are updated automatically with the changes in the system operating conditions.

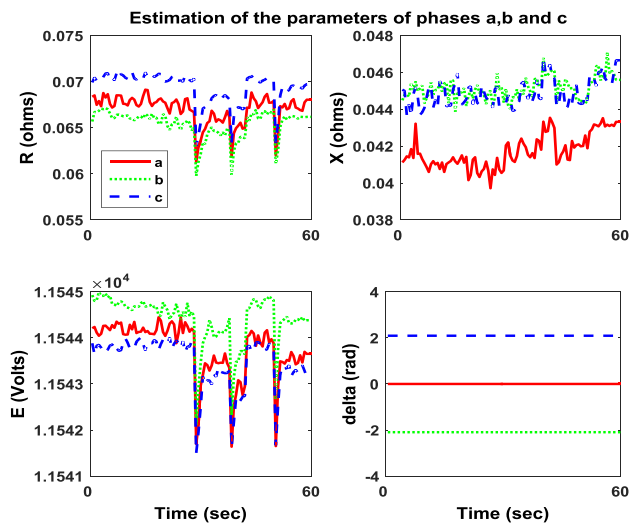


FIGURE 8. Estimation of the parameters of phases a , b and c of the reduced EPFL network model.

Figures 9 and 10 compare the voltage and current phasors provided by PMU1 and PMU2 measured in the actual EPFL feeder network, with those of the equivalent network. As the figures show, the reproduced voltage and current phasors are similar to those measured in the actual network. In order to analyze the difference between the measured values and the reproduced values, the average absolute error is calculated. As shown in Fig. 9 and Fig. 10, the average absolute estimation error is at most 0.2746 % for all the voltage and current phasors.

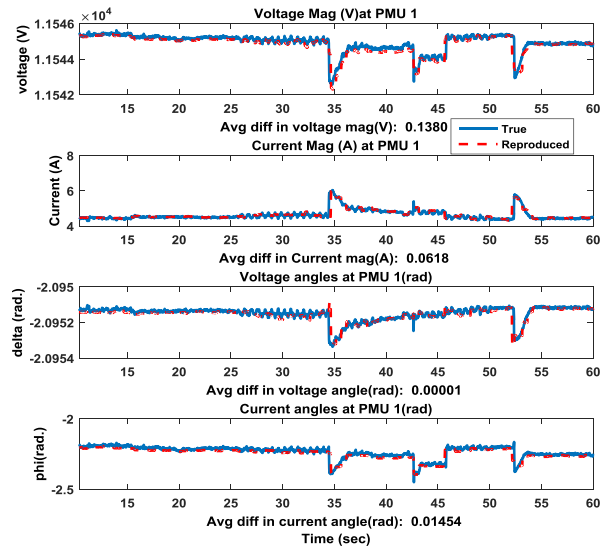


FIGURE 9. Measured phasors versus reproduced phasors of phase ‘ b ’ for PMU 1.

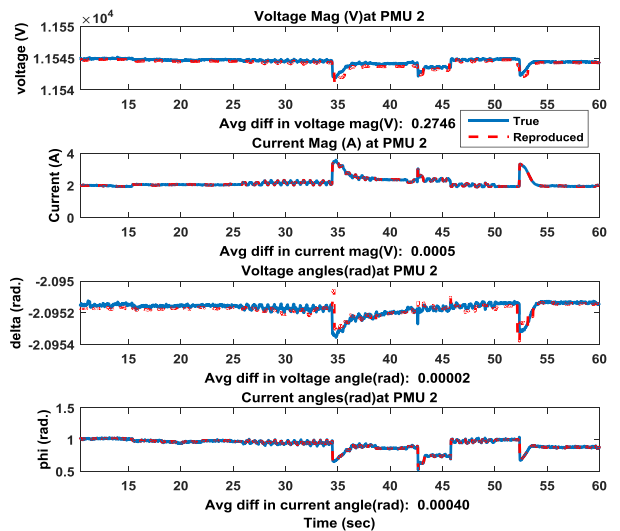


FIGURE 10. Measured phasors versus reproduced phasors of phase ‘ b ’ for PMU 2.

The sensitivity of the output of the SSMS application is evaluated by calculating the mean, maximum and minimum values of the end-to-end TVE using (1). The results are summarized in Table 1. The standard deviation (SD) is calculated for each voltage and current phasor. The end-to-end TVE and

TABLE 1. ¹ End-to-end TVE for case study 1.

Phasors	End-to-end TVE (%)			
	Mean	Max	Min	SD
V1	0.0019	0.0275	1.88e-5	0.0022
I1	2.1705	30.420 ²	0.0190	2.5520
V2	0.0032	0.0297	1.77e-4	0.0025
I2	0.0523	1.3033	2.63e-4	0.0796

the SD for both the voltage phasors is small, whereas for current phasor of PMU 1 the values are higher with the largest mean end-to-end TVE of 2.1705%.

Top part of Fig. 11 and Fig. 12 compare the active power at PMU 1 and PMU 2 measured in the EPFL feeder network, with those of the reproduced equivalent network. As the figures show, the reproduced active power matches the true actual power with sufficient accuracy. Average absolute mismatch (error) in the active power for PMU 1 and PMUs 2 are plotted in the bottom part of Fig. 11 and Fig. 12 respectively.

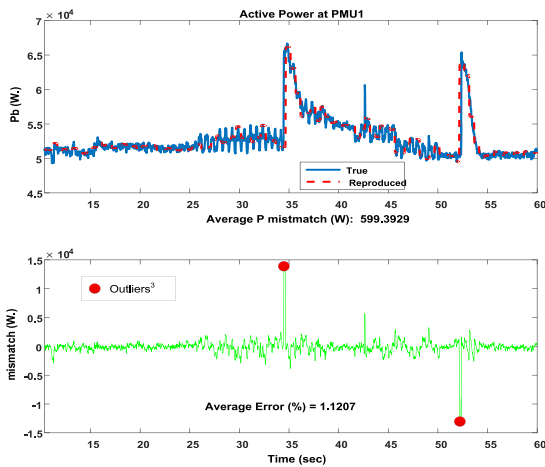


FIGURE 11. Active power comparison of phase 'b' for measured and reproduced network for PMU 1.

In addition to that, a comprehensive error analysis is performed for the active power (P) and the reactive power (Q) for each phase for both PMU 1 and PMU 2. The results for the error analysis of P and Q are given in Table 2 and Table 3 respectively. As the tables show, the maximum error in P and Q for both PMU 1 and PMU 2 are 1.344 % and 11.82 %, respectively.

2) CASE STUDY 2 [ACTIVE NETWORK CONDITIONS (A SUMMER WEEKEND)]

In this case study, a PMU data set is selected for the time of year of 2015 when the EPFL campus feeder network was mostly active, i.e. a significant amount of active power was

¹Error plots of the data used to compile this table are shown in Appendix 2.
²At t=53 sec, sudden rise in current magnitude causes this high value of error for only 0.4 seconds. The value is marked with a red circle in Fig. 31, in Appendix 2.
³The outliers in the error are due to improper tracking of the active power during a short period when sudden variations occur in the active power.

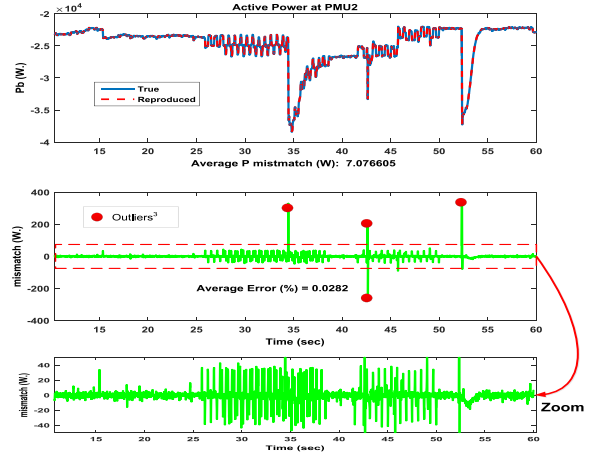


FIGURE 12. Active power comparison of phase 'b' for measured and reproduced network for PMU 2.

TABLE 2. P & Q comparison for PMU 1.

P	P & Q comparison for PMU1	
	Average error in P (W)	Average error in P (%)
P1a	687.84	1.344
P1b	599.39	1.120
P1c	575.12	1.023
Q	Average error in Q (var)	Average error in Q (%)
Q1a	860.11	7.84
Q1b	850.94	11.82
Q1c	948.42	7.90

TABLE 3. P & Q comparison for PMU 2.

P	P & Q comparison for PMU2	
	Average error in P (W)	Average error in P (%)
P2a	7.2210	0.0285
P2b	7.0766	0.0282
P2c	5.0682	0.0208
Q	Average error in Q (var)	Average error in Q (%)
Q2a	19.31	1.805
Q2b	15.62	1.541
Q2c	17.51	1.488

injected by the PVs. Fig. 13 shows a power profile for two days of the active power intake by the EPFL feeder from 23rd May to 25th May, 2015. The figure shows two dips in the power profile which corresponds to the time of day when the PVs were injecting a significant amount of power. During this time, the active power intake from the grid reduces (less external power is needed to feed the local loads). On the other hand, during night time when PV production falls, a significant amount of active power is drawn from the grid.

PMU data from 23rd of May 2015 between 10:43-10:45 (when the network was mostly active), as shown in the

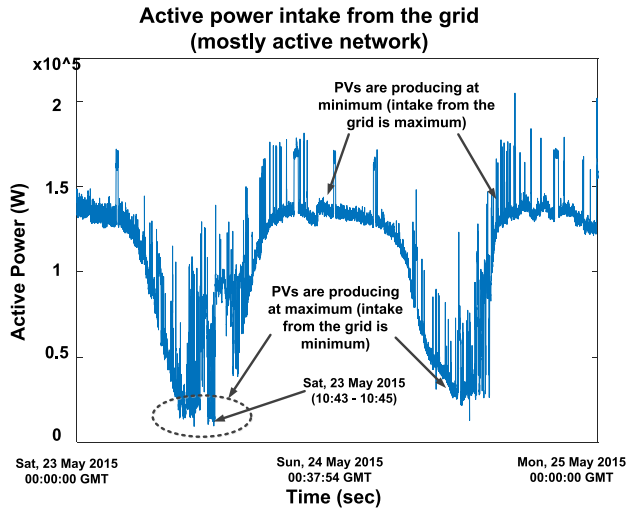


FIGURE 13. Active power intake from the grid (a weekend-day in summer, 2015).

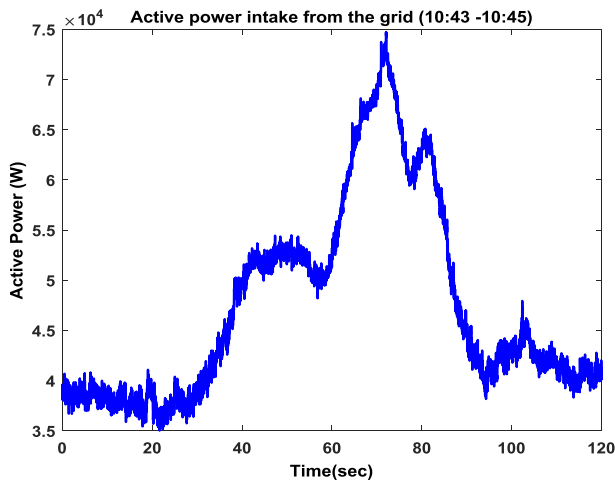


FIGURE 14. Active power intake under network active conditions (10:43-10:45), 23 May 2015).

encircled part (bottom left) of Fig. 13, was selected for analysis and is shown in Fig. 14.

Fig. 15 and Fig. 16 compare the voltage and current phasors, measured by PMU1 and PMU2 in the EPFL feeder network, with those of the reproduced equivalent network. As the figures show, the reproduced voltage and current phasors accurately match those of the actual network. Moreover, the average estimation error (as shown in Fig. 15 and 16) is quite small for both the voltage and current phasor for both PMUs. The maximum estimation error is 0.3899 % for all the voltage and current phasors.

3) CASE STUDY 3 [(PASSIVE NETWORK CONDITIONS (A WINTER NIGHT)]

In this case study, PMU data is selected from 2015, when the EPFL campus feeder network was passive, i.e. minimum active power injected by PV. Figure 17 shows a power profile for two days of the active power intake from 22nd Jan to 24th Jan, 2015. The two peaks shown in the figure corresponds to

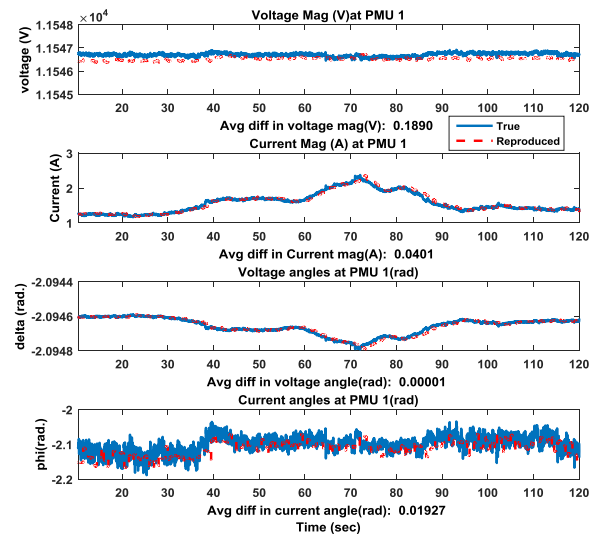


FIGURE 15. Measured phasors versus reproduced phasors of phase 'b' for PMU 1 (active network conditions).

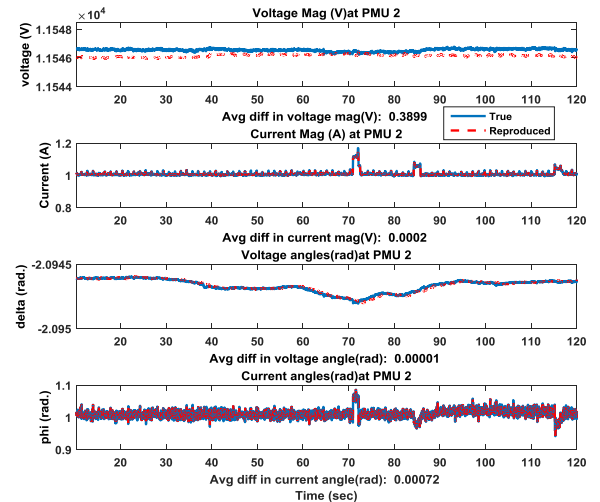


FIGURE 16. Measured phasors versus reproduced phasors of phase 'b' for PMU 2 (active network conditions).

the time of day when the active power intake from the grid was at its maximum. PMU data is selected from Jan 22nd, 2015 between 10:03-10:05 (when the network was mostly passive), as shown in the encircled part (top left) of Fig. 17. The selected power profile is shown in Fig. 18.

A comparison of the voltage and current phasors is performed; results are shown in Fig. 19 and Fig. 20. As the figures show, the maximum estimation error is 1.4908 % for all the voltage and current phasors.

4) CASE STUDY 4 (SOLAR ECLIPSE 2015)

In this case study, PMU data is selected corresponding to the solar eclipse event occurred on 20th March 2015 which was partially observed in Lausanne, Switzerland. The solar eclipse reached its maximum obscuration of 69.63 % at 10:31, as shown in Fig. 21. The immediate effect of the solar

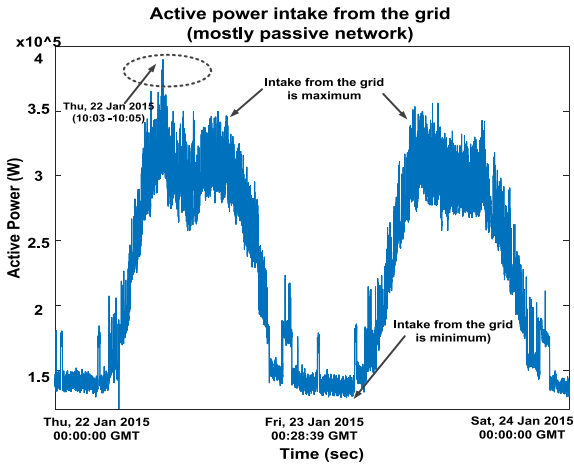


FIGURE 17. Active power intake from the grid (weekdays in winters 2015).

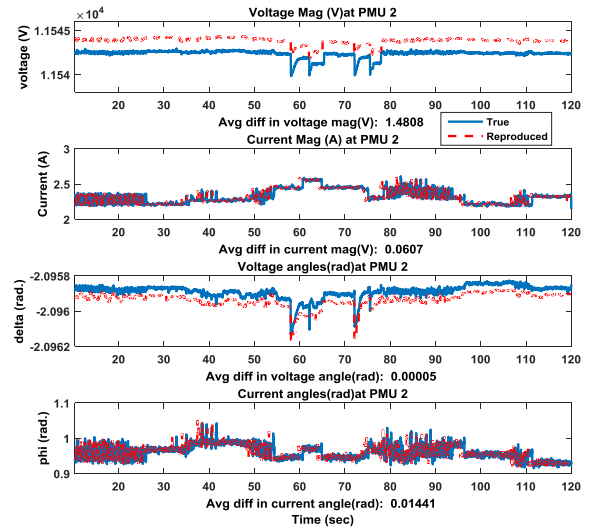


FIGURE 20. Measured phasors versus reproduced phasors of phase 'b' for PMU 2 (passive network conditions).

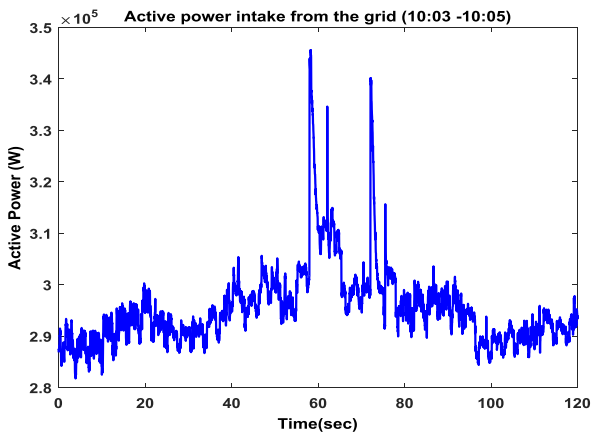


FIGURE 18. Active power intake under passive network conditions (10:03-10:05, 22 Jan 2015).

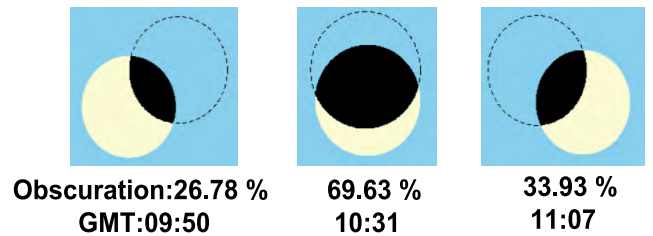


FIGURE 21. Phases of the partial solar eclipse on 20th March 2015 in Lausanne [13].

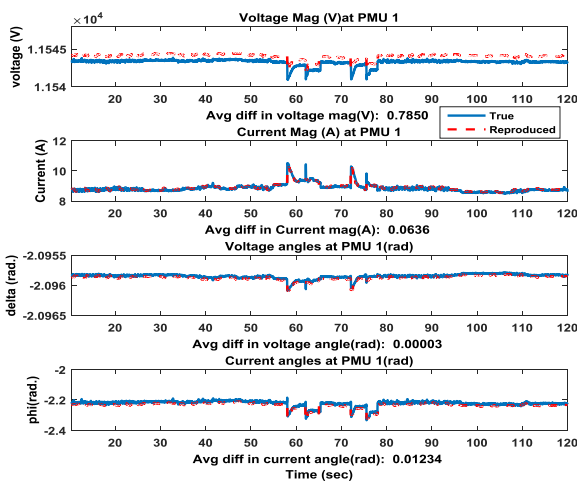


FIGURE 19. Measured phasors versus reproduced phasors of phase 'b' for PMU 1 (passive network conditions).

eclipse on the EPFL campus feeder is an increase in the power intake from the external grid. This is due to the fact that the generation from the PV panels decreases due to the decreased amount of direct irradiance.

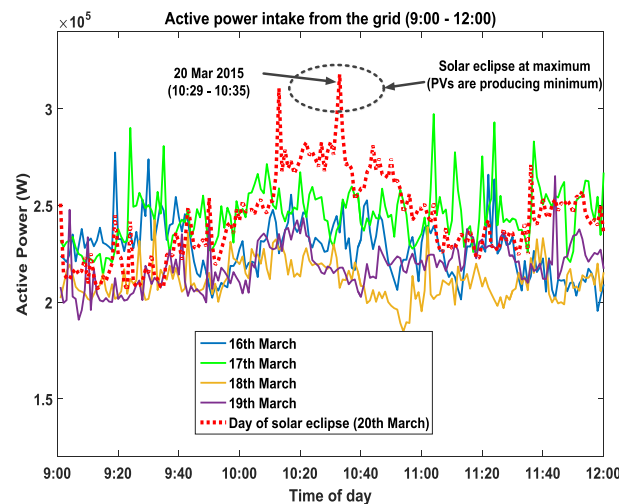


FIGURE 22. Active power intake from the grid between 09:00-12:00 during Solar Eclipse (1 minute averages).

This impact can also be observed from Fig. 22, which compares the active power intake from the grid (1 minute averaged) during 09:00-12:00 for 5 days, i.e. 16th March until 20th March. The figure shows that the red line, which repre-

sents the day of the eclipse, is different from the responses for the other days. In particular, the peak (encircled in Fig. 22) corresponds to the period when the eclipse was at 69.63 % obscuration.

A power profile for 6 minutes of the PMU data is selected from 20th March, 2015 between 10:29 -10:35 (when the eclipse was at 69.63 % obscuration), as shown in the encircled part (top middle) of Fig. 22. The selected power profile is shown in Fig. 23.

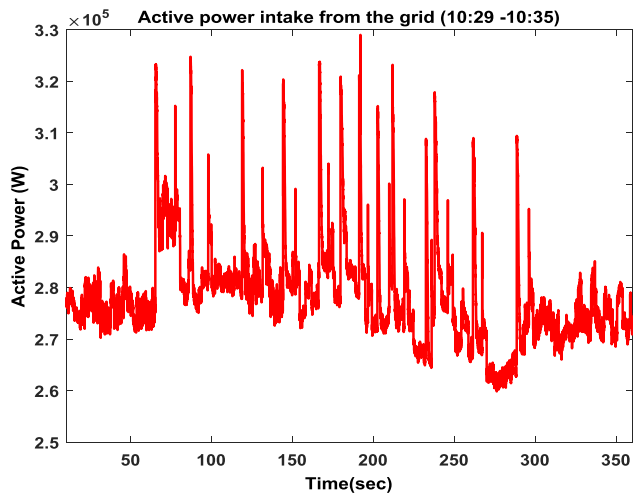


FIGURE 23. Active power intake from the grid during the obscuration (10:29-10:35, 20 Mar 2015).

Figure 24 and 25 compares the voltage and current phasors during peak time of the solar eclipse (10:29-10:35). As the figures show, the maximum estimation error is 1.1977 % for all the voltage and current phasors as shown in Fig. 24 and 25. It is worth noticing that sudden variations in the active power

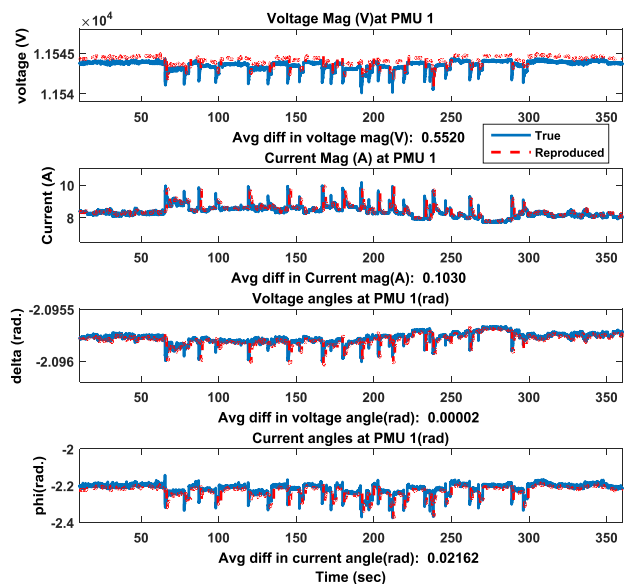


FIGURE 24. Measured phasors versus reproduced phasors of phase 'b' for PMU 1 (during solar eclipse).

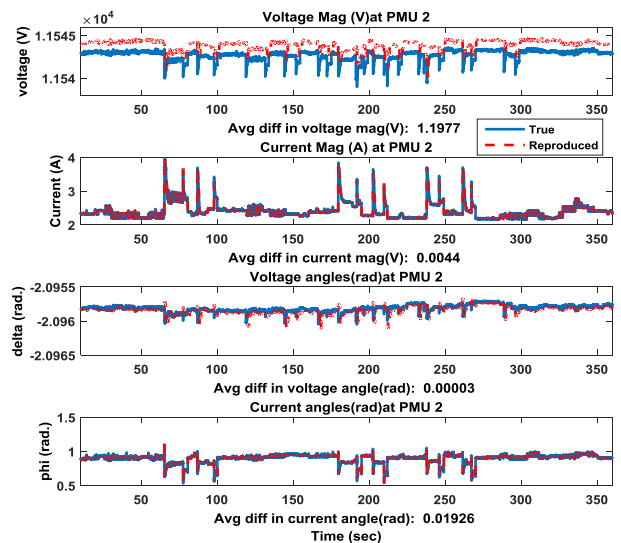


FIGURE 25. Measured phasors versus reproduced phasors of phase 'b' for PMU 2 (during solar eclipse).

intake during the eclipse caused frequent voltage dips. Note that the SSMS application is able to track these variations.

V. DISCUSSION

The previous studies show that the SSMS application provides a reduced equivalent model with sufficient accuracy. In addition, it also shows that it is capable of tracking frequent variations due to local loads inrushes as well as PV power fluctuations. However, this ability has limitations that depend upon the update rate of the SSMS application, which is system dependent and needs to be determined for every system where the application is used.

In this section, case study 1 is extended to perform a comprehensive analysis for evaluating the impact of different updates rates in the SSMS application. Figure 26 shows the

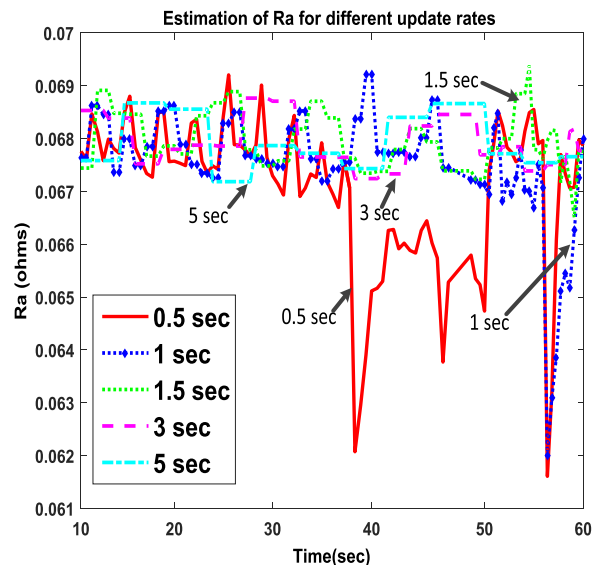


FIGURE 26. Estimation of "Ra" for different update rates.

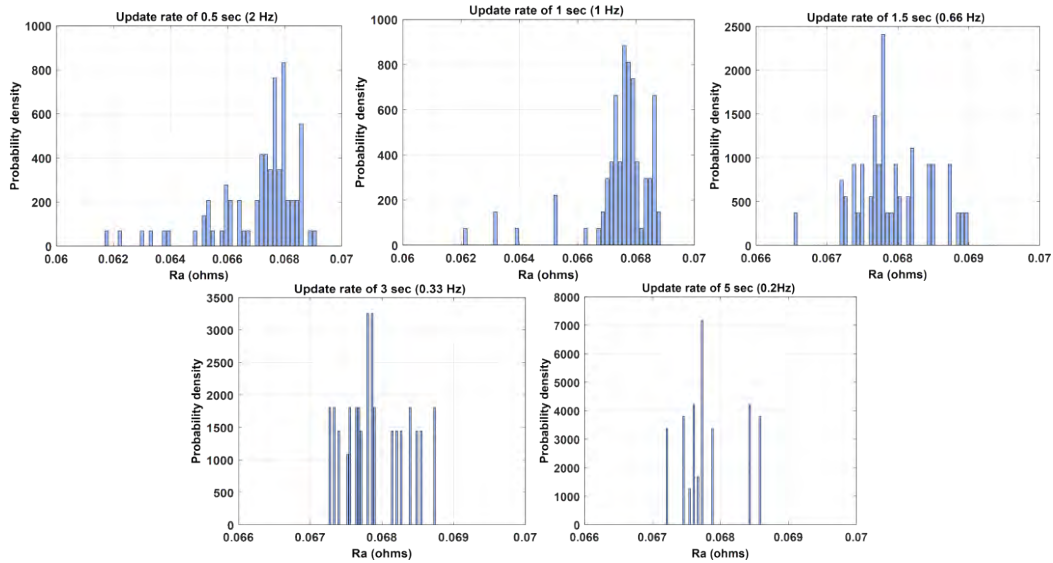


FIGURE 27. Probability density estimates of “Ra” for different update rates.

estimation of the reduced model parameter ‘Ra’ for different update rates of the SSMS application. The inherent update rate of the SSMS application is 0.5 sec. In this analysis, the SSMS application was configured to generate updates every 1 sec, 1.5 sec, 3 sec and 5 sec. As the figure shows, by slowing down the update rate, information can be lost. For instance, when updating the SSMS application every 1.5 sec or more, it could not track the dip in Ra at $t = 35$ sec. On the other hand, slower update rates lead to faster estimation speed of the application.

Figure 27 shows how the probability distribution of the estimated parameter ‘Ra’ changes while varying the update rate of the SSMS application. The figure shows that slowing down the update rate results in a reduced number of estimations. Figure 28 compares the mean, maximum and

minimum values of the estimated parameter ‘Ra’ for different update rates. The figure shows that different update rates have a limited impact in the mean value of the estimated parameter ‘Ra’. This shows that the SSMS application captures the quasi-steady state behavior for the update rates analyzed.

Figure 29 shows how the SSMS application reproduces the active power at PMU 1 for different update rates. The figure shows that for an update rate of 1.5 sec or more, the SSMS application could no longer “track” the active power, in particular, a large peak in the active power at $t = 35$ sec could not be accurately tracked. However, note that the quasi-steady state of the network, for which the application is built, is adequately captured.

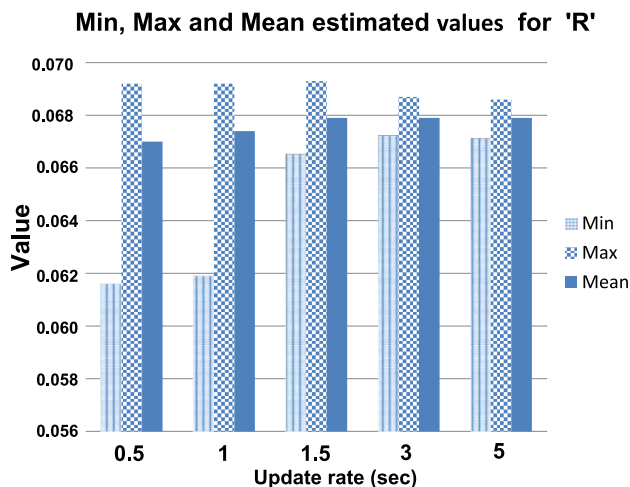


FIGURE 28. Mean, maximum and minimum estimated values for “Ra” for different update rates.

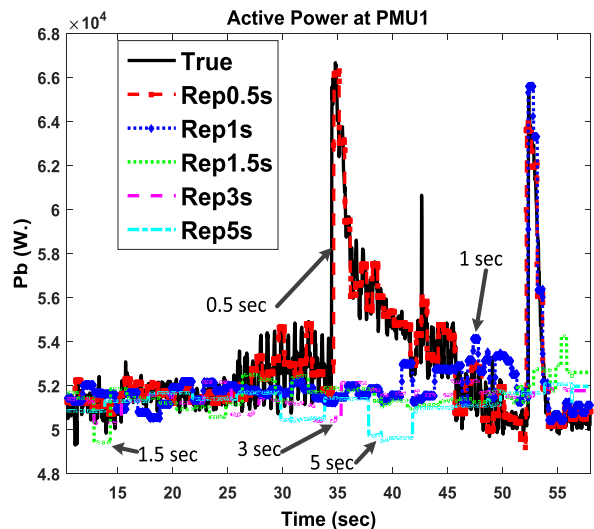


FIGURE 29. Active power at PMU 1 for different update rates of the SSMS application.

A tradeoff between accuracy (tracking) and speed (update rate) has to be considered by the user (e.g. system operators) to configure the application. It should be kept in mind that a faster update rate could provide a better estimation accuracy and hence a better tracking. That is to say, that a fast update would enable to capture more variations. This comes with the cost of higher computing burden for the application. On the other hand, if updates are required less frequently, then a faster application response could be achieved at the cost of reduced tracking while keeping the quasi-steady-state accuracy.

Figure 30 compares the average error caused by the SSMS application in reproducing the active power at PMU 1 for different update rates. As the figure shows, increasing the update rate would lead to a higher average error in the reproduced active power, due to the loss of its tracking ability. Note that the error is low considering the simplicity of the reduced model.

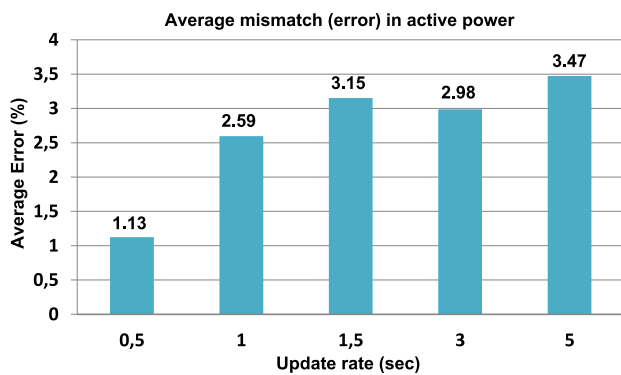


FIGURE 30. Average error in the reproduced active power at PMU 1 for different update rates.

VI. CONCLUSIONS

This paper has presented a comprehensive experimental validation of a PMU application for Steady State Model Synthesis (SSMS) of active distribution networks. The validation is performed utilizing real PMU measurements at the distribution network of EPFL. The validity of the SSMS application has been shown by testing it extensively under various network operating conditions.

It was demonstrated that the SSMS application can produce accurate equivalent reduced models of the section of the network bounded by PMUs. The performance of the application was successfully validated for the case when the EPFL network was under active and passive operating conditions. In addition, the SSMS application was tested by utilizing PMU data during a solar eclipse event, which showed satisfactory performance. The maximum estimation error was 1.4908 % for all the voltage and current phasors for all the case studies.

Ideally, the update rate of the application should automatically adapt to evolving network conditions. However, a method has to be developed, implemented and tested vigorously before such functionality can be used.

APPENDIX 1

EPFL network, line parameters: length L in km, resistance R in Ω/km , reactance X in Ω/km , and susceptance B in S/km . The subscripts 0 and 1 stand for zero and positive sequence, respectively.

	L	R_0	X_0	B_0	R_1	X_1	B_1
Line 1	0.46032	0.159	0.113	1,3e-4	0.159	0.113	1,3e-4
Line 2	0.0728	0.159	0.113	1,3e-4	0.159	0.113	1,3e-4
Line 3	0.07168	0.159	0.113	1,3e-4	0.159	0.113	1,3e-4
Line 4	0.03472	0.159	0.113	1,3e-4	0.159	0.113	1,3e-4

APPENDIX 2

End-to-End TVEs along with the mean values corresponding to Table I.

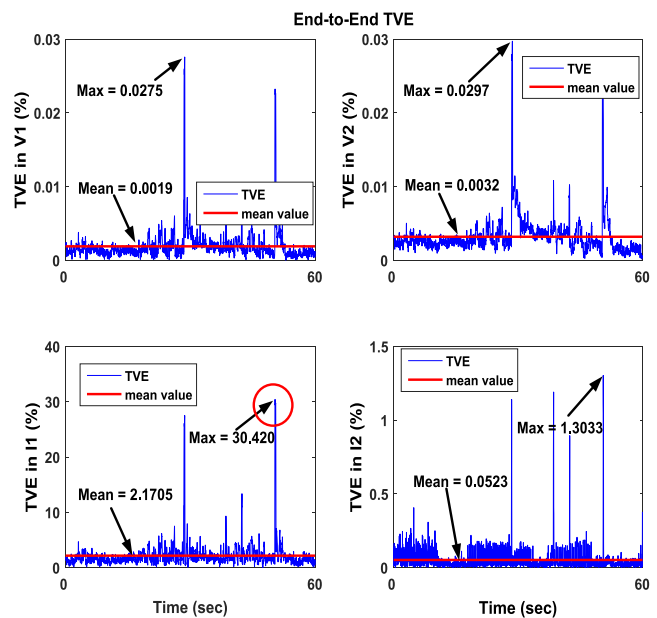


FIGURE 31. End-to-End TVE for different phasors for case study 1.

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