Synchrophasor Applications Facilitating Interactions in Transmission and Distribution Operations

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Abstract— **Dynamics of distribution grids are becoming more and more complex to analyze due to their transition from passive networks to active ones. This has necessitated the increase of observability between Transmission and Distribution (T&D) grids for operational security and real-time security assessment. This paper presents an overview of the IDE4L project, funded by the European Commission, where a system of PMU data-based monitoring applications has been developed to facilitate TSO-DSO interactions.**

Index Terms— **DSO, dynamic feeder rating, Kalman filter, mode estimator, PMU, steady state model synthesis, TSO, voltage stability analysis.**

I. INTRODUCTION

The increasing penetration of renewable energy sources together with the market-driven behavior of the demands is making the distribution grids more and more dynamic. These dynamics in tandem with those triggered by the interactions with the transmission grids have necessitated the increase of observability between Transmission and Distribution (T&D) grids for operational security and real-time security assessment. However, this is challenging with today's approach as currently most transmission system operators (TSO) have limited distribution network observability (i.e. too few measurements at the distribution level), insufficient network modeling information, deficient model information management, and computational issues for handling larger and larger models in network management functions [1].

There has been a recent interest in North America and Europe to explore the potential of utilizing Phasor Measurement Units (PMU) at the distribution level [2-7]. Real-time synchrophasor data can be used to extract key information (both "static" and "dynamic") to be used in distribution management system (DMS) functions, and also, such information can be sent to TSOs to be used in their operational functions.

Funded by the European Commission's FP7 program (7th FRAMEWORK Program for Research and Technological Development), the IDE4L (Ideal Grid for All) project is being conducted to define, develop and demonstrate distribution grid automation system, IT platform and applications for active distribution grid management [8]. The project is composed of several work packages to cover different aspects of active grid management. As part of work package 6 of the project, tighter integration of the operation of T&D grids through exchange of key dynamic information between TSOs and DSOs (Distribution System Operator) are being investigated. The key information exchange will be performed by coupling the use of PMU data from different voltage levels of the grids, coherently. The use of PMU data instead of the conventional measurements allows the developed applications to perform with higher speed. In addition, the applications dealing with grid dynamics require high resolution data which cannot be provided by the conventional measurements.

This paper presents an overview of the system of PMU data-based monitoring applications, developed in the IDE4L project, to extract key information out of the active distribution grids to be used in the DMS functions, and also to be sent to TSOs to be used in their operational functions.

II. ARCHITECTURE IMPLEMENTATION FOR SYNCHROPHASOR DATA COLLECTION AND PROCESSING

Figure 1 illustrates the synchrophasor data collection and processing architecture that has been implemented in this work. As the figure shows, the PMU measurements polluted by noise, outliers, and missing data are sent to a Phasor Data Concentrator (PDC) which, in turn, streams the data through a Wide Area Network (WAN) over TCP/IP on IEEE C37.118.2 protocol to a workstation computer holding Statnett's Synchrophasor Development Kit (S^{3}DK). S^{3}DK is a real-time data mediator which parses the PDC data stream and makes it available to the data processing unit [9].

Moreover, additional gateways have been developed in this work to transmit the PDC data stream on IEC 61850-90-5 protocol [10,11]. In this protocol, PMU data transfer is done by mapping and encapsulating the PMU data (according to IEEE C37.118.2) in GOOSE/Sampled Value messages and sending them over UDP/IP. The gateways sit at the server side (PDC) to generate IEC 61850-90-5 messages and at the client side (data processing unit) to parse IEC 61850-90-5 messages, acting as a data mediator for transmitting the PMU data. Therefore, the client side IEC 61850-90-5 gateway

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compliments the S^{3}DK data mediator by providing compliance with the IEC 61850-90-5 standard.

As Figure 1 indicates, the data processing unit plays an important role in the architecture. This is because PMU measurements are normally polluted with bad data. Discrete events, such as, tap changer operation results in outliers in PMU measurement which can affect the performance of target applications. The other problem is the missing data that is not acceptable for many applications as calculations may be affected. Moreover, PMU measurements are often contaminated with noises which can lead to wrong results. Hence, PMU measurements should be first curated from these pollutions before they can be fed to any application.

Furthermore, measurements obtained from PMUs during different events in power systems contain different signal features at different time scales. Hence they contain features of different types of power system dynamics. In addition, not all PMU applications need the same type of signal. In order to feed this data to different applications effectively, it should be processed in different ways before being fed. For example, for a conventional state estimation, the presence of oscillations around the steady state will adversely impact the performance of the application [12]. Therefore, there is a need to extract the signals required for each application from the PMU measurement before they can be fed to the applications [13].

In order to overcome the abovementioned problems, an enhanced Kalman Filter (KF) technique has been utilized in the data processing unit for both bad data removal and extraction of the proper signal feature from the PMU data [14]. Figure 2 compares the raw data of a voltage phasor with its curated version, i.e. the output of the enhanced KF. As the figure shows, the curated data is free from outliers and noise.

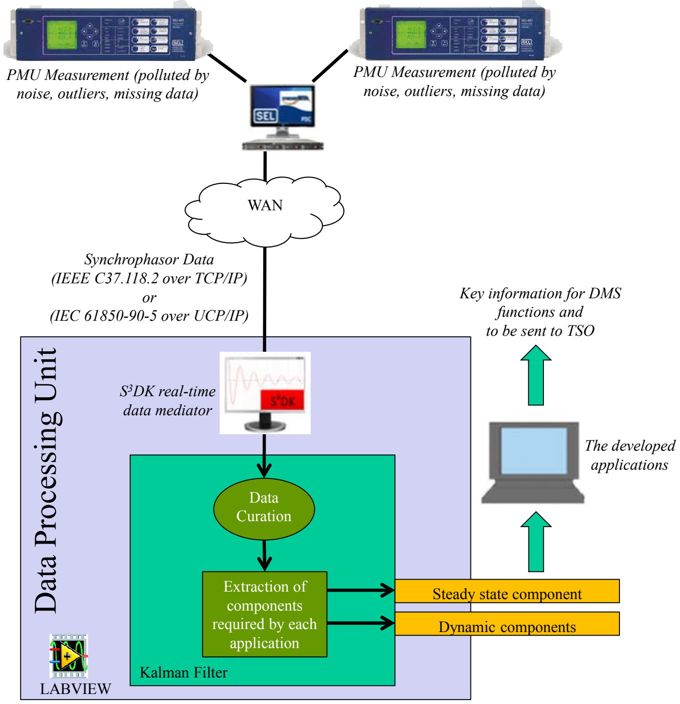
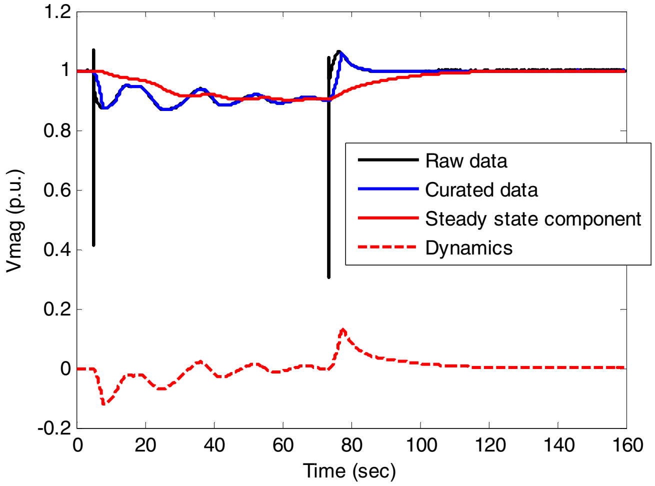
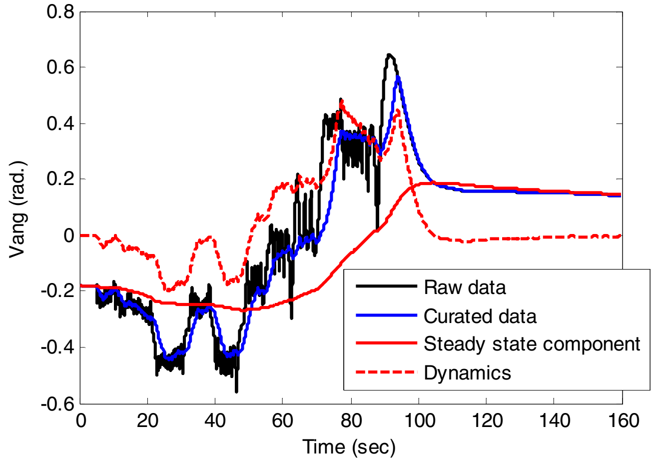


Figure 1. The implemented architecture.



(a) voltage magnitude (per unit)



(b) voltage angle (radian)

Figure 2. Raw data, curated data, and extracted features of a voltage phasor.

In addition, the system's dynamic response (oscillations) and the steady state component of the signals have been extracted from the curated phasor data. More details on the enhanced KF can be found in [13,14].

Finally, the appropriate signal features are fed to the developed real-time monitoring applications. Note that further application-specific data processing is performed within the developed applications. The outputs of the applications are to be used by the DMS functions; however, some key dynamic information is selected to be sent to TSOs to support the management functions. A few selected developed applications are explained in the next section.

III. SYNCHROPHASOR APPLICATIONS FOR TIGHTER INTERACTION OF TSOS AND DSOS

This section summarizes selected PMU data-based monitoring applications, developed during the IDE4L project, in order to provide key information out of the distribution grids and to facilitate TSO-DSO interactions. Performance of the developed applications has been assessed by real-time hardware-in-the-loop simulations on a reference active distribution grid model [15].

A. *Quasi-Steady State Model Synthesis*

TSOs need to determine reduced models of distribution networks to be used in their grid management functions and to have more insight over distribution networks. Currently, some TSOs are able to determine reduced models of limited portions of the distribution networks however the models are updated yearly. Also, available models have assumptions, such as pure loads, that are no longer valid for active distribution networks.

Assuming that PMU measurements are available at the boundary buses of a distribution grid, a three-phase quasi-steady state equivalent model can be synthesized as illustrated in Figure 3 [14]. The quasi-steady state model synthesis application was tested to synthesize the equivalent model of the reference active distribution grid model presented in [15]. Real-time voltage and current synchrophasors were acquired from PMU 3 and PMU 4, shown in Figure 4, to produce the equivalent model of the section bounded by the two PMUs. The reference grid was simulated in real-time using an Opal-RT simulator within a hardware-in-the-loop simulation setup.

Figure 5 depicts a snapshot of the developed application showing variations in phase ‘a’ of the synthesized model parameters while two consecutive discrete events occurred in the test grid. The two events were created as follows: 1) A lateral MV feeder disconnects at Node 834 at t = 40 s, and 2). A wind farm generation of 1 MW (0.2 p.u.) disconnects at Node 854 at t = 70 s. As Figure 5 shows, the disconnection of the lateral feeder (Event 1) mainly impacts the value of R^a and X^a. This is because when the lateral feeder disconnects, the currents flowing through all phases of the main feeder reduce accordingly which, in turn, decreases the voltage drop induced on all phases through the mutual coupling. In case of Event 2, the disconnection of the wind farm, located inside the bounded section of the two PMUs, causes E^a to drop from 0.982 p.u. to 0.93 p.u.

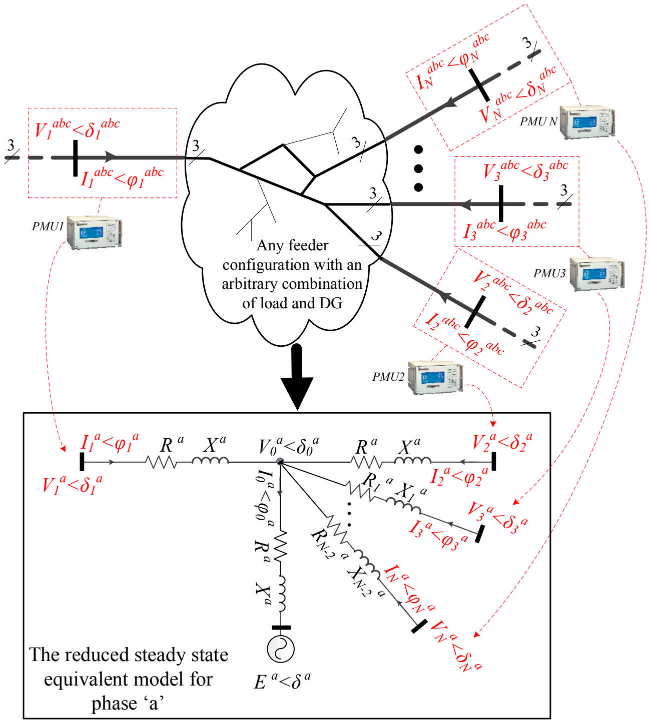


Figure 3. Synthesized steady state model of the monitored distribution grid.

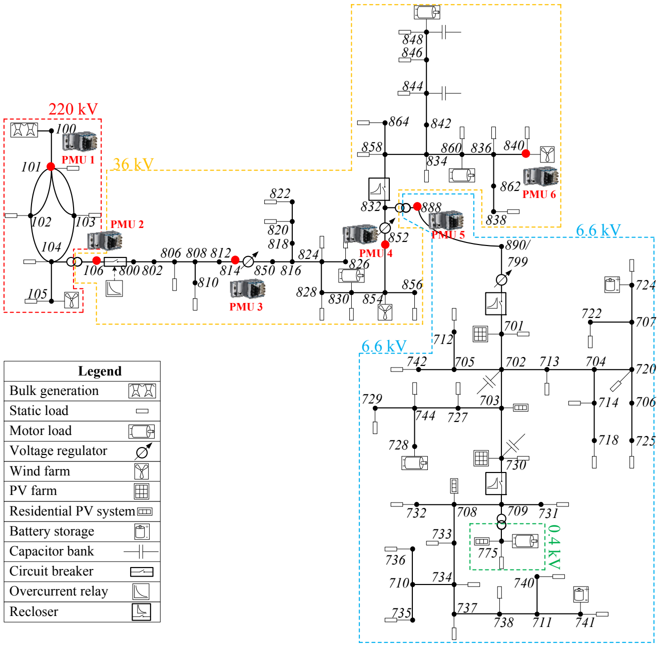


Figure 4. The reference active distribution grid model.

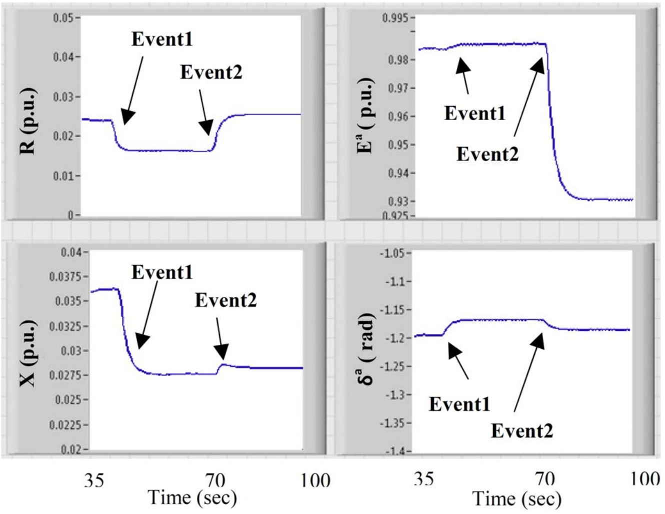


Figure 5. Snapshot of the steady state model synthesis application.

B. *Decoupled Voltage Stability Assessment*

The transition of distribution grids from passive to active has brought up challenges to available voltage stability assessment methods. This is mainly due to the underlying assumptions that have been used to develop them.

Given that PMU measurement is available at the bus of interest, voltage stability assessment can be performed in real-time by computing the system Thevenin equivalent and using the load-line impedance matching theory. Moreover, it is possible to decouple the effects of the transmission and the distribution grids on the voltage stability at the bus of interest provided that PMU measurement is available at the point of common coupling (PCC) between the T&D grids [16]. The aim of decoupling the effects is to assist TSOs and DSOs by identifying and quantifying the need of voltage support services in different parts of the power system, and implicitly determine who should provide them. This is done by splitting the system Thevenin equivalent into two circuits each representing one of the grids, as shown in Figure 6. The circuit parameters can be calculated using the PMU data from the load bus of interest and the PCC.

The voltage stability assessment application was tested on bus 888 (i.e. considered as a load bus) at the LV level of the reference grid model shown in Figure 4. Data from PMU 5 (i.e. $\mathrm{PMU}_{\mathrm{LoadBus}}$) and PMU 2 (i.e. $\mathrm{PMU}_{\mathrm{PCC}}$) are acquired to perform the assessment and also to decouple the effects of the transmission and the distribution grids.

Figure 7 shows a snapshot of the application containing three P-V (voltages versus active power) curves. While the yellow curve incorporates the impact of both T&D grids, the green and the red curves denote the effect of the distribution grid and the transmission grid, respectively. As the curves indicate, the distribution grid has the higher share on the voltage instability of bus 888. Note that the curves and the instability indices are updates in real-time. The snapshot, shown in Figure 7, corresponds to a time period when the distributed generation units (DG) at the MV level are all out of service. Figure 8 shows the curves at the same bus when the DGs are back in service. In the latter case, the T-model, representing the distribution grid in Figure 6, has lower branch impedances but higher E_{pd}. On comparison of the figures, it is clear that the addition of the DGs has improved the effect of the distribution grid on the voltage stability of bus 888.

C. *Mode Estimator*

Accurate and real-time estimation of active distribution grids oscillatory modes has become ever so important in dealing with complex interactions with the transmission grid and the growing number of power electronics controlled distributed generation. Modal frequencies and damping are useful indicators of distribution grid stress, usually increasing with increased load or reduced grid capacity. Timely extraction of these and related parameters from grid measurements has considerable potential for near real-time dynamic security assessment.

In this work, PMU measurements are harnessed to obtain mode estimates of active distribution grids [17]. In quassi-steady state, the developed application acquires ambient data, and runs an Auto-Regressive Moving Average (ARMA)-based, *Modified Yule Walker* method to estimate modal parameters. If ringdown condition (i.e. transients) is detected, the application uses a separate *Ringdown Analyzer* algorithm which is based on Eigensystem Realization Algorithm (ERA) and operates only for the ringdown portion of the system response. In addition, an index based on the estimated modes and damping ratios is defined to assess the distribution grid dynamic stability.

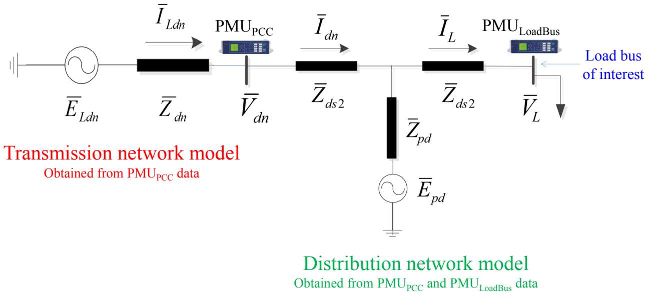


Figure 6. Splitting system Thevenin equivalent using PMU data.

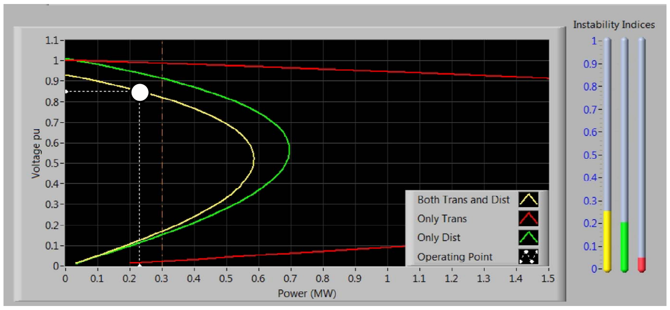


Figure 7. P-V curves at bus 888 when all MV DGs are out of service [16].

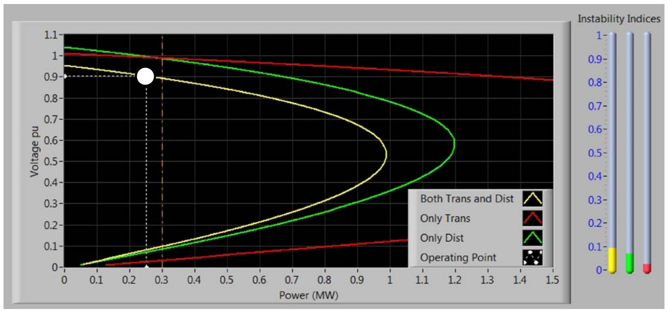


Figure 8. P-V curves at bus 888 when all MV DGs are back in service [16].

The application has been assessed under both centralized and decentralized architectures. In the centralized mode, the application runs the mode estimation algorithm and processes all the PMU data from various locations in one iteration as in a set of data from a multi input multi output (MIMO) system and estimates single set of modes depending upon the order of the system. In this architecture mode, the application sits on the DMS computers. In the decentralized mode, multiple instances of the application apply the algorithm individually to single PMUs or groups of PMUs. This means that for each PMU or each group of PMUs, there should be a processing unit at the secondary substation to run the algorithm. The estimated modes by the processing units are then collected by a central processing unit, i.e. the DMS computers. The decentralized implementation is aimed to effective identification of local modes present in the system which might not be observable in the centralized implementation. It is worth noting that the PMU data being fed to the application remains the same in both architecture modes.

The mode-meter application was tested to identify the modes present in the reference active distribution grid model shown in Figure 4. PMU data was acquired from different voltage levels of the grid. As before, the reference grid was simulated in real-time using an Opal-RT simulator within a hardware-in-the-loop simulation setup. The reference grid possesses an inter-area mode of 0.41 Hz, due to the oscillation in the main generating unit, and a local mode of 1.7 Hz, due to a forced sinusoidal variation in the local load demand, at the LV level. The modes were previously identified by Fast Fourier Transform (FFT) analysis of the recorded PMU data for the purpose of validating the mode-meter application.

Figure 9 shows the results for the centralized architecture in terms of Probability Density Function (PDF) plots. The PDF plots suggest high density of estimates around 0.41 Hz that is indeed the inter-area mode. The damping ratio detected ranges from 0% to 5%. In addition, the local 1.7 Hz mode is poorly detected as the PDF plot depicts a high level of deviation. Figure 10 shows the results from the decentralized architecture which tries to improve the identification ability of local mode. The estimates taken for this plot are only from PMU 5 at the LV level where the local mode is present. The plot suggests high density of estimates at around the frequency of 0.41 Hz and also at around the frequency of 1.7 Hz which is the local mode. On comparison of the plots it is clear that the local mode is better identified by the decentralized architecture.

D. *Feeder Dynamic Rating*

Extension of existing distribution grids requires consent from the authorities and a significant investment. This can take several years to be implemented. Adding to these circumstances, the increase of generation installations at lower voltage levels, that pose challenges for grid operation, results in increased pressure on electric utilities to make optimum use of existing facilities. Dynamic thermal rating of a conductor (i.e. the conductor current that produces maximum allowable conductor temperature at a specific location and time along the power line) can be computed by feeder dynamic rating systems in order to utilize the conductor full capacity.

The feeder dynamic rating application, developed in this work, acquires data in real-time from weather station (for ambient data), PMU (for line loading), and GPS positioning sensor (for conductor sag) [18]. The application utilizes a Kalman filter to reliably estimate the conductor temperature based upon which the ampacity is computed for each phase of the feeder separately, making the application applicable to distribution grids where unbalances are present.

Figure 11 illustrates the block diagram of the proposed feeder dynamic rating algorithm. As shown in the figure, the algorithm is initiated by feeding the real-time conductor sag measurement to the state change equation block that allows to solve for an estimate (termed herein as 'measurement') which enables an indirect measurement of the conductor's temperature (number 2 in Figure 11) [19]. However, as the sag measurement may contain errors due to GPS-inaccuracies or sensor's inaccurate positioning, the conductor temperature obtained from the state change equation should not be directly used to compute the real-time ampacity. Another mean to obtain an estimate of the conductor's temperature is to use the IEEE 738 standard [20]. In this work, the IEEE 738 standard is used to predict the conductor's temperature (number 1 in Figure 11) in each time step. This actually forms the

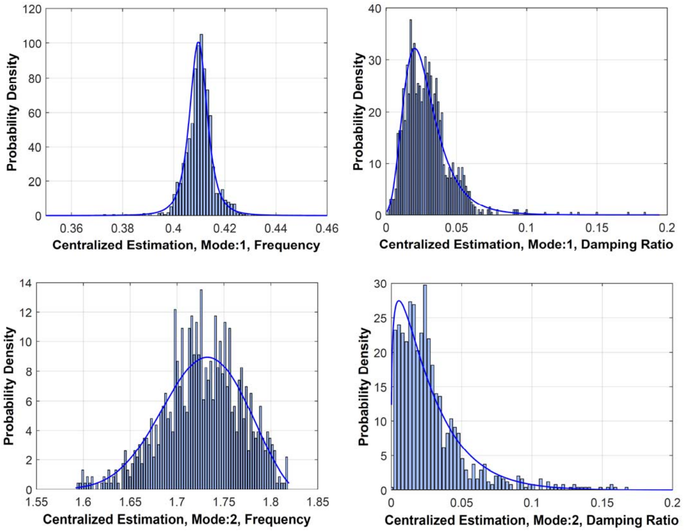


Figure 9. Estimates from centralized estimation; TOP: PDF of Mode 1 frequency (left), PDF of Mode 1 damping ratio (right); BOTTOM: PDF of Mode 2 frequency (left), PDF of Mode 2 damping ratio (right).

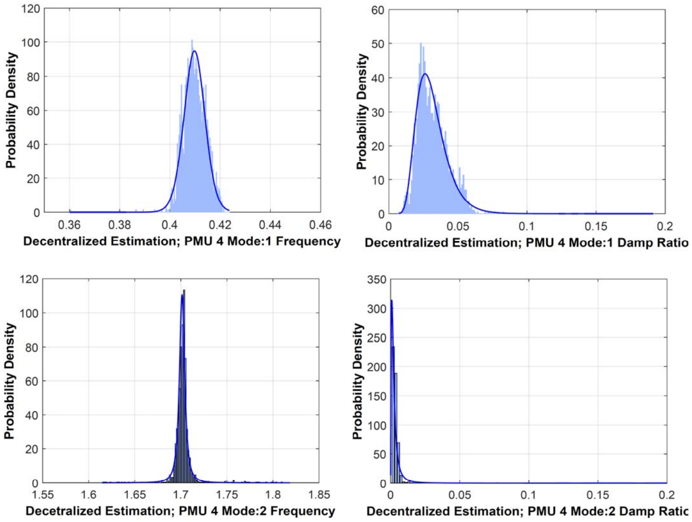


Figure 10. Estimates from decentralized estimation; TOP: PDF of Mode 1 frequency (left), PDF of Mode 1 damping ratio (right); BOTTOM: PDF of Mode 2 frequency (left), PDF of Mode 2 damping ratio (right).

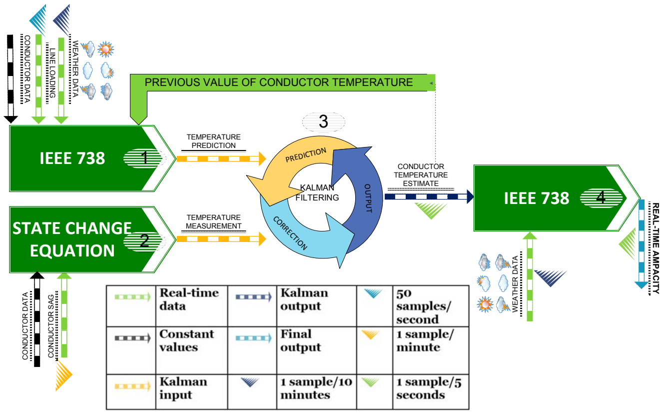
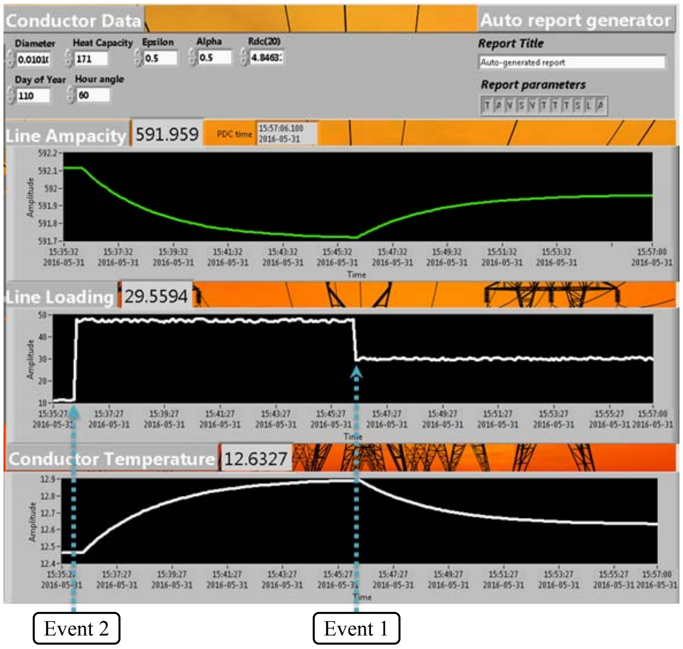


Figure 11. Block diagram of the developed feeder dynamic rating applicatiion.

prediction step of the proposed Kalman filter as the 'predicted' value is basically the forward projection in time of the previously estimated conductor temperature. The 'measurement' estimated using the state change equation and the 'predicted' value from the IEEE 738 standard are merged using a Kalman filter to produce a more accurate estimate of the conductor temperature (number 3 in Figure 11). The Kalman filter not only improves the certainty of the estimates but it is exploited here as a tool to merge data that is updated at different rate. As shown in Figure 11, while the line loading is updated 50 samples/second by PMUs, the conductor sag measurement and ambient conditions are available at 1 sample/minute and 1 sample/10 minutes, respectively. While merging two inputs, the Kalman filter uses sample-and-hold technique for the input with the slower updating rate. Having an accurate estimate of the conductor temperature from the Kalman filter, the IEEE 738 standard is brought to use again; this time to calculate ampacity of the conductor (number 4 in Figure 11).

Figure 12 shows a snapshot of the application while it is used to determine the dynamic rating of the line 800-802 of the grid shown in Figure 4. The events, implemented during this test, are the same as the ones described in Section III.A. As the figure shows, while disconnection of the wind farm leads to a decrease in the line rating, disconnection of the MV lateral allows the line rating to increase. This is, in fact, because the two events affect the current loading of the line.


Conductor Data

Diameter 0.0101(
Heat Capacity 171
Epsilon 0.5
Alpha 0.5
Rdc(20) 4.8463:
Day of Year 110
Hour angle 60

Auto report generator

Report Title: Auto-generated report

Line Ampacity 591.959
PDC time 15:57:06.100 2016-05-31

Line Loading 29.5594

Conductor Temperature 12.6327

Figure 12. Snapshot of the feeder dynamic rating application.

IV. CONCLUSIONS

This paper presented an overview of the system of PMU data-based monitoring applications, developed in the European Commission IDE4L project, to extract key information out of the active distribution grids. The extracted information is to be used in the DMS functions, and also to be sent to TSOs to be used in their operational functions.

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