Synchrophasor Applications for Distribution Networks, Supporting The IDE4L Use Case

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Abstract— **Distribution grid dynamics are becoming increasingly complex to analyze due to their transition from passive to active networks. This transition requires to increase the observability and awareness of the interactions between Transmission and Distribution (T&D) grids, particularly to guarantee adequate operational security. As part of the work carried out in the EU-funded IDE4L project, a specific use case, containing PMU-based monitoring functions, has been defined to support the architecture design of a distribution grid automation system. As a result, the architecture can accommodate for key dynamic information extraction and exchange between Distribution System Operator (DSO) and Transmission System Operator (TSO). This paper presents the use case and focuses on the technical aspects related to the development and implementation of the PMU-based monitoring functionalities.**

Index Terms— **active distribution grid, Kalman filter, PMU, SGAM, use case.**

I. Introduction

To facilitate adequate technical functioning of the overall electric power system, the interactions between the technical operation of distribution grids and the main transmission grid requires to "exchange information" that can help in the technical functions of both network operators. As of today, it is challenging for Distribution System Operators (DSOs) to provide and maintain a network model of their electrical grid, which if constantly updated, could help in extracting key information about the network's state. In addition, DSOs currently do not have access to nor exchange much measurement data with the Transmission System Operators (TSO), and if they do, very little (or non) of these measurements are shared in hard real-time, nor do they have high sampling resolution and time-synchronization. This means that the measurement data available is too limited in quantity (i.e. locations and signals), and also in "observability" (i.e. the content of the frequency spectrum available due to sampling resolution) [1].

Therefore, in the current situation, a short-term solution to enhance "information exchange" would be to make new measurement devices that provide real-time, high-sampled data across operational boundaries from which information can be extracted. To this end, the work within the *Ideal Grid For All* (IDE4L) project, funded by the European Commission, considered the utilization of synchronized phasor measurements with millisecond resolution, i.e. real-time data from Phasor Measurement Units (PMU) [2]. This approach is sensible considering the recent trends in North America and Europe to explore the potential of utilizing PMUs at the distribution level [3,4]. The implementation of such PMU-based "information exchange" has to go through a properly designed and implemented architecture that can satisfy all application-dependent technical requirements while considering the different actors and operational boundaries involved.

The IDE4L architecture is built upon the 5-layer Smart Grid Architecture Model (SGAM) framework that has been developed by the CEN-CENELEC-ETSI Smart Grid Coordination Group [5]. The SGAM framework is the main response to the EU Mandate M/490 on development of a framework to support European smart grid deployment [6]. The main inputs to the architecture design are the use cases that describe the architecture requirements, actors and functionalities. The use of SGAM aids in developing a common understanding between domain experts and IT experts [7]. The IDE4L architecture is constructed based on several use cases one of which is the "Distribution grid dynamic monitoring" defining PMU-based monitoring functions that can provide key dynamic information for both Distribution Management System (DMS) and TSOs.

This paper presents an overview of the "Distribution grid dynamic monitoring" use case with more focus on the technical aspects of the functionalities developed to derive dynamic information of active distribution grids using PMU data. The paper begins by presenting an overview of the use case in Section II. Sections III and IV explain the core functionalities for derivation of the dynamic information. Conclusions are drawn in Section V.

II. The Use Case Definition

As indicated in the previous section, the objective of this use case is to manage the new complexity and inter-dependence between electric power transmission and distribution grids, that have raised as a result of the 'energy transition'. One strategy to achieve this is through exchange of key dynamic information between TSOs and DSOs and also

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between DMS functions. Key information extraction and exchange will be performed by coupling the use of PMU data from different voltage levels, across the operational boundaries of the grids, coherently.

As shown in the figure, synchrophasors are provided by PMUs distributed on the feeders, installed at the Primary Substation (PS) or at the Secondary Substation (SS). The synchrophasors are then collected by the PS-level and the SS-level Phasor Data Concentrators (PDC) which, in turn, stream the data through a Wide Area Network (WAN). The data is transferred either over TCP/IP on IEEE C37.118.2 protocol or over UDP/IP on IEC 61850-90-5 protocol to a higher level in the architecture hierarchy. The data is finally delivered to DMS computers at the DSO for real-time processing and extraction of dynamic information, performed by newly developed monitoring applications. The outputs of the applications are to be used by other DMS functions; however, some key dynamic information is selected to be sent to TSO to support the EMS functions.

As Figure 1 indicates, because some of the synchrophasor applications can be implemented in distributed fashion within the architecture, data processing and information derivation is performed at both the Station and the Operation zones.

The actors involved in this use case are transducer (i.e. instrumentation chain including CTs and VTs), PMU, PDC, communication interface, DMS, and EMS [8]. The functions involved in this use case are electrical conversion, synchrophasor calculation, data acquisition, data concentration and time-alignment, data exporting, data curation, extraction of different time-scale components from the PMU data, and derivation of key information out of the data.

As mentioned before, once the use case description is available, it is possible to realize the use case mapping onto the SGAM layers. The following sections of the paper elaborate on the last three functions involved in this use case.

III. Data Curation and Extraction of Components

PMU measurements are normally polluted with undesirable noise and contain 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. Hence, PMU measurements should be first curated from these pollutions before they can be fed to any application [9].

Furthermore, measurements obtained from PMUs during different events in power systems contain different signal features at different time scales, i.e. 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 [10]. 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.

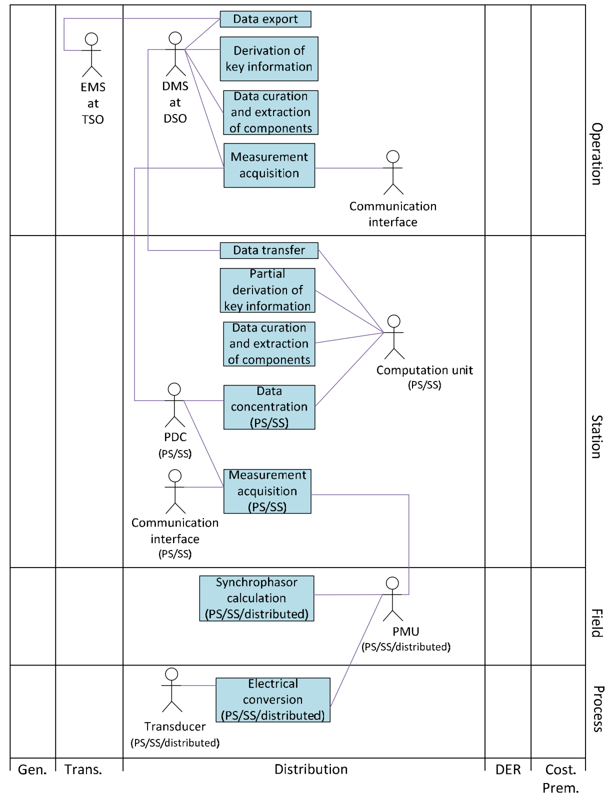


Figure 1. Diagram of the "grid dynamic monitoring" use case mapped on the *Smart Grid Plane*.

In order to overcome the aforementioned problems, an enhanced Kalman Filter (KF) technique has been utilized for both bad data removal, i.e. data curation, and extraction of the proper signal feature from the PMU data [11]. Considering the curated data as states of a linear discrete time process, the PMU raw data can be related to the curated data using linear stochastic process and measurement equations as stated in (1).

$$\begin{aligned} \boldsymbol{x}_k &= \boldsymbol{A}\boldsymbol{x}_{k-1} + \boldsymbol{B}\boldsymbol{u}_k + \boldsymbol{w}_{k-1} \\ \boldsymbol{z}_k &= \boldsymbol{H}\boldsymbol{x}_k + \boldsymbol{v}_k \end{aligned} \tag{1}$$

where $\boldsymbol{x}$ is the state vector, $\boldsymbol{z}$ is the measurement vector, $\boldsymbol{A}$ is the n x n matrix that relates the state at previous time step k-1 to the state at current step k, which is assumed to be constant in each iteration, $\boldsymbol{B}$ is the control input which relates input u to the state $\boldsymbol{x}$ and $\boldsymbol{H}$ is the m x n matrix which relates state $\boldsymbol{x}_k$ to the measurements z_k. The process noise $\boldsymbol{\omega}_k$ and measurement noise $\boldsymbol{v}_k$ are assumed to be two mutually independent random variables with normal probability distributions

$$\begin{aligned} p(\boldsymbol{w}) &\sim N(0, \boldsymbol{Q}) \\ p(\boldsymbol{v}) &\sim N(0, \boldsymbol{R}) \end{aligned} \tag{2}$$

where $\boldsymbol{Q}$ is the process noise covariance matrix and $\boldsymbol{R}$ is the measurement noise covariance matrix.

The states of the process, i.e. the curated data, can be obtained by cleaning up the measurements, i.e. the PMU raw data, using the two KF steps, namely *Prediction* and *Correction*, for each frame of measurement. The prediction step, stated in (3), is responsible of projecting forward (in time) the previous state $\hat{\boldsymbol{x}}_{k-1}$ and the error covariance estimate $\boldsymbol{P}_{k-1}$ to obtain the a priori state estimates $\hat{\boldsymbol{x}}_k$ and the a priori error covariance estimate $\boldsymbol{P}_k^-$ for the next step k:

$$\begin{aligned} \hat{\boldsymbol{x}}_k^- &= \boldsymbol{A}\hat{\boldsymbol{x}}_{k-1}^- + \boldsymbol{B}\boldsymbol{u}_{k-1} \\ \boldsymbol{P}_k^- &= \boldsymbol{A}\boldsymbol{P}_{k-1}\boldsymbol{A}^T + \boldsymbol{Q} \end{aligned} \tag{3}$$

Whereas the correction step, stated in (4), is responsible for feedback by incorporating a new measurement z_k into the a priori estimate to obtain an improved a posteriori estimate:

$$\begin{aligned} \boldsymbol{K}_k &= \boldsymbol{P}_k^-\boldsymbol{H}^T(\boldsymbol{H}\boldsymbol{P}_k^-\boldsymbol{H}^T + \boldsymbol{R})^{-1} \\ \hat{\boldsymbol{x}}_k &= \hat{\boldsymbol{x}}_k^- + \boldsymbol{K}_k(\boldsymbol{z}_k - \boldsymbol{H}\hat{\boldsymbol{x}}_k^-) \\ \boldsymbol{P}_k &= (\boldsymbol{I} - \boldsymbol{K}_k\boldsymbol{H})\boldsymbol{P}_k^- \end{aligned} \tag{4}$$

where $\boldsymbol{K}$ is an n x m matrix known as the Kalman gain matrix, z_k is the actual measurement at step k, $\boldsymbol{H}\hat{\boldsymbol{x}}_k^-$ is the predicted measurement, $\hat{\boldsymbol{x}}_k$ is the a posteriori estimate which is a linear combination of an a priori estimate $\hat{\boldsymbol{x}}_k^-$ and a weighted difference between z_k and $\boldsymbol{H}\hat{\boldsymbol{x}}_k^-$.

The accuracy of a KF output is influenced by the measurement and process noise covariance matrices, i.e. $\boldsymbol{R}$ and $\boldsymbol{Q}$. Therefore, these two parameters can be exploited in a proper way to perform bad data processing and also extracting the proper signal feature of the PMU data. In this work, $\boldsymbol{R}$ is updated depending upon the quality of the measurements and presence of different features to filter out the bad data and remove any unwanted signal features. Whereas $\boldsymbol{Q}$ is updated to treat the unmodeled process noise which is, in our case, any change in the desired feature of the measured signal.

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. In addition, the system's dynamic response (oscillations) and the steady state component of the signals have been extracted from the curated phasor data.

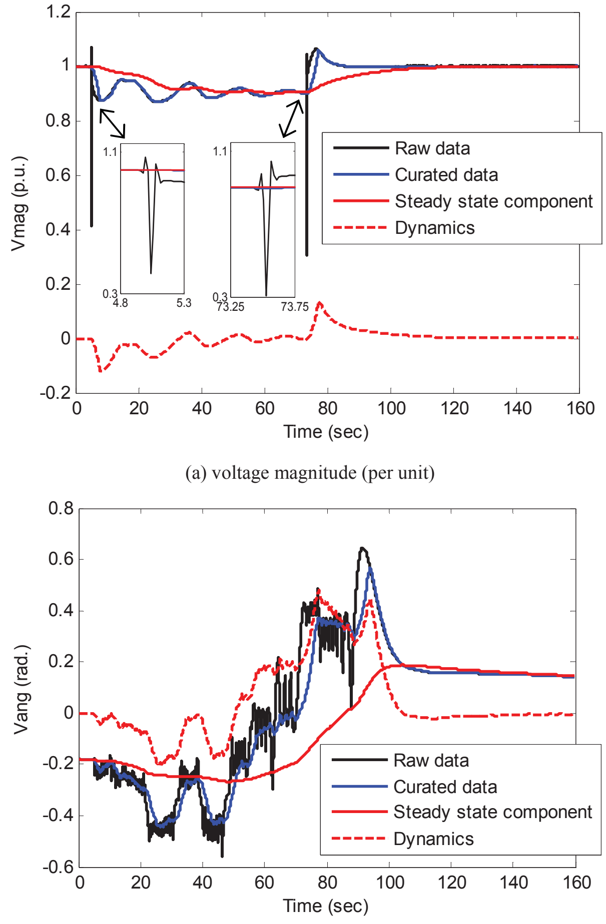
The appropriate signal features are then fed to the developed real-time monitoring applications, explained in the next section, for derivation of key information.

IV. Derivation of Key Dynamic Information

Several applications have been developed in the IDE4L to extract key dynamic information of active distribution grids using PMU data. However, due to space limitations, a couple of them are selected for presentation in this section.

A. Mode Estimator

Accurate and real-time estimation of active distribution



(a) voltage magnitude (per unit)

(b) voltage angle (radian)

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

grids oscillatory modes is important when dealing with complex interactions between 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 [12]. 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 a 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.

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 at the operation zone. 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 station zone to run the algorithm. The estimated modes by the processing units are then collected at the operation zone 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 a reference active distribution grid model presented in [13]. As shown in Figure 3, PMU data was acquired from different voltage levels of the grid. 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 4 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

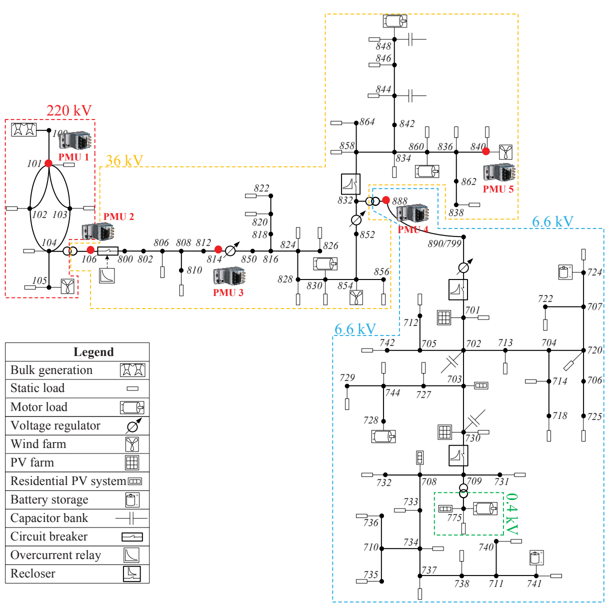


Figure 3. The reference active distribution grid model.

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 5 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 4 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.

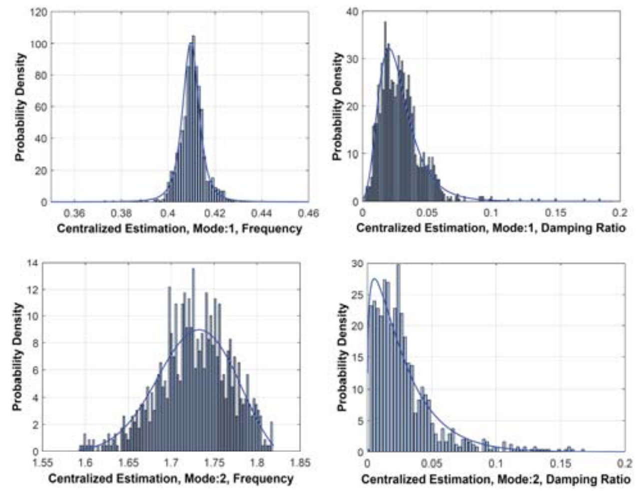


Figure 4. Estimates from centralized estimation; TOP: PDF of Mode 1 frequency (left), PDF of Mode 1 damping ratio (right); BOTTOM: PDF of Mode 2 frequency (left), PDF of Mode 2 damping ratio (right).

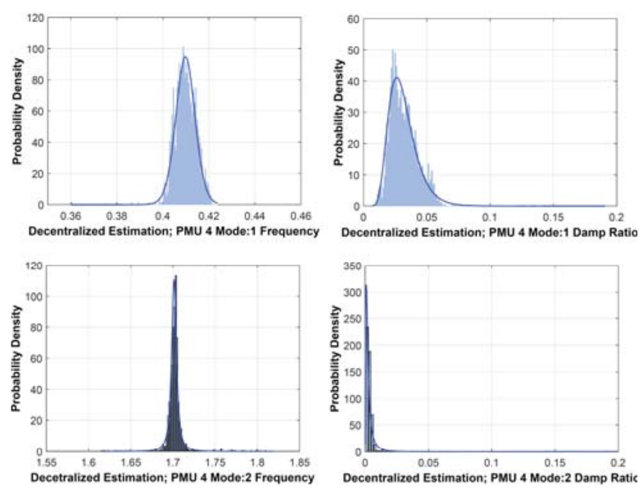


Figure 5. Estimates from decentralized estimation; TOP: PDF of Mode 1 frequency (left), PDF of Mode 1 damping ratio (right); BOTTOM: PDF of Mode 2 frequency (left), PDF of Mode 2 damping ratio (right).

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 [14]. 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 3. Data from PMU 4 (i.e. $PMU_{LoadBus}$) and PMU 2 (i.e. PMU_{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

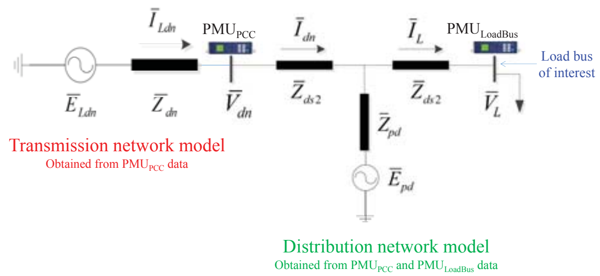


Figure 6. Splitting system Thevenin equivalent using PMU data.

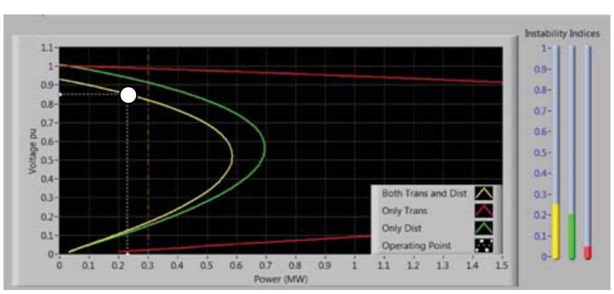


Figure 7. P-V curves at bus 888 when all MV DGs are out of service [14].

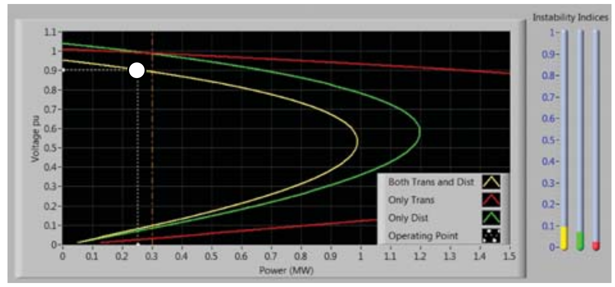


Figure 8. P-V curves at bus 888 when all MV DGs are back in service [14].

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.

V. CONCLUSIONS

This paper presented a use case, containing PMU-based monitoring functions, to support the architecture design of the distribution grid automation system; such that the architecture can accommodate key dynamic information exchange with TSOs and within the DMS.

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