MIGRATING TOWARDS A SMART DISTRIBUTION GRID: STATE OF THE ART

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ABSTRACT

Today, distribution utilities all over the US are beginning to migrate towards a smarter and more reliable distribution grid, requiring the incorporation of advanced automation and control strategies to the existing distribution grid. This paper provides a detailed investigation of smart distribution grid (SDG) concepts in order to provide a comprehensive explanation to a power distribution utility engineer about the future advanced distribution management system (ADMS) which will perform advanced distribution automation (ADA). It discusses the issues and challenges that may surface while designing and implementing an ADMS for the SDG and proposes effective solutions.

INTRODUCTION

Distribution system automation strategies, established and implemented as early as the late 1980s, are continuously evolving. They have now taken a new shape as the SDG, with the development of sophisticated electrical and communication interface and advanced control strategies. Some of the characteristics of the future distribution grid are emphasized in brief in references [1]-[2]. The SDG concept is the method of operating the distribution grid more efficiently and effectively by means of ADA applications. These applications, broadly classified as substation automation (SA), feeder automation (FA) and customer automation (CA), are the fundamental blocks of the SDG concept and are driven by the functionality of customer-side connected distributed energy resources (DER), as shown in Figure 1. The interface and control between these applications is key, and can be accomplished using the existing state-of-the-art communication technologies and equipment advancements.

Distribution utilities in the US are already in the process of advanced metering infrastructure (AMI) and meter data management systems (MDMS) deployment as the first steps towards SDG and they are also prepared to extensively incorporate distributed energy resources (DER), especially, intermittent resources like wind turbine generators (WTG), photovoltaic generation (PV), plug-in hybrid electric vehicles (PHEV) and various forms of distributed energy storage. Hence the control strategy and interfacing of the three ADA applications (SA, FA, and CA) will significantly depend upon the functionality of the deployed DER and its amount of penetration to the distribution grid.

In this paper, we present four crucial aspects that are highly relevant to the SDG concept:

- We address the challenges relating to utilizing the AMI/MDMS data for ADA functions, and propose viable solutions.
- We propose an ADMS concept for the first generation SDG. The words "first generation" here refer to the distribution grid in the next 5 to 10 years which will incorporate the well-established DER technologies like WTG, PV and PHEV. For this concept, PHEV are envisioned as the main energy storage devices in the near future. The proposed concept presents an ADMS which interacts with both the distribution side and transmission side.
- We illustrate the functionalities required for the advanced distribution network analysis (ADNA) tool which is the heart of an ADMS.
- We present the challenges of incorporating PHEV on the low voltage secondary distribution system and propose solutions to mitigate the challenges associated with thermal loading and voltage drop constraints. These issues are illustrated using PSS®SINCAL simulation examples.

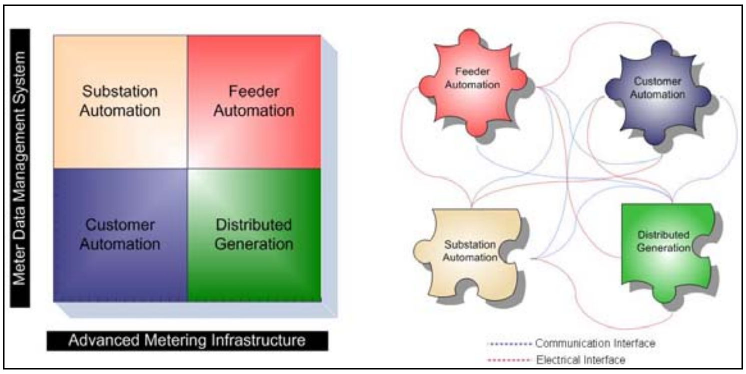

Figure 1: Fundamental Block Diagram of the Smart Distribution Grid Concept

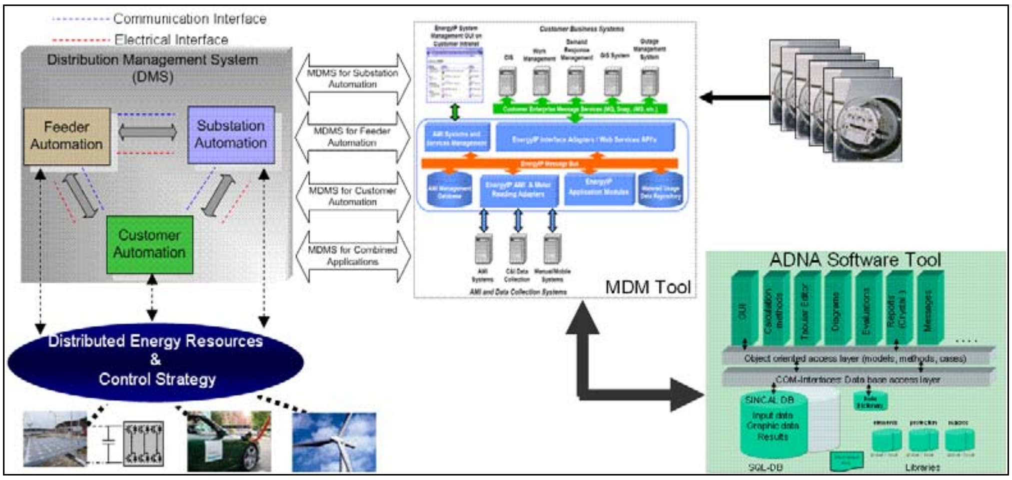

Figure 2: Conceptual Diagram of AMI/MDMS Information Flow to ADMS

UTILIZATION OF AMI/MDMS DATA FOR ADA FUNCTIONALITY

The Advanced Metering Infrastructure (AMI)/Meter Data Management Systems (MDMS) which is believed by the distribution utilities to be the first step on the road to a smarter distribution grid, is the core component for processing the metered data to be applied in SA, FA, and CA and also for combined and interlinked applications. Presently utilities in the US are actively implementing AMI/MDMS functionality for their respective distribution grids. Figure 2 shows the conceptual methodology of updating the metered data to ADMS in 15 minute intervals through a MDMS platform interface. The major role of MDMS is to process the 15 minute metered data specifically for each ADMS automation function.

The MDMS database can also be linked with the ADNA software tool database in order to perform offline network analysis for short term network planning applications. The 15 minute load profile interval data at each distribution transformer is metered and updated through the database linking the MDMS and the ADNA software tool. The load/generation profiles can be entered in short intervals and the results obtained after the load flow analysis will provide very detailed information on the system conditions (like element utilization, loadings, system losses, voltages, etc) on a short term basis (15 minute intervals).

FIRST GENERATION SMART DISTRIBUTION GRID

The words "First Generation" here refers to distribution system advancements in the next 5 to 10 years which would incorporate the currently existing well-established DER technology pertaining to WTG, PV and PHEV. Other DER technologies, though researched and developed extensively, have only just begun to emerge into the industry at present. PHEV batteries are envisioned as a main energy storage device for the near future.

ADMS CONCEPT FOR FIRST GENERATION SMART DISTRIBUTION GRID

A simple example of a first generation smart distribution grid is presented: this is a primary substation with 3 medium voltage distribution feeders (1 blue, 2 red and 3 green) as shown in Figure 3, supplying residential and commercial consumers, and with 2.5 MW of coincident peak load in each feeder,. The feeders are assumed to have appropriate load transfer switching between each other. In each feeder the DER penetration and the load type are the following:

- Feeder 1 has nearly 3 MW installed capacity of PV generation, and residential load.
- Feeder 2 has a few PHEV charging stations, and residential load.
- Feeder 3 has 1.8 MW installed capacity of wind generation, and commercial load.

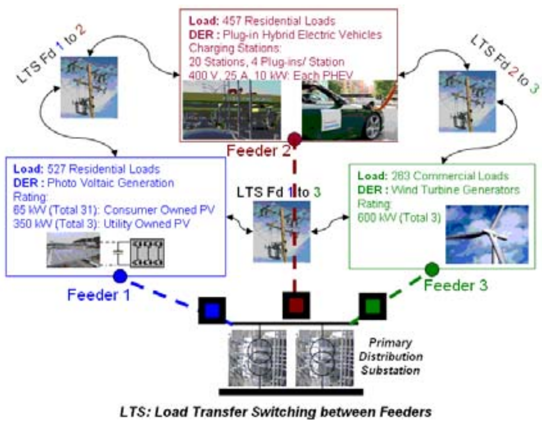

Figure 3: First Generation Smart Distribution Grid

The DMS control strategy has to be developed taking into account the AMI and the DER penetration of the first generation smart distribution grid. The main challenge in this case is to implement a control strategy for high variability of DER output hourly, daily, and weekly in feeders 1, 2 and 3. PV and wind have, for the most part, an inverse generation dispatch relationship (i.e. typically wind generation picks up during the evening and early morning; PV dispatches during the daytime when the sun shines). Another interesting challenge is the control of PHEV charging and discharging as other DER dispatch varies. Aggregated PHEV with vehicle-to-grid capabilities may also be used for demand dispatch to provide frequency regulation to support transmission system. [3]

Using the example system described above, we propose a concept of controlling and monitoring the distribution grid with a high penetration of DER. This concept depicts an ADMS system which interacts both with the distribution side and transmission side as shown in Figure 4 and explained in the following paragraphs.

On the distribution side, advanced predictive analysis is required to determine the wind and solar generation forecast. Application of advanced weather modelling techniques can be applied to obtain the generation profiles for the very near term future. The short interval meter data, in addition to load forecast techniques and load behaviour predictions using weather modelling, will be used to obtain the load profiles for the very near term future. The generation and load profiles are updated to the distribution network analysis (DNA) software tool which performs the analysis for optimal network reconfiguration and distribution system reliability impact analysis. The network analysis results of system conditions from the DNA tool are fed to the primary distribution grid controller which uses the information for the following control commands:

- Integrated volt/var control (blue dotted curved arrow)
- Switching control command (breaker/switch) to switches which are located in and between the feeders (red dotted curved arrow)
- PV and WTG power electronic switching control commands (yellow and light blue dotted curved arrow)
- Demand Response and direct load control command (black dotted straight arrow line)

The controller also interacts also with the transmission side EMS for frequency regulation by controlled dispatching of aggregated PHEV [3]. Also, in many instances the PHEV charging and discharging will be based on distribution load management. In addition to these two above aspects, the third most important criteria for PHEV is that the consumer should attain a satisfactory or sufficient state of charge within a period of time.

Hence the PHEV charging and discharging control depends on the three following control aspects, which makes it a very complicated optimization problem:

- Transmission side frequency regulation command (purple dotted curved arrow)
- Distribution side load management command (purple dotted curved arrow)
- Satisfactory state of charge for the consumer when plugged in

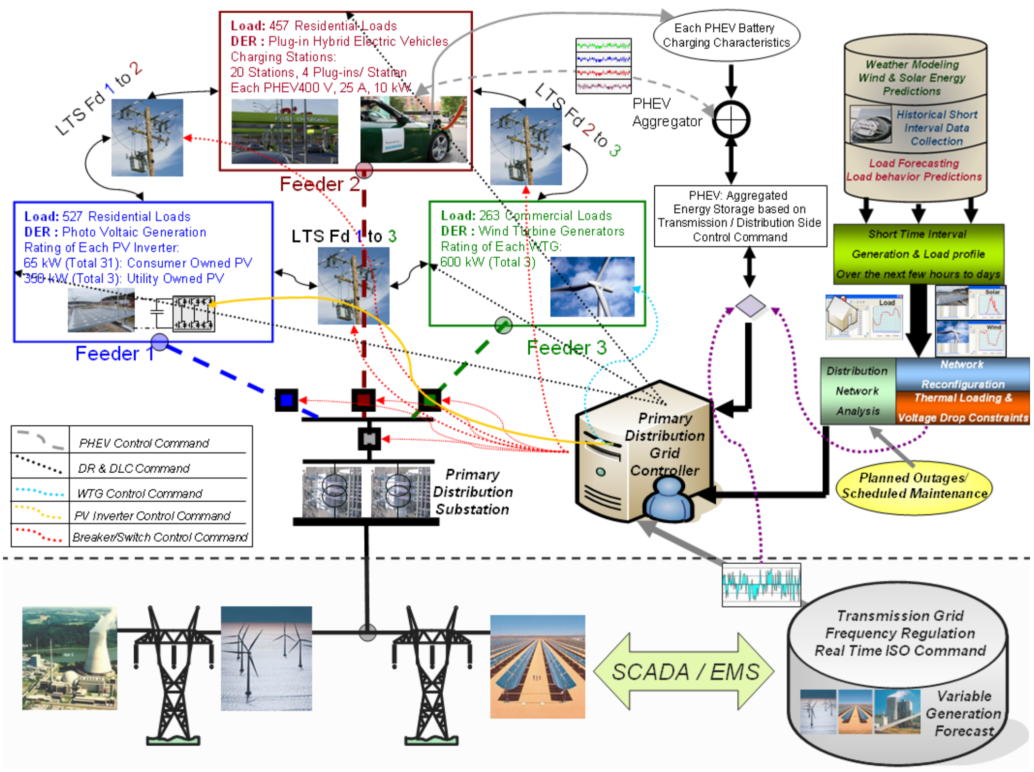

Figure 4: Conceptual Diagram of AMI/MDMS Information Flow to ADMS

FUNCTIONAL REQUIREMENTS FOR AN ADNA TOOL

One of the significant aspects of the future ADMS is the incorporation of offline advanced distribution network analysis (ADNA) software tools in order to perform near real time network analysis. In this section, we present an example of an ADNA software tool and list the major functionalities that can be utilized with ADMS.

The ADNA software tool should contain a library of fully regulating DER models in order to model the dynamic behaviour of DER units under normal and emergency conditions. It should also have the ability to model both single-phase and three-phase DER units to support unbalanced simulations. The tool must also have an optimization toolbox which supports functions like; optimal load flow, optimal branching, optimal loss reduction, optimal capacitor placement, optimal switching, and load balancing. For future work, these software tools may also incorporate algorithms for probabilistic optimal load flow, probabilistic load assessment, probabilistic DER distribution, etc.

An example of an ADNA software tool is PSS®SINCAL, currently used by several distribution utilities, and which has the above-mentioned capabilities in addition to some of the following major functionalities:

- Unbalanced 3-phase representation
- Detailed modelling of substations and distribution switching components
- GIS based functionality
- Transformer Feedback detection scheme
- Detailed load modelling and consumer load profile modelling
- Estimation of load using load trimming
- Handling complicated meshed networks along with accurate protection system modelling
- Distribution Contingency analysis and remedial actions
- Efficient Reliability analysis Tool

CHALLENGES AND SOLUTIONS ASSOCIATED WITH INCORPORATION OF PHEV TO SECONDARY LOW VOLTAGE DISTRIBUTION SYSTEMS

Most areas in the US (suburban and rural) have overhead secondary low voltage (LV) networks. A typical configuration of an overhead LV network is shown in the figure below where a 1-phase secondary transformer is supplying a few residential loads. The number of consumers connected to the secondary distribution transformer depends on the thermal loading of the secondary lines and transformer and the voltage drop in the LV network.

The typical ratings of overhead transformers are 25 kVA, 50 kVA and 75 kVA, and typical LV network conductors are 4/0, 3/0, 2/0, 1/0, #2, #4 and #6 triplex aluminum type conductors. A typical coincident peak load per consumer (home) is 2 kVA.

Present overhead LV networks were designed to operate on or just within the loading and voltage drop constraint limits, supplying the existing load demand. The configuration shown in Figure 5 has 2 consumers per utility pole and 200 ft of secondary conductor between each pole.

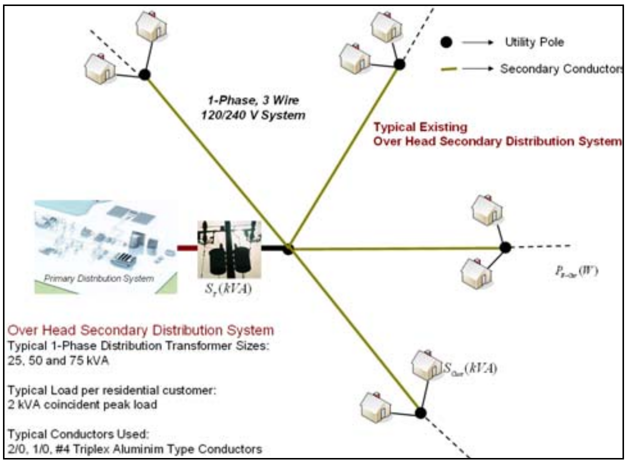

Figure 5: Typical Overhead Secondary LV Network (Existing)

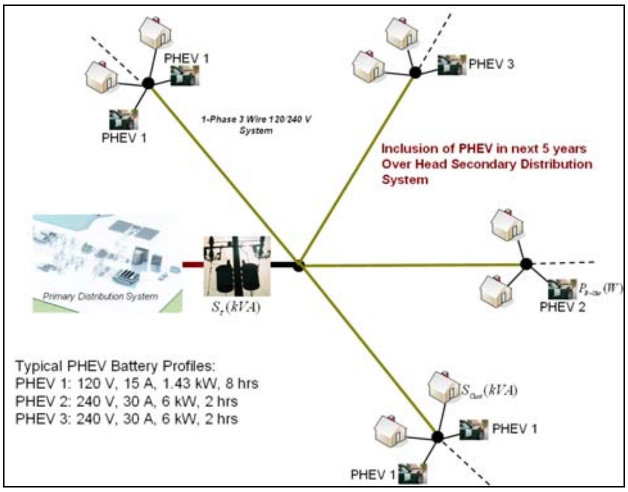

Figure 6: Typical Overhead Secondary LV Network (with PHEV inclusion)

A typical secondary overhead LV distribution system single phase, 3 wire, 120/240 V system was modeled in PSS®SINCAL representing 25 kVA transformer, #4 triplex Al conductor as shown in Figure 5. The existing LV system was modeled satisfying the standard voltage and thermal loading constraints (i.e. 70% loading of transformer and 2% voltage drop in the secondary conductors) which enables 8 consumers (2 kVA coincident peak load/consumer) to be connected to the 25 kVA LV system. A representation of a future 25 kVA LV system was modeled with the inclusion of three types of PHEV battery charging profiles representing level 1 and level 2 charging standard as shown in Figure 6 [4]. The 24 four load profile of the home load and PHEV charging profile are shown in Figure 7. Load flow simulations were carried out over a 24 hour period in 15 minute intervals for the 25 kVA LV system with and without PHEV. As can be observed in Figure 8 the transformer loading with the inclusion of PHEV exceeds 100% and reaches 120% at about hour 23. As can be observed in Figure 9 the voltage falls below 95% from hours 22 to 24.

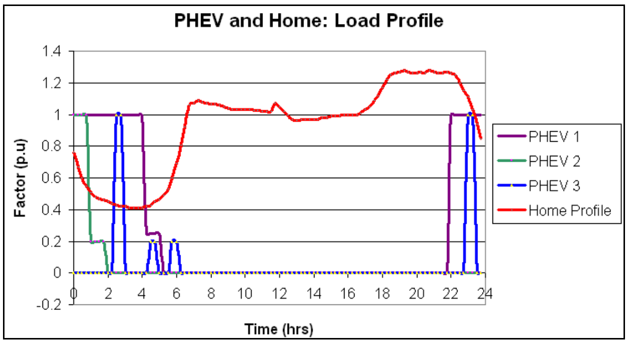

Figure 7: Home Load and PHEV Charging Profile

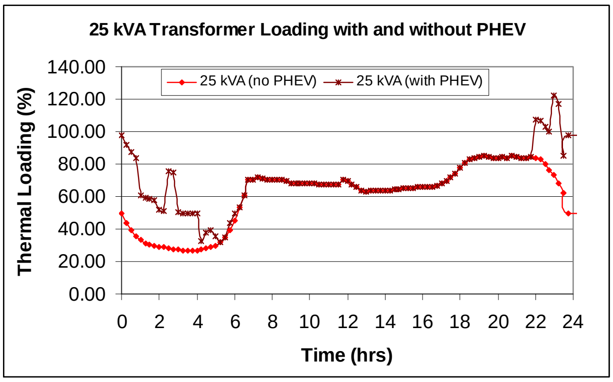

Figure 8: Transformer Loading with and without PHEV

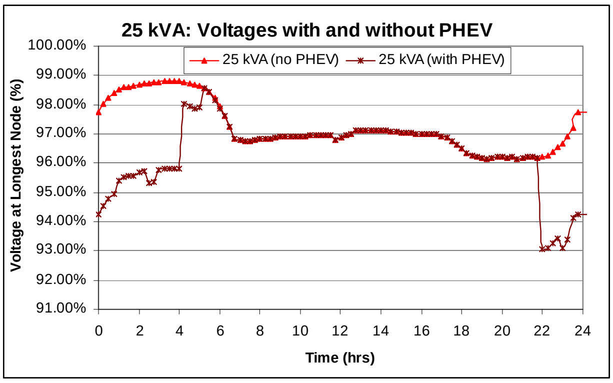

Figure 9: Voltage at the Lowest Voltage Node with and without PHEV

It is evident from the simulation results that the inclusion of PHEV over the next 5 years with only grid-to-vehicle charging capability would present a challenge of increased load demand and hence an increase in thermal loading and voltage drop problems. One obvious option would be to replace the existing equipment or assets with higher rated equipment. But this will involve a huge investment on assets of the distribution system. Another solution would be to implement a control strategy for DER and energy storage systems on the secondary LV level and control and optimize the operation of DER, energy storage systems and charging of the PHEV.

CONCLUSION

It is crucial for a power distribution utility engineer to have an accurate vision of the near future SDG. On this aspect; this paper has presented the challenges and solutions associated with AMI/MDMS data utilization for ADA functions, and it presented a vision of the future SDG with an example distribution system and proposed the solutions for implementing an ADMS. The functionalities required for an ADNA software tool were discussed. This paper also illustrated, with an example case study, the impacts of incorporation of PHEV on an overhead LV secondary distribution network.

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