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Smart grid adaptive volt-VAR optimization: Challenges for sustainable future grids

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ABSTRACT

In recent years, smart grid technologies such as Distribution Management Systems (DMS) and Advanced Metering Infrastructure (AMI) have created remarkable opportunities for distribution grids in terms of operation, control and optimization. The advent of AMI has created considerable amount of data that can be used in optimization applications. Other smart grid functionalities could increase the performance of energy conservation and optimization solutions. As such, this paper aims to review the main requirements of two important smart grid adaptive energy conservation and optimization solutions called Volt-VAR Optimization and Conservation Voltage Reduction, in terms of control, measurement, communication and standards for grids.

Contents

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1. Introduction

Electrical distribution networks across the world are witnessing a progressive infusion of smart grid technologies into many aspects of their infrastructure and operations. Technologies such as EMS, DA, DMS and AMI have been used to address present, and future needs of the distribution networks for automation, control, monitoring and optimization. These technologies provide electric power utilities with multiple layers of intelligence over their current and future assets (Farhangi, 2010). Moreover, they boost distribution network efficiency and reliability by utilizing dispersed generation resources such as Distributed Energy Resources (DER), Community Energy Storages (CES) and renewable energy resources. On customer side, demand side management and Demand Response (DR) have empowered customers to get involved in load shifting and energy conservation programs.

Typically, there are two types of DR: price-based and incentive −based. The key objective of price-based DR is to engage customers in modifying their consumption in response to the price signals periodically. Different types of price-based DR have been employed in distribution networks such as Time-of-Use pricing (TOU), Critical Peak Pricing (CPP), Real-Time Pricing (RTP), and Peak Load Pricing (PLP). On the contrary, incentive-based approach aims to use incentives to perform an efficient DR. From customers' point of view, incentive-based DR could be a program in which consumers have the right to choose whether to participate in market or not. It is known that the price-based DR imposes fluctuating wholesale electricity prices upon consumers. However, incentive-based DR keeps a flat retail rate on the customers' side and proposes financial incentives and/or discounts to the DR providers. With their participation, the customers have become wiser on their decisions as well as their usage trend. Moreover, they have grown accustomed to using clean energy. As such, customers have become more vulnerable to system outages as the lifestyle of most customers heavily depend on communication and information technologies such as internet, cellular phones, and TVs than before. As such, many utilities attempt to supply reliable and high quality power to guarantee customer satisfaction. On the other hand, the expansion of smart grid technologies has provided an unprecedented opportunity for utilities to improve the efficiency, operational performance and Quality of Service (QoS) levels of their grids by gaining a lot more visibility over their service thru technologies such as AMI. AMI is one of the main core components of smart grids as it collects data from smart meters in quasi real-time intervals. Different applications such as grid restoration, energy conservation and optimization can be achieved using AMI system (Balakrishna, Rajagopal, & Swarup, 2015).

One of the well-known techniques conventionally employed to optimize voltage and/or reactive power of a network is called "Volt-VAR Optimization (VVO)". A typical VVO aims to simultaneously regulate distribution network node voltages and minimize distribution network losses by utilizing Volt-VAR Control Components (VVCC) such as On-Load Tap Changer of transformer (OLTC), Voltage Regulators (VR), switchable shunt Capacitor Banks (CB) and other available VVCCs in the system. Moreover, it tries to keep consumer's voltage levels within ANSI C84.1 standard range or EN 50160 standard range in Europe. In 1990s, new distribution features such as Distribution Automation (DA) and Distribution Management Systems (DMS) have been developed. Roytelman and Shahidehpour were the first researchers who assessed the VVC issue for DMS (Roytelman & Shahidehpour, 1993; Roytelman, Wee, & Lugtu, 1995). Since 2000s, great efforts have been spent in designing and developing voltage and reactive power optimization solution for distribution networks in both academic and industrial settings (Auchariyamet & Sirisumrannukul, 2009; Rahideh & Gitizadeh, 2006; Alencar de Souza & de Almeida, 2010; Saric & Stankovic, 2009).

As the value of VVO on loss reduction and energy efficiency improvement is very important, many utilities consider VVO or Volt-VAR control as a part of their DMS. Presently, it is conceivable to design novel VVO solutions with higher level of efficiency and effectiveness in compliance with smart grid technologies and features such as AMI, DER, CES, and Electric Vehicles (EV). Initial VVO techniques employed to statically minimize distribution network losses and to improve voltage profile of the system through semi-coordinated methods using static data. In brief, these VVO strategies present an integrated process of controlling voltage levels and reactive power that could lead to system optimization in mid/long-term operating periods. To respond to consumer's demand within real-time or quasi real-time intervals, advanced VVO techniques have to track load changes.

With the expansion of AMI through smart metering development programs at customer's premises, it is now possible to produce an extensive amount of consumer data that can be collected from termination points for various optimization, control and energy conservation aims such as energy conservation and optimization. AMI provides an environment for data collection, time-of-use rates and load-demand data that can be used in energy conservation, outage management, loss reduction and other optimization and control aims of distribution grids. Accordingly, new AMI-based VVO techniques can be constituent components of future distribution grids enabling the optimization of distribution networks in quasi real-time or close to real-time. This could lead to a more accurate VVO by bringing a real-time dynamic VVO from substation downstream to the edge of the feeders. Hence, it is more feasible to upgrade the conventional static VVO systems into real-time, adaptive and dynamic VVO solutions via smart grid capabilities. As Advanced Metering Infrastructure operates in quasi real-time based on smart meter data collection that is typically every 5, 10 or 15 min, smart grid Volt-VAR Optimization solutions have to optimize distribution grid in quasi real-time intervals as well. Moreover, proposing approaches such as predictive VVO that can operate dynamically in real-time are going to emerge in active distribution grids. Collecting data in quasi real-time, e.g. every 15 min from smart meters, and perform close to real-time through predictive VVO engines could significantly improve system level of performance and efficiency. Moreover, system measurement layer would keep sending required data of the VVO engine in quasi real-time to assist smart grid-based VVO solutions on tracking load changes.

The availability of dispatch-able energy resources in smart grid networks such as EVs, Vehicle to Grid (V2G) systems, CES systems, smart inverter technologies and sustainable/renewable resources can make smart grid-based VVO more affordable and practical. In recent years, penetration of DER at customer's premises has changed the structure, operation and performance of smart distribution networks. DERs such as Micro-Combined Heat and Power units (Micro-CHP), wind turbines and Photovoltaics (PV) have been employed for different operational needs in distribution grids. Hence, diversity in type and technology, as well as DER penetration could have considerable impacts on distribution network optimization and control applications such as VVO.

Few studies have just pursued the smart grid issues on VVO (Jauch, 2009; Jauch, 2011; Uluski, 2010). Possible effects of smart grid actual functions on load tap changers of distribution transformer discussed in Jauch (2011). The abovementioned papers have focused on concepts such as: advantages, challenges and functional requirements of VVO in smart grids which could be considered as the early stages of smart grid-based VVO design. Thus, such reviews could assist in forming the basis for the smart grid-based Volt-VAR Optimization algorithms. In September 2011, IEEE standard 2030 (IEEE Std., 2011) was published. IEEE 2030 presents a comprehensive guide for smart grid interoperability. As explained, some

Table 1
Summary of Smart Grid Important Standards.

Organization	Standard Name	Standard Name	Standard Name	Standard Name	Standard Name
IEEE	2030: interoperability of energy technology & IT operation with the grid and end-user applications & loads	2030.1: guide for electric-sourced transportation infrastructure	2030.2: interoperability of energy storage systems integrated with grid infrastructure	2030.3: test procedures for energy storage equipment and systems for grid applications	1547.7 (2013): guide to conducting distribution impact studies for distributed resource interconnection
IEC	TR 62357: Service Oriented Architecture (SAO)	61970: Common Information Model (CIM)/EMS	61850: power utility automation/substation automation	62351: smart grid technologies' security	61851: general requirements of EV conductive charging system
IEC	61968: Common Information Model (CIM)/DMS	62056: data exchange for meter reading, tariff and load control	61508: functional safety of electrical/electronic/programmable electronic systems	60870: Tele-control (SCADA)	13273-1-2015: energy efficiency and renewable energy sources- common international terminology

research papers have tried to address different aspects of smart grid and their specifications (Spatti, da Silva, Usida, & Flauzino, 2010; Vaccaro, Velotto, & Zobaa, 2011; Xiao et al., 2010) before IEEE 2030 standard. Most such papers have focused on concepts, key challenges, and initial requirements of VVO in smart grids (Electric Power Research Institute (EPRI), 2011; Jauch, 2009; Uluski, 2010; Vaccaro et al., 2011) without considering interoperability issues. Some other works such as Schneider and Weaver (2014) and Uluski (2013) have investigated the main issues new smart grid technologies, such as VVO, may face in complying with IEEE 2030 standard. It has to be mentioned that more than 100 standards have been defined regarding different smart grid technical aspects. Table 1 summarizes the most important and recent smart grid standards.

2. Key findings from literature survey

From literature survey, it can be concluded that more theoretical work is required to explain and suggest new smart grid-based VVO techniques in compliance with IEEE 2030. In other words, there is a salient gap between conventional VVO and new innovative smart grid-based VVO in terms of efficiency, and optimization level.

It has to be stated that other institute such as National Institute of Standard and Technology (NIST) provided several guidelines, frameworks and roadmaps for smart grids as well focusing on key areas such as: interoperability, demand response, wide area situational awareness, DER, energy storage, electric transportation, communication, AMI, distribution grid management, and cyber security.

As microgrid components are following peer-to-peer, plug-and-play architectures to ease system usage, increase the efficiency of the grid and increase grid power quality, DERs can be connected through a peer-to-peer structure to their local measurement and control systems. On the other hand, microgrid component's plug and play structures let microgrid expansion without re-structuring the network. In order to smarten-up distribution networks, it is possible to control different microgrids that are connected to each other through measured real-time data of DERs such as generated active and reactive power as well as loads. AMI infrastructure could provide this opportunity to measure required data of microgrid components for control and optimization purposes. Table 2 summarizes the history of VVO. Hence, this paper tries to address different requirement aspects of novel smart grid adaptive VVO solutions for present and future distribution networks. VVO control topology, measurement, and harmonizing standards considerations and challenges are substantial issues which this paper is studied in detail for present and future smart grid adaptive VVO solutions.

Moreover, this paper shows how control topologies of smart grid adaptive VVO solutions have to be in-line with distributed command and control topologies of smart microgrids. It explains how other energy conservation techniques such as Conservation Voltage Reduction (CVR) could benefit VVO solutions and can be a part of VVO objectives. Furthermore, it reviews smart grid components and their impacts on recent smart grid VVO solutions. As most recent VVO solutions are operating with AMI data, performance analysis of the AMI system as well as analysing different communication technologies for the AMI-based VVO solutions are discussed in this paper. Last but not least, this paper investigated the main features of an advanced smart grid adaptive VVO, reviews required standards of it and offers IEC 61850 as one of the best candidates for smart grid adaptive VVO communication protocol.

As it can be seen from Table 1, novel smart grid adaptive VVO solutions are moving toward using new VVCCs such as CES, EV and DERs. Moreover, they are going to be integrated with other DMS applications to provide more efficient and reliable energy conservation and optimization solutions.

3. Smart grid adaptive VVO architecture

Generally, VVO approaches adopted across the board in recent years by different utilities and/or companies is "Centralized-VVO" (network-based) (Auchariyamet & Sirisumrannukul, 2009; Rahideh & Gitizadeh, 2006; Alencar de Souza & de Almeida, 2010; Saric & Stankovic, 2009; Jauch, 2009; Uluski, 2010; Diaz, Harnisch, Sanhueza, & Olivares, 2010; Mohd, 2009; Krok & Genc, 2011; Rahimi, Marinelli, & Silvestro, 2012; Shen & Baran, 2013). In centralized VVO, the processing system is placed in a central controller unit, i.e., DMS, in the so called "Utility Back-Office". The DMS uses relevant measurements that are taken from termination points, (utility subscribers) to determine the best possible settings for field-bound VVCCs (Manbachi et al., 2014). These settings are then loaded to such assets through existing downstream communication pipes, such as Supervisory Control and Data Acquisition (SCADA). The main challenge of centralized-VVO in integrated real-time and quasi real-time VVO solutions would be the huge amount of data that should be transmitted from AMI to back-office and from VVO to VVCCs. This may lead to a "Data Tsunami", SCADA blockage, system failure and unreliable AMI data transfer. Moreover, centralized VVO uses Geographic Information System (GIS) and network topology as the basis to determine the optimization targets for each tributary. However, due to the challenges on accessing real-time downstream sensory inputs, such functions rely on statistical load profile, rather than real-time load profiles. In contrast, "Decentralized-VVO" techniques try to use local controls to optimize the operation of VVCCs on few feeders. That is the reason some may call this approach "substation or feeder-based" approach.

In this technique, VVO rely on the data received from customers to optimize specific distribution feeders. Lately, there seems to be a lot more interest in decentralized control approach (Vaccaro et al., 2011; Xiao et al., 2010; Fakham, Colas, & Guillaud, 2011; Fakham,

Table 2
History of Volt-VAR Optimization Solutions.

Attributes	1st Generation (1980–1990)	2nd Generation (1990–1998)	3rd Generation (1998–2008)	4th Generation (2008–Now)	Near Future
Load Profile	Static	Static	Static	Quasi real-time, Source: Aggregated AMI data	Dynamic, Source: Disaggregated AMI data
Topology	Local	Local	Centralized thru SCADA	Distributed thru Local Control	Distributed thru Intelligent Agents (IAs)
Control Assets	Substation-based	Substation-based	Substation-based	Feeder-based	Feeder-based+ Customer Assets
VVCC	LTC/CB/VR	OLTC/VR/CB	OLTC/VR/CB	OLTC/VR/CB	OLTC/VR/CB CES/EV/DER
Ancillary Functions	N/A	Early CVR studies	Independent CVR	Integrated CVR	Integrated CVR + DMS

Ahmidi, Colas, & Guillaud, 2010; Zamani & Baran, 2014; Ibrahim & Salama, 2014; Ibrahim & Salama, 2015). In (Oureilidis & Demoulias, 2016) an adaptive decentralized control method is proposed for loss reduction. A new decentralized method for real-time control of active distribution networks presented in Bernstein, Reyes-Chamorro, Le Boudec, and Paolone (2015). Some researches such as Manbachi et al. (2014) propose decentralized-VVO approach based on pervasive control, DA (Distribution Automation), AMI (Advanced Metering Infrastructure) and DMS (Distribution Management System). Decentralized-VVO approach utilizes VVO engines which are located in the field, i.e. at medium voltage distribution substation, and in close-proximity to the relevant assets to improve voltage and reactive power according to local attributes of the distribution network and global attributes received from DMS/SCADA. Fig. 1 compares centralized-VVO and decentralized-VVO.

In decentralized approach, real-time local measurements do not need to travel from the field to the back-office and the new settings for VVO assets are determined locally, rather than by a centralized controller. Hence, this approach could lead to less data bandwidth requirements, better system reliability and faster optimization process. Furthermore, it seems that this VVO topology is more in-line with distributed command and control topology of smart micro-grids as data collections and control commands are fully distributed along different components of feeders. This VVO structure could also ease integration of local dispatch-able energy sources such as battery storage systems and EVs which can make future VVO solutions more affordable and practical. Considering the fact that both topologies could be used for smart grid adaptive VVO depending on grid operational and economical needs, achieving real-time coordination of VVO objectives with features such as: integrated VVO with distributed command & control architecture, coordinated optimization of conventional and new VVCCs, and the ability of evaluating the impact of different load conditions over VVO could bring great benefits to utilities in terms of optimal grid operation and cost savings.

4. Conservation voltage reduction in smart grid adaptive VVO

One of the well-known energy conservation techniques that has been taken into consideration by many North American utilities in the last two decades is "Conservation Voltage Regulation" or "Conservation Voltage Reduction" (CVR). As ANSI C84.1 standard (EPSE, 1995) has defined a band for the acceptable values of service voltage at termination points (e.g. 114–126 V in North America), CVR tries to decrease consumer's voltage level into the lower limits of ANSI band, i.e. 0.95 to 1 per units, to reduce the energy consumption. In EN 5060: 2000 designed for European grids, acceptable lower limit band, i.e. slow low voltage reduction, is up to −10% (Copper Development Association, 2016). In 2008, a research survey conducted by the Northwest Energy Efficiency Alliance (NEEA) showed that 1% voltage reduction on average, will yield a drop of 0.7–0.8% in power consumption (Global Energy Partners LLC, 2008). Moreover, this study derived that CVR could save 1–3% of total energy, 2–4% of kW demand, and 4–10% of kVAR demand (Schwartz, 2010). According to a comprehensive research made by the Department of Energy's Pacific Northwest National Laboratory (PNNL) in August 2010, CVR could potentially provide peak demand reduction as well

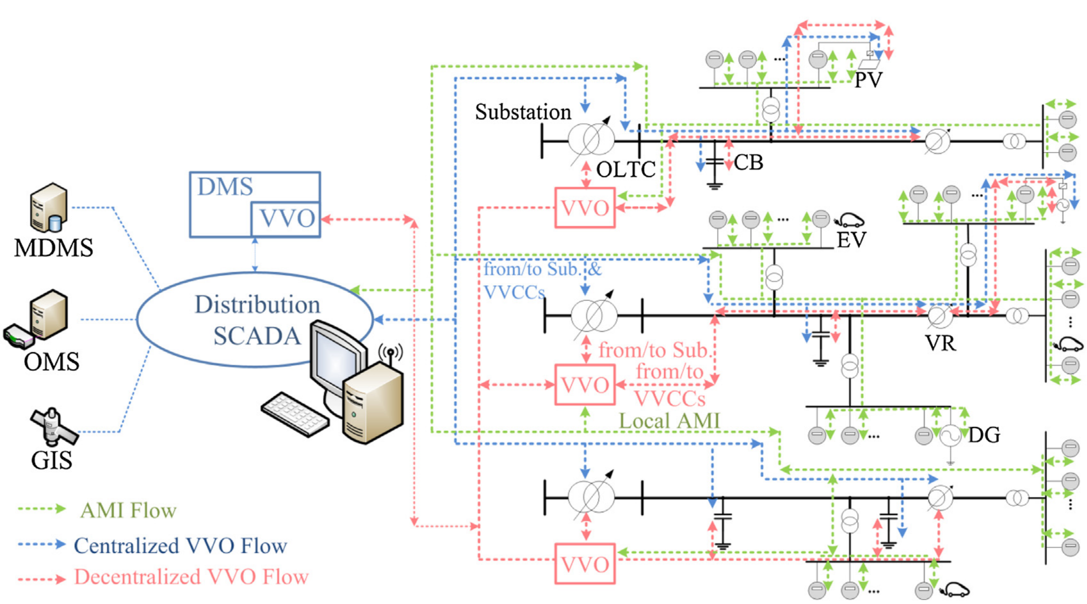

Fig. 1. Centralized AMI-based VVO vs. Decentralized AMI-based VVO.

as annual energy reduction of approximately 0.5%-4% depending on feeder specifications (Schneider, Tuffner, Fuller, & Singh, 2010). Complete deployment of CVR on all distribution feeders would provide 3.04% reduction in annual energy consumption and if CVR was applied only on high value distribution feeders, the annual energy consumption could be reduced up to 2.4% (Schneider et al., 2010). This study also proved the necessity of accurate load modeling for new CVR techniques. In addition, other reputed research institutes, such as Electric Power Research Institute (EPRI) worked on CVR strategies for many years. Study on the potential benefits of CVR by EPRI showed that by 3% voltage reduction it would be possible to typically achieve a 2.1% demand and energy reduction (Wakefield, 2011). The abovementioned studies ascertained the fact that CVR could benefit distribution grid in a variety of different ways in full conformance with the grid specification. Today, CVR could be employed through conventional voltage control assets such as Load Tap Changer of Transformer (LTC) in distribution substation, VRs along distribution feeders, conventional reactive power control components such as switchable shunt CBs and new VVCCs such as smart inverters, etc. Principal advantages of CVR include, but not limited to, demand reduction, energy consumption saving, reducing downstream substation and/or feeder overloading, increasing home appliance lifetimes, decreasing complaints on low-voltage and/or high-voltage events and lowering customer's electricity bill. From the abovementioned studies, it can be concluded that most CVR projects performed "pilot" and few distribution utilities implemented CVR in reality. Many of electric power utilities preferred to primarily perform CVR pilot projects as they could further perform cost-benefit analysis and get familiar with CVR benefits. Another reason was due to so called "Lost-Revenue" that electric power utilities may face while performing CVR. As reducing Medium Voltage (MV) side of distribution grid leads to lost-revenue for electric power utilities (i.e. utilities may sell less power to their consumers) some may consider this as an obstacle for CVR implementation and development.

As CVR control actuators such as OLTCs and VRs could be categorized as VVCC, and as CVR and VVO objectives are well-matched, many researchers and/or utilities suggest considering CVR as an integral component of VVO solutions. Therefore, it is conceivable to deem CVR as a new addition to novel VVO solutions. Consequently, new VVO techniques would be able to perform energy conservation and demand reduction besides performing loss and VVCC operating cost minimizations and voltage regulation. Therefore, one of the most important features of a smart grid adaptive energy conservation and optimization solution is the consideration of CVR in its objective function.

5. Advanced smart grid components for grid optimization

VVCCs are the main control actuators of VVO solutions. In order to maintain the voltage level of system nodes within desired limits, and to conserve energy according to CVR approach, voltage regulating tools such as OLTCs and VRs are typically used. OLTCs and VRs are the most common voltage regulating tools in distribution grids. Moreover, shunt capacitors have been used in distribution networks to regulate voltage and control reactive power flows of the grids. For VVO purposes, switchable shunt capacitor banks are used to regulate voltage and control reactive power of the system during different operating time intervals. With the expansion of smart grid sources, it is now possible to develop a smart grid adaptive VVO solution capitalizing on the availability of different smart grid resources such as EV, DER, CES and PMU.

5.1. Electric vehicles (EVs)

Generally speaking, penetration of dispatch-able resources on customer side or co-generating loads such as EV has brought new opportunities and challenges to distribution networks. Diverse research studies have reviewed the impact of EVs on distribution networks. However, the foremost gap in research studies can be the shortcomings of studies encompassing the effects of EVs on a reliable VVO. Furthermore, new studies have proven the fact that new EV inverter technologies could provide reactive power injection (positive or negative injection (aka absorption)) opportunity for future grids (Kisacikoglu, Ozpineci, & Tolbert, 2011a; Kisacikoglu, Ozpineci, & Tolbert, 2011b; Fasugba & Krein, 2011; Ehsani, Falahi, & Lotfifard, 2012; Kisacikoglu, Ozpineci, & Tolbert, 2013). This may impose extensive impacts on the optimization, VAR amount and the number of active distribution network switchable CBs. Thus, in near future, it may be possible to employ a small percentage of EVs as reliable reactive power generation sources in a V2G (Vehicle to Grid) mode in order to reduce active and/or reactive power loss of the grid. It has to be mentioned that large amounts of harmonics from EV charging stations may increase network line loss (Yang, Zhang, Wang, & Gao, 2012). The result of Yang et al. (2012) showed that for small-size EV charging stations, no harmonic mitigation measures are needed. However, for large and medium-size EV charging stations, the order of the harmonic current which may exceed the standards has to be determined and then proper filters can be added to the EV charging station to avoid EV harmonic negative effects. Various studies have assessed the impact of EV penetration on distribution networks (Zhang, Ai, Liang, & Dong, 2014; Bosovic, Music, & Sodovic, 2014; Kriukov & Gavrilas, 2014; Leou, Su, & Lu, 2014; Hoog, Alpcan, Brazil, Thomas, & Mareels, 2015) but it seems that new studies have to be performed to evaluate the impact of different EV penetration levels on the proposed AMI-based VVO solutions, which encompass CVR as a constituent component. EV penetration throughout distribution feeders could affect AMI-based VVO technologies in areas such as: loss minimization, control components, operating conditions and CVR performance, as VVO load characteristics and/or models could be changed in different EV penetration scenarios. Hence, the necessity of studying the impact of EV penetration on AMI-based VVO technology is now felt more than before.

Although distribution planners intend to provide command and controls strategies to adjust co-generation impacts on loads, but at the same time these dispatch-able energy sources can be a tool for system service optimization. For instance, new studies have proved that new inverter technologies could provide reactive power injection/absorption opportunity for microgrids (Manbachi, Farhangi, Palizban, & Arzanpour, 2016a). Using these types of technologies such as V2Gs (Vehicle to Grid) with reactive power support capabilities have considerable impacts on optimization, reactive power need, size and the number of switchable shunt CBs in distribution networks as it would be possible to employ a percentage of EVs as reactive power compensator source in V2G mode to reduce active and/or reactive power loss and to conserve energy. Therefore, one might need to acknowledge this feature as one of EV's potential advantages. The work listed as Manbachi et al. (2016a) shows the capability of a VVO using V2G dispatch on increasing the efficiency of distribution grids. Moreover (Leemput, Geth, Van Roy, Büscher, & Driesen, 2015), investigated the impact of reactive power support in LV distribution grids using EVs.

5.2. Distributed energy resources (DERs)

Penetration of DERs throughout smart grid in general, and within distribution feeders in particular, has added to grid complexity, as well as uncertainties that affect conventional monitoring, optimization and control systems. Hence, utilities are trying to verify the impact of DER penetrations on their monitoring, control and optimization systems. As mentioned before, DERs are used for different operational aims. VVO, as a part of smart distribution network optimization solution has to operate within microgrid constraints. These constraints are typically regarding to the active and the reactive power generation of microgrids as well as microgrid control. The main aim of microgrid control is to provide control over network and ease grid with autonomous components. Microgrid control constraints enables proper interface switch of the system to island microgrid during fault, power quality and other network unintentional events. By clearing fault and/or event, microgrid control re-connect microgrid to the macro-grid autonomously through using standards such as IEC 1547 (IEEE Std., 2003). Moreover, each DER controls power in different microgrid operational modes. For instance, DERs employ power vs. frequency droop controls to follow required demand during microgrid island mode of operation. This control provides frequency load-shedding when there is not adequate generation in the system. In addition, each DER performs voltage control to ensure system stability. As such, microgrid voltage control constraints ascertain that there is no large circulating reactive power flowing between DERs, especially in microgrid with high penetration of DERs. For this reason, voltages vs. reactive power droop controllers are employed. Voltage set-point can be defined based on the reactive powers generated by DERs. When reactive power becomes capacitive, local voltage set-point decreases but inductive reactive power rises the voltage of set-point. As such, new VVO techniques require to be integrated with microgrid sources and loads. Smart grid VVO need to function in compliance with microgrid control and communication topologies using recent protocols and/or standards. Moreover, smart inverter technologies could change the interactions between VVO and DERs in future. For instance, DERs could perform as reactive power compensators of the grid in specified operational conditions. In other words, they could be categorized as new VVCCs of grids.

It is important to briefly discuss the interactions of renewable generation sources with smart grids. Typically, there are some renewable sources such as PV and wind turbines that are called intermittent resources as their power generation could vary depends on parameters such as solar radiation or wind speed. Applying these sources could improve smart grid efficiency specially during peak times as they could be integrated with battery energy storage systems. If the peak is in the time that PV or wind turbines are generating power, they could directly perform peak shaving. If the peak time is not in a time that PV or wind turbines are generating power, their power could be stored in batteries that are used for peak shaving. It has to be reminded that a grid with high penetration of intermittent resources could face with several operational issues such as reverse power flow in distribution grid, additional power flow in transmission system and grid stability (voltage and frequency issues). Reverse power flow happens where intermittent source generation becomes more than system load consumption. This often comes with voltage raise that could violate ANSI or EN 50160 standard bandwidth. Moreover, reverse power flow could create excess power flows from distribution grid to transmission system. PV inverters in an interconnected grid could have different fixed cut-off frequencies, defined by the national grid codes. During abnormal conditions, these fixed threshold values can cause loss in generation capacity. Voltage and frequency issues become more visible in conditions that the grid needs to perform in island mode. It would be hard for an islanded microgrid with high penetration of intermittent resources to keep voltage and frequency within standard range.

Regarding PV impact on smart distribution grid, several research studies (Alyami, Wang, Wang, Zhao, & Zhao, 2014; Liu, Aichhorn, Liu, & Li, 2012) have focused on overvoltage issue caused by high penetration of PV's. Some investigated coordinated control of PV with Battery Energy Storage (BES) system (Kabir, Mishra, Ledwich, Dong, & Wong, 2014; Alam, Muttaqi, & Sutanto, 2013a) while some others attempted to see the impact of PV high penetration on low and medium voltage distribution network (Alam, Muttaqi, & Sutanto, 2014; Alam, Muttaqi, & Sutanto, 2013b; Tonkoski, Turcotte, & El-Fouly, 2012). From literatures, it can be concluded that as penetration of PV units within distribution networks may potentially affect VVO, it is necessary to evaluate the impact of these micro-generation units on a new smart grid AMI-based VVO. Other recent works studied VVO planning and management in the presence of DGs (Daroj, 2013) and proposed simple new Volt-VAR Control for DGs (Shang, Zheng, Li, & Redfern, 2013). In brief, VVO approaches are going to be smarter as they tend to adapt and upgrade their approach based on new capabilities brought about by smart grid technologies.

5.3. Community energy storage (CES)

Energy storage technologies is one of the key attributes within the context of smart and more sustainable power systems (Zhou, Mancarella, & Mutale, 2015). Community Energy Storage (CES) is one of the recent advanced smart grid technologies that provide distribution grids with lots of benefits in terms of stability, reliability, quality and control. As it benefits both costumers and utilities, this technology has become a crucial element in microgrid designs. CES is typically located at the edge of the grid, close to customers and DERs to smooth the impacts of intermittent DERs and help the integration of these sources in the network. New types of substation CES units could provide voltage regulation though their four quadrant inverters without the need to have OLTC in substations anymore. In recent years, CES has become more applicable in customer side DERs. The main tasks of CES in distribution networks can be summarized as peak-shaving, smoothing DER's intermittencies (output shifting/leveling), improving power quality (voltage and reactive power supports), islanding during outages, and regulating frequency. In brief, CES systems provide interesting capabilities in terms of energy management, feeder optimization and local control for the grid. This could definitely help smart grid adaptive VVO objective. High penetration of CES units can also change VVO using new VVCC tools such as smart inverters more than conventional OLTC, VR and CBs.

As it is known, typical OLTCs are able to increase or decrease feeder voltage level from −10% to +10%. Some conventional OLTCs are comprised of 32 taps to regulate feeder's voltage level. As CES systems include 4-quadrant inverters that could regulate the voltage at their location, high penetration of CES might reduce OLTC tap switching operation as the grid voltage do not need to be regulated much at the substation due to CES regulations. It is important to mention that using CES could also have other benefits to the grid such as peak shaving, voltage smoothening in different feeder nodes and providing power in islanding mode, that OLTC do not have these benefits. As such, selecting proper solution for voltage regulation (whether to choose OLTC or not) of future grid would be a key challenge for distribution network planners.

The availability of dispatch-able energy sources in smart grid networks such as EVs, and CES systems (through smart inverter technologies) could make smart grid-based VVO solutions more affordable and practical. Diversity in type and technology, as well as penetration of these sources could have considerable impact on the VVO performance. In that regard, smart grid adaptive VVO approaches may accelerate widespread deployment of CES, and/or other microgrid sources. Few works, such as Manbachi et al. (2016b) and Thomas, Walker, and McCarthy (2012), studied the impact of EV dispatch-able resources on smart grid adaptive VVO. Others, such as Hung and Mithulananthan (2011), checked the impact of CES

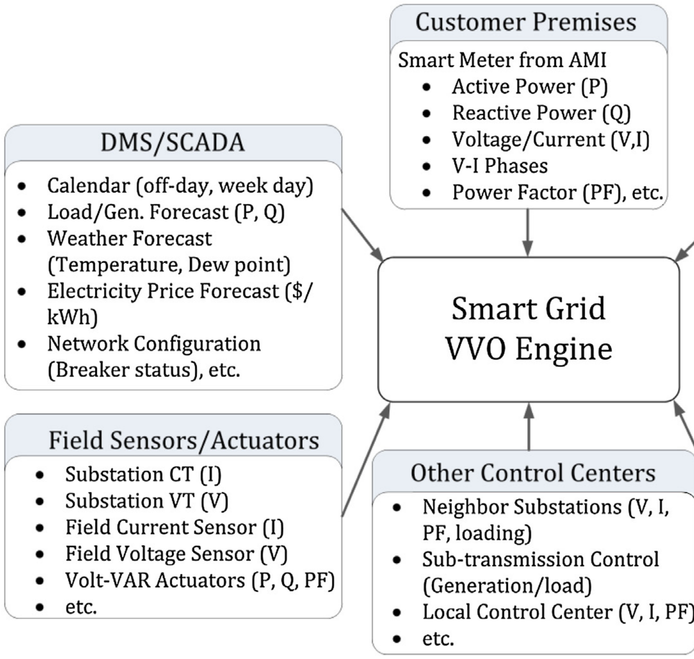

Fig. 2. Measurement inputs of smart grid adaptive VVO engine.

on VVO sub-tasks. For instance Hung and Mithulananthan (2011), only evaluates the impact of CES on CB size and allocation, which is only one out of many tasks of advanced smart grid adaptive VVO solutions. From the abovementioned literature survey, it can be concluded that although some CES and VVO functions, such as reactive power support and peak shaving, are common, there is still a huge gap between CES and smart grid adaptive optimization engine studies.

5.4. Phasor measurement units (PMU)

Phasor measurement units (PMUs) are the most widely used Synchronized Measurement Technology (SMT) device for power system applications (Chakrabarti, Kyriakides, Bi, Cai, & Terzija, 2009a). Phasor Measurement Units (PMUs) are by default used for transmission system monitoring, control and protection. As the cost of PMUs is reducing, they will be used in greater numbers, probably to achieve full system observability (Chakrabarti et al., 2009a). Moreover, the advent of phasor measurement units makes possible the use of remote wide-area signals which enables various applications (Chompoobutrgool & Vanfretti, 2015) such as wide-area real-time state estimation (Pignati et al., 2015). The invaluable benefits of PMUs in transmission systems have encouraged many utilities to use these synchrophasor units for distribution network control, monitoring and protections objectives as well. With PMUs, it is possible to measure voltage and current phasors in real-time based on GPS clock, and generate accurate time stamping for the relevant data. These values could help smart grid adaptive VVO solutions to be more accurate. PMUs facilitate the realization of a Wide Area Monitoring, Protection and Control (WAMPAC) by rendering the time-synchronized measurements from widely dispersed locations (Chai et al., 2015). For active distribution networks, PMUs need to satisfy more requirements regarding phase accuracy and harmonic rejection (Chakrabarti, Kyriakides, & Eliades, 2009b). Moreover, the future AMI-based VVO solution could act in more dynamic way regarding system changes using PMUs.

6. Measurement unit roles in smart grid adaptive energy conservation and optimization solutions

As different VVO inputs, measurement units could play a key role in smart grid adaptive VVO realization. Fig. 2 depicts possible measurement inputs for a smart grid-based VVO.

Regarding VVO measurement inputs, parameters such as voltage, current, active and reactive powers are collecting from customers' smart meters in quasi real-time. At a same time, decentralized VVO could achieve local attributes from the field controllers such as capacitor bank status, voltage regulators or OLTC tap, etc. If there are other sensors within distribution feeders such as Current Transformer (CT) or Voltage Transformer (VT), the VVO engine could receives their voltage and current parameters to observe the grid in a better manner and in different locations of the feeder. As stated, PMU measurements such as voltage and current angles could help VVO to calculate grid loss more effectively. Simultaneously, the VVO engine has to be in contact with other parts of the smart microgrid such as neighbour substation and/or local control center. The VVO engine could receive active and reactive power data of neighbour substations to avoid overvoltage issue on transformer primary (high voltage side of the grid). Different types of local controllers such as load, VVO components and DER controllers, can send parameters such as three-phased unbalanced voltage, current, generated/consumed active and reactive powers to the VVO engine.

As explained, decentralized substation-based VVO requires data from AMI. Hence, the consumer data such as voltage, current, active and reactive power can be sent by the smart meters, smart meter agents or measurement aggregators. Similarly, smart grid-based VVO needs to receive the required global attributes from DMS/SCADA. Other data such as the availability of EV, CES, and DER for helping VVO could be considered as VVO inputs as well. Smart grid adaptive VVO has to reliably communicate with DMS/SCADA, AMI, and other pre-determined control centers in order to have a complete view of grid conditions in real-time. VVO unawareness of grid present condition may lead to inaccurate grid optimization or VVCC operation failure. It has to be stated

Table 3
Communication Requirements for Smart Grid Applications (Patel et al., 2011).

Application	Transmission Type	Direction	Frequency	Latency	Bandwidth	Real-time Operation
AMI	Periodic or Event-based, unicast	Two	Low	High	10 kb/message/node	Low
Automated Demand Response	Periodic or Event-based, unicast	One/Two	Medium	Medium-high	14–100 kbps/node	Medium
Feeder Automation	Periodic or Event-based, multicast	Two	high	low	50–200 kbps	High
Electric Vehicle	Event-based, unicast	Two	Event-based	Low-medium	9.6–56 kbps	Medium-High

that IEC 61000-4-30 (Neumann, 2007) standard defines measurement methods for power quality of distribution grids. Moreover, IEC 61000 (Neumann, 2007) aggregated paradigm is used for measurement of grid parameters. Smart meters are following this standard specification for different purposes such as reporting rate and recording events.

The optimal control commands generated by the VVO engine that has to be sent to specified VVCCs need to be fully tracked and the effectiveness of each control command has to be checked at each operating time interval. As one of the newest distribution grid measurement tools, PMUs could enhance the precision and the efficiency of smart grid-based VVO solutions. As such, different types of measurement systems shown in Fig. 2 could facilitate the utilization of smart grid adaptive VVO in present and/or future distribution grids.

7. Performance analysis of AMI systems for energy conservation and optimization applications

As explained, AMI systems could provide smart grids with critical functionalities such as two-way communication between customers and utilities for remote measurement reading, remote meter management, data recording, event logs, security logs and outage reporting (Patel, Aparicio, Tas, & Loiacono, 2011). Typically, AMI systems do not require high packet size but, when providing service for large area with huge amount of data collection points, throughput and response time have to be taken into account in order to select proper communication network technology. In general, the core functional requirements of AMI systems include but not limited to smart meters, Data Acquisition System (DAS), and communication network. Smart meters provide systems with customer's required interval data as well as other residential services such as Time of Use (TOU) rate. DAS gives tools for the management of energy, reporting system, alarming, outages, smart meter failures and data collection within specified time interval, e.g. 15 min and communication network has to create a reliable two-way communication between customer and utility and/or control center for different AMI purposes. Typical AMI systems are comprised of three main architectural parts (Hart, 2010): communication register which deals with communication data transfer, meter register that determines required data for different applications such as kW, kVAR, TOU, etc., and core metrology which is the core management part of an AMI system. According to Hart (2010), one of the trends that could significantly impact AMI within smart grid concept is to have data available locally. In other words, the availability of local data is in-line with decentralized control and command topology of smart microgrids and other smart grid applications such as decentralized VVO. Hence, it is important to study AMI system performance compared with other smart grid applications as AMI could be integrated with other smart grid application. Table 3 presents smart grid application requirements based on Patel et al. (2011). As it can be observed from Table 3, AMI systems has lower frequency, lower real-time operation and lower bandwidth requirements compared with other smart grid applications of Table 1.

Additionally, AMI systems can be compared with other related smart grid technologies such as Distribution Automation (DA), Energy Management Systems (EMS) through SCADA. Table 4 shows the main requirements of these smart grid technologies based on Jeon (2011).

From Table 4, it is clear that the AMI systems need less reliability level compared with other critical applications such as distribution automation and protection. For AMI systems, different communication technologies exist. Cellular, RF, WiMAX, Power Line Communication (PLC), and wireless regional area network, e.g. IEEE 802.22. The AMI structure, the number of data collection nodes, area of coverage and AMI costs are some of the factors that could determine which technology is more suitable for the smart grid AMI deployment. As such, Table 5 represents typical communication technologies for the AMI systems based on Patel et al. (2011) and Rashed Mohassel, Fung, Mohammadi, and Raahemifar (2014). AMI systems use different standards and/or protocols such as TCP/IP, UDP, CIM, DNP, C12.22, IEEE 802.15, and Zigbee in order to provide functionalities across three levels of their operation: Wide Area Network (WAN), Home Area Network (HAN), and Local Area Network (LAN). AMI systems consist of smart meters that record revenue data or other customer parameters such as, current, voltage, power factor and reactive power that are needed for VVO application.

Hence, they could be an important part of advanced VVO solutions. These systems are able to make a two-way communication between customer and utility data center or VVO engine. Therefore, AMI is the first step to a sophisticated smart grid adaptive energy conservation and optimization. In order to exchange data between smart meters and VVO engine, a reliable, secure and cost effective communication is necessary. There are many different communication medias that could be considered for this purpose such as Broad band power line communication (BPLC), Narrow band power line communication (NB-PLC), copper or fiber optic, wireless, centralized or mesh networks. One of the most important factors during considering a communication media is the application's requirements. AMI needs a low data rate from Customer Premier End (CPE) which is smart meter until the data collection point and a medium data rate from collection point until utility control/billing center. Typically, Distribution Automation needs low and medium data rates and SCADA requires a medium data rate

Table 4
Communication Requirements for related Smart Grid Technologies.

Technology	Data Rate	Latency	Reliability
AMI	Low	High (up-to few seconds)	Medium
Distribution Automation (DA)	Low-Medium	Low (below 1 sec)	High
PMUs for DA applications	Medium	Low (about 20 ms)	High
SCADA for EMS/DMS	Medium	Low (100–200 ms)	High
Protection	High	Low (less than 10 ms)	High

Table 5
Typical Communication Technologies Available for the AMI Systems.

Technology	Main Features
Cellular	56-115kbps for GPRS, 50-100 Mbps for 4G-LTE, 2 Mbps for 3G (Rashed Mohassel et al., 2014), High throughput, extensive coverage from 10 to 100 kilometers, limited number of connections to support in 3G (Patel et al., 2011).
RF Mesh	Great coverage with lower transmission power, robust, self organizing, costly, from high bandwidth applications to low-power smart devices (Patel et al., 2011).
WiMAX	From 40 to 300 Mbps, low latency (less than 100 ms roundtrip) (Patel et al., 2011), complete control with traffic management.
PLC	Less than 10 ms latency, 5 km range, up-to 500 kbps data rate (Rashed Mohassel et al., 2014), need to bypass pole-mounted transformers in Narrow Band-PLC.
IEEE 802.22	Less than 20 ms latency, wide range: 100 km, data rate: 18 Mbps, no Quality of Service as of faulty spectrum sensing (Patel et al., 2011).

Table 6
Solution 1. Basic quasi real-time smart grid VVO.

Quantified data input	Voltage (V), Active Power (kW) (delivered and received), Reactive Power (kVAR) (delivered and received) or Power Factor (PF)
Data Filtering	Not Necessary
Applicability	One/two Feeder(s) with eight to ten data collection points/deployable to smart grids with Distributed Energy Resources (DER)
Load forecasting	Not necessary
System Output	Control commands to Tap-changer, VR and Capacitor Banks (CB)
Time Interval	Every 15 min
Suggested Control Architecture	Decentralized VVO-feeder based
AMI cost related to VVO solution	Low

communication. As a very simple example for an AMI application, if there are 3000 smart meters with polling interval of 15 min, and if we assume the packet sizes are 100 bytes, the record size would be 100 byte*3000 = 0.3Mbits. It means it takes 2.5 s to transfer these data with a 120 kbps link between smart meters and data collector. As it was mentioned earlier, smart grid adaptive VVO is done by monitoring, controlling and optimizing the voltage, loss, operating costs of control components and energy conservation within substation and along distribution feeders. Regardless of the control approach (centralized or decentralized), three different solutions could be considered for advanced VVO engines. Accordingly, proper communication technology has to be selected for each solution based on each solution requirement. It has to be stated that conventional VVO application falls in the category of distribution system applications which are not time sensitive such as protection. However, advanced VVO solutions try to operate with other DMS applications in real-time such as feeder reconfiguration. In these cases, VVO would be time sensitive as well. Table 6 gives the first smart grid VVO solution. AMI-based VVO in first solution is considered as a quasi real-time application due to its data collection time interval.

This could be an initial smart grid VVO with decentralized control that is not time-critical from VVO point of view and it could cover few measuring points, i.e. one or two feeders. However, AMI-based VVO designed based on the second approach (Table 7) and third approach (Table 8) will move toward more advanced smart grid adaptive solution, and would be more close to real-time applications. Based on different smart grid AMI-based VVO scenarios, it would be possible to come up with bandwidth estimation for each VVO application. For instance, the packet size as well as number of measuring points increased but polling interval decreased in 3rd solution compared with 2nd solution. As such, 3rd solution may

Table 7
Solution 2. Semi-Smart real-time VVO.

Quantified data input	V, kW (delivered and received), kVAR (delivered and received) or PF, Current (A)
Data Filtering	Not necessary
Applicability	Two/four feeders with close to 40 data collection nodes. One/two substation(s), small distribution networks/deployable to smart grids with Distributed Energy Resources
Load forecasting	Not Necessary
System Output	Control commands to Tap-changers, VRs and CBs, System reconfiguration, CVR Factor
Time Interval	Every 5 minutes
Suggested Control Architecture	Decentralized VVO
AMI cost related to VVO solution	Medium

Table 8
Solution 3. Advanced smart grid adaptive VVO.

Quantified data input	Voltage (V), A, kW (delivered and received), kVAR (delivered and received) or PF, Phase shift/Angle, Energy values (Wh, VARh) delivered and received, Instantaneous voltage, Event data from multi-agent, Tap position, Cap. Bank position & temperature, VR Position, DER or Renewable Generation active/reactive flows, Breaker positions
Data Filtering	Necessary
Applicability	Medium & Large-scale distribution networks with lots of measuring nodes (can also be operated in small-scale networks)/deployable to smart grids with DERs
Load forecasting	From DMS for predictive VVO (increases system accuracy and efficiency)
System Output	Control Commands to Tap-changers, VRs and Cap. Banks, Reconfigure distribution network in real-time, Breaker reconfiguration, VVO integration with other DMS applications, CVR Factors, Conserved Energy
Time Interval	Less than 1 minutes
Suggested Control Architecture	Decentralized for small/medium scale grids, centralized for large scale grids, decentralized for microgrids, centralized for Macro-grids.
AMI cost related to VVO solution	High (if centralized), Medium (if decentralized)

Table 9
Network Performance Requirements for AMI-based VVO Solutions.

Requirements	Monitoring and Sensing	Switching and Protection	Advanced Decentralized Control
Application	Asset monitoring, Power quality Monitoring, Maintenance	Fault detection, Feeder reconfiguration, Outage management	Smart Grid adaptive VVO: In-line with DMS feeder reconfiguration and system protection
Bandwidth	Low	Medium	Low
Latency	High (Minutes)	Low (Millisecond)	Medium (Seconds)

need communication medium with more bandwidth. Since data is going to be transformed along distribution feeders, by multiplying the number of data collection nodes with the polling interval and with the packet size, the bandwidth estimation can be obtained. Table 8 gives an overview of network performance requirement for recent advanced AMI-based VVO solutions. As it was mentioned in three different smart grid VVO scenarios, this application is typically not considered as a time-sensitive application and does not need a high bandwidth and can tolerate a high media.

Therefore, a reliable and economic communication technology that meets these criteria (Low bandwidth, high Latency) can be investigated for future AMI-based VVO engines. However, as advanced VVO solutions needs to operate with other automation and protection applications, proper communication standard/protocol need to be chosen. In Manbachi et al. (2015), a real-time communication platform presented for quasi real-time VVO engine using DNP3 protocol. Table 9 gives an overview of network performance requirement for recent advanced AMI-based VVO solutions. The results of Manbachi et al. (2015) show that due to DNP3 constraint (measurements are fragmented into a maximum of 2048 byte packets before its given to the TCP layer, individual confirmations have to sent by the master when each fragment is received) and delays introduced due to the synchronous reading and writing by the application, the communication platform hits its limit rendering VVO engine from its proper functionality in very high network delays (Manbachi et al., 2015). Using IEC 61850 Manufacturing Message Specification (MMS) client server-based measurement could solve the issue raised in Manbachi et al. (2015) in the presence of high network delays. Communication technologies are evaluated for IEC 61850-based distribution automation system in Kanabar, Kanabar, El-Khattam, Sidhu, and Shami (2009).

It compared IEC 61850 GOOSE messages with metering messages in terms of data rate for wired and wireless technologies to indicate potential applications of various communication systems at distribution level for the future smart grids (Kanabar et al., 2009). Moreover, in order to operate autonomously without any interruption and/or failure, future VVO solutions need to receive system configuration updates at their operating time intervals. System configuration updates can be sent from DMS to the VVO engine. These updates can be sent to the VVO engine through IEC 61850 MMS. Hence, VVO engine would be able to modify its optimization strategy when it realized that there is a system reconfiguration. New IEC 61850-based VVO solution is discussed in next section. Hence, new communication standards could reach energy conservation and optimization techniques to higher levels of reliability, optimality and efficiency.

8. Required standards for smart grid energy conservation and optimization

Smart grid adaptive solutions of future have to be in-line with distribution network, operator and utility needs. Hence, proper standards need to be used in order to ensure system compatibility and interoperability. One of the most crucial factors of a reliable smart grid adaptive VVO solution is the presence of a

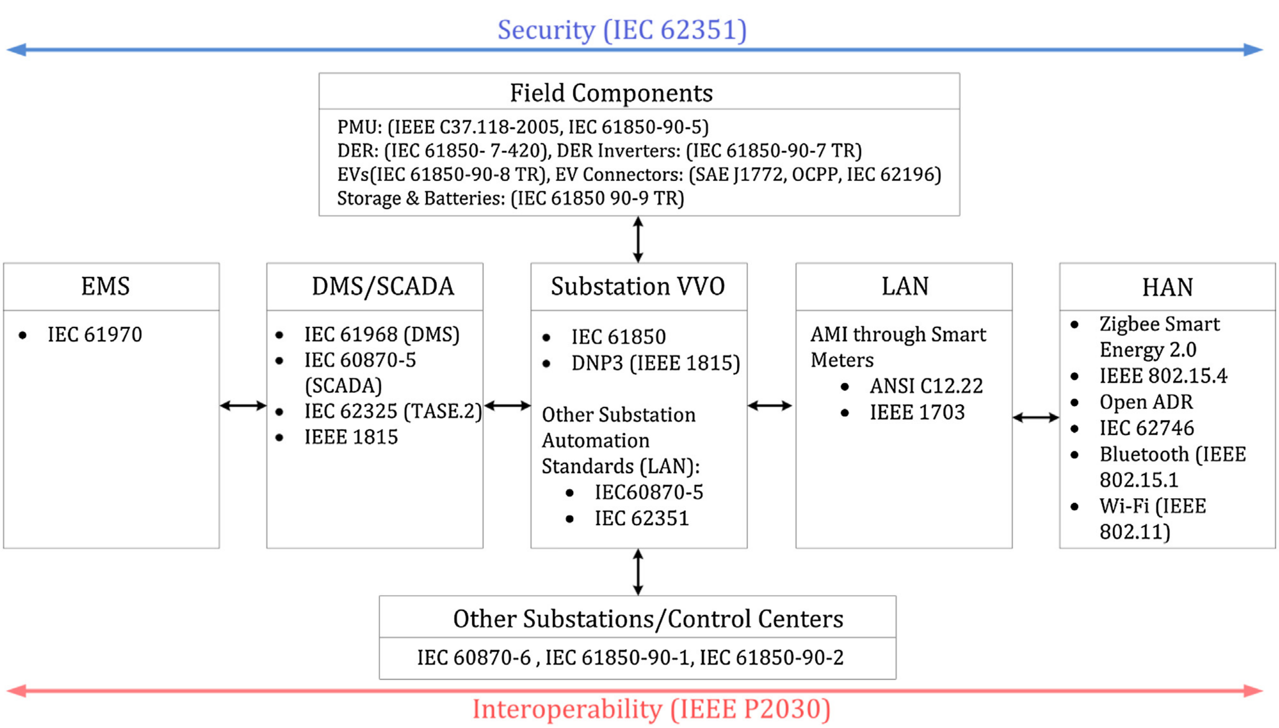

Fig. 3. Substation-based smart grid adaptive VVO links with other grid standards.

Table 10
Distribution grid standards and their impact on IEC 61850-based VVO.

Task	Standard	Working Group	IEC 61850-based VVO
IEC 61850 Distribution Feeder Automation	IEC 61850-90-6	IEC TC57 WG17	Directly deals with VVO, DSCADA, FLISR and Anti-Islanding protection communication
DNP3 and IEC 61850 Gateway	IEEE 1815-1	IEC TC57 WG10	Could help standard integration
Harmonizing CIM and SCL	–	IEC TC57 WG19	Could help standard integration
Communication between Substations with GOOSE	IEC 61850-90-1 TR	IEC TC57	Could ease IEC 61850 control commands between substations
Communication between Control Centers and Substation	IEC 61850-90-2 TR	IEC TC57	Could ease IEC 61850 control commands between VVO and other control centers
PMU Integration with IEC 61850	IEC 61850-90-5	IEC TC57	Could ease PMU usage for VVO application through IEC 61850
Web Services Interoperability	IEC 61850-8-2	IEC TC57	Could provide more interoperability for VVO
IEC 61850 for Condition Monitoring	IEC/TR 61850-90-3 Ed. 1.0	IEC TC57 WG10	Directly affects LTC
Mapping IEC 61850 to Web Protocols	EC/TR 61850-80-3 Ed. 1.0	IEC TC57 WG17	Could provide VVO web-service
Communication with Demand Response	PWI 62325-452-5 Ed. 1.0	IEC TC57 WG16	Could affect CVR effectiveness
Object Models for DER Scheduling	PWI 61850-90-10 Ed. 1.0	IEC TC57 WG17	Could affect DER sources used for VVO

reliable bi-directional communication infrastructure that can provide communication between different measurement systems and the VVO engine, and between VVO engine and field-bounded VVCCs. The required standards for smart grid adaptive VVO solutions have to be in compliance with recent automation system standards and should provide the system with flexibility, extendibility and interoperability. Fig. 3 presents the relationship of a smart grid-based VVO system with other related system standards in smart grids.

As explained before, smart grid-based VVO engine in decentralized substation-based approach can reside inside medium voltage substation. Hence, substation standards such as DNP3 or recent IEC 61850 (IEC, 2012) could be suitable candidates for smart grid-based VVO applications. IEC 61850 provides a standard way to implement automation (Giustina et al., 2015). This standard defines an object oriented hierarchical data model with semantics that enables data abstraction and provides information on the data to be exchanged as well as the mechanisms of data exchange. The data models are application independent, designed originally to identify objects within substation but in recent years, the standard is extended to incorporate data models of components outside the substation. Very few, if any, smart meters are able to support IEC 61850. In North America, smart grid adaptive VVO solutions have to work with ANSI C12.22 (American National Standards Institution, 2008), i.e. the main AMI standard in US and Canada. Moreover, smart grid VVO solutions have to be in-line with IEC 61968 (TC, 2013) and IEC 60870 (TC, 2014) that are DMS and SCADA standards respectively in order to communicate with these systems and to receive system global attributes. The communication between smart grid-based VVO and other controllers and agents can be provided by IEC 60870-6 (TC, 2014). The communication between VVO engine and different VVCCs in the field can be provided by different standards shown in Fig. 3.

Today, a few CBs, PMUs, EVs and DERs could support IEC 61850 standard. As the IEC 61850 standard is growing widely in distribution networks, it seems that this standard could be an appropriate candidate for present and future smart grid adaptive VVO solutions. IEC 61850 provides smart grid VVOs with more interoperability, flexibility and extendibility. Fig. 4 shows an example of a smart grid-based VVO in compliance with IEC 61850 standard. In Fig. 4, measurement units located at process bus send IEC 61850 Sampled Values (SCSM, 2012a) and/or GOOSE to the Intelligent Electronic Devices (IEDs). The IEDs, i.e. MMS servers, send IEC 61850 MMS values to the IEC 61850-based VVO which operate as an IEC 61850 MMS client at the station level. IEC 61850 utilizes Substation Configuration Description Language (SCL) for device configurations. SCL data enables IEDs to exchange measurement and control data in an interoperable environment. The Merging Unit (MU) can digitize the measured outputs and publish them as sampled values into the process bus through Ethernet. Breaker IED/Switch IED (SIED) are able to generate IEC 61850 GOOSE messages in order to inform changes in the status of breakers or switches. All MUs and SIEDs are synchronized to a single time reference. A station bus in substation level enables communication between IEDs that are responsible for station measurement, monitoring, control and protection. As explained, the communication could be either with client server based IEC 61850 MMS protocol (SCSM, 2012b) or with a publisher subscriber-based GOOSE service. Remote control centers could have access to measurement and control data via the Wide Area Networks (WAN) through the network gateway using IEC 61850 MMS as well.

9. Harmonizing standards

In order to design a more efficient smart grid adaptive VVO based on IEC 61850, some standards need to be in-line with each other. Hence, efforts have been devoted to linking related standards in order to harmonize different parts of present system with each other and with future systems. The impact of each standard on IEC 61850-based VVO is given in Table 1 as well. Typically, harmonizing Common Information Model (CIM) and Substation Configuration Language (SCL) could lead to more reliable communication between DMS and smart grid IEC 61850-based VVO engine. Moreover, DNP3 integration with IEC 61850 could help smart grid adaptive VVO in its communication with VVCCs that are operating with DNP3 protocol. IEC 61850 extensions (shown in Table 10)

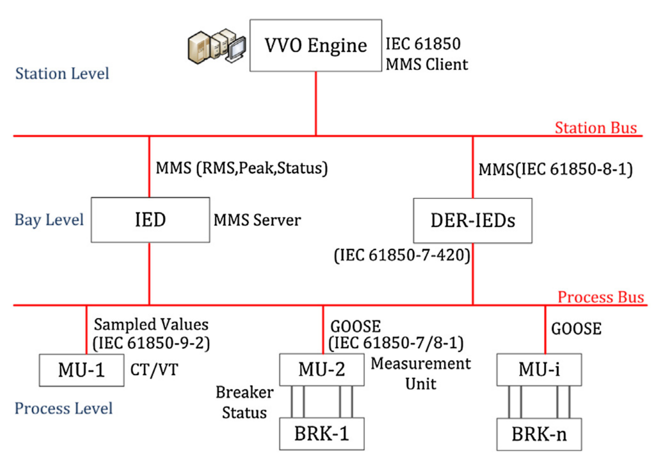

Fig. 4. Sample structure of IEC 61850-based smart grid adaptive VVO.

could help IEC 61850 incorporate other smart grid components and systems.

10. Conclusion

In conclusion, smart grid adaptive energy conservation and optimization solutions can be designed in order to increase system level accuracy, efficiency, energy and cost savings through advanced smart grid features and technologies such as AMI, DER, CES, PMU, and EV. PMU and AMI data could significantly help energy conservation and optimization approaches such as VVO to perform closer to real-time. CES could significantly help energy conservation and optimization specially in peak time intervals. Using decentralized approach could avoid high AMI cost related to VVO for many future distribution networks. Moreover, it is in-line with microgrid deployment programs of utilities as microgrids use distributed control and command architectures.

Electric Vehicles could assist energy conservation and optimization using smart 4-quadrant inverters that could be integrated with advanced VVO engine to support active and/or reactive power during different operational conditions. Predictive VVO solutions could emerge to perform energy conservation and optimization in real-time by predicting ahead time intervals. Advanced smart grid VVO solutions are going to be integrated with other Distributed Management Systems such as load forecasting and feeder fault recognition and system reconfiguration. Proper reliable communication platform has to be chosen based on VVO architectural, operational and economic needs. Advanced communication protocols such as IEC 61850 MMS and GOOSE could significantly improve VVO performance and reliability as it can send system the updates of system configuration to the VVO engine. This could lead to a VVO engine that could operate consciously and autonomously without interruption by any system faults/failure. Therefore, it is possible for utilities and network planners to take the benefits of new smart grid infrastructural functions and systems on presenting more efficient and sustainable energy conservation and optimization solutions into consideration for grid real-time operation and planning purposes.

In a path towards reaching the abovementioned targets, utilities and network planners are facing technical and economic challenges that have to be taken into account. As the control structure of many distribution networks are still centralized, moving towards decentralized approach would be challenging for many utilities. For performing CVR as a part of smart grid-based VVO, precise load modeling is essential and challenging for utilities as new loads and generating sources are changing the behaviour and characteristics of loads. High penetration of EVs in near future could significantly affect CVR performance as it could change grid load characteristics. Moreover, high penetration of DERs in the system could face utilities with grid dynamic instabilities. Although, employing storage systems could improve the negative impact of high penetration of DERs in the grid as they could store the excess amount of the supply for several purposes such as peak shaving but the amount of battery and the integration of battery management with smart grid VVO could still be challenging. Using CES could also change the way of using conventional VVO control components such as OLTC. This could be a challenging issue as many of conventional grid are equipped with OLTCs. Hence, further investigations need to be done to find the optimal locations of CES within the grid. Regarding PMUs, although they could definitely improve VVO in terms of precise data capturing and efficiency but, their high costs is still a barrier for novel VVO solutions to use PMUs. Micro PMU studies are going to be more investigated in recent years to overcome the high cost of PMUs and to extend PMU applications in distribution networks. As explained in this paper, IEC 61850 could improve smart grid adaptive VVO in terms of reliability and interoperability, however, designing more precise and efficient merging units at the process bus are still a challenging work for utilities. Harmonizing standards is another challenge discussed in this paper that utilities and grid planners need to work more in order to design VVO solutions with higher levels of efficiency, performance and reliability in near future.

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