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Article

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Provided in Cooperation with:

International Journal of Energy Economics and Policy (IJEPP)

Reference: Shahin, Moustafa/Topriska, Evangelia et. al. (2020). Evaluation of distributed energy resource interconnection codes and grid ancillary services of photovoltaic inverters : a case study on Dubai solar programme. In: International Journal of Energy Economics and Policy 10 (2), S. 512 - 520.

<https://www.econjournals.com/index.php/ijeep/article/download/8758/4934>.

doi:10.32479/ijeep.8758.

This Version is available at:

<http://hdl.handle.net/11159/8318>

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Evaluation of Distributed Energy Resource Interconnection Codes and Grid Ancillary Services of Photovoltaic Inverters: A Case Study on Dubai Solar Programme

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Received: 21 September 2019

Accepted: 27 December 2019

DOI: <https://doi.org/10.32479/ijee.8758>

ABSTRACT

This paper evaluates the technical aspects of grid-connected photovoltaic (PV) systems and distributed energy resources (DERs) interconnection grid codes. The advanced functions of smart PV inverters and smart grid solutions are discussed as well as the gaps of the existing grid codes that hinder DER ancillary services. An online survey targeted the key stakeholders and industry experts have been conducted to investigate advanced inverters potential of providing DER ancillary services to distribution grids. The survey results are discussed in details and recommendations for the reactive power support of DER inverters and DER interconnection codes enhancements are presented.

Keywords: Distributed Energy Sources, Distributed Energy Resource Interconnection Grid Codes, Distributed Energy Resource Ancillary Services, Distributed Energy Resource Integration, Advanced Inverters Capabilities, Volt/Var Control

JEL Classifications: P48, Q42, Q48

1. INTRODUCTION

In the UAE, the use of clean energy sources and low-carbon electrification are receiving increasing attention. The target set to diversify the energy mix, is that clean energy will reach 25% of Dubai's total energy share by 2030 (Dubai Carbon, 2017). Dubai's solar roof-top photovoltaic (PV) programme called "Shams Dubai" was launched in 2015 to encourage household and building owners to install PV panels for electricity to feed their own loads and export the surplus to the utility grid. In 2 years, more than 1354 buildings have already installed PV panels on their roofs and generated a total capacity of 125 Megawatts (DEWA Shams Dubai, 2019).

The "Interconnection code" refers to the set of rules and regulations that utilities, PV project developers and facility owners must follow when connecting inverter-based distributed energy

resources (DER) to the grid. The interconnection grid codes in general focus on the electrical behaviour of the inverters and how they should interoperate with the existing utility systems (Basso, 2014).

However, the existing interconnection grid codes of renewable DER in Dubai have imposed restrictions to limit massive energy exports to the grid and lacked the support for advanced inverter capacities. Those restrictions could limit larger PV deployments and hinder the achievement of the strategic targets to increase Dubai's share from clean energy sources to 75% by 2050 (Dubai Carbon, 2017).

Alternatively, advanced inverter functionalities and smart grid technologies such as ADA and AMI could be the solution to enable higher PV penetration while supporting the grid performance and provide ancillary services. This paper evaluates renewable DER

integration based on advanced control of PV inverters and study DER interconnection grid codes enhancements needed to enable the implementation of advanced inverter capabilities in a smart grid context.

This paper evaluates the technical and regulatory challenges of adopting advanced inverter functions to enable grid ancillary services and support the voltage regulation of distribution feeders. This paper is structured as follows Section III provides a brief review of relevant literature. Section IV describes the survey methodology for evaluating DER integration technology and interconnection of PV inverters in Dubai. Section V provides detailed qualitative and quantitative analysis of the survey results. Finally section VI presents the key conclusions and recommendations.

2. LITERATURE REVIEW

2.1. Renewable DER Integration Challenges

Several studies have been carried out to investigate the challenges of accommodating high penetration of renewable distributed generation while maintaining the grid performance (Palmitier et al., 2016b) (Lupangu and Bansal, 2017). DER integration challenges have been classified in the literature to technical and non-technical challenges including regulatory, interconnection process and economical challenges as illustrated in Figure 1.

A study by International Renewable Energy Agency (IRENA) emphasized the importance of developing integrated strategy that covers technical, regulatory and economic aspects in order to tackle DER integration challenges successfully. The common theme of all implemented measures was to introduce additional flexibility into the existing power systems to accommodate renewable distributed resources at different voltage levels (IRENA, 2017) (Palmitier et al., 2016b).

A study by the international energy agency's PV (IEA's PV) power systems programme on urban PV electricity policies concluded that grid-connected PV (GC-PV) can be the solution to growing demand in the dense urban environment. In the perspective of a large PV deployment, it is quite important to have upfront good integration policies to assure that GC-PV is deployed with the maximum benefit to the community while reducing actual installation barriers associated with grid codes and permits (IEA PVPS, 2009-2016). Sweco et al. investigated DER integration strategy to provide flexibility to the distribution power system and highlighted that the technologies needed for DER integration are available; the key challenge is to adjust to the regulatory framework and DER interconnection policy to make them market ready (Sweco, 2015). A summary of the strategies that provide flexibility measures for smooth DER integration are summarized in Table 1 (IEA PVPS, 2009-2016).

Figure 1: Challenges of distributed energy resource integration into distribution grids

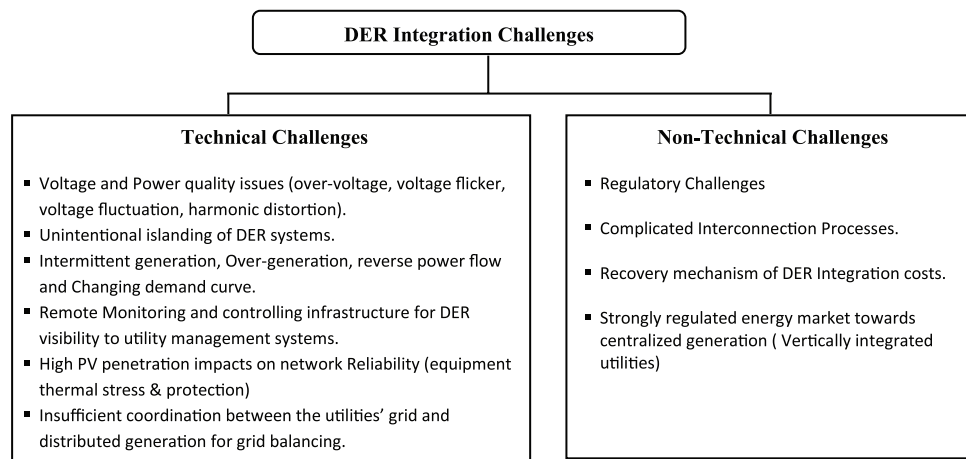


Table 1: Summary of der integration approaches

DER integration approaches	Description	DER ancillary services
Smart grid enabled der operations	Advanced functions of smart inverters Integrated AMI, ADA and smart inverter Active network management	Reduce the impact of DER intermittency Grid balancing Voltage regulation CVR Reduce the impact of DER intermittency/voltage flicker Grid balancing
Demand side management	Automated demand response Load shaping/control	
Energy storage	Distributed storage enables smooth DER integration	Reduce the impact of DER intermittency/voltage flicker Spinning reserve Black start Grid balancing
Grid reinforcement	Capital investment for T and D network design	Voltage regulation Frequency regulation Flexibility in T and D network design

CVR: Conservation voltage reduction, DER: Distributed energy resource

2.2. DER Interconnection Grid Codes

DER interconnection codes have a key enabler role to facilitate higher share of renewable energy generation. According to recent studies by the IRENA, interconnection grid codes and regulations remain crucial to enable successful renewable energy transformation of the existing power systems. As the renewable energy resources expand, the existing energy policies and regulatory framework needs to be revamped in order to accommodate the growing renewable penetration levels (IRENA, 2016).

The key objective of DER Interconnection grid codes is to facilitate connections of DER systems to the grid while maintaining the operational requirements of the grid. The two competing policy goals that should be reconciled for balanced interconnection grid codes are:

- Green energy policy to ensure a sustainable growth of DER share in the energy mix
- Grid operational requirements including voltage regulations, power quality and reliability.

The interconnection grid codes should evolve hand-in-hand with the smart grid and DER technology development such as smart meters and advanced inverter capabilities. The developed grid codes shall also specify clear guidelines for DER remote management including remote DER monitoring, control by the utility and the required communication architecture (CEC, 2011). The operational grid codes usually specifies voltage violation constraints of all network buses to remain within the statutory limits of $0.95 \leq V_{p.u} \leq 1.05$ in steady-state and the steady-state currents to remain within the feeder and device rated current limits (Seuss et al., 2014).

The IRENA study and IEA-PV program emphasised on the importance on adopting an integrated strategy that covers technical, regulatory and economic aspects in order to tackle DER integration challenges successfully. The driver of interconnection policy for most of distributed generation programs in Europe and USA was to support market development and green technology (IRENA, 2016) (IEA PVPS, 2016). As a result, the interconnection standards overlooked the coordinated integration of DER systems and focused on accommodating and tolerating them. Most interconnection regulations mandate instantaneous trip of DER systems during any disturbance at the distribution grid. This approach has exacerbated voltage and frequency disturbances and led to unnecessary outages in countries with high PV penetrations levels like Germany, Italy and USA. Recently, several countries specified active power curtailment and reactive power control capabilities in their DER interconnection grid codes to overcome those challenges reported by DER pioneering countries (Kraicz et al., 2017).

2.3. DER Interconnection Grid Codes in Dubai

DER interconnection regulations of solar PV resources in Dubai consist mainly of three grid code documents issued by the Dubai Electricity and Water Authority (DEWA):

- i. Connection Conditions for Distributed Renewable Resources Generation (DRRG) Connected to The Distribution Network Version 1.1. This document includes the policy and regulations for solar DER interconnection in Dubai (DEWA Shams Dubai, 2015a)
- ii. Standards For Distributed Renewable Resources Generators Connected To The Distribution Network Version 2.0. This standard provides technical regulations about DER integration and interconnection to distribution grid (DEWA Shams Dubai, 2016)
- iii. Connection Guideline for DRRG connected to the Distribution Network Version 1.1. Provides general guidelines for solar DER interconnection process (DEWA Shams Dubai, 2015b).

The technical requirements for DER interconnection is given in Table 2 segmented based on maximum installed PV capacity (P_{mc}).

According to Shams Dubai regulations, GC-PV systems exceeding 400 kW shall provide static reactive power support based on the ratio P/P_n (where P_n is the rated active power of the inverter), in a way that the DER must absorb lagging reactive power above 50% of its nominal power in order mitigate the overvoltage as shown in Figure 2 (DEWA Shams Dubai, 2016).

Overall it can be concluded that the existing Shams Dubai grid codes did not support advanced inverter functions like dynamic volt/var droop control, volt/watt and power factor control modes of PV inverters. Further, some constraints were imposed on the maximum PV power generation and the annual connection capacity to avoid the challenges of intermittent uncontrolled distributed generation. For instance, new connections will be put

Figure 2: Reactive power support requirements as per Shams Dubai grid codes

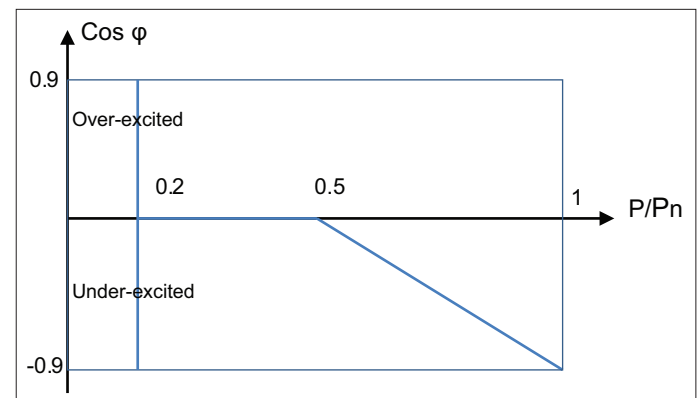


Table 2: DER interconnection requirements in Dubai

DER maximum capacity	Reactive power support	Active power curtailment	Remote control	Remote monitoring
$P_{mc} < 10 \text{ kW}$	Limited	Required	Not required	Not required
$10 \text{ kW} \leq P_{mc} \leq 100 \text{ kW}$	Required	Required	Required	Not required
$100 \text{ kW} < P_{mc} \leq 400 \text{ kW}$	Required	Required	Required	Required

DER: Distributed energy resource

on hold in case the predefined limit of annual connection capacity has been exceeded (DEWA Shams Dubai, 2016).

2.4. Advanced Inverter Functions for Grid Ancillary Services

The primary component in GC-PV systems that manage the integration of DER system is the DC/AC inverter. Modern inverter has evolved to enable remote control of their output to actively support the grid performance and provide ancillary services in many novel ways. In the past, ancillary services were provided exclusively by bulk conventional generation and transmission assets. In the future with increasing share of inverter-based renewable DER, ancillary services have to be provided by DER systems such as support for voltage regulation, volt/var optimization, peak load reduction through conservation voltage reduction (CVR) and improving power quality (EPRI, 2013) (Al-Shetwi and Sujod, 2018).

Palminier et al. investigated several active and reactive (volt/var) power management strategies of PV integration at different penetration levels. This could be achieved typically through controlling on-load tap changers (OLTCs) of transformers, capacitor banks and line regulators. A techno-economic assessment of different volt/var strategies to enhance PV hosting capacity concluded that OLTCs of distribution transformer could be effective can prove only when PV penetration level exceeds beyond 75% (Palminier et al., 2016b). For lower penetration levels (typically between 15% and 75%), PV inverter's reactive power support and active power control have been demonstrated in several studies to mitigate voltage regulation and power quality issues that could occur due to large PV deployment in the distribution grid.

Smith et al. investigated the inverter volt/var control through a simulation study and concluded that advanced inverter functions could address DER integration challenges and support grid performance. Similarly, several simulation studies concluded that volt/var management through PV inverters is an effective strategy for distribution voltage regulations however, feeder characteristics shall be taken in considerations (Smith et al., 2011) (Hashemi et al., 2013) (Casey et al., 2010).

Alobeidli and Moursi compared different coordinated volt/var control strategies using conventional methods like on OLTCs and inverter-based control. They reported that inverter-based strategy could improve feeder voltage profile and maximize reactive power reserve up to 80% (Alobeidli and Moursi, 2014).

Rylander et al. and others analysed the potential performance benefits of advanced inverter control on different distribution feeders. The advanced volt/var function of the inverters improved feeders hosting capacity between 43% and 133% (Rylander et al., 2016).

The new release of the interconnection standard for DER in North America, IEEE 1547-2018, allows broader inverter support in distribution feeder voltage regulation by changing DER reactive power generation. Smart DER inverters shall be capable to actively

control its reactive power output as a function of voltage, active power output or based on power factor control (IEEE 1547, 2018).

In conclusion, it has been proven in the literature that advanced smart inverter functions and volt/var control are cost-effective strategies to improve PV hosting capacity of distribution feeders and help to mitigate adverse voltage impact compared to the conventional voltage regulation methods through OLTC which are more costly and have a slower response compared to smart inverters.

Modern GC-PV systems use advanced inverters that become smart enough to operate autonomously according to pre-established software settings and with the addition of communications capabilities, DER systems can be directly monitored and controlled by utilities to modify or override their autonomous operations. DER systems can receive remote emergency commands, demand response pricing signals or schedules of modes/commands to cause the inverters to change their electrical characteristics such as voltage levels, energy production rate, and active or reactive power outputs according to daily, weekly, or seasonal timeframes within the standard requirements of the interconnecting grid codes [Table 3].

A survey has been conducted to assess the advanced inverter functions and interconnection grid code readiness of PV inverters.

3. SURVEY METHODOLOGY

An online survey is designed to investigate the effectiveness of the integration strategy and smart grid solutions to address existing challenges of DER interconnections grid codes and identify the required improvements to realize the full potential of advanced inverters and smart grid technologies for DER integration. The survey is distributed through the Google Forms platform to the key stakeholders of roof-top PV solar program and industry experts. The following are the key objectives of the research survey:

- Collect information about the existing GC-PV projects in Dubai
- Investigate the market and regulatory readiness for implementing advanced inverter functions
- Identify the viability of distributed energy storage with GC-PV systems
- Identify the key gaps of the existing interconnection grid codes that could obstruct the proposed DER smart grid integration approach
- Respondent's feedback and recommendations to improve the existing renewable interconnection grid codes in Dubai.

3.1. Sampling Method

The survey was circulated to sixty (60) participants representing different groups of roof-top solar stakeholders: the utility industry (DEWA), Approved PV inverter manufacturers; enrolled consultants and contractors of Shams Dubai programme (DEWA Shams Dubai, 2017). The final participants sample consisted mainly of solar contractors (44.4%), followed by technical experts including utility experts 36.1%, Shams Dubai's Consultants (11.1%) PV/inverter manufactures (4.4%) and finally smart grid consultants 1%, as shown in Figure 3.

3.2. Survey Structure

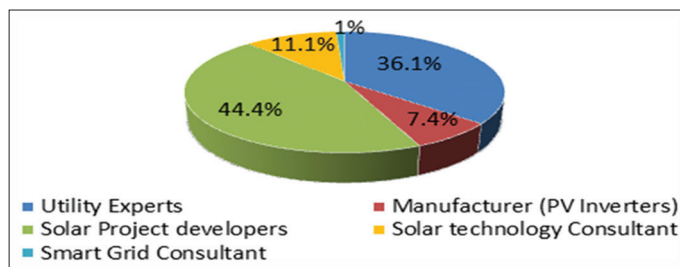
The questionnaire is subdivided into the following four main sections:

- A general information section about distributed GC-PV systems in Dubai
- Advanced PV inverter section to investigate the existing configurations of smart PV inverters and remote monitoring/dispatch capabilities
- A PV storage section to collect information and insights of industry's experts about the potential of the different type of PV storage systems for future support by interconnection regulations
- A regulatory and grid codes section which includes questions to investigate the technical and regulatory gaps of the existing interconnection in terms of support of advanced inverter functions.

4. SURVEY RESULTS

Overall 36 respondents filled out the questionnaire out of 60 questionnaires that were circulated to PV and utility experts. Thus, the response rate of the survey is approximately 60% which is perceived as satisfactory response rate considering the selected sampling method and targeted expert respondents (Baruch, 1999).

Figure 3: Survey participants' background



4.1. GC-PV Systems in Dubai

The majority of PV systems (71%) installed in Dubai are connected to residential loads with relatively low system capacity <20 kW. Commercial loads and industrial loads represent less percentage in terms of numbers of connected PV systems, 23% and 6% respectively as shown in Figure 4. The PV system size (rated capacity) of commercial PV systems representing 23% of total installed PV capacity in Dubai ranges between 10 and 400 kW. The industrial loads represent only 6% of the total installed PV capacity with a relatively large rated capacity ranging between 100 kW to several megawatts.

The different configurations of how grid-tied PV panels are connected to DC/AC inverters can be categorised as central inverter, string inverter, multi-string and ac module inverters.

A central inverter topology, where a single stage inverter is connected to all PV modules, suffers from some limitations in terms of reliability and complex maximum power point tracking.

For string/multi-string inverter topology, a single inverter is used for a group of connected PV modules in a string enabling better MPPT for PV panels with different orientations. The inverter is integrated with the PV modules during manufacturing time in AC module topology. Hence the module output is AC and can be directly synchronized with the grid (Nema et al., 2011). An additional classification for hybrid inverter has been included in this survey to study the application of commercial hybrid inverters that can be directly connected to both solar panels and battery storage in off-grid and on-grid modes. According to the global solar PV inverter market research, the global solar inverter market shares reported that string inverter applications have surpassed those of central inverters in 2017 and expected to continue its rise in the next 5 years (Moskowitz, 2018).

Table 3: Advanced inverter functions for grid ancillary services

Classification	Inverter functions	Description
Autonomous functions: Behavior controlled by inverter's pre-configured operating parameters (defined during system commissioning) Parameters can be re-configured, activated or deactivated at later date through on-site changes or remotely No communication capability is required	Low-/high-voltage ride-through	Defines voltage range for which inverter remains on-line
	Low-/high-frequency ride-through	Defines frequency range for which inverter remains on-line
	Volt-var control (dynamic reactive power injection)	Adjusts reactive power output based on service voltage
	Soft-reconnect	Soft-reconnect help to avoid sharp spikes when large numbers of distributed resources reconnect to the distribution system after power outages
Commanded functions: Direct control of inverter behavior from remote operator commands or feedback, based on conditions at the point of connection Communication architecture and remote control infrastructure are required	Ramp-rate controls	Smooth PV output for default/emergency conditions
	Fixed power factor	Provide reactive power based on fixed power factor
	Remote connect/disconnect command to DER system	Electrically connects to or disconnects from the grid
	Set/limit real power	Curtailment of active power for demand response
	Respond to real power pricing signals	Adjust output power based on TOU
	Update/overwrite autonomous functions	Utility could update preconfigured parameters based on seasonal schedules or upon request
	Provide black-start capability	Storage management of hybrid inverters
	Provide spinning reserves	

DER: Distributed energy resource, PV: Photovoltaic

The most common topology used in grid-tied solar PV projects is found to be that of string inverter in more than 86% of PV projects. Hybrid inverters were used in 8% of PV projects. Central inverters and hybrid inverters used in 6% and 8% of PV projects respectively. Hybrid inverters are typically used for commercial applications in non-urban areas with limited access to reliable grid supply as reported by the survey respondents and presented in Figure 5.

The correlations between the different survey variables were analyzed as shown in Table 4 using IBM SPSS version 20. It can be concluded from the strong correlation between PV capacity, inverter topology and load type that string inverters are predominantly used for small and medium size PV systems in residential and commercial projects primarily due to its modularity and flexibility. Whereas, central inverters are typically used in large-scale PV or utility scale solar projects. On the other hand, the correlations between the PV size or load type with using PV storage were insignificant [Table 4].

Current GC-PV systems use advanced inverters that could operate autonomously according to pre-established software settings. Furthermore, with the introduction of communications capabilities to PV inverters, DER systems can be directly monitored and controlled by utilities to modify or override their autonomous operations. Smart PV inverters can receive remote commands and change settings to control their electrical characteristics such as voltage levels, energy production rate, and active or reactive power outputs (EPRI, 2012). Hence, the advanced

inverter functions could be grouped into autonomous functions as shown in Figure 6 and remote management functions using telecommunication interface as illustrated in Figure 7.

The communication protocol that can be implemented for remote monitoring and control of inverter based PV systems is predominantly Modbus protocol which has been used in 83% of local monitoring of PV systems for operational and maintenance requirements, as shown in Figure 8. A small percentage (11%) of proprietary communication protocols are used by PV inverter manufactures in comparison to open protocol like DNP3 or IEC61850 which is considered as the future protocol for advanced inverter management as indicated by surveyed inverter manufactures.

4.2. The Key Barriers of Enabling DER Ancillary Services

The participants were asked about their feedback on the key barriers of utilizing DER systems for providing ancillary services to distribution network operators (DNOs) [Figure 7].

One of the key barriers of DER ancillary services reported by the majority of respondents (73%) is the unclear requirements for the utility's remote management of DER inverters. For instance, DER interconnection grid codes did not provide clear guidelines for remote monitoring and remote control of GC-PV systems (DEWA Shams Dubai, 2015a). 64% of the respondents believed that the absence of incentives or compensation mechanisms for

Figure 4: Load types of photovoltaic systems (left) and the rated kW capacity (right)

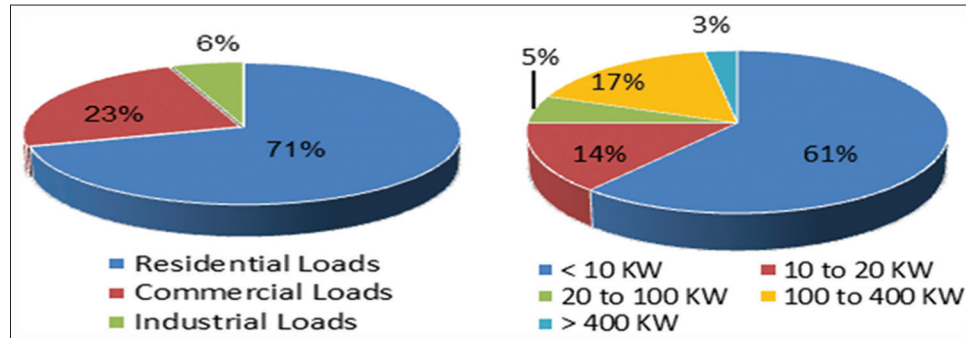


Figure 5: Inverter topology used in photovoltaic projects

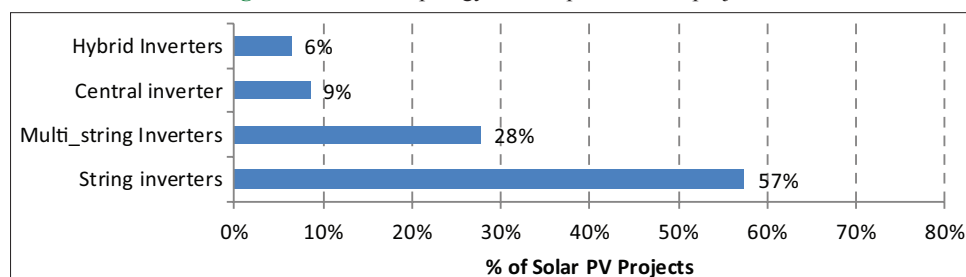


Table 4: Correlation between PV capacity, inverter topology, load type and PV storage

Correlation co-efficient Spearman's rho (ρ)	Load Type	Inverter Topology	PV Storage
PV capacity			
ρ	0.612*	0.536	-0.213
Sig. (2-tailed)	0.001*	0.002*	0.554

*Indicates significant correlation at 98% confidence level. PV: Photovoltaic

DER ancillary service providers is among the main barriers. DER owners should be compensated for the lost active power generation because of reactive support and voltage regulation services.

56% of the respondents believed that DER interconnection codes are lagging behind the technological advances of smart inverters, many of the advanced inverters capabilities are recognised by the existing grid codes. 49% of the respondents viewed that the stringent DER interconnection process and restrictions on maximum PV capacity could hinder DER ancillary services. Finally, hybrid inverters with integrated storage are not allowed for grid interconnection in the existing grid codes which limits the benefits of distributed energy storage as reported by 22% of the survey respondents.

4.3. DER Ancillary Services

The ancillary services or operational supportive functions that can be provided by PV inverters to DNOs have been listed in terms of their priority as shown in Figure 8. The ancillary services related

to voltage regulation came on top as seen by the majority (80%) of the survey respondents. Similarly, flatten the voltage profile across distribution feeders (i.e., minimise voltage deviation between the supply voltage at substation bus compared to the load voltage) is reported by 75% of the respondents.

Other key ancillary services to DNOs using advanced PV inverter control are preserving operations of conventional voltage regulators including LTCs and shunt capacitor banks 70% and defer voltage regulators additions (63%).

Reactive power control of PV inverters could support power factor correction and reduces distribution feeder losses (65%). Supporting demand response through CVR 58%. Finally, providing back-start capability of PV-inverter is reported by 15% of respondents that is to partially restore the feeder supply to operation without relying on the transmission network to recover from a total or partial shutdown (Ding et al., 2017).

Figure 6: Communication protocol applied for remote management of solar photovoltaic systems

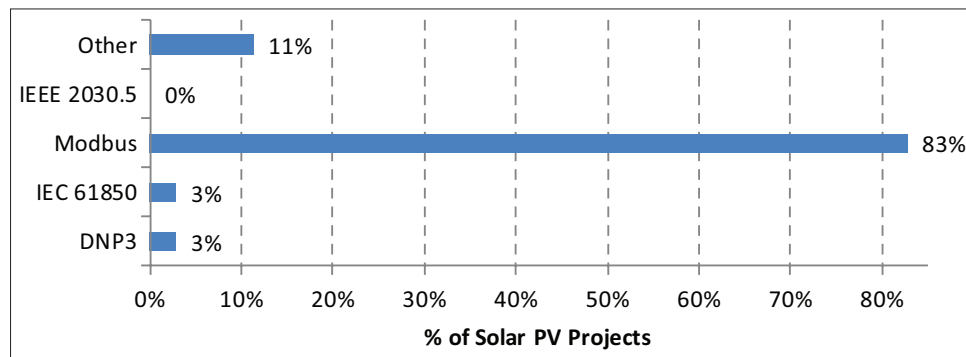


Figure 7: The key barriers of distributed energy resource ancillary services

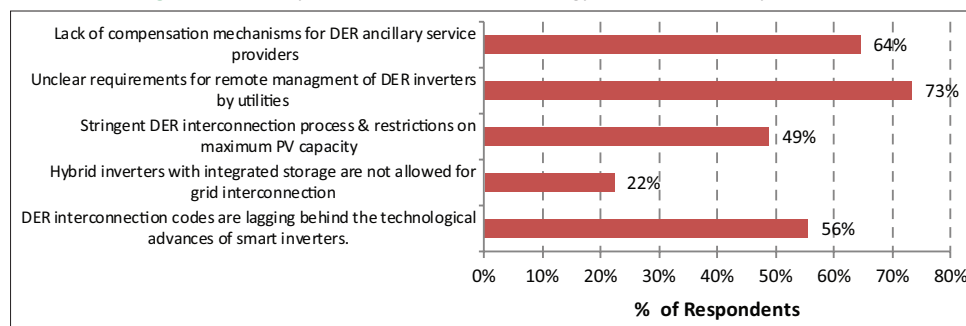
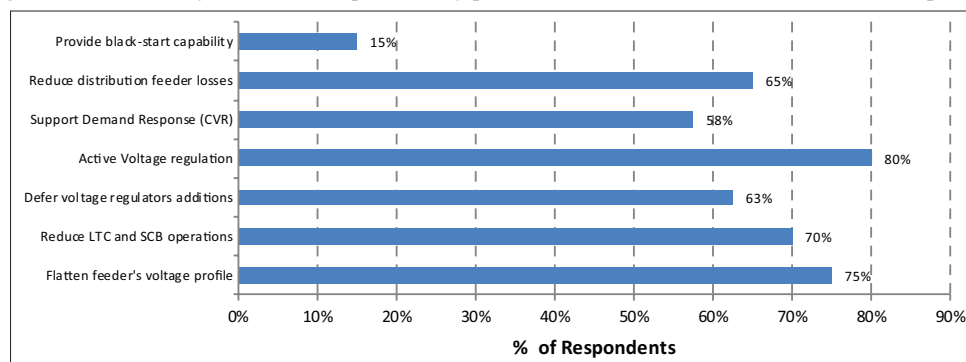


Figure 8: The ancillary services to be provided by photovoltaic inverters to distribution network operators



5. CONCLUSIONS

In conclusion, the survey results revealed that advanced smart inverter functions and smart grid integration are strategies to improve PV hosting capacity of distribution feeders and help to mitigate adverse voltage impact compared to the conventional voltage regulation methods through transformer's OLTC which are more costly and have a slower response compared to smart inverters. The majority of respondents (72%) viewed that advanced inverter functions offer a viable solution to address the challenges of DER integration. Fifty eight percent (58%) of the respondents considered that energy storage is not currently economical for GC-PV systems especially in Dubai and the gulf region.

The advanced PV inverter capabilities (steady state and dynamic volt/var control) could lead to operational benefits for utilities by alleviating voltage flickers, reducing feeder losses, and drastically reducing regulator switching operations, thereby extending their lifespan and potentially deferring the investment in new voltage regulators. On the other hand, providing voltage ancillary services by reactive power generation incurs a cost on PV owners due to lost active power production. There are no technical barriers to realize the ancillary services by PV inverters however; the barriers are mainly stringent DER interconnection grid codes, lack of support of advanced inverters capabilities and lack of incentives/compensation mechanism for inverter ancillary services.

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