



Review Article

Research on Microgrids at the University of Malta

A. Micallef^{*1}

¹University of Malta, Department of Industrial Electrical Power Conversion, Msida, Malta

Abstract. This article presents some of the work done in recent years by the microgrids research team at the Department of Industrial Electrical Power Conversion (IEPC). Research activities are dedicated towards enabling secure, reliable, and carbon free electricity systems. To date, the main contributions by the department were made to the operation, control and management of microgrids in low voltage (LV) distribution networks, ship electrification (shipboard microgrids) and low voltage DC microgrids. The paper also presents a few of the significant results achieved by the department to date including a hierarchical control architecture for single phase microgrids, control algorithms of power electronic converters for AC and DC microgrids, energy and power management strategies, power quality improvement algorithms and technologies, demand response strategies and devices, and the effective integration of renewables and energy storage systems.

Keywords: Microgrids, Electric Transportation, Demand Response, Power Quality

1 Introduction

The decentralisation of energy generation is a recent phenomenon caused by the wide-scale integration of distributed renewable energy sources (RES). RES in low-voltage grids (e.g. small-scale photovoltaic systems) generate energy closer to the consumers. The instantaneous penetration of RES can vary considerably even during the course of the day due to the end consumers usage patterns and due to the intermittent and variable output of the RES. For example, without factoring in the intermittency due to cloud coverage, the integration of photovoltaic (PV) generation affects dramatically the shape of the net-demand curve due to its variable output. PV generation increases the system's downward ramp in the morning and the upward ramp in the evening causing the so-called "camel

curve" net-demand characteristic to change into the "duck curve". High instantaneous PV penetrations might also create an oversupply situation in the middle of the day, resulting in a negative net demand (i.e. reverse power flow). In addition, if the instantaneous penetration of RES were more than 50%, the system would be operating as an inverter-dominated grid with the corresponding challenges of stability, quality and reliability (Kroposki et al., 2017).

Microgrids are self-contained electricity distribution networks in which the RES together with energy storage systems (ESS) and local loads work cooperatively as a single local system and typically have a single point of common coupling (PCC) as an interface with the main grid. Microgrids can either operate autonomously in stand-alone (islanded) mode or they can be integrated into the present distribution networks (grid-connected operation) without the need to modify the existing power systems. Microgrids also offer a solution to remote electrification (i.e. provide electricity in areas where grid connection is not a viable option) and offer better supply reliability to the end user when compared to the conventional electric grid. Microgrids (AC, DC or hybrid AC/DC) are key elements for integrating high levels of renewable energy resources as well as distributed energy-storage systems as these maximise energy efficiency and improve the reliability of the local electrical network.

This article presents some of the research work performed in recent years by the microgrids research team at the Department of Industrial Electrical Power Conversion. The department has been applying microgrid concepts and technologies to a number of applications by cooperating with academia and industrial partners. The rest of the paper shall present a few of the significant results achieved by the department to date and is organised as follows, with each section focusing on a specific topic. Section 2 describes the hierarchical control structure for control and management of microgrids and mi-

*Correspondence to: A. Micallef (alexander.micallef@um.edu.mt)

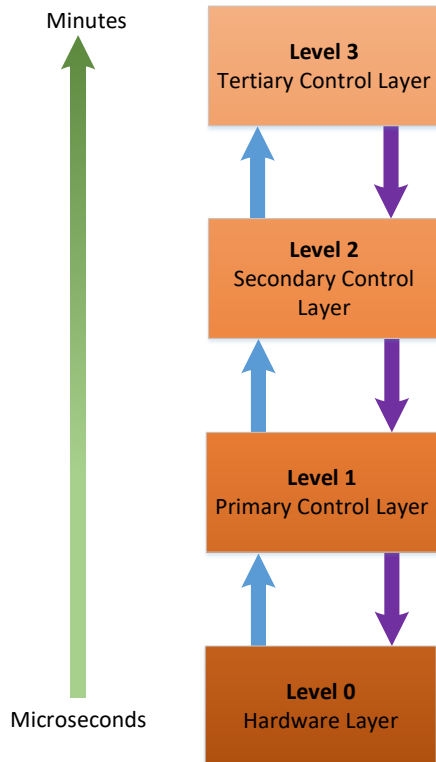


Figure 1: Hierarchical control architecture for microgrids.

crogrid clusters. Section 3 describes research activities on single phase microgrids while Section 4 describes the activities on low voltage DC microgrids. Section 5 deals with microgrids for the electrification of transportation while Section 6 describes the demand response strategies and devices for microgrid applications.

2 Control and management of microgrids

The hierarchical control strategy for microgrids is a widely accepted structure that consists of four distinct layers (Guerrero et al., 2011). The layers are shown in Fig. 1 where the bandwidth of the control loops is the highest at the physical level and decreases as the levels increase. Each layer has distinct roles for the effective implementation of grid-connected and stand-alone (islanded) microgrids.

2.1 Hardware layer

The power electronic converters (PECs) are the building blocks that enable the formation of the microgrid. The PECs convert power from one form to another and allow



Figure 2: A microgrid DC-to-DC converter implemented for the DC microgrid in the IEPC labs.

the formation of AC, DC and hybrid (AC/DC) microgrids. The PECs enable the connection of RES, ESS and various loads in the microgrids according to the selected network architecture. The converter level control (Level 0) within the PECs, determines the switching pattern for the solid state power semiconductors based on the operation of the inner voltage and current control loops. Three laboratory-scale setups have been developed by the department of IEPC to date for different network architectures. The first setup consists of a single phase AC microgrid consisting of three DC/AC inverters connected to a common AC grid that can work either in stand-alone or even in grid-connected operation. The second setup consists of a three phase microgrid consisting of two DC/AC inverters connected to a common AC grid that can work only in stand-alone mode. The final setup consists of a DC microgrid consisting of two unidirectional DC/DC converters and a bidirectional DC/DC converter connected to battery storage system. One of the DC/DC converters that was implemented for the DC microgrid in the IEPC labs is shown in Fig. 2.

2.2 Primary Control Layer

The primary layer (Level 1) is the application layer, implemented within the PEC, that uses local information to impart basic microgrid functionality and provides the reference set points for the PEC inner control loops. The role of the primary control loop is to maintain the balance between supply and demand to ensure that the microgrid remains stable under varying load conditions. A block diagram of the primary control loops of the DC/AC

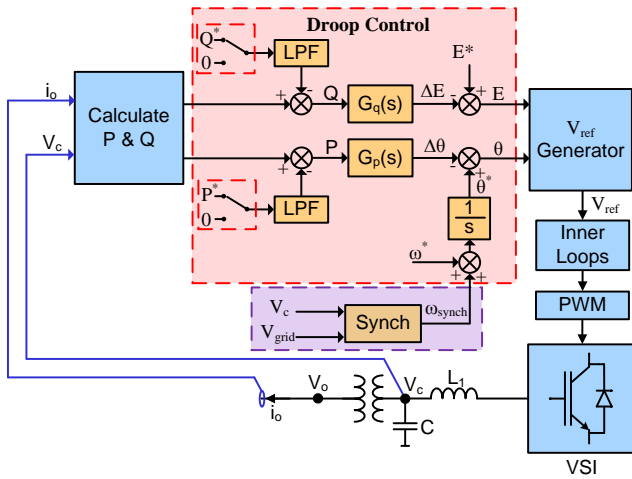


Figure 3: Block diagram of the primary control loops of the DC/AC power electronic converters for single phase microgrids.

power electronic converters for single phase microgrids is shown in Fig. 3. The PECs that are deployed in either AC, DC or hybrid microgrids typically use droop control in the outer loop for distributed power sharing. The droop strategy varies according to the type of microgrid and it enables the parallel operation of PECs without any communication among the PECs albeit having a number of limitations (Micallef et al., 2014). This layer also includes virtual impedance loops in the inner loops of the converters that are typically used to improve the power sharing. Virtual impedance loops emulate various complex impedance behaviours and can be applied in both single-phase, three-phase and DC microgrid PECs, albeit with some important differences (Micallef et al., 2017a).

2.3 Secondary Control Layer

The secondary control layer (Level 2) implements the control and management algorithms for the optimal operation of the microgrid. The secondary layer provides the reference set points for the primary control loops. Algorithms in this layer are concerned with energy balancing of ESSs, black start management, power quality improvement, synchronisation voltage and frequency restoration. The secondary layer also coordinates the transition from grid-connected to islanded operation and vice-versa. The secondary control functionality can be implemented either as centralized, decentralized (or quasi centralised) or distributed, as shown in Fig. 4, with each architecture having its own advantages and limitations. In a centralized system (Fig. 4a), the RES, ESS and loads are all connected to a central microgrid controller (MGCC). The MGCC stores data and user information to assign set-points to each entity within the microgrid so as to attain the mi-

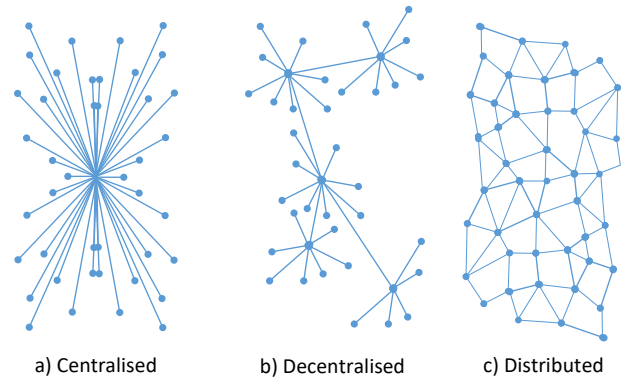


Figure 4: Representation of Centralised, Decentralised and Distributed microgrid architectures.

crogrids goals. In a centralised system, the main limitation is that the MGCC is a critical point of failure. Decentralized systems (Fig. 4b) do not have one MGCC but they use multiple central controllers, each of which usually assigns set-points to each entity within the microgrid. The decisions are taken locally as the different actors usually have different goals. A decentralized system can be just as vulnerable as the centralised but it is more tolerant to faults. Finally, the distributed system (Fig. 4c) is similar to the decentralized, but it eliminates centralization. In a distributed system, all entities have equal rights and decisions are taken through consensus among the all the actors.

2.4 Tertiary Layer

The tertiary control layer (Level 3) is the highest level of the hierarchy that implements energy management and power flow control strategies. The tertiary layer supervises the operation of the microgrid, regulates the power import/export from the microgrid, coordinates the operation of microgrid clusters, implements energy management strategies that optimise single or multiple variables (cost, efficiency, etc.). The tertiary layer is implemented as a centralised architecture since the decisions at this level impact the whole microgrid or microgrid clusters.

3 Single Phase Microgrids

Renewable energy sources are being integrated into single-phase low-voltage distribution networks to produce energy closer to the consumer. The formation of low-voltage microgrids can achieve high-energy efficiency and can also increase the reliability of the electrical supply. However, the combined power injected by the local RES into the grid can cause power quality issues during scenarios where the generation exceeds the demand. In Micallef et al. (2015)

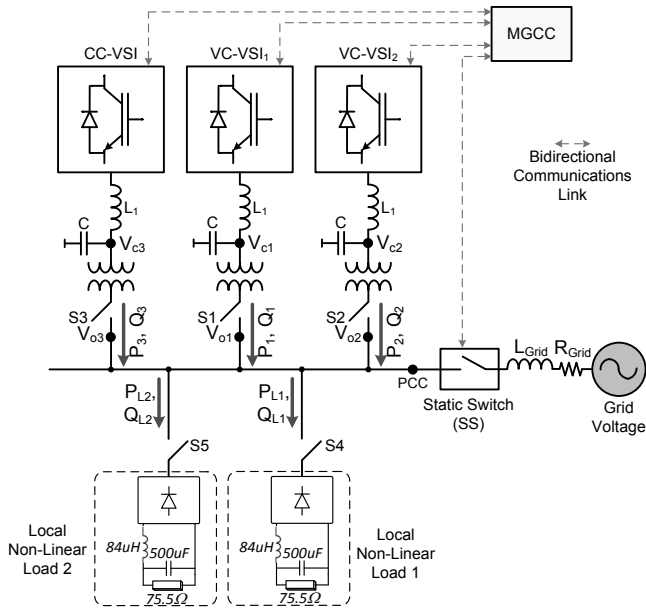


Figure 5: Block diagram of the AC single phase microgrid topology by IEPC (Micallef et al., 2015).

and Micallef et al. (2017a), we designed, simulated and implemented a single phase microgrid that emulates a group of neighbouring households in a residential area that are connected together to form a microgrid. A block diagram of the considered microgrid topology is shown in Fig. 5. Research activities by the department have addressed the limitations of the decentralized operation of parallel PECs using conventional droop control including the voltage and frequency deviations, fundamental and harmonic current sharing. Solutions to overcome its inherent limitations and optimize the performance of the microgrid were also designed, modeled and experimentally verified. A summary of the main contributions shall now follow.

3.1 Power Quality Mitigation

The authors have highlighted the main power quality issues related to single-phase microgrids in Micallef (2019), together with a critical review of methods and algorithms to mitigate these phenomena. While various research studies have been proposed in literature concerning power quality mitigation in three-phase microgrids, not all of these solutions can be applied directly to their single-phase counterparts. Power quality issues of consequence that were identified for single phase microgrids include: reactive power exchange; voltage and frequency fluctuation; and current and voltage harmonic distortion.

In Micallef et al. (2017a), we proposed selective harmonic control loops by proportional resonant controllers

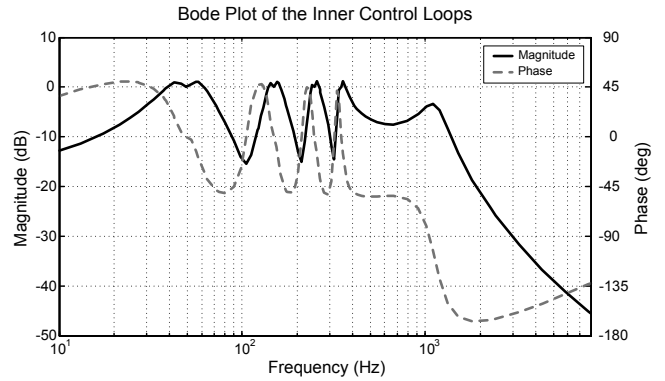


Figure 6: Bode plot of the inner control loops of a microgrid inverter with proportional resonant controllers (Micallef et al., 2017a).

that are implemented in the primary control layer of the PECs themselves in single-phase microgrids. The proportional resonant controllers adapt to the varying droop frequency since the frequency of the microgrid voltage varies due to the droop control. An additional advantage of proportional resonant controllers is that selective harmonic control can be integrated into the controller quite easily by cascading additional resonant transfer functions tuned at the required frequencies. An example of the frequency response of the inverter inner control loops with proportional resonant controllers is shown in Fig. 6 where bandpass characteristics are introduced in the frequency response at the 3rd (150Hz), 5th (250Hz) and 7th (350Hz) harmonic in addition to the fundamental frequency (50Hz).

Virtual impedance loops in literature were based on resistive and/or inductive impedances that degrade the voltage harmonic distortion at the PCC to improve the fundamental power sharing. Thus, we proposed a resistive-capacitive virtual impedance loop in Micallef et al. (2014) and Micallef et al. (2017a) that improves the power sharing among the PECs, reduces the harmonic currents output by the RESs and also improves the voltage harmonic distortion at the PCC. The resistive-capacitive virtual impedance loop in principle emulates a virtual capacitive bank connected in series with the output of the inverter as shown in Fig. 7. The capacitive virtual impedance reduced the voltage total harmonic distortion at the PCC by 22.7% during experimental tests with an improvement in both the fundamental and harmonic current sharing.

In Micallef et al. (2015), we proposed secondary control loops shown in Fig. 8, that restore the microgrid voltage and frequency while eliminating the reactive power exchange between the PECs in single-phase microgrids. In addition, the primary and secondary control loops in Micallef et al. (2015) enable the microgrid to trans-

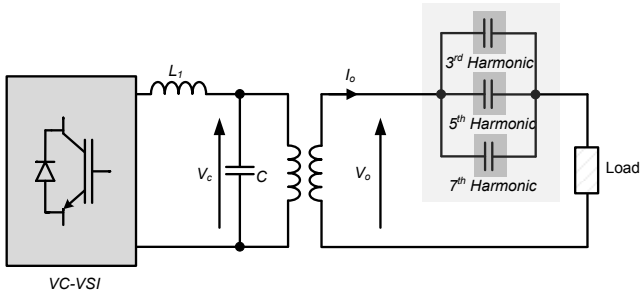


Figure 7: Schematic representation of the resistive-capacitive virtual impedance loop (Micallef et al., 2017a).

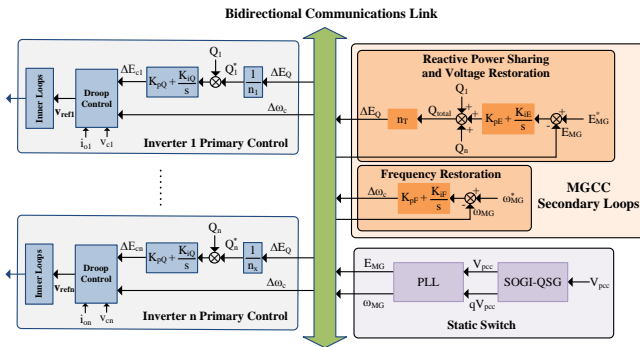


Figure 8: Secondary control loop for voltage and frequency restoration, reactive power sharing, and seamless transitions between grid connected and islanded operation. (Micallef et al., 2015).

ition from islanded to grid-connected operation and vice versa without any disconnection times for the consumer. The communication bandwidth is selected as a compromise between the total data that needs to be transferred through the network infrastructure and the transient response that is required from the secondary control loops. A high data bandwidth implies a fast transient response for the secondary control loops, while providing a high data transmission rates. Results have shown that low bandwidth communications can be used to achieve the required functionality with bandwidths as low as 1Hz. In Micallef et al. (2017b), we have also demonstrated how integrating RES in LV single phase microgrids can result in improved power quality of the electrical grid. A similar hierarchical architecture was employed for grid connected operation that avoids the voltage rise effect at the PCC from occurring by regulating the active and reactive power outputs from the PV inverters.

4 DC Microgrids

DC microgrids are gaining popularity due to their advantages over their AC counterparts. DC microgrids have lower conversion losses since PVs, batteries and

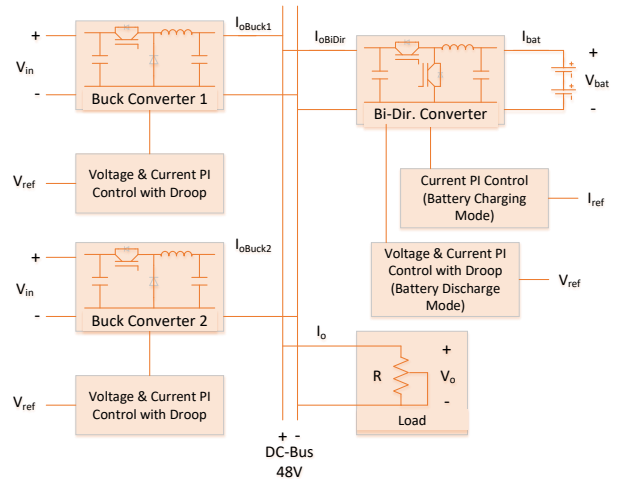


Figure 9: Block diagram of the DC microgrid topology by IEPC.

other RES have a DC output and thus these need less conversion stages (fewer PECs required). In addition, DC microgrids do not require any synchronisation or phase/frequency regulation. Another advantage is that the DC microgrid is not affected by power quality effects on the AC side (e.g. voltage sags, dips, etc.). These advantages make the DC microgrid attractive for numerous applications such as residential (behind-the-meter) installations, electric transportation (e.g. maritime microgrids), and offshore applications, amongst others.

For typical DC microgrid applications, the DC bus voltage is maintained by the utility through an AC/DC converter, while local loads and RESs are connected to the DC bus through DC/DC converters. The voltage level of the DC bus is dependent on the application and is regulated by the droop control loops implemented in the PECs. In Zammit et al. (2016), we describe the design of the primary control loops for parallel step down (buck) DC/DC converters in a behind-the-meter DC microgrid with conventional droop. For this application, a 48V DC bus was selected since this voltage level is considered inherently safe ("IEEE standard for dc microgrids for rural and remote electricity access applications", 2021) and does not require any additional safety considerations for behind the meter applications. However, should the residential building require high power consumption, then the bus voltage should be increased to reduce the system losses. In addition, we have also integrated a secondary voltage restoration loop to keep the desired voltage in the DC microgrid for varying load conditions. In Zammit et al. (2019) and Zammit et al. (2020), we proposed a novel droop control method termed as combined voltage and droop (CVD) for DC microgrid applications that is

built on the I-V droop method. The three droop methods were designed, modelled and simulated to compare their operation and performance where the proposed loop obtained faster dynamic operation without compromising the power sharing capabilities. The converters were then designed, modelled and built to form an experimental DC microgrid setup. A block diagram of the DC microgrid topology by IEPC is shown in Fig. 9.

5 Transportation Electrification

The international drive towards maximizing fuel efficiency is accelerating the development of battery-hybrid vessels, while the integration of alternative fuels (e.g. hydrogen, ammonia, etc..) is still in the early stages. Hundreds of ships with installed batteries are already in operation, including numerous retrofits and upgrades. Marine batteries are still undergoing rapid development and can provide various benefits even though they cannot presently solve the challenges related to long distance shipping. Short distance ferries are one of the few segments that have already seen uptake in both all-battery powered and hybrid solutions. Alternative fuels (e.g. hydrogen, methane) are showing great promise for long distance shipping although significant effort is required to scale up these technologies.

5.1 Maritime Microgrids

Maritime vessels (ships, ferries, tugs, etc..) tend to be one-offs or built as a small series, tailored for their specific owner, operator and purpose. The challenge is to choose the right power system topology and equipment for each vessel according to the specific operational profile thereby minimising emissions and maximising energy efficiency. Modern vessels adopt integrated power systems architectures, connecting the generators, propulsion and other loads to a common AC or DC bus (Sulligoi et al., 2016). The electrification of ships due to the integration of batteries and alternative energy technologies (e.g. hydrogen fuel cells), is transforming ship power systems into highly dynamic microgrids. Microgrids onboard maritime vessels (also defined by maritime microgrids in literature) operate in islanded mode when the vessels are out at sea, and in grid-connected mode when these are connected to the shore-side electricity. An example of a maritime microgrid with a DC bus architecture is shown in Figure 10.

We have applied control strategies and technologies used in terrestrial microgrids to the marine sector, such as voltage and frequency control algorithms, power quality improvement strategies, power-sharing methods, and energy management strategies. Our recent work has focused on the modelling and simulation of the electrical

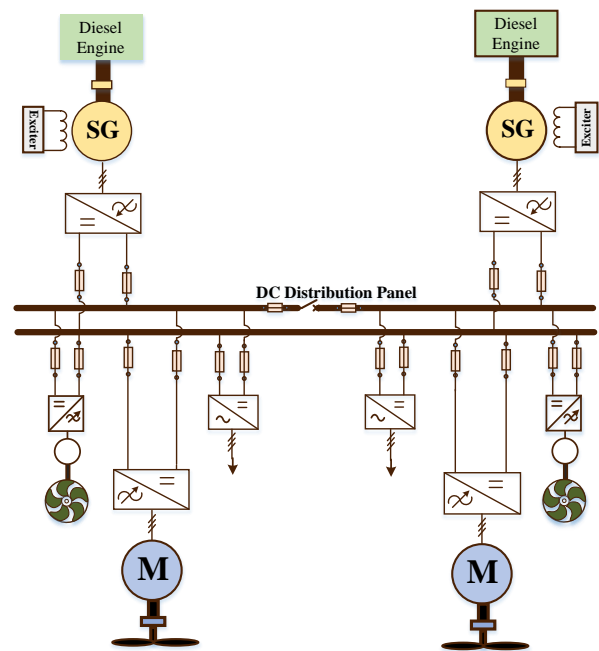


Figure 10: A line diagram of a modern maritime microgrid (Micallef et al., 2021).

power system of a hybrid MVDC ferry (Micallef et al., 2021). A DC bus architecture provides a number of advantages such as: (1) the diesel gensets can achieve higher efficiency (reduction in fuel consumption) since the AC/DC converter enables the gensets to run at variable speed; (2) simpler integration of battery energy storage since only DC/DC conversion is required; (3) faster and simpler parallel connection of gensets; and (4) reduced transmission losses. Rectifiers have fundamental importance in these architectures since this equipment provides the conversion from the AC voltages of the generator to the DC bus voltage. Therefore, these converters have a direct impact on the quality of the DC bus voltage. In Micallef et al. (2021), we have considered in detail the operation of an active front end (AFE) with LCL filter and a 12-pulse series-type diode rectifier and compared their performance with respect to DC voltage regulation capabilities and AC-side current harmonics. The hybrid MVDC ferry microgrid shown in Fig. 10 (excluding the bow thrusters) was modelled and simulated, whereby the parameters for the model were extracted from the data-sheets of real equipment as provided by the industrial partner. The AFE was seen to exhibit better voltage regulation capabilities due to its fast control loops proving more effective than the 12-pulse rectifier during load changes. By feeding the DC link voltage directly into the automatic

voltage regulator (AVR), the generator excitation for the 12-pulse series rectifier implementation is adjusted to keep the voltage at the desired reference. During this time, the DC bus voltage shows an underdamped response with maximum voltage variations of up to 100V peak-to-peak, that could potentially destabilize the shipboard power system. On the other hand, the AFE shows faster voltage regulation capabilities with negligible DC bus voltage variations due to the designed fast control loops. The current output at the fundamental frequency (60Hz) is at 973.5A and 1007.6A for the 12-pulse and AFE respectively. The AFE also does not exhibit low-frequency harmonics and only shows switching frequency harmonics centred around the switching frequency, at 4.88kHz (2.92%) and 5.12kHz (2.79%), respectively. The resulting inverter-side current THD is of 4.4% while the generator-side THD is at 0.9%. The 12-pulse series rectifier has low frequency content at harmonic numbers $12K \pm 1$, however the transformer arrangement removes the 5th and 7th harmonics typically present in 6-pulse rectifiers. The 12-pulse rectifier spectrum resulted in harmonic frequencies at the 11th (7.53%), 13th (5.1%), 23rd (1.34%) and 25th (1.15%). The resulting generator-side current THD is of 9.3%. Both rectifiers show a significantly improved performance when compared with the conventional 6-pulse rectifier, however these advancements come at a higher complexity and cost. With the introduction of energy storage, hydrogen fuel cells and renewables on maritime vessels, maritime microgrids are transitioning towards a hybrid AC/DC power distribution architecture. In this context, we are presently collaborating with industry and academia towards the effective integration of batteries and alternative fuel systems in maritime microgrids.

6 Residential Demand Response

Demand response (DR) aims to manage the electricity demand such that this matches the available energy resources without adding new generation capacity (Haider et al., 2016). In Chen et al. (2017), the DR strategies are categorised as either direct (incentive based) or indirect (price based) as shown in Fig. 11. Through direct demand response programs, the consumers are offered incentives such that the distribution system operator (DSO) has remote control of participants' appliances (e.g. heating, ventilating, and air conditioning (HVAC), water heaters, or pool pumps) during certain hours of the day. Indirect demand response programs modify the consumer behaviour through price-based demand response strategies (e.g. time-varying price signals) to reduce energy usage during peak hours. Hence, end-users have a central role since these have to modify their habits by shifting their electricity consumption.

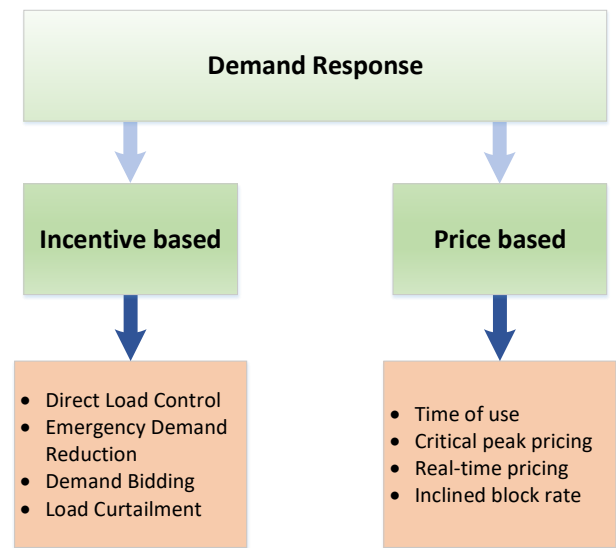


Figure 11: A block diagram summarising the demand response strategies.

The electricity consumption data and the corresponding load profiles are vital for the implementation of demand response programs. In Settino et al. (2019), we presented a detailed analysis of the electrical consumption and PV generation profiles of a Maltese dwelling. The monitoring was carried out for over one year at a resolution of 30 seconds for both the electricity consumption and the electricity generated by a photovoltaic system installed on the roof-top of the dwelling. The electrical demand varies widely on a day-to-day basis and has also seasonal variability thus making any accurate predictions of the consumption very difficult. The PV generation profile is also dependent on the season and can be intermittent due to variations in cloud coverage. An example of the determined seasonal daily profiles is shown in Fig. 12. The figure shows the mean and standard deviation at 30 minute intervals for both the PV generation and consumption. The self consumption ratio over the evaluated period was of 53.5%, (i.e. 53.5% of the electricity produced by the PV system is directly used while the remaining 46.5% is injected into the grid.) Therefore, battery ESS play an important role in demand response programs to increase self-consumption and provide additional services to the local electricity network.

Storage systems when combined with solar generation technologies enable the implementation of demand side strategies without being limited by the available controllable devices (e.g heating, ventilation and air conditioning). Energy management algorithms to maximize self consumption can ensure that the local generation matches

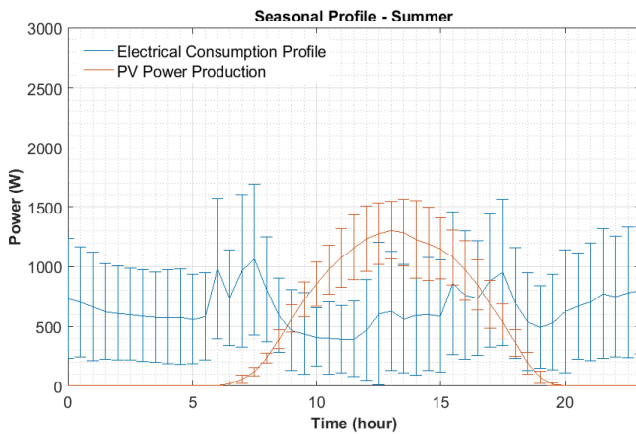


Figure 12: Summer seasonal daily consumption and PV generation profiles of a Maltese dwelling. (Settino et al., 2019)

the demand consequently reducing power variations and risks of over-/under-voltages. In (Settino et al., 2018), we performed a study of available solar technologies and storage systems. A comparison of photovoltaic systems coupled with solar thermal collectors, heat pumps and solar cooling technologies was carried out in terms of conversion efficiency, environmental impact and installation cost. The study determined that there is no definitive answer to which is the best overall technology. The performance of existing technologies strongly depend on the location, climatic conditions, loads (such as electrical and thermal) and existing policies. An in-depth analysis on a case by case basis should be performed to determine the best solution which suites the user's needs. A note worth mentioning is that PV systems with batteries show to have the lowest global warming potential (GWP), but the high initial cost of battery storage limits their usage. However, the prices for residential-scale battery ESS have reduced significantly in the past 5 years.

In Micallef et al. (2020), we proposed an electric spring-based (ES) residential smart water heater that can store excess PV generation as thermal energy. The block diagram of the considered LV microgrid and main household elements is shown in Fig. 13. The ES smart water heater is suitable for integration in both direct and indirect demand response programs. The ES smart water heater is a power-to-heat energy storage device that maintains the microgrid PCC voltage at the desired magnitude by controlling the active power absorbed by the water heater. The designed ES smart water heater is suitable for both grid-connected and islanded microgrid operation since the ES is synchronized with the PCC voltage. Simulations based on real PV and residential consumption data were used to verify the effectiveness of the proposed solution.

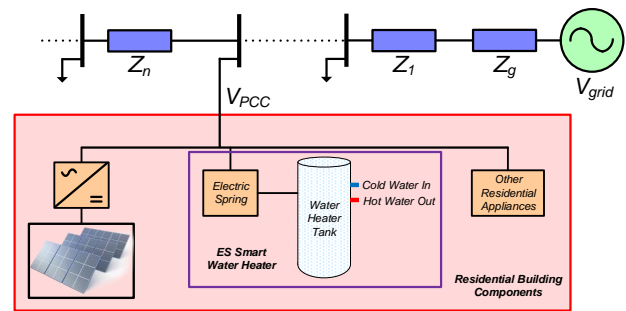


Figure 13: Block diagram of the considered microgrid scenario and main household components. V_{PCC} is the local PCC voltage being targeted by the operation of the ES smart water heater.

It can be observed that the ES water heater reduced the voltage at the PCC to the nominal voltage reference avoiding reverse power flow into the grid.

7 Conclusion

In the past decade, microgrids have gained a lot of traction as these play a key role to address modern-day energy challenges. There are still various open technical and non-technical (policy, regulation, economic) challenges and opportunities for widescale deployment. This article has summarised some of the research activities by the microgrids research team at the Department of IEPC. The presented work summarizes our contributions to the operation, control and management of microgrids in a number of applications.

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