

Design Factors for Developing a University Campus Microgrid

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Abstract - Recent decentralization of electricity systems together with the decarbonization and several changing societal demands are giving rise to different application scenarios such as microgrids. A microgrid is a small-scale electrical system which consists of several loads and sources (conventional and renewables) that can either operate autonomously in a stand-alone mode or interconnected with the main grid. The design and development of such a smart microgrid in a university campus is proposed within the 3DMicroGrid project (funded through the ERANETMED European Union's initiative). This paper reviews the main components and characteristics of similar microgrids developed around the world. Furthermore, this study provides the design guidelines, the main functionalities, the key components and the control architecture for developing the microgrid proposed by the 3DMicroGrid project. A simulation model has been developed and initial results are demonstrated for the operation of this microgrid. The recommendations and insights are replicable to any solar priority country for future microgrids pilots.

Keywords—controllable loads, grid-connected mode, hierarchical controller, islanding operation, microgrid, peak-shaving, photovoltaics.

I. INTRODUCTION

Decarbonization, digitalization, and decentralization are all major sources of disruption for energy utilities. The main bottleneck is the demand-supply mismatch in energy systems [1]. This involves increasing levels of complexity on the electric power networks and on the electricity market and regulations. Eventually, this framework will contribute to new business and management modeling, finance and investment schemes for sustainable energy where microgrids are emerging.

The idea of microgrids initially appeared in the literature almost two decades ago [2] for enabling the massive and reliable integration of renewable energy sources (RESs) without requiring highly complex algorithms to manage all the renewables. Microgrids are actually small electricity networks consisting of several loads, Distributed Energy Resources (DERs) generated by conventional or renewable primary sources and energy storage systems (ESSs) [3]. Conventional DERs usually consist of a number of diesel generators equipped with associated primary controllers (i.e., governor and exciter). On the contrary, DERs based on renewable energy mainly involve photovoltaics or wind power systems, which are

connected to the microgrid through a power electronics inverter (synchronized and managed by an embedded controller) [4]. Similarly, a proper integration of ESS also requires a smart bidirectional inverter. The electrical loads of a microgrid are usually separated into controllable and uncontrollable loads and are categorized into clusters to allow the execution of effective energy management and load-shedding techniques [5].

A main functional requirement that defines a microgrid is the ability to operate in parallel with the main power grid (interconnected mode) and independently (stand-alone/ islanded mode) [3]. Thus, a microgrid is usually interconnected with the main power grid through a single Point of Common Coupling (PCC) in order to allow a smooth transition between the two operating modes. During interconnected mode, microgrids are treated by the main power system as a single element that can generate or consume electricity and can respond to appropriate control signals sent by the distribution system operator in order to regulate their interaction with the main grid. On the other hand, during autonomous operation, the microgrid is responsible for maintaining its voltage and frequency stability. Thus, to enable such operational capabilities in a microgrid, an intelligent monitoring and control system is required in both functional modes for managing its overall operation using either decentralized or hierarchical (primary, secondary, and tertiary) control techniques [6]. The main elements and the configuration of a typical microgrid are presented in Fig. 1.

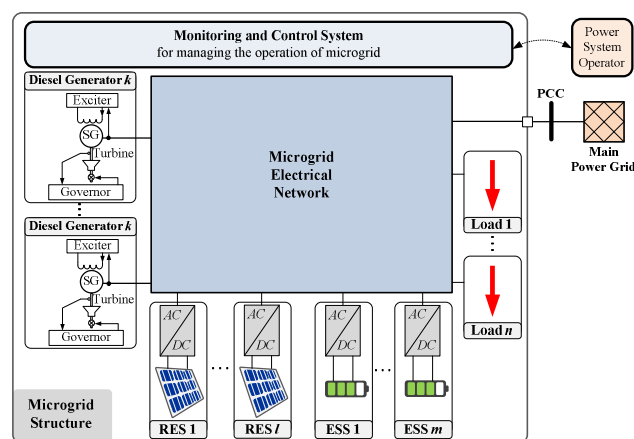


Fig. 1. A typical configuration of a microgrid.

To enable the development of microgrids a number of geographical and techno-economic constraints need to be ensured. University campuses usually satisfy these constraints, since (a) the DERs and loads are located nearby and are connected to the same network, (b) the campuses are usually connected to the main power grid through a single substation (point of common coupling), and (c) the same authority manages all the DERs and loads. As a result, several pilot projects use university campuses for demonstrating novel ideas in the framework of smart grids and microgrids. The overarching goal of these projects is to: improve the microgrid's performance, reliability and efficiency [7], [8]; integrate renewables in combination with storage options in a microgrid framework [9], [10]; engage students, faculty and staff to improve energy efficiency on campus level [11], [12]; and facilitate research and education infrastructure for microgrids [13], [14]. The 3DMicroGrid project (funded through the ERANETMED European Union's initiative) proposes the design and development of a smart microgrid. The objective of this project is to transform a part of the main campus of the Malta College of Arts, Science and Technology (MCAST) into a pilot microgrid to validate monitoring, control and managing techniques applicable for microgrids.

The aim of this paper is to review the main design factors of the proposed MCAST microgrid. Then, the structure of the demonstration pilot is presented along with the key components and its main operating modes. Initial simulation results for the operation of the proposed microgrid are also presented according to realistic load profiles and environmental conditions. The recommendations and insights are replicable to any solar priority country for upcoming development of microgrids.

The paper is structured as follows: in Section II the window of opportunity is presented through a literature review while in Section III, the design guidelines regarding the required characteristics of generation, load and storage units are provided. Section IV presents the approach that is inherited for the control architecture of the microgrid. Initial results for the main operating modes are presented in Section V. Finally, in Section VI, the main conclusions are drawn.

II. EXISTING MICROGRIDS

Microgrids are small-scale controllable electrical systems which contain several energy sources and loads that can work connected or isolated from the distribution grid. In this section, a review of the existing types of microgrids is presented.

A. Institutional or Campus Microgrids

University or institutional campuses usually satisfy the main technical requirements to be transformed into microgrids. An institutional campus consists of several buildings which are located nearby to each other, they are electrically connected through the campus network, and they are operated and managed by common technical and financial services. In addition, all the loads and generation units of each building are usually connected to a common controller where their operation can be monitored and coordinated. Another important characteristic is that a university campus is usually connected to the distribution

grid through a substation (single PCC) which allows simple decision making and straightforward transition between autonomous and interconnected operation of the campus.

Several campus microgrids are implemented worldwide to serve as testbeds and illustrate the benefits of utilizing this kind of system into the power grid. More specifically, the Illinois Institute of Technology developed a microgrid, which is composed of 2 x 4 MW combined cycle gas units, a small wind turbine, and a 500 kWh battery storage unit. Furthermore, a microgrid is implemented by the New York University which consists by a 13.4 MW combined heat and power (CHP) unit (able to supply 22 buildings of electricity and 37 buildings with heat) and a 2.4 MW steam turbine. Another impressive example is illustrated by the Hangzhou Dianzi University in China. This microgrid system is made up of 120 kW solar system (PV) combined with a 120 kW diesel generator and a number of fuel cells as part of the renewable energy sources. Any excess energy produced, can be stored in a 100 kW capacitor and a 50 kWh battery storage unit.

B. Remote Microgrids

These types of microgrids systems are essential to provide electricity to remote villages, small islands or parts of the country which are difficult to be reached by the main grid. Remote microgrid systems are usually the largest types of microgrids and they always operate in island-mode operation.

For example, these microgrids are found in Indonesia, a country which is made up of more than 20,000 islands and which makes it impossible to connect to a single main grid. Generation units are usually made up of a combination of renewable energy sources and traditional diesel generators to ensure that load requirement is supplied at all times.

Another example of remote microgrid is currently developed within the TILOS project that is funded by the European Commission through the H2020 framework. This project aims to develop a remote microgrid in Tilos, a Greek island with a population of 500 people whose power system is only linked to two neighboring islands (Kos and Kalimnos). This microgrid will be based on a photovoltaic park of 160 kW installed capacity, a sole wind turbine able to produce up to 800 kW, and two battery containers of 1.44 MWh/400 kW each.

C. Commercial or Industrial Microgrids

These types of microgrids are similar to the campus/institutional microgrids where the microgrids are built to meet the specific client's requirements. In these cases, the microgrids must be prepared to increase the load requirements when needed since these may vary through time.

III. DESIGN GUIDELINES FOR MICROGRID DEVELOPMENT

This section presents and defines the design guidelines required for a successful implementation of a university campus microgrid. In addition, an explanation of key components constituting the microgrid and their main characteristics are also provided. A microgrid is divided in three main parts (i) the energy consumption, (ii) the energy generation, and (iii) the energy storage, all within a bounded and controlled network.

A. Load Profiles and Load Clustering

A crucial aspect for developing a microgrid is to identify the energy demand which the system has to satisfy. Ideally, the loads of the microgrid should be categorized into several clusters that can be individually managed by a central controller. This categorization is especially important for the implementation of controllable loads which can be used in load shedding schemes and energy management optimization scenarios, providing more flexibility and sustainability to the microgrid.

Different control actions are required for managing each type of loads. Thus, some loads (i.e., lights) can be controlled through controllable circuit breakers (on/off actions), while other loads can be managed by sending some operating set-points (i.e., temperature set-point in an air-conditioner). The load clusters are usually separated into essential, non-essential and thermal loads. Essential loads consist of fixed loads that always need to be satisfied. Non-essential loads are loads that may be shed in cases where energy demand of the microgrid cannot be satisfied while thermal loads provide flexibilities to the microgrid operator in order to shift or managed the load profile characteristic within a day. It should be noted that particular requirements for the electrical installation of each building consisting the microgrid need to be ensured a priori to allow the proper clustering of loads.

After the load clustering, it is important to perform a measurement campaign for the total energy demand and to identify the load profiles for each load cluster. Afterwards, the load profiles can separately be analyzed according to seasons (i.e., winter, spring, summer, autumn) and the type of day (i.e., working day or holiday). Such an analysis of the load measurements can give a useful insight of how the load demand varies throughout the year and what should the generation and storage capacity of the microgrid be in order to satisfy this demand.

B. Network Configuration

Apart from the categorization and the profiles of the loads, the identification of a suitable network configuration is also important. The majority of existing microgrid solutions are implemented in a circular configuration which satisfies the “N-1” criterion for ensuring the resilience of the microgrid even under a failure of a critical component (i.e., line, substation). The network of a microgrid is connected to the main grid through a single controllable breaker (single PCC). Such a single PCC, allows a straightforward and seamless transition between interconnected and islanded mode.

C. Generation and Storage Units

One of the most crucial components for the development of a microgrid is to include proper generation and storage units in the design of the system. The selected units must be able to cover the majority of the demand, whenever the microgrid operates in an islanded mode. The generation side of a modern microgrid can be separated into controllable and uncontrollable generation. The former, can be further divided into flexible generation (such as diesel/gas generators or fuel cells) and battery storage systems (BSSs). The latter, includes the installation of RESs, which have a varying generation output according to environmental and

weather conditions (such as wind turbines and photovoltaic systems). Although renewable energy output cannot be controlled, various control architectures have been proposed to provide support for microgrids, such as voltage controls through reactive power output.

The inclusion of controllable generation units is essential for the successful implementation of the microgrid. This is because the existence of solely RESs in the system cannot ensure the provision of adequate power whenever is needed and the adoption of optimized operating scenarios. Therefore, this paper utilizes a diesel generator equipped with associated controllers, such as an exciter (type AC5A) and a speed regulator (based on the isochronous governor model). The governor controller is able to change the generator’s active power output according to set points derived from the microgrid central controller for a proper energy scheduling during the interconnected mode. The adopted BSS operates in such a way so that it can charge or discharge according to the microgrid operator in order to cover the energy demand or manage the energy scheduling of the microgrid. A BSS of 15 kW/20 kWh is initially suggested for the MCAST microgrid. Lastly, regarding RESs, a total penetration of 63 kW peak of photovoltaics (PV) is considered for the proposed microgrid. These PVs are equally distributed in three buildings of the MCAST campus (with 21 kW peak PV installation in each building). The PV inverters are capable of providing reactive power support in case it is needed, thus contributing to the voltage stability of the microgrid. It is worth mentioning that the rated power for the diesel generator and the BSS should be appropriately selected to satisfy the base and intermediate loads of the microgrid in order to enable its islanded operation.

More information regarding the microgrid to be implemented in MCAST campus is provided in the single line diagram of Fig. 2. In this figure, one can note the following: the proposed microgrid is based on three buildings (D, F and J), the “N-1” criterion is ensured by the network connection of the two substation in both medium and low voltage side, and the single PCC is ensured by the connection of the microgrid to the main grid through a circuit breaker on the medium voltage side of substation SS1. Further, all the buildings have PVs installed on their rooftops, and all the load types of each building can be controlled through the two main switchgears. It is also noted that the thermal loads for air conditioning can be controlled through ON/OFF actions and managed through temperature set-points. Moreover, for the realization of a microgrid, it is necessary to install at least a diesel generator in building J and a BSS in building F in order to allow the effective operation of the microgrid in islanded mode.

IV. CONTROL ARCHITECTURE

Apart from the availability of all the aforementioned components, it is also necessary to include a control scheme in the design, in order to achieve an efficient and resilient operation of the microgrid. More specifically, this control scheme must satisfy certain characteristics. First of all, it must be able to transit smoothly to grid-connected or islanded mode whenever is required. The transition to islanded mode may occur after requisition by the power system operator or after the microgrid senses voltage or frequency violations on the main grid voltage

supply. It should be noted that under certain contingencies, the overall resilience of the main power system can be enhanced if the main grid operator commands the microgrid to go in islanding mode [15]. During the grid-connected operation, the microgrid will be synchronized with the main grid. In this mode, the microgrid operator should be able to regulate the active and reactive power exchange with the main grid according to predefined profiles (as they have been agreed with the power system operator). Moreover, the microgrid should be able to provide additional voltage or frequency support to the main grid when receiving new command signals by the power system operator. In islanded mode, the microgrid is responsible for maintaining its own frequency and voltage stability [16]. Lastly, in both operating modes, the control scheme must be able to provide set-points and coordinate optimally all the microgrid's components. An example can be the application of economic dispatch or optimal power flow (OPF) in order to find the optimal operating scenario that satisfies a low operating cost.

Generally, two control architectures are commonly known, the decentralized and the centralized [17]. The former refers to a control structure where a minimum communication infrastructure is required and every energy source of the microgrid is equipped with a combination of a primary and a secondary controller [18]. The latter requires the existence of a central secondary controller along with the necessary communication infrastructure in order to be able to coordinate all the primary controllers [19], [20]. This work utilizes a hierarchical centralized control architecture combined with

single master operation (SMO) [17]. SMO means that in case of islanding, the diesel generator is chosen to act as the master of the microgrid (for maintaining the voltage and frequency stability), while all the other generation units (PV and BSS) operate in PQ mode (for regulating only their active (P) and reactive (Q) power generation) in a synchronized way with the diesel generator.

The hierarchical control can be separated into primary, secondary and tertiary control. Primary control constitutes the first and faster level of control. Therefore, it is an uncoordinated droop control, responsible to maintain the voltage and frequency levels after a disturbance. Due to this reason, any remaining voltage or frequency oscillations after a severe disturbance in the microgrid can be compensated by the actions of a secondary controller. The tertiary control is the higher level of control hierarchy where more advanced scheduling algorithms regarding the microgrid operation can take place. These algorithms include: decision making for transition to islanding or grid-connected mode, techniques to regulate the power exchange with the main grid, methods for resources allocation, OPF and economic dispatch in order to minimize the operating cost of the microgrid, etc. The operation of the proposed microgrid according to some tertiary techniques is presented in Section V.

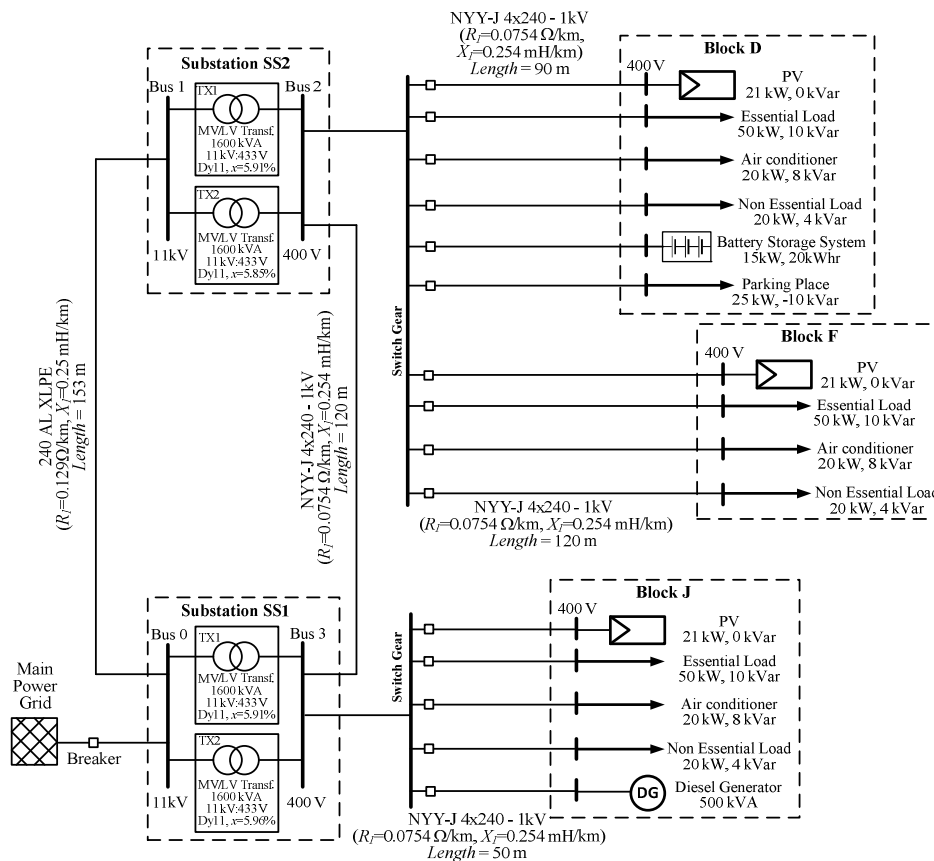


Fig. 2. MCAST microgrid single line diagram

V. OPERATING MODES AND INITIAL RESULTS

This section presents some initial results regarding the MCAST microgrid performance according to different operating modes. A phasor simulation model is developed in MATLAB/Simulink for emulating the operation of the microgrid. The phasor simulation is capable of testing the operation of the microgrid during an entire day according to load and PV generation profiles of the actual microgrid, as obtained through measurement campaigns. The sampling period for the load and generation profiles is 1 min. The control architecture for managing the operation of the microgrid has been developed using a sampling frequency of 1 Hz for managing the fast transition between interconnected and islanded mode. Two case studies are presented here in order to demonstrate the operation of the microgrid in different functional modes.

The first case study focuses on the transition between grid-connected and islanded mode. As already mentioned in Section IV, the decision for the microgrid to operate autonomously (islanded mode) can be taken after sensing voltage-frequency violations on the main grid conditions or after a command is sent by the power system operator. The latter case is examined in this scenario. Fig. 3 illustrates the power exchange between the microgrid and the main grid (P_{grid}) during grid connected and islanded modes. Initially, the microgrid operates in grid connected mode. At $t = 08:00$ the main grid operator sends a command to the microgrid for transition to islanding operation mode. At this point, the microgrid controller needs to ensure a minimum power exchange with the main grid (by regulating the PV and BSS production and by shedding some loads if necessary) and then to open the main breaker for operating autonomously. The transition procedure needs to be very fast with a response time (for the microgrid) within 1-2 seconds. The microgrid is then operated in islanded mode until 17:40. At this point, the microgrid operator closes again the main breaker in order to return to grid connected operation. For the smooth transition to the grid connected mode, the microgrid controller ensures that all the requirements for the resynchronization are satisfied (i.e., 0.1 Hz maximum frequency deviation, voltage angle difference less than 20° , voltage magnitude difference less than 5%) before closing the main breaker.

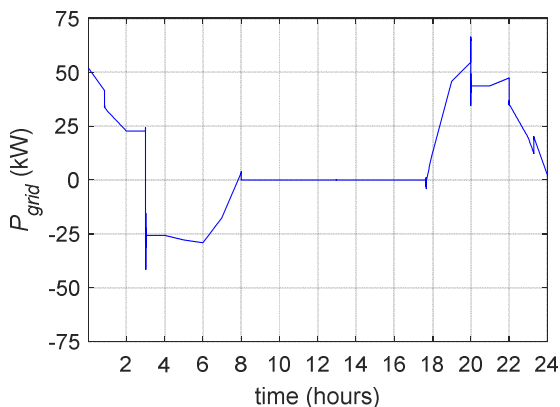


Fig. 5. Active power exchange between the microgrid and the main grid during grid connected mode (00:00-08:00 and 17:40-24:00) and islanding mode (08:00-17:40).

The second case study focuses on the regulated power exchange between the microgrid and the main grid. For this purpose, two control modes have been designed: the constant power mode and the peak shaving mode. In the former, a controller is designed to manage the flexible components of the microgrid (i.e., BSS, PV, diesel generator, and flexible loads) to achieve a constant power exchange. In the latter, the controller ensures that the maximum power will not be exceeded in any case. The structure of the Proportional Integral (PI) based controller for the two operational modes is presented in Fig. 4.

According to Fig. 4, when the constant power mode is activated, the PI controller makes sure that the power exchange

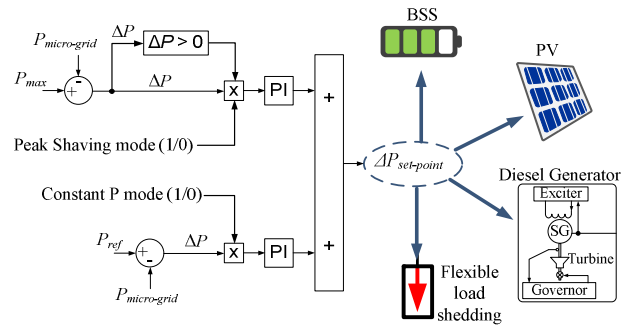


Fig. 3. Constant power and peak shaving controller for regulating the power exchange between the microgrid and the main power system.

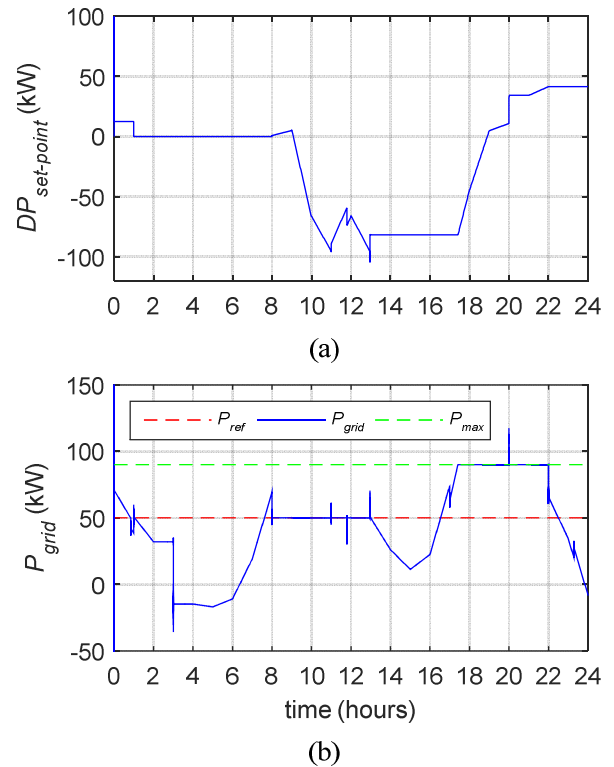


Fig. 4. The operation of the microgrid during constant power mode (08:00-13:00) and during peak shaving mode (17:35-22:00). The simulation results regarding (a) the required power set-point that needs to be allocated to the flexible power components is presented and (b) the power exchange between the microgrid and the main grid.

between the microgrid and the main grid will follow a reference power (P_{ref}) that has been pre-agreed between the power system and the microgrid operators. In a similar way, when the peak shaving mode is activated, the PI controller ensures that the power exchange between the microgrid and the main grid (P_{grid}) will never exceed an upper limit (P_{max}). In both modes the $\Delta P_{set-point}$ resulted by the controller, defines the power deviation that needs to be properly allocated to all the flexible resources of the microgrid for achieving its objective. For the purpose of this work, $\Delta P_{set-point}$ is allocated between the diesel generator and the BSS according to its rated power. Simulation results demonstrating the microgrid's operation during the constant power and peak shaving modes are presented in Fig. 5. More specifically, Fig. 5 shows the microgrid operation according to the constant power mode between 08:00 and 13:00, while it ensures a constant power exchange of 50 kW. Furthermore, the peak shaving mode is activated between 17:35 and 22:00, during which the microgrid consumes a maximum active power of 90 kW.

It should be noted that the constant power and peak shaving control modes that are presented in this section focus only on the regulation of the active power. Similar approaches need to be inherited for the case of reactive power exchange, for allowing the power system operator to utilize microgrids for the flexible voltage regulation of the main grid.

VI. CONCLUSIONS AND FUTURE WORK

The main objective of the 3DMicroGrid project is to develop a university campus microgrid in Malta. This paper presents the main design factors considered for the development of such a microgrid. The overall system description, the key components constituting the microgrid, and the required control architecture for enabling an advanced operation of the proposed microgrid in different operating modes are demonstrated. Furthermore, some initial simulation results are presented to evaluate the microgrid performance under several functional modes. The design guidelines and insights given by this paper can be used to replicate similar types of microgrids in any solar priority country.

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