Guidelines for the Design of Residential and Community Level Storage Systems Combined with Photovoltaics (PV)

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Abstract— **This paper describes a methodology and guidelines to design a battery storage system at both residential (distributed) and community (centralized) level, where a common AC low voltage (LV) distribution feeder is used under a high PV penetration scenario in Cyprus. For this purpose, the methodology considers the load profile of typical residential households in Cyprus in order to gain insights about the sizing of the battery storage (rated power and energy) and the power converters (rated power). In addition to the above, electrical and mechanical parameters are discussed in order to provide guidelines for the design of such a storage system. Finally, electrical sensors that are used for gathering the necessary data for the correct operation of the system are proposed, as well as the communication interfaces and protocols for achieving a reliable communication between them.**

Keywords-Photovoltaics, Energy Storage Systems, Distributed storage, Centralized storage, Energy management

I. INTRODUCTION

The decarbonization of the distribution grid is urgently needed in order to develop a green and resilient energy system. This can be accomplished with the integration of higher shares of renewable energy sources (RES) in the energy mix. However, the unobstructed deployment of RES, such as solar photovoltaics (PV), in the distribution system poses many challenges which are mainly associated with their variable and intermittent nature. This also makes energy dispatch a very difficult task to be dealt with. In light of the above, the utilization of Energy Storage Systems (ESS) is considered as a reliable solution capable of supporting the operation of the distribution system and providing the desirable flexibility to the energy system whilst improving the penetration of RES [1].

Energy storage systems can be allocated either at a centralized or distributed level and can be used to balance the generated RES electricity without risking grid security with the further penetration of renewables. In addition to this, energy storage can support demand response (DR), load levelling and other services depending on the allocation level which can be transmission, distribution or local [2, 3]. Considering residential allocation, "behind the meter" storage offers significant services to support the grid and also benefit the prosumer (consumer with local RES system). Such services are the increased self-consumption [4] and the ability for backup power in case of grid outage. In addition to this, by applying suitable energy management algorithms, the prosumer revenue can be increased in cases where Time-of-Use (ToU) tariff management applies. On the other hand, different services can be applied to support the operation of the grid. The most important ones are frequency and voltage support (i.e. aid in regulation) which can be achieved by compensating active and reactive power respectively. Finally, the efficiency of the electricity system can be improved and grid losses can be reduced since energy can be stored locally.

Different storage technologies such as hydrogen and compressed air have shown a significant development over the last decades, with pumped-hydro storage (PHS) to be the most favourable option. Now, this scenario is gradually changing since new storage technologies exist offering even more important services to the electricity grid. In particular, electrochemical storage and especially Battery Energy Storage Systems (BESS) are emerging as a very promising and competitive storage option for both distributed and centralized storage applications. Nevertheless, BESS technology is still at its infancy and technological improvement is needed in order to lift off the barriers concerning safety and financial compensation before it becomes a reliable and affordable solution. This paper presents a methodology for sizing a battery storage system, both power and capacity, by using residential load data from Cyprus as well as guidelines for its design. The experience gained from designing residential storage systems which share the same AC low voltage (LV) distribution feeder is shared in this work as guidelines for the components selection of such systems.

The work is carried out from the perspective of choosing suitable parameters for the storage systems in order to perform different services. Therefore, by taking into consideration the on-site energy consumption, the PV generation and the environmental conditions, the electrical and mechanical parameters of the system components are considered. Finally, various sensors and communication protocols that are necessary for data acquisition and monitoring are discussed in order to ensure a secure and stable data exchange.

II. SYSTEM OVERVIEW

A. *Sizing of BESS*

Typical residential premises in Cyprus have installed roof-top PV systems with a capacity of up to 3 kWp for single-phase (1-PH) systems with an annual energy yield of 4800 kWh and up to 5 kWp for three-phase (3-PH) systems with an annual energy yield of 8000 kWh. Conversely, the annual expected energy consumption for a 1-PH household in Cyprus is 5000 kWh/yr whilst for a 3-PH household is 8000 kWh/yr. This situation renders the Net-Metering scheme [5], which comprises the only available policy framework for residential PV systems in Cyprus, as a favorable and cost-effective solution since the produced and consumed energy can be balanced. However, the primary drawback of this scenario is that the peak PV generation and electricity demand do not coincide. This results in a large amount of produced energy being injected to the distribution network, which virtually serves as a storage unit. Conversely, consumption peaks occur when PV production is low. This situation has substantial impact on the electricity network operation since load congestion is more likely to occur, thus increasing losses in the distribution grid.

Energy storage has a vital role to play in this scenario. By shifting the produced PV energy to points where electricity demand is high, the efficiency of the existing power system can be improved. Therefore, different parameters must be taken into account to optimally size the battery system and achieve a resilient solution which can reduce the dependency of the prosumer on the electricity network and also support grid operation.

In the case of Cyprus, the expected annual energy profile of typical households was used in order to provide a credible measure about the storage sizing. The first critical parameter to consider is the average energy profile of PV production and household consumption. As shown in Fig. 1, the monthly average energy production of a 3 kWp PV system in Cyprus may vary between 8 and 16.8 kWh and strictly depends on the season with different ambient temperature and solar irradiation. On the other hand, energy consumption during the PV production hours, remains within a range of 8 to 10 kWh and it peaks up to 16 kWh in the summer period. The battery size must be such that excess energy can be stored locally to supply the household in case of sudden electricity demand variations. As a consequence, the average usable capacity[1] of the battery unit can be sized in accordance to the maximum energy difference between PV production and consumption, which in that case is around 6.4 kWh. In order to achieve a reasonable lifetime and cost of a Lithium-ion battery, a Depth of Discharge (DoD) of 80% is recommended and hence the nominal battery capacity has to be 8 kWh. Finally, by observing the load demand curve, the maximum load power throughout the year occurs in July and it is equal to 1.68 kW. To allow for various grid services and especially frequency support, it is advised that the rated grid power of the power converter is scaled up by 50%, thus a 2.5 kW converter should be chosen. In the aforementioned methodology, the effective capacity of a BESS was estimated for a typical household in Cyprus and

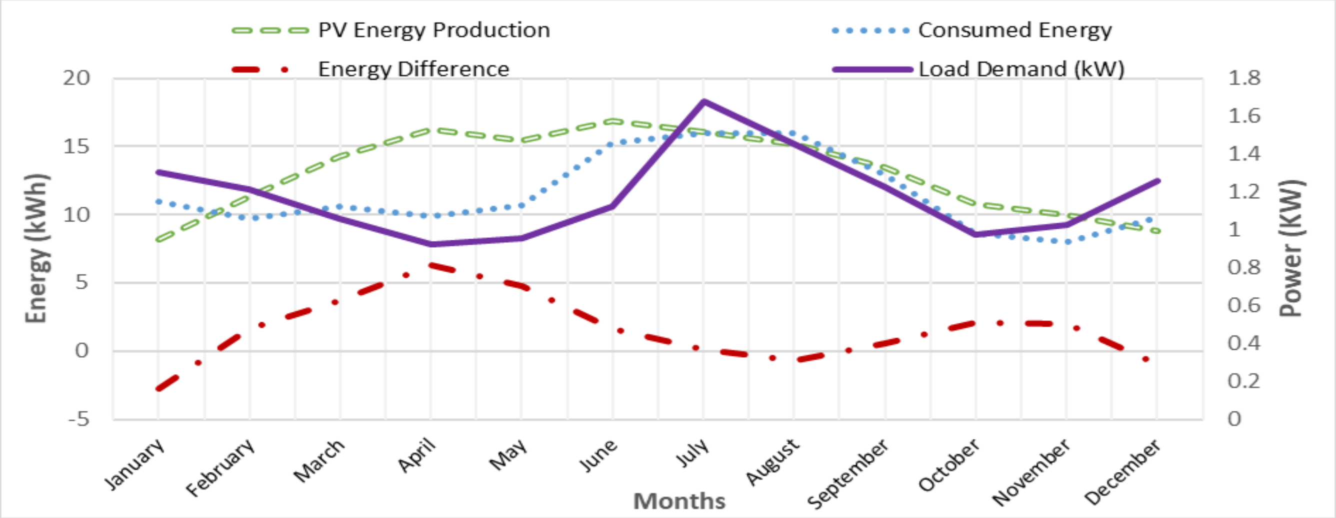

Figure 1: Per month average energy production for a 3 kWp PV system compared to the average consumed electricity and the average maximum peak load demand of 300 typical households in Cyprus.

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[1] Usable capacity: is defined as the actual capacity of the battery unit meaning that the nominal capacity must be sized depending on the maximum Depth of Discharge (DoD) of each unit.

can be utilized either for residential or community level. The community storage size can be scaled depending on the number of households connected to the same LV distribution feeder. Nevertheless, extensive analysis is required to evaluate the optimum storage share between residential and centralized storage and will not be examined in this study.

B. *System Configuration*

A market research took place to identify the existing battery storage system technologies which are combined with PV systems. Two common configurations exist, the AC-Coupled and the DC-Coupled which can be distinguished from the connection method of the Battery unit. In an AC-Coupled system, the PV and the Battery systems are connected to a common AC-bus which is then connected to the grid and the domestic load [6]. The system configuration is shown in Fig. 2 and includes a typical solar PV converter which consists of a DC-DC converter, operating as the Maximum Power Point Tracking (MPPT) unit, and an on-grid inverter. In addition to this, a bidirectional Battery converter is utilized and consists of a Charge Controller (CC) unit and an on/off grid inverter [7].

On the contrary, two different configurations can be found for a DC-Coupled system. The first one is called “Retrofit” system and embeds a CC to an existing PV system for charging and discharging the battery. Even though “Retrofit” systems can be easily fitted to existing installations, this solution poses significant limitations to the system operation and it is not recommended. Further to this, a DC-Coupled system can also be developed by using a single power converter which is called “Hybrid” converter as shown in Fig. 3. In this case, power from the PV array and the Battery unit is utilized via a common DC-bus inside the Hybrid converter [6]. This unit employs a DC-DC converter which operates as the MPPT system and an additional DC-DC converter which operates as the battery CC unit. The connection to the grid is made through a common bidirectional on/off inverter [7].

In both cases, a bidirectional electricity Smart meter and a Grid switch (AC contactor) are also placed for the connection to the grid. An embedded Energy Management System (EMS) serves as the central controller of the system which receives information from the solar PV converter about the energy yield and the import and export electricity from the Smart meter in order to perform suitable actions to regulate the power flow through the battery unit and the grid. The Grid switch is used to isolate the system from the grid in case of a grid outage and potentially allow backup power to the load from the PV and/or the battery [6, 7].

The aforementioned configurations can be used for residential systems which combine PV and energy storage systems. However, at the community level, usually there is no direct PV production, hence the AC-Coupled system is the only applicable configuration. Therefore, a Battery unit and a suitable Battery converter are the only required equipment to form a community storage system connected to the grid.

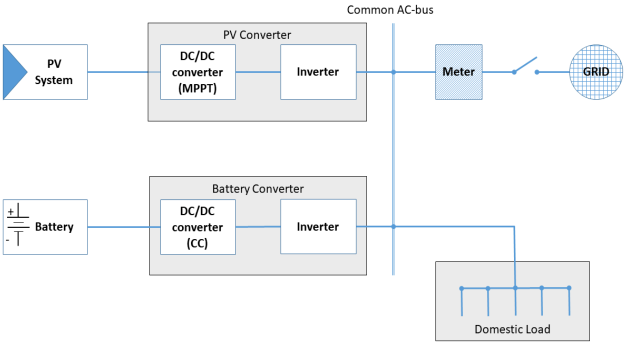

Figure 2: Schematic diagram for the AC-Coupled system. [8]

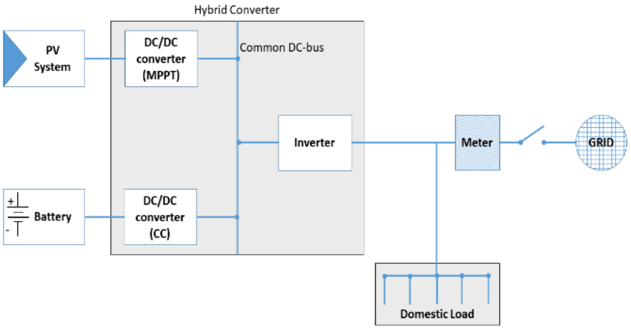

Figure 3: Schematic diagram for the DC-Coupled “Hybrid” system. [8]

III. STORAGE SYSTEM DESIGN

This section analyses the most important technical parameters for the power converter and the battery unit that must be taken into consideration when designing a PV system in conjunction with BESS. The analysis can be used for both AC-Coupled and DC-Coupled residential systems.

In this study, Lithium-ion battery units are considered for both residential and community levels. The technological progress of Lithium technology over the last few years has resulted in a very high unit efficiency, high energy and power density [9], thus making them a very flexible and suitable solution for installations where space availability is important. As a consequence, Lithium technology battery units can be utilized to achieve different storage services on the utility and behind the meter level and provide the desirable flexibility and support to the existing energy system.

A. *Important Design Parameters*

In this section, the technical parameters, which can aid in the design of a storage system, are separated in two categories. The first one describes the most important electrical parameters of the power converters and the battery unit while the second one deals with the mechanical aspects of the devices.

A.1 Electrical Parameters

Converter Power: One of the most important parameters for the choice of the power converter is its power rating. It is obvious that, for example, the maximum grid power of the converter must adhere to the grid codes of each country or the PV input to the converter has to be rated at the maximum power of the PV array at least. However, what is less obvious is the power rating of the converter with ambient temperature. Many manufacturers specify the rated converter power at an ambient temperature of 25°C and the power derating curves provided by the manufacturer must be considered for the maximum operating power at elevated ambient temperatures in hot countries such as Cyprus. In addition, for a Hybrid converter, the total power (PV, battery and grid) has to be taken into account for operation at the required conditions at elevated ambient temperature. The nominal grid power of the converter should be sized based on the premise load demand and the maximum injected power into the grid shall follow the grid codes of each country. Although reactive power exchange with the grid does not produce any real work, it is very important that the inverter can withstand the required reactive power in addition to specified active power since the exchange of reactive power dissipates heat in the power switches of the converter. This is similar to the increased cable losses due to reactive power in an electrical network, the reactive power does not produce any real work but the cable losses increase due to the increased current. The nominal PV input of the converter should have a minimum value equal to the maximum output power of the PV array based on seasonal variations, i.e. ambient temperature and solar irradiation variation through the year. If this is not met, PV energy will be lost since the converter will be the limiting element in the circuit. The nominal battery power of the converter affects the charging time of the battery and also determines the maximum load that can be supplied to the premise load or the grid. This in turn affects the various services the battery can offer such as back-up power, frequency and voltage support. It is important that the battery and grid power rating allow for power boost for several seconds in case rapid frequency support is demanded.

Nominal Voltage: The nominal grid voltage of the converter shall be rated at the grid nominal voltage plus the voltage variation allowed by the grid codes (in Cyprus for example it is 230 V AC +/-10%). Good inverters also can withstand short voltage surges and dips, hence, it is good practice to look for the relevant standard in the datasheet as described in the standards section. Converters which support off-grid operation (i.e. back-up service) shall keep their output voltage regulation within the variation allowed by the grid codes when operating in off-grid mode. The converter nominal PV input voltage shall be able to handle the maximum PV array voltage. Since the PV array voltage increases as the temperature decreases, the rated PV voltage shall be considered at the lowest ambient temperature possible at the place of installation.

The battery voltage is also an important parameter because it varies with the state of charge (SOC) of the battery. Care must be taken that the converter battery voltage range is lower and higher than the minimum and maximum battery voltage respectively.

Nominal Frequency: The converter shall be able to operate at the nominal frequency of the grid and within the frequency variation allowed by the grid codes. What is more, the converter should not shut down in case of under or over frequency in order to allow for frequency support if desired.

Total Harmonic Distortion (THD): The THD is a measure of the output power quality of the converter. The less this value is the better the power quality is. It is important that the converter complies with the relevant standards as shown in the standards section otherwise it can interfere with other devices in the network.

Power Factor (PF): The converter should be able to adjust its PF within the acceptable limits denoted by the grid code in order to be able to aid in voltage regulation of the grid.

Inverter Design and Peak Efficiency: The inverter can be transformer-less or with transformer, however, the transformer-less technology is the preferred choice due to the higher efficiency. The recommended minimum efficiency of the inverter is 95%.

Standards: All the equipment sold in the EU must conform to relevant standards concerning its electrical safety and operation. The following standards, which were extracted from the Low Voltage Directive and the Electromagnetic Compatibility (EMC) Directive, are the required minimum recommended for the power converters (Table I) and battery units (Table II) in a PV system with BESS. The battery standards presented are only for Lithium-ion batteries since they are the most widely used batteries for small to medium scale systems.

Power Converter

TABLE I. MINIMUM RECOMMENDED POWER CONVERTER STANDARDS

Category	Number	Description
EMC	EN61000-3-2[a]	Harmonic current emissions (≤ 16 A per phase).
	EN61000-3-12[b]	Harmonic current emissions (≤ 75 A per phase).
	EN61000-3-3[a]	Voltage changes, voltage fluctuations and flicker (≤ 16 A per phase).
	EN61000-3-11[b]	Voltage changes, voltage fluctuations and flicker (≤ 75 A per phase).
	EN61000-6-1 or EN61000-6-2	Immunity.
	EN61000-6-3 or EN61000-6-4	Emissions.
Electrical Safety	EN50178 [replaced by EN62477-1]	Power electronic converters and equipment.
	EN62109[c]	Power converters for PV systems.

a. Applicable to distributed household systems.
b. Applicable to centralised systems.
c. Only required for PV and Hybrid converters.

For connection to the grid, the VDE4105 is required by the DSO in Cyprus, in other countries it could be different.

Battery Unit

TABLE II. MINIMUM RECOMMENDED BATTERY UNIT STANDARDS

Category	Number	Description
Battery Safety	IEC62281 or UN/DOT 38.3	Transportation testing for lithium batteries.
	IEC62133 or UL1642	Safety test for lithium batteries.
	EN62619	Safety requirements for secondary lithium cells and batteries.
EMC	EN61000-6-1 or EN61000-6-2	Immunity.
	EN61000-6-3 or EN61000-6-4	Emissions.
Electrical Safety	EN50178 [replaced by EN62477-1]	Power electronic converters and equipment.

A.2 Mechanical Parameters

Ingress Protection (IP): The IP rating protects the equipment from environmental conditions and also humans from accidental electric shock. A minimum of IP20 protection is required for all products to prevent human fingers from entering the equipment, however, we suggest a minimum of IP40 is recommended in household environments where children might be present. For equipment which is for outdoor use, a minimum of IP65 is recommended such that the equipment is dust and water jet proof.

Ambient Temperature and Relative Humidity: The ambient temperature and relative humidity are two parameters which vary widely at different locations. Therefore, it is important that the equipment can operate safely within the environment it is exposed. The suggested operating range is -40°C to 50°C and 5% to 95% for ambient temperature and relative humidity respectively. The exception to the temperature range is the battery since its lifetime is highly dependent on temperature and its operating range is around 25°C (usually +/-10°C).

Cooling: Adequate cooling is of utmost importance for the optimum performance of the equipment. Since the manufacturer deals with it to ensure reliable operation it is wise to choose natural convection (if possible) for equipment which will be installed indoors for a quiet operation (no fan noise) and forced air cooling for equipment which will be installed outdoors for a smaller size and lower cost.

Installation: Space sufficiency is another important parameter to consider. It is advised to evaluate the available space of installation before selecting the system components and also consider the manufacturer's installation guide. For instance, heavy components might not be able to be wall-mounted. In addition to the above, proper room ventilation is necessary especially when the system is placed in small closed areas. The type and the heat extraction capabilities of the ventilation system depend on the wall thermal conductivity values (U-values) and the thermal capacity of the air in the enclosed volume.

B. Sensors, Data acquisition and Communication

Data acquisition is very important for the BESS system to operate correctly, reliably and provide the desired battery services. However, this is not possible without efficient communication between the various data acquisition sensors and the energy management system (EMS). The most important external sensor for the distributed household applications is the Smart meter which measures the net energy exchanged between the BESS and the grid. This is useful in regulating the energy flow and estimating the most optimum operating point based on the desired services. Smart meters have an embedded communication protocol which is usually the RS485, a serial transmission standard allowing fast and reliable data transfer for long distances. If available, the voltage and frequency of the grid can be measured by the Smart meter otherwise they can be measured by the internal sensors of the converter.

The EMS of the storage system is usually embedded in one of the power converters (i.e. Battery or Hybrid converter) or it is implemented in an additional external controller. Data acquisition between the EMS and the other secondary units, such as the PV converter, battery management unit (BMS) and the Smart meter, is important for monitoring and controlling the entire system and can be done by using different communication interfaces and protocols. The central EMS control unit is typically equipped with integrated communication adapters which can be connected to different monitoring and control systems and provide system supervisory and robustness. Any communication interface that is supported from both the central controller and the secondary units can be used, however it is recommended to select well-known communication interfaces such that the flexibility and expandability of the existing system is not restrained regardless of the manufacturer. In light of the above, a recommended communication between the central and the secondary units is a common web-based link where an Ethernet cable connects the devices together, allowing data to be transmitted between the devices of the system. The data can be then delivered to the central controller which is responsible for making the necessary operational decisions where at the same time data can be transmitted through the web for monitoring by facilitating a modem/router. Furthermore, Ethernet communication makes it easy for the system (specially distributed households) to be transformed to a Grid ready system and receive commands from the DSO. In a similar way, the Controller Area Network (CAN bus) standard which is a bitwise based protocol designed to allow the communication between devices with the absence of a host computer, is also a desirable interface.

Another parameter to consider is the centralized storage system supervisory and communication with the Distribution System Operator (DSO). Even though behind the meter storage services such as increased self-consumption, peak shaving and Time of Use (ToU) tariff management can be achieved locally by manipulating the distributed storage system capabilities, a centralized-based control is necessary for the future systems allowing the DSO to finely tune the operational settings and thus adjust the power flow of the grid. In addition, the DSO can conditionally apply utility storage services such as VAR control, voltage and frequency control and optimally manage the feeder load. A proposed solution capable for handling the aforementioned tasks is the Supervisory Control and Data Acquisition (SCADA) control system architecture [10]. SCADA is a well-established system mainly for monitoring and controlling multiple industrial equipment, however it is also applicable to electrical networks. More specifically, it can be used in cases where more than one systems need to be connected and monitored remotely from a central controller. This type of supervisory system is strongly recommended when designing a centralized storage system in order to provide the aforementioned utility services and achieve a secure monitoring network. For the centralized storage, three current transformers (CTs) are essential for measuring the 3-PH distribution line current and regulating the energy flow. The local substation bus voltage can be measured by the internal Battery converter sensors or the voltage of a nearby feeder, which needs voltage regulation, can be provided by the SCADA system. The grid frequency can be measured from the Battery converter as well, however, it would be better if it is provided by the SCADA system to avoid any mismatch between the grid control system frequency value and the Battery converter due to its measuring tolerance. The CTs are usually of analogue output and hence the device monitoring them, which is usually the Battery converter, should have analogue inputs otherwise an external analogue to digital converter supporting communication (e.g. CAN-bus, Ethernet, etc.) must be installed.

IV. CONCLUSIONS

In summary, this work presented a methodology for sizing battery energy storage systems (BESS) installed on PV systems. The methodology can be used for both the two primary configurations, the AC-Coupled and the DC-Coupled system. By analyzing the PV energy yield, the average electricity consumption and also the residential load peak power for each month, the most important design parameters to consider are the size (power and capacity) of the power converter and the battery unit. They are important since they strongly depend on the load profile of each prosumer and also on the PV production. The aforementioned analysis suggests that the converter power has to be 150% of the maximum domestic load and a DoD of 80% of the battery to allow flexibility to the coupled PV-BESS system and reasonable battery lifetime. This paper also discusses various electrical and mechanical parameters which can be used as a guideline for the design of a battery storage system.

Furthermore, electrical sensors for the acquisition of the necessary data for the system operation were proposed as well as communication protocols between the various system components. The use of fast, reliable and well-established communication protocols such as RS485 and web-based interfaces can allow secure data transfer and acquisition to the entire system. Finally, the necessity of SCADA control system is reported in order to allow the DSO for remote supervision.

ACKNOWLEDGMENT

This work has received funding from the European Union's Horizon 2020 research and innovation programme under the project TwinPV (Grant Agreement No. 692031).

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