Grid-PV-Diesel Hybrid System Management

Application to MED-Solar Project Scenarios

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***Abstract*—This paper addresses the functional design of an energy management system (EMS) applicable to hybrid energy systems (HES) formed by the power grid, photovoltaic (PV) generators, diesel generators, and energy storage systems (ESS). The implementation of these HES and their EMS is related to the MED-Solar Project which main objective is the construction of four pilot plants in three countries of the Mashreq area (Lebanon, Palestine and Jordan), in order to show that the utilization of these systems can reduce some energy problems present in these countries and, therefore, becoming attractive for different economic sectors.**

***Keywords*—hybrd electric systems; energy management system; PV-diesel-grid hybridation; MED-Solar Project**

I. INTRODUCTION

The MED-Solar Project (www.medsolarproject.com) is linked to the multilateral Cross-Border Cooperation in the Mediterranean Sea Basin Program (CBCMED) [1]. This program is part of the European Neighborhood Policy (ENP) [2] and its financing instrument, named European Neighborhood and Partnership Instrument (ENPI) [3] for the 2007-2015 period. The ENPI-CBCMED program aims to promoting the cooperation between the European Union (EU) and partner country regions placed along the shores of the Mediterranean Sea by dealing with the common challenges. In coherence with this objective, participating countries have agreed to define the following four priorities:

1. Promotion of socio-economic development.
2. Promotion of environmental sustainability through the use of renewable energy (RE) sources.
3. Promotion of better conditions for ensuring the mobility of persons, goods and capitals among the territories.
4. Promotion of cultural dialogue and local governance.

The MED-Solar Project is inscribed in the second priority and, more specifically, in the second measure of this priority, measure devoted to the promotion of RE use and improvement of energy efficiency contributing to addressing, among others, the climate change.

In following sections the objectives pursued and the entities that develop this project are presented. The status of the electrical system in the countries of the partnership, which are the target of actions of the project, are summarized. Finally, design alternatives of HES for these countries are evaluated, and the possible structure for an EMS is also proposed.

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II. MED-SOLAR PARTNERSHIP MEMBERS

Public and private actors, organized in Mediterranean cross-border partnerships, may participate in this program and the main beneficiaries include regional and local public authorities, non-governmental organizations, associations, development agencies, universities and research institutes, as well as private actors operating in the fields of intervention of the Program. The cooperation area is defined by 14 countries, which represent 76 territories. These countries are: Cyprus, Egypt, France, Greece, Israel, Italy, Jordan, Lebanon, Malta, Palestine, Portugal, Spain, Syria and Tunisia.

The lead partner and leader of the MED-Solar Project is *Trama Tecnoambiental* (TTA, www.tta.com.es), a Spanish company based in Barcelona, Catalonia (Spain). The rest of the partnership is composed by the following organizations:

- *Universitat Politècnica de Catalunya - BarcelonaTech* (UPC), from Catalonia, Spain.
- Solartys, from Catalonia, Spain.
- *Commissariat à l'énergie atomique et aux énergies alternatives* (CEA), from Rhône-Alpes, France.
- Energy Research Center (ERC), from State of Palestine.
- United Nations Development Programme (UNDP) - Lebanon, from Beirut, Lebanon.
- National Center for Research and development (NERC) Energy Research Program, from Amman, Jordan.

In their respective countries, all the partners are forerunners in the field of solar energy and part of the local dynamics in terms of solar and RE development and implementation.

III. MED-SOLAR PROJECT OBJETIVES

The main objective of the MED-Solar Project can be summarized as the research, promotion and implementation of innovative technologies and know-how transfer in the field of solar energy (especially PV). The achievement of this objective will result in the construction of four HES in private or public facilities (hospitals, schools, administrative buildings, etc), and granted through public tenders.

Project actuations are focused on the project countries located in the Mashreq area (Lebanon, Palestine and Jordan), mainly due to the fragility of their production and distribution power systems. The weakness in the electric power service in these three countries (failure to increase the contracted capacity, frequent outages, etc.) does not allow the security of

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supply in critical facilities or the proper development of small and medium enterprises. In order to ensure the power supply, the public and private sectors have to face huge investments in gensets as backup system whose operation is expensive. As an additional drawback, this causes heavy dependences on foreign countries as far as fuel supply is concerned.

This project addresses a solution to reduce the use of diesel generators (high polluting and expensive devices) by installing a solar PV power plant with a transient ESS associated to them. When the grid is available, the PV energy will be injected to the grid. In case of power outage, the load feed is assured by the PV plant. In addition, it can be coupled to the diesel generator if the PV generation is not enough. The transient ESS will guarantee the continuity of the power supply for very short-term variations of PV generation or during the time needed to switch-on the diesel generator.

The implementation of PV technology in the three target countries is in pre-commercial stages, requiring more demonstration projects to attract various economy sectors. That is why the MED-Solar Project focuses on four pilot plants based on PV power in the range of 80-100 *kWp*. The impact of such systems can have is evident:

- Reduction of national electricity bills, as the cost of electricity that the government may be subsidizing is reduced.
- Reduction on fuel use and CO_2 emissions, since most of the electricity generated in these countries corresponds to thermal generation from fossil fuels.
- Increased capacity development of SMEs, since the use of the proposed systems allows users to increase the electrical power consumption (in order to increase production) without increasing the energy demanded to the grid.

IV. The Electric System in Target Countries

The electrical systems in the three countries involved in this project have in common electricity production based on the use of fossil fuel-driven generators. Consequences of this kind of production are reflected in a high dependence on foreign fuel supply, high operating costs and high air pollution. Besides these common problems, there are issues that particularly affect each country. Therefore, a brief review of these three electrical systems is presented.

A. Jordan

The data presented were obtained from the annual report of the National Company of Electric Energy of Jordan (NEPCO) in 2013 [4]. The total installed power in the country was of 3.45 *GW*, whereas the peak power load was of 3.12 *GW* (representing a ratio about 1.1), and the consumed energy was 14.6 *TWh*. This energy is produced primarily in thermal power plants supplied by diesel (41.2 %), heavy fuel oil (HFO: 31.7 %) and natural gas (24.6 %). Only the 0.4 % is produced from renewable energy sources (wind, biogas and hydropower) and the remaining 2.1 % was imported from Egypt.

According to data released by the IFC (International Finance Corporation) [5], the number of power outages in a typical 2013 month is of 0.2 and the average outage duration is of 0.2 hours.

B. Lebanon

These data were obtained from the 2012 report of the International Energy Agency (IEA) [6]. The total installed power in the country was of 1.7 *GW* and the peak power of 2.8 *GW*, representing a gap of 1.1 *GW*. The energy demand is about of 15 *TWh*, whereas the energy supplied by the grid is of 11.5 *TWh*. The difference of approximately 23 % between demand and grid production is supplied by a large number of private diesel generators representing an approximate cost of $ 1,300 million. The energy delivered by the grid was primarily produced by thermal plants supplied by diesel (91.2 %). Only the 6.6 % is produced form RE (hydropower) and the remaining 2.2 % was imported from neighboring countries (Egypt and Syria).

According to the IFC [5], grid outages take place daily, being most of them pre-programmed, since the periods of grid availability are known. Although the average duration of outage is 5.2 hours, the real duration differs between urban and rural areas.

C. Palestine

The presented data were extracted from the annual energy report for the year 2012 of the Central Bureau of Statistics of Palestine (PCBS) that can be consulted on-line at the web page: http://www.pcbs.gov.ps/. The energy demand in Palestine is of 5.4 *TWh*, being 91.4 % of this amount imported from neighboring countries (Jordan, Israel and Egypt), whereas the remaining 8.6 % is produced by a single thermal plant located in the Gaza Strip.

The IFC [5] reports that the number of power outages in a typical 2013 month is 8.7, and its average duration is 3.7 hours.

The above data highlight the dependence of these countries on fossil fuels for electricity generation and the dependence on other countries for energy resources supply. In this regard, the Palestinian case is particularly critical because, besides the need of importing fuel, nearly 91 % of the electricity consumed in the country should be also imported.

From a reliability supply point of view, two cases can be distinguished. The first one is the case of Lebanon where power outages occur daily with an average duration of 5 hours. This involves the operation of generators for long periods of time, since it is nearly impossible to use ESS to supply the required power. In this case, the ESS is used as an energy bridge, ensuring the power supply between a grid outage and the start-up of diesel generators. The second case corresponds to Jordan and Palestine, where power outages are less frequent and of shorter duration. In this case, besides using the ESS as an energy bridge, it can be used to implement strategies for managing peaks on demand (know as *peak shaving*).

According to this, next steps should start by sizing the HES proposed for each country to further describe the energy management needs in each HES for its proper operation.

V. Proposed Hybrid Energy System (HES)

The HES design is constrained by two major issues, namely: *a*) it should take maximum profit of the infrastructure facilities available at the installation site, and *b*) the design should be based on commercial equipment to minimize the need of technological developments.

Regarding this, the HES design should take into account a set of given conditions. Among others, these conditions are consumption profile, the presence of the grid, the number and rated power of diesel generators, and the use or not of an automatic system for the gensets management. Furthermore, the HES can be controlled either by a remote control or by a human operator. Finally, the design for the HES should integrate PV generation and batteries-based ESS into the available infrastructures.

The architecture of the HES is strongly conditioned by several economic constrains related to the available budget for the HES construction and, on the other hand, the differences between the electric systems in the target countries also advise the implementation of different HES. The HES architecture proposed in each case is described below.

A. Jordan and Palestine case

The use of gensets in these two countries is not intensive, but they are used during outages for feeding the loads connected in the facilities under consideration. The facilities considered in both countries have in common a large value of peak load: 170 *kW* in Palestine, and 130 *kW* in Jordan.

These values of load peak power involve the use of battery inverters with a cost which clearly exceeds the available budget for the project implementation. Accordingly, the proposed architecture is shown in Fig. 1, where the connection point of the PV inverter and loads is located at the input of the battery inverter. In this architecture, the battery inverter rated power can be lower than the load peak power, and it also allows the possibility of critical load management.

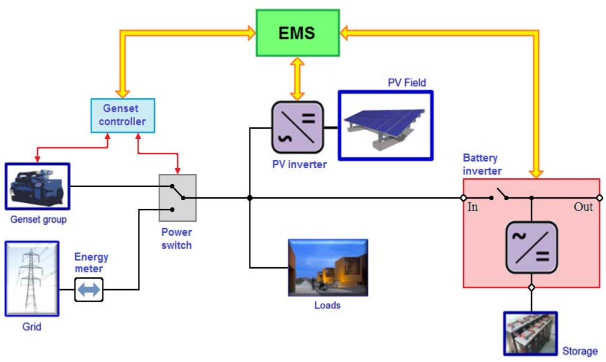

Fig. 1. HES proposed for the Jordan and the Palestine cases

B. Lebanon case

The case of Lebanon is substantially different because the outages in this country are daily and its duration can be several hours. As a consequence, the use of diesel power generators is intensive, and it is also common to use several gensets with different rated power, in order to adapt the power generation to the expected demand.

The large value of the peak power in the two considered facilities for the implementation of the MED-Solar pilot plants (about 125 *kW*) also involves the use of battery inverters with cost that clearly exceeds the available budgets.

The HES architecture proposed for the Lebanese case is presented in Fig. 2. In this architecture the PV generator is split in two different parts. The first one is connected at the battery inverter input node together with the non-critical loads, the grid and gensets. The second PV generator is connected at the output node of the battery inverter along with the critical loads, creating a network that can operate autonomously.

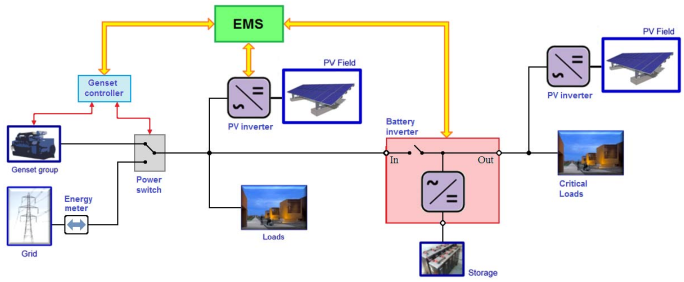

Fig. 2. HES proposed for the Lebanon case

VI. Proposed Energy Management System Architecture

A general approach of Energy Management System (EMS) design is based on different levels of decision-making with a clearly defined hierarchical structure. A simple but widely used structure is based on three levels in the decision making process, namely: Operational, tactical and strategic levels [7-9].

This approach allows the definition of the overall objectives of the system, the frequency of decision making (long, medium and short term), and the interactions between different levels. When this structure is applied to the design of an EMS, higher levels are assigned to the management of the energy flow, intermediate level take in charge the management of the power and the lowest level corresponds to the management of the elements belonging to the physical layer of the system. The desired behavior of the EMS can be described in terms of operational, tactical and strategic levels as follows:

A. Operational level

This level takes directly in charge the equipment of the HES, namely PV inverter, battery inverter, gensets and controllers, and the automatic transfer switch (ATS). The decision-making at higher levels should be translated to the operational level by means of properly programming the variables of the equipment which are accessible.

B. Tactical level

This level corresponds to the first to be programmed in the EMS, and is in charge of managing the power flow in the HES. The instantaneous power balance is automatically performed by the equipment used at the operational level. However, the tactical level should plan the power distribution from a system point of view by determining the values to be programmed in the equipment of the operational level in order to assure the system functionality under foreseen operation, such as:

- Battery charging current limitation.
- Limitation of the power delivered by the PV generator.
- Peak shaving management.
- Priority loads management.
- Management of the power spinning reserve.

C. Strategic level

This level is of the highest hierarchy and will implement the strategies for energy management within the proposed HES. At this level, the decisions can be taken considering, for instance, the existence of hourly rates, the cost of fuel, the forecast of demand and photovoltaic production evolution, etc. In any case, the strategies must assure the energy supply to the loads with high security at the lowest cost.

VII. Proposed Energy Management System Operation

EMS capabilities are directly related with the available functionalities on the operational level, because the power and energy management must be supported by the normal operation of the devices used in the HES implementation. In this regard, the tactical level is supported by the operational level and, as a consequence, the functionalities assigned to the tactical level cannot be described if the operational level is not perfectly defined. The definition of features that should be available in the operational level is discussed below and then, the issues related with the tactical and strategic levels are addressed.

A. Definition of operational level functionalities

The functionality required by the EMS involves different functions that must be based on features of the elements used in the implementation of the HES. The relation between the EMS functionalities and the features of the HES elements is:

1) Management of critical loads: This feature is usually implemented as a normal operation of battery inverters. These inverters have two different outputs, one is devoted to feed non-critical loads and the other one to feed critical load. The inverter control system monitors the input node in order to detect grid outages. When an outage is detected, the output dedicated to non-critical load is disconnected in less time than a grid period. The output devoted to critical loads is then energized by batteries.

2) Peak shaving: The implementation of this feature is based on the possibility to externally set the input power of the battery inverter, it is usually incorporated by manufacturers as a normal operation mode of battery inverters and it is referred as “power assist”, “grid assist” or “smart-boost”, depending on the manufacturer. Depending on the architecture adopted for the HES, the appropriate programming of the battery inverter can be performed only once during installation, or it must be done in real time according to the power demanded by loads.

3) Fuel saving: This feature aims to interconnect power systems based on diesel and PV generators. However, this connection must be done in a controlled way, in order to ensure that the geneset operates in its safe operating range in terms of minimum power and power factor. In this case, the implementation of this feature is based on the possibility to externally programing the output power of the PV inverter.

4) Spinning reserve (SR) management: This feature is irrelevant when the HES considered uses only one genset, because the genset rated power will be greater than the maximum power peak expected in load consumption. However, when the HES is based in more than one genset, this is an important functionality addressed to prevent malfunctions due to sudden variations in power demand or in PV generation. The main objective of this management is to ensure that the rated power of the genset in operation, at a given time, is able to absorb a simultaneous load rise (between 15 % and 20 %) and PV production decrease (between 60 % and 80 %). While the SR is ensured, no EMS actions are needed. Nevertheless, if an insufficient SR is detected, the EMS must act accordingly ‘starting’ a new genset. The utilization of genset controllers with a remote start signal support is necessary to automatically ensure the proper SR.

B. EMS tactical level operation

The EMS operation at tactical level depends on which is the power source used for feed the loads. The power source used in each case depends on its availability and on the decisions taken at the strategic level. Relying only on the power sources availability, the transitions between the 4 modes of operation defined for the EMS functionality are depicted in Fig. 3.

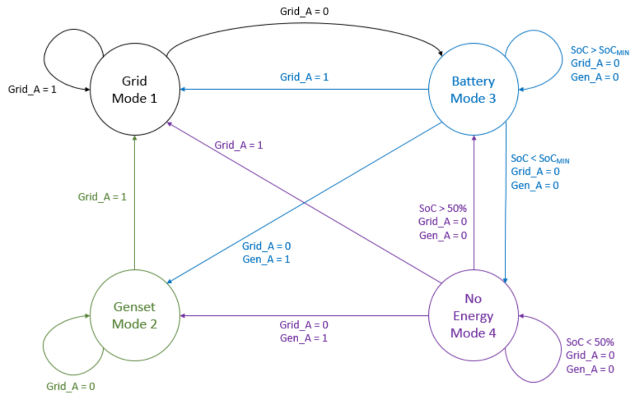

Fig. 3. Transitions between the different operations modes of the EMS

All the transitions between states can be defined in terms of three parameters or variables. Two of them are binary and are related to the availability of grid and genset as power sources:

- ***Grid_A***. Related to the grid availability. This parameter is set to “0” during outages, and it is set to “1” when the grid is operating normally.
- ***Gen_A***. Related to the diesel generator availability. This parameter is set to “0” when the genset stands, and it is set to “1” when the genset is operating normally.

The third parameter is the state of charge (***SoC***) of the ESS battery. The value of this parameter is used in order to determine if the battery is discharged or if the battery is reasonably charged (SoC greater than 50 %).

The transitions between states indicated in the diagram shown in Fig. 3 are automatically produced in response to events that occur in the HES and the operation of the HES in each state is imposed by the functionality of elements used in the HES implementation (operational level).

It is interesting to note that transitions imposed by strategies planned at the EMS strategic level could be added to the transition diagram. However, these additional transitions do not modify the functionality of the HES in each of its four modes of operation, reason why they are not considered.

Mode 1. AC bus connected to the grid. In this operating mode the features that could be implemented are:

AC bus voltage regulation. Assuming a weak grid, the EMS has to be able to configure the active and reactive power injected to the grid by the PV generator in order to control the AC bus voltage value. If a strong grid is assumed, the PV generator could deliver to the grid all the available power. This functionality must be implemented by the EMS tactical level, but it must be supported by the PV generator. In this regard, the selected PV inverter must include, as standard feature, the remote and real-time programing of the active and reactive output power set point values.

Peak shaving. This function limits to a maximum value (P_{max}) the power delivered by the grid (P_{grid}). The excess of energy is supplied by the ESS (P_{out}). The peak shaving operation is shown in Fig. 4, and the battery inverter set point is obtained from a power balance at the battery inverter input as is indicated in Eq. (1).

$$P_{out} = \begin{cases} 0 & if\ P_{grid} < P_{max} \\ P_{load} - (P_{max} + P_{PV}) & if\ P_{grid} > P_{max} \end{cases}, \quad (1)$$

where P_{load} is the power demanded by loads.

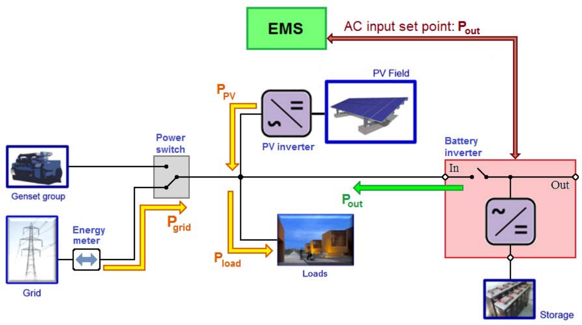

Fig. 4. Peak shaving implementation in Jordan and Palestine case

Mode 2. AC bus connected to the genset. In this operating mode the features that could be implemented are:

Fuel saving. The EMS must be able to set some parameters of PV inverter in order to implement this feature. It has to set the active and reactive power injected in the AC bus by the PV inverter in order to have control over the operating region of the diesel generator. The genset must operate delivering the 30 % of its rated power to minimize mechanical failures. Furthermore, the genset must operate with a power factor that is within its safe operating area (between 0.8 and 1). The fuel saving operation is shown in Fig. 5 and it has not dependence with the HES considered because the genset is connected in the input node of the battery inverter. In this node is also connected a PV inverter, which must be configured by the EMS in terms of power delivered to the AC bus.

The set point of the PV inverter (P_{PV}) is obtained from a power balance that involves the PV inverter output node and it is calculated by Eq. (2). Where P_N indicates the genset rated power, P_{MPP} indicates the available power in the maximum power point of the PV generator, and P_{gen} indicates the power delivered by the genset.

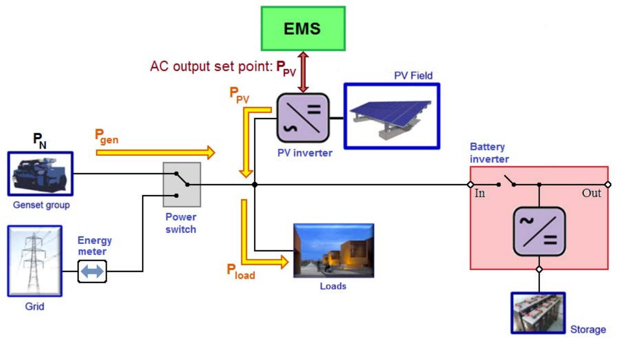

Fig. 5. Fuel saving implementation

$$P_{PV} = \begin{cases} P_{MPP} & if\ P_{gen} > 0.3 \cdot P_N \\ P_{load} - 0.3 \cdot P_N & if\ P_{gen} < 0.3 \cdot P_N \end{cases} \quad (2)$$

Spinning Reserve (SR) management. The SR management must be implemented if the HES considered utilizes more than one genset. The EMS must monitor the power production of the PV generator (P_{PV}) and the power demanded by load (P_{load}) in the battery inverter input node, and it also need information about the rated power of the active genset (P_N). The SR is defined by Eq. (3):

$$SR = P_N + P_{PV} - P_{load} \quad (3)$$

The spinning reserve at any time (SR_i) should be sufficient to deal with variations in load consumption (up 20 %) and in PV generator production (down 80 %) and can be calculated using Eq. (4).

$$SR_i = P_N + 0.2 \cdot P_{PV}(t_i) - 1.2 \cdot P_{load}(t_i) \quad (4)$$

If SR_i becomes negative during a certain period of time, the EMS should start the process of starting a new genset. The new genset can operate in parallel with the active genset or can substitute it. In any case, this process should be managed by a specialized gensets controller.

Mode 3. AC bus connected to the battery inverter. This mode of operation is only available in EES that involves the management of critical loads.

AC bus regulation. This feature is automatically performed by the battery inverter because it is usually included by manufacturers as standard feature. Fig. 6 shows the power balance in the battery inverter output node. In this case, it is assumed that the battery is not fully charged.

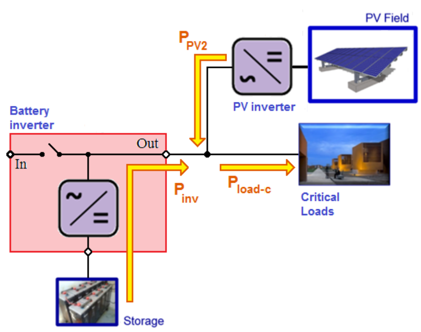

Fig. 6. Power balance in the battery inverter output node

If the battery is charged, the battery inverter cannot manage negative power and this situation leads to AC bus instability when the PV generation (P_{PV2}) is greater than the critical load power demand (P_{load-c}). When this situation occurs, the battery inverter can act in two different ways: 1) the battery inverter uses a frequency droop control in order to modulate the PV inverter output power (in this case, a PV inverter with this feature is needed); or 2) the battery inverter uses a shift frequency control in order to stop the PV inverter. In this case, the PV inverter used does not need any additional functionality, because all grid-connected inverters incorporate an anti-islanding protection based on frequency shift.

Mode 4. No energy source available. This operating mode implies the no availability of all power sources.

In the case of Jordan and Palestine, this mode appears when a fault occurs on the grid and the genset is not operative. When this situation arises, the battery inverter will remain disconnected because it has not enough rated power to feed the load, even if the battery is fully charged. In the Lebanese case, this mode appears when a fault occurs on the grid, the genset is not operative and the battery is discharged. In this situation, non-critical loads remain without power and only critical loads can be powered if the batteries have enough energy. The battery inverter generates the AC bus in its output node and the PV inverter can also deliver energy to critical loads. If this particular situation continues for a long time, the battery may be discharged, the battery inverter shutdown is forced and this operation mode becomes active.

C. *EMS strategic level operation*

The definition of the strategic level depends on the features to add to the HES functionality. It is essential to define clear objectives of energy management and translate them into several sets of rules which will be evaluated with different priority levels.

Depending on the objectives to be achieved, this EMS level will be responsible for deciding whether to switch from one operational mode to another. In this regard it should be clarified that certain changes in operation modes are an automatic response of the operational level to events occurring in the HES; for example, the transition from mode 1 to mode 3 when an unforeseen outage occurs. However, other changes in the operational mode may be determined by the strategic level under certain economic considerations. For example, the transition between mode 1 and mode 3 can occur in low demand conditions, without forecast to grow, if there is reasonable photovoltaic production, without expectations to decrease, and also the *SoC* of the battery is above a certain predefined level.

The platform selected for the EMS implementation is based on the hardware developed by Webdom Labs and its complete development is scheduled in late June 2015. Webdome [10] is a Spanish company that develops and markets systems and technology to provide solutions for control and energy saving.

VIII. CONCLUSIONS

This work is devoted to describe the architecture and the functional design of the Energy Management System (EMS) projected for the management of the Hybrid Energy Systems (HES) proposed for the target countries involved in the MED-Solar Project. It is planned to start the construction of the four pilot HES in early April 2015, so they will be operational in mid-year. One of these HES will be built at the Al-Huson University College campus, located in Irbid, Jordan. The second one will be built at the An-Najah National University Hospital facilities, located in Nablus, Palestine. The other two HES will be built in Lebanon, one in the facilities of the Amal Educational Institutions, in Beirut and the other in the Akkar Wholesale Market facilities located in Abdeh.

An architecture based on three conceptual operative levels has been proposed for the EMS implementation:

<u>Operational level.</u> This level is based on the standard features implemented by manufacturers in the equipment used for the HES construction.

<u>Tactical level.</u> As the instantaneous power balance is automatically performed by the operational level, the tactical level plans the power distribution from a system point of view and programs consequently the set points of the HES devices.

<u>Strategic level.</u> This level implements the strategies for energy management in the proposed HES in accordance to economic issues.

Finally, the tactical level has been defined based on four operation modes, depending on the energy source that powers the loads and the EMS functionality at this level was defined accordingly to the power strategies that can be implemented by the operational level. These power strategies are basically four:

- Critical loads management (*power bridge*).
- Management of loads peak power (*peak shaving*).
- Fuel saving feature.
- Spinning reserve management.

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