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Optimization of Auxiliary Power Supply (APS) Systems with Photovoltaic Modules

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Abstract— Auxiliary power supply (APS) systems are increasingly used for low power rating home appliances (e.g. televisions, water dispensers, etc.) and lighting (e.g. CFL lamps) in countries where long power rationing schemes are applied. In general, these systems charge a 240AH (Ampers-Hours) bank of batteries as long as the grid is on and then convert the stored energy into AC current to supply a load of 400W during the rationing time which sometimes last for several hours (four to six hours). Thus, such systems would be able to afford all these hours if and only if the battery bank of the APS was fully charged. Unfortunately, the practice shows that this target (full charge of the battery bank) cannot be achieved mainly due to the short on period of the grid – while in lucky times (when there are no sporadic interruptions) the on period of the grid does not exceed six consecutive hours, the average time needed to fully charge the battery bank at 20 amps charging current is twelve hours. This paper shows how a small number of solar photovoltaic (PV) modules can be used as an additional charging power source to overcome this problem. Besides the major reduction in the size of the PV modules, an average saving of 61.5% in the energy drawn from the utility is achieved.

Keywords— Hybrid supply systems, solar photovoltaic modules, off grid.

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1 INTRODUCTION

AUXIliary power supply systems are increasingly used for low power rating home appliances and lighting in countries where long power rationing schemes are applied. In general, an APS system takes advantage of the on period of the grid to charge a battery bank that should be as big as to continuously supply the loads mentioned above for a given number of hours i.e. the rationing period.

The fact that APS systems are relatively cheaper and easier to use than a small size silent petrol generator makes them so popular. For example, it is so rarely to find even one house not backed up with an APS system in almost all Lebanon's cities and villages. However, the majority of the households are still using the utility supply to charge the battery bank of their APS systems as solar PV modules or small scale wind turbines are still not properly marketed as an additional battery charging source and subsidized neither by the government nor the private financial firms.

Unluckily, besides hydro power, the only type of renewable energy systems that has been moderately used in Lebanon (the 300 sun day country) is the solar thermal collectors. These are used to replace electric ones and were found to save approximately 8% of the total generated electricity over 10 years [1][2][3]. Similarly, another reduction in the country's yearly electricity bill (which has recently exceeded the level of $500 million) can be achieved if PV panels were exploited as an alternative charging source for APS systems. An approximate calculation shows that a 1KW APS system with a 24V-240AH battery bank would consume around 4.5KWh per day if a 20A charging current was provided. This is accounted to 90% of the electric heater daily electricity consumption (5KWh) as reported in [3].

Our main target is to reduce the amount of the energy daily drawn from the grid by at least 253,000 APS systems if we assumed that only 50% out of 505,180 Lebanese households [4] use APS systems as a backup power source. That is the country would save at least 415MWh per year and thus decrease the annual emission of CO2 by 17,868 tons if thermal power stations were used [5].

2 Integration Of solar PV power Source with APS systems

APS systems are increasingly used for low power rating home appliances (e.g. televisions, water dispensers, etc.) and lighting (e.g. CFL lamps) in countries where long power rationing schemes are applied. A 1KW APS system with 240AH battery bank and 90% efficiency can supply four 11W CFL lamps, one 200W TV set and one 100W laptop computer and 40W fan for 6 hours. The short on period of the grid and its irregular interruptions make APS systems useless and eventually lead to a severe damage to its battery bank. Consequently, an additional stable charging source is an obligation. One option for such a source in a country like Lebanon, with an average daily solar insolation of 4.7 KWh/m^2, can be PV modules [6]. Table 1 below illustrates the averaged values of solar insolation on a horizontal surface.

TABLE 1

SOLAR DATA FOR LEBANON

Month	Coastal Insolation, kWh/m^2/day	Interior Insolation, kWh/m^2/day	Coastal sunshine hours (Hrs)	Interior sunshine hours (Hrs)	Day length, (Hrs)
January	2.4	2.4	4.6	4.5	10
February	3.2	3.4	5.6	5.5	10.8
March	4.1	4.4	6.4	6.4	11.8
April	5.5	5.9	7.7	8.5	12.9
May	6.6	7.2	10.1	10.5	13.8
June	7.3	8.5	11.5	13.1	14.2
July	7.0	8.4	11.4	13.2	14
August	6.3	7.7	10.6	12.4	13.2
September	5.3	6.5	10.4	11.2	12.1
October	4	4.7	8.1	9	11
November	2.9	3.3	6.4	6.7	10.2
December	2.3	2.4	5	4.8	9.8

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3 SYSTEM COMPONENTS AND OPERATION

The components of the solar PV-Grid integrated home power system are illustrated in Fig. 1:

1. PV modules
2. Solar charge controller
3. Deep cycle lead acid 120AH – 24V battery bank
4. 100A rating 220V-50Hz Automatic Transfer Switch (ATS)
5. Deep cycle lead acid 120AH – 24V battery bank
6. 1KW-220V- true sine APS system

Although similar researches [10] [11] [13] [13] have tried to tackle the problem investigated in this paper, we are approaching it in a way that does not only reduces the electricity bill of households, but also simplifies the implementation of the power management unit i.e. the ATS unit and deceases the number of PV panels needed.

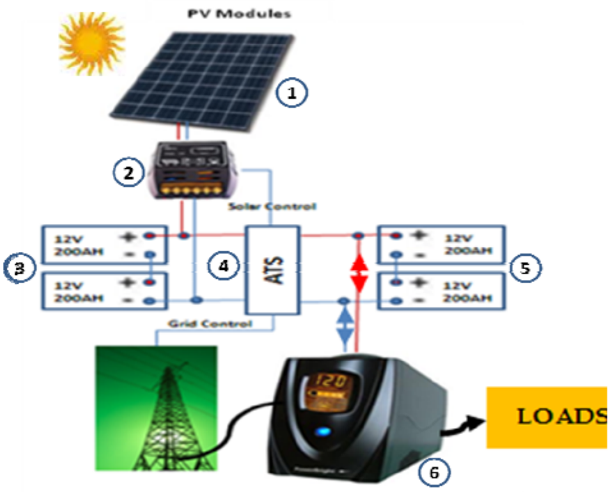

FIG. 1: A SCHEMATIC DIAGRAM FOR THE PV-GRID POWER SYSTEM

3.1 PV modules

A solar module, also known as solar panel, photovoltaic module or photovoltaic panel, is essentially an assembly of electrically interconnected photovoltaic cells which convert sunlight directly into DC electricity current based on a physical phenomenon called “photovoltaic effect” [7] as shown in Fig. 2[7]. Sun light (photons) falls on the surface of solar plate consisting of P-N semiconductor material generate electron hole pair and accumulate charges on opposite plate resulting in generation of electricity while connected across the load.

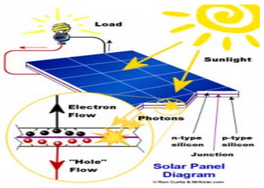

FIG. 2: SOLAR ELECTRICITY GENERATION

PV cells are manufactured using silicon. Although single crystal silicon is the most efficient flat plate technology (15-16% conversion efficiency), it is still the most expensive and so PV cells made from multi-crystalline silicon are the most popular as they are less expensive to produce, but are also slightly less efficient [8][9]. The efficiency of multi-crystalline solar PV panels when installed in Lebanon is shown in Table 2.

TABLE 2
ENERGY EFFICIENCY OF TYPICAL MULTI-CRYSTALLINE SOLAR PV PANELS

Particulars	Units	Typical Values
Solar energy input	KWh/m2/day	4.7
Electric energy output	KWh/m2/day	0.75
Overall efficiency	%	16

The solar module can be used as a component of a larger photovoltaic system to generate and supply electricity in commercial and residential applications. Each module is rated by its DC output power under standard test conditions, and typically ranges from 100 to 450 watts. Because a single solar panel can produce only a limited amount of power, most installations contain multiple panels.

Practically every application that requires electricity to operate can be powered using a correctly sized photovoltaic system. The only limitation is the economic cost of the equipment and, in some cases, the size of the photovoltaic array. Nevertheless, in our case a small number of solar modules are needed, the most cost effective solution is the installation of photovoltaic modules rather than a small size petrol or diesel generator [11]. PVs have no moving parts to be maintained, do not consume petrol (i.e. no CO_2 emission) and are silent.

In order to be able to fully charge a 24V - 120AH battery bank in about six hours, we used two pairs of 120 Wp multi-crystalline Kyocera solar PV modules each connected in series to produce 10A at 24 Volts. Thus, the installed solar PV modules produce an overall of 20A, and thus be able charge only the half of the total battery bank size.

3.2 Solar Charge Controller

The used solar charge controller is the WEELSEE WS-C2430 model which has a 20A maximum output charging current, 30A load current, and can be exploited with both 12/24V PV combinations. WS-C2430 applies to all types of photoelectric panels and various types of batteries. Moreover, it regulates the voltage and current coming from the solar panels going to the battery using a pulse width modulation (PWM) strategy. Instead of a steady output from the controller, it sends out a series of short charging pulses to the battery - a very rapid "on-off" switch. The controller constantly checks the state of charge of the battery to determine how fast to send pulses, and how long (wide) the pulses will be.

The solar controller WS-C2430 is also equipped with an advanced LCD man-machine interactive function, so the user can adjust the charging voltage and as well record some important data as the charging and load AH. However, in our application we do not need to record the load AH as our loads draw AC power from the APS which is directly connected to the battery bank [14].

3.3 Automatic Transfer Switch

The ATS consists of an ordinary 220V-50Hz power Dual Pole Dual Throw (DPDT) controlled by both the grid and the solar PV modules through a 24V DC relay.

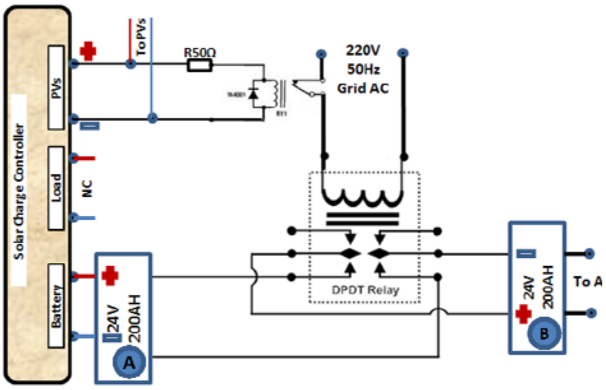

FIG. 3: A SCHEMATIC DIAGRAM FOR THE ATS, (NC: NOT CONNECTED)

The diagram in Fig. 3 shows that the DPDT will disconnect the two sets of the battery bank when the grid is on during the daylight, but connect them together during nights; rainy/cloudy days or the grid is off. Such a functionality of the ATS helps not only an optimal use of the PVs during the daylights (more energy is drawn from PVs, especially when set A is already fully charged), but also a longer supply period during the nights by doubling the battery bank delivering energy to the APS.

Table 3 depicts the truth table of the ATS. Actually, it is surprisingly similar to that of the "&" logic gate. Alternatively, the DPDT and relay used in the actual implementation of the ATS can be replaced by solid state DC current switches that use Field Effect Transistors (FET).

TABLE 3: THE ATS' TRUTH TABLE

Inputs		**Output**	**Time**
PVs	**Grid**	**ATS**	
on	off	off	**Daylight**
on	on	on	
off	on	off	**Night**
off	off	off	

3.4 The Battery Bank

Each of the batteries included in the battery bank is 12-200AH deep cycle lead acid battery. As opposed to automotive lead acid batteries which deliver short, high-current bursts for cranking the engine, this type of batteries is designed to be regularly deeply discharged using most of its capacity, and thus best choice for PV panels. Although these batteries can be cycled down to 20% charge, it is recommended to keep the average cycle at about 50% discharge, as there is a direct correlation between depth of discharge on the battery and the number of charge and discharge cycles it can perform. This feature explains why the life span of the deep cycle batteries could be longer when used in a PV-Grid system like ours where the chance of reaching the 20% maximum discharge level is almost not probable.

3.5 The Auxiliary Power Supply

Types of APS systems vary mainly in output waveform which can be either of square or sine shape. While the latter can only be used with all kinds of loads (e.g. LED and CFL lighting lamps, notebook and desktop computers, water dispensers, electric fans, TV sets, etc.) the former cannot be used with applications having motors, transformers or power supplies designed around low harmonic content sine waves. In addition, the same RMS value of an equivalent sine wave will have a much higher crest factor. Thus, if your components are only expecting a peak of X volts, and you force feed it something significantly higher than X, it will blow out.

A 1KW-220V-50Hz APS is used in our PV-Grid system. With a 20A charging capacity it is suitable to be installed with our PV-Grid system as it is only responsible to charge the half of the battery bank – 120AH during the on grid period. In addition, it provides protection against low (≃20.8V) and high (>27.6V) battery voltage. That is, the battery bank is protected against deep discharge as well as overcharge.

Although the used APS offers overload protection, it cannot be directly connected to the electric circuit of the house unless heavy home appliances such as refrigerators, microwaves, washing machines, electric water heaters, etc. are disconnected in the absence of the grid. This is usually overcome by separating the wiring circuits feeding these loads from those devoted for lighting and other low power loads like TV set, stereo, etc. The separation is typically done by installing a new by side wiring circuit dedicated for the heavy loads. However, we have devised a way in which heavy loads disconnect themselves as soon as the grid is off. We will report our findings about this way of load self-disconnection in another communication.

4 RESULTS

The solar insolation data of Table 1 are used to assess the amount of energy generated by the four 120Wp Kyocera multi-crystalline PV panels integrated in our auxiliary power system. Only coastal data is considered since our system is installed in Beirut which is located on a peninsula at the midpoint of Lebanon's Mediterranean coast. Knowing the solar insolation value *SI*, the total area of the used PV modules *A* as well as its conversion efficiency *E* and working voltage *V*, one can directly deduce the expected PVs' AH output per day from the following equation:

$$AH/_{day} = \frac{SI \times E \times A}{V} \times 1000$$

The actual AH was daily read and recorded from the solar charge controller and then averaged at the end of each month.

Table 4 shows the expected and actual averaged AH together with the monthly PV/Grid share (percentages) in the energy drawn by the loads for a period of one year. Note that the total 400W load (*Load Energy*), which is assumed to be constant and does not change during the total rationing time (10 hours), is supplied by either the PVs or the grid.

Table 4: Expected vs. Actual PVs energy collected from a coastal location in Lebanon: Beirut district

Month	Expected Coastal PVs Output (AH/day)	Averaged Actual PVs Output (AH/day)	PV/Grid Shared Energy (%)
January	48	40	24/76
February	64	69	42/58
March	82	86	52/48
April	110	116	70/30
May	132	142	86/14
June	146	158	95/5
July	140	160	96/4
August	126	138	83/17
September	106	122	73/27
October	80	90	54/46
November	58	63	38/62
December	46	46	28/72

Thus, the daily PV energy share/percentage *PV%* and *Grid%* can be respectively defined as:

$$PV\% = \frac{Actual\ PVs\ Energy}{Load\ Energy}$$

And

$$Grid\% = 100 - PV\%$$

Consequently, an almost zero value of the *Grid%* indicates very small sharing of the grid in the load energy and that the load was almost solely energized by the sun. Consider the data recorded for *PV%* and *Grid%* AH shares in June and July as an example for such a case. The grid share is higher than that of the solar one only for four months (January, February, November and December and lower for the rest of the year (see in Fig. 4).

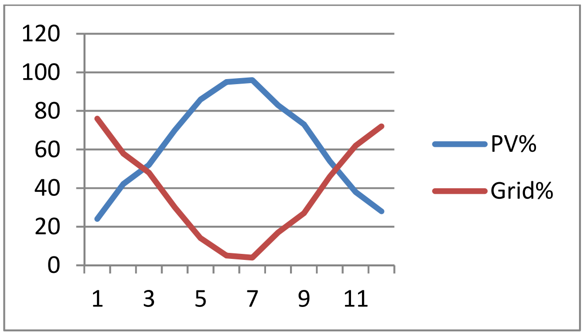

FIG. 4: PV% VS. GRID% SHARES IN THE LOAD ENERGY OVER ONE YEAR

Therefore, the average total solar energy harvested throughout the year allowed a save of 61.5% of the total yearly load consumption. That is, our system has scored higher energy saving than that reported in [12] without relying on a fuzzy controller which needs extra work to build its knowledge base decisions. We also believe that PV-Grid with fuzzy control would not reach higher PV sharing score if applied in areas with a long rationing hours during nights like ours where the load is always high, the battery bank is either at its medium or small state of charge, and thus higher diesel generator power share if the number of the PV panels is not increased. In addition, the output voltage of the "bi-directional converter" in the system introduced in [11] needs to be fine-tuned so that it is perfectly equal to that of solar charge controller especially during "shortfall" periods. Otherwise the higher charging voltage of the PVs will prevent the current flow between the converter and the batteries in charging mode even in semi cloudy weather or when the utility voltage decreases below the rating voltage i.e. 220V. Furthermore, the saved energy in one APS system reduces the electricity bill of homeowners by approximately $93 per year, if the tariff in Table 5 for the Lebanese utility company (Électricité Du Liban - EDL) is considered. Moreover, the government, and thus the EDL, would save (if 253,000 PV-Grid APS systems were installed) more than $17.5 million/year as the real cost of one KWh is $0.078 [9].

TABLE 5: TARIFF USED BY EDL FOR RESIDENTIAL CONSUMERS

Consumption fraction (KWh)	0-100	101-300	301-400	401-500	>500
Cost (cents)	2.33	3.67	5.33	8	13.3

Although our PV-Grid APS system is essentially designed to partially compensate the absence of the grid – only low power loads are fed, it is equipped to automatically switch the load to draw its energy from PVs only when the batteries are fully charged and the grid is on during the daylight. Nevertheless, this feature is only applied during the daytime in warm seasons (i.e. mostly spring and summer seasons) on days where the grid is off for four hours only as shown in the rationing scheme in Fig. 5.

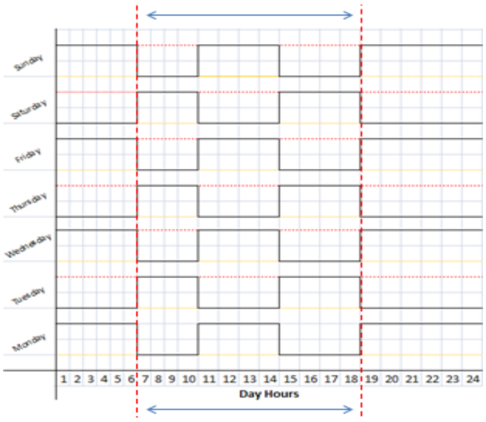

FIG. 5: RATIONING HOURS SCHEME FOR VILLAGES AND CITIES OUTSIDE THE CITY OF BEIRUT

5 CONCLUSION

The discussion in this paper is related to the integration of solar PV panels with grid to help lengthening the power supply period of an APS system usually used for low power rating home appliances and lighting in countries where long power rationing schemes are applied. A system design for an optimal use of a small number of PVs in such a system is investigated. The obtained results indicate that dividing the battery banks in two halves and then dedicating the PVs to charge one half and the grid the other decreases energy drawn from the grid by 61.5%, and thus help in the reduction of electricity bill and pollution. PV-Grid hybrid systems has gained high acceptance especially amongst Lebanese villagers as well people living in cities as it is cheaper in the long term than a petrol/diesel generator, less space is needed for PV panels, and can meet their energy demand during the off grid period in an efficient and continuous manner without the need for any other energy source. In addition, the amount of money that the utility company (the government in Lebanon) can save by encouraging citizens to adopt the introduced PV-Grid integration can be used to subsidize PV-Grid systems, and thus reducing the electricity bill year after year.

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