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FACULTY OF ELECTRICAL ENGINEERING

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UNIVERSITY „GOCE DELCHEV” - SHTIP
FACULTY OF ELECTRICAL ENGINEERING

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FIRST INTERNATIONAL CONFERENCE

ЕТИМА / ETIMA 2021

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PREFACE

The Faculty of Electrical Engineering at University Goce Delcev (UGD), has organized the International Conference ***Electrical Engineering, Informatics, Machinery and Automation - Technical Sciences applied in Economy, Education and Industry-ETIMA*.**

ETIMA has a goal to gather the scientists, professors, experts and professionals from the field of technical sciences in one place as a forum for exchange of ideas, to strengthen the multidisciplinary research and cooperation and to promote the achievements of technology and its impact on every aspect of living. We hope that this conference will continue to be a venue for presenting the latest research results and developments on the field of technology.

Conference ETIMA was held as online conference where contributed more than sixty colleagues, from six different countries with forty papers.

We would like to express our gratitude to all the colleagues, who contributed to the success of ETIMA'21 by presenting the results of their current research activities and by launching the new ideas through many fruitful discussions.

We invite you and your colleagues also to attend ETIMA Conference in the future. One should believe that next time we will have opportunity to meet each other and exchange ideas, scientific knowledge and useful information in direct contact, as well as to enjoy the social events together.

The Organizing Committee of the Conference

ПРЕДГОВОР

Меѓународната конференција ***Електротехника, Технологија, Информатика, Машинство и Автоматика-технички науки во служба на економија, образование и индустрија-ЕТИМА*** е организирана од страна на Електротехничкиот факултет при Универзитетот Гоце Делчев.

ЕТИМА има за цел да ги собере на едно место научниците, професорите, експертите и професионалците од полето на техничките науки и да претставува форум за размена на идеи, да го зајканува мултидисциплинарното истражување и соработка и да ги промовира технолошките достигнувања и нивното влијание врз секој аспект од живеењето. Се надеваме дека оваа конференција ќе продолжи да биде настан на кој ќе се презентираат најновите резултати од истражувањата и развојот на полето на технологијата.

Конференцијата ЕТИМА се одржа online и на неа дадоа свој допринос повеќе од шеесет автори од шест различни земји со четириесет труда.

Сакаме да ја искажеме нашата благодарност до сите колеги кои допринесоа за успехот на ЕТИМА'21 со презентирање на резултати од нивните тековни истражувања и со лансирање на нови идеи преку многу плодни дискусии.

Ве покануваме Вие и Вашите колеги да земете учество на ЕТИМА и во иднина. Веруваме дека следниот пат ќе имаме можност да се сретнеме, да размениме идеи, знаење и корисни информации во директен контакт, но исто така да уживаме заедно и во друштвените настани.

Организационен одбор на конференцијата

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GRID-CONNECTED HYBRID PV SYSTEM WITH BATTERY STORAGE

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Abstract

Photovoltaic systems (PV) are an integrated set of photovoltaic modules with all the necessary components that are dimensioned to receive solar energy and convert it into electricity that would be adequately powered by some DC and/or AC consumers. Depending on how they work, photovoltaic systems can be divided into stand-alone PV systems (off-grid), grid-tied PV systems connected to the electricity distribution network (on-grid), and hybrid PV systems as a combination of the previous two systems.

In this paper, we will consider the operation of a hybrid grid-connected PV system with battery storage which transforms solar energy into electricity and allows the storage of excess generated electricity in the batteries. Additionally, this system provides, if needed, the excess generated electricity to be delivered directly to the power grid. The proposed hybrid system could optimize all three energy sources PV modules, batteries, and power grid, and continuously deliver quality power to connected consumers. Properly sized and controlled hybrid PV systems significantly increase the use of so-called green energy from renewable energy sources and increase the independence and continuous power supply of the consumers.

Keywords: *renewable energy sources, PV systems, inverters, batteries, hybrid systems*

Introduction

The energy potential of the Sun as a renewable energy source is very large and the use of solar energy can be realized by converting it into heat and electricity. Solar energy can be converted into electricity in many ways, but the simplest way is that one with photovoltaic (solar) cells which is based on the photovoltaic effect. Converting solar energy into electricity using properly sized photovoltaic systems not only provides economically viable and overtime free electricity, but it also protects the environment from the pollution that accompanies the production of electricity from conventional energy sources, reduces CO_2 emissions into the environment which is one of the benefits of using solar energy.

The *photovoltaic effect* (PV) is a quantum-mechanical process wherein photovoltaic cells the energy of solar radiation is converted into electricity, or more precisely, it is the occurrence of the creation of voltage or adequate electricity in a semiconductor material, usual silicon with appropriate impurities added to its atoms, under its exposure to light-photons as the smallest carriers of solar energy packets.

PV cells are made with a certain technological procedure where a very thin layer of *n*-type semiconductor is applied to a *p*-type semiconductor and thus creating a so-called *pn*-junction with a shape that allows light to fall spatially on a larger surface and with the help of the photovoltaic effect produces electricity.

PV systems are systems designed to receive solar energy and convert it into electricity in a form that can be used by consumers, sent to the distribution network, or stored in appropriate power batteries and used when the need for energy arises, usually when the solar radiation is reduced, at night or due to problems with the electricity distribution. For a PV system to function flawlessly, it needs to be properly selected, sized, and integrated. The basic components of a photovoltaic system are the PV *module* (as a system of PV cells), the *inverter*, and the *batteries*.

The PV cell is a major part of the photovoltaic system. The output power of a cell is quite small; therefore several cells are properly connected in modules to provide adequate usable output power. Photovoltaic cells in the module can be connected in series or parallel. In practice, cells are connected in series because the serial connection of the cells increases the magnitude of the module voltage, and the current through them remains the same.

The PV module as a system of interconnected PV cells can further be used as a stand-alone or connected in a system with other modules with the same characteristics with the main task of the module converting solar energy into electricity. Multiple modules mounted on a common load-bearing structure constitute a PV *panel*. The panels can further be properly connected in an array or grid. The array can be consisting of one to several thousand modules, depending on the required output power, making a PV power plant. For the modules to give optimal results in converting solar energy into electricity, they are usually connected in series, facing south at a certain angle that corresponds to the local latitude. It is recommended that during the day there is no shading on the modules, the length of the so-called sundial at that location is maximum and there is good ventilation under and around the panels to avoid major overheating while exposed to the sun. The most practical application is monocrystalline and polycrystalline modules that are characterized by high durability of about 25 years.

In addition to the PV modules when dimensioning a photovoltaic system, *inverters* are also of great importance. These two components, PV modules, and inverters are crucial for the optimal functionality and the cost of a PV generation project. They constitute 70% of the total investment costs of the PV system. The inverter is the most exploited part of a PV system, and its main function is to convert direct current into alternating current, as well as to maintain appropriate power, to control the quality of electricity production (e.g. voltage and frequency) that is delivered to the grid, and for communication with the power network.

Several types of inverters differ in how they are connected to the system and are responsible for the efficiency of the system:

- central inverters (for the whole system),
- string inverters,
- micro-inverters,
- hybrid inverters, etc.

Each of these four types has its advantages and disadvantages. Which type will be chosen depends on the type of system and compatibility with other components of the PV system, as well as on several other factors such as site temperature, product safety, sustainability, altitude, servicing, and total costs. To ensure optimal efficiency and durability of the system, proper sizing is very important, and therefore when choosing an inverter the ratio between the power of the photovoltaic system and the power of the inverter should be 1: 1, it should be adjusted to the operating parameters of the module. If the inverter is overloaded, the results could be power loss and premature aging of the devices.

In addition to PV modules and inverters, more and more systems use *batteries* as an additional source of energy according to the needs of the system, especially in areas where there is an unstable electrical network or stand-alone systems. Properly sized and connected batteries form a battery energy storage system (battery bank) which provides power storage and improves the reliability in systems that require more power. Also, they provide better energy stability of its network and savings of clean energy that will is stored during the day and will be used in the evening or case of power outages. Batteries are a good investment especially in systems that produce more energy than they can consume; however, utilization of batteries means higher investment costs and therefore the batteries should be well-chosen according to their capacity and quality and according to the real needs and expectations of the system. Installing batteries within the system can be a great way to get the most out of photovoltaic modules. There are many different types of batteries on the market, however, lead-acid and lithium-ion batteries are mostly used to store energy generated by photovoltaic systems [1], [2], [3], [4].

1. Types of photovoltaic systems

PV systems are an integrated set of photovoltaic modules with all the necessary components that are dimensioned so that they can receive solar energy and convert it into electricity that would be adequately powered by several DC or AC consumers.

Depending on how they work, PV systems can be divided into:

- **Stand-alone PV systems** (autonomous or Off-Grid PV systems),
- **Grid-tied PV systems,** (PV systems connected to the electricity distribution network or On-Grid PV systems), and
- **Hybrid PV systems** (PV systems that are a combination of the previous two systems).

Stand-alone (autonomous) PV systems (Off-Grid)

Stand-alone PV systems are systems that are not connected to the power grid, thus operate separated from the electricity distribution network. In these systems, the production and consumption of electricity the system should be well-balanced because the production of energy depends on weather conditions. These systems usually require an additional battery system for energy storage that can be used at night or during bad weather. The charge controller takes care of the proper charging and discharging of the battery, and the inverter enables the use of the produced energy in standard household appliances with standard electrical installation. Such systems are suitable for powering isolated and lonely buildings, for example in rural areas, locations far from the electrical grid where connection to the grid is very expensive, as well as for individual buildings where there is no electrical grid such as remote buildings for signaling, warnings, telecommunication transmitters, lighthouses, systems for monitoring, etc.

Advantages of these stand-alone networks are that they are energy independent of the distribution network, they can supply even the most remote places for which there is no possibility to connect to the electrical grid, there are no bills for payment of electricity, etc. It is also an advantage that for a start if the energy needs are modest, a smaller system can be dimensioned, which can be later upgraded over time if the need for electricity increases. For larger systems, the system should be well sized from the very beginning to cover 100% of the loads expected in the system. In case of prolonged inconvenience because of the stability of the power supply, it is advisable to add a generator (running on diesel, gasoline, etc.) as the backup energy generator. It would be switched on when the batteries could not cover all the needs of the consumers of that system. This method may be a better and cheaper choice instead of investing in a huge battery bank that would rarely be fully utilized).

The main disadvantage of this system is that the energy from this system cannot be sent to the grid, thus the whole system cannot be subsidized if there are such incentive programs. Another disadvantage is that this system has more expensive components and thus higher initial costs. Batteries themselves are more expensive and reduce the efficiency of the system because their capacity degrades over time. However, sometimes, despite this higher initial cost, it may be cheaper to go with the installation of a battery bank than to pay a very expensive fee for connecting to a remote power distribution line [1], [3], [4].

PV systems connected to the electricity distribution network (On-Grid PV system)

PV systems connected to the electricity distribution network use the distribution network as a backup power source (virtual battery), or as a consumer for the excess energy generated by PV modules. These systems work interactively and in parallel with the electricity distribution network, and despite the PV modules, additionally, they contain only an inverter. The direct current from the PV modules with the help of an inverter is converted into alternating current and with adjusted voltage through a distribution board and electrical installation supplies the consumers that are supplied in two ways. In periods when the photovoltaic modules produce less power than required, the control device also includes the grid as a backup source, so that the electricity consumption is always satisfied. In periods when the modules produce more than the required electricity, the surplus is taken over by the electrical grid. Overnight consumption by the system (usually home appliances), is provided exclusively by the distribution network. The control device adjusts the operation of the PV modules with variable consumption so that the operating point of the IU characteristic is closest to *the maximum power point* (MPP), to achieve the most efficient operation of the module. This device that enables optimal operation of the system in different operating modes regardless of the intensity of solar radiation or changes in loads is called *the maximum power point tracker* (MPPT). MPPT works on the principle of adjustment on the resistance of the circuit to extract maximum power from the system.

On-grid PV systems are very efficient because they have fewer components and thus the initial investment is lower than stand-alone systems. Another advantage is that by connecting to a distribution network, this network acts in a kind of virtual battery where the excess generated energy can be transferred, or energy can be withdrawn, in case of need of the network system. This system also affects the mitigation of the peak load of the distribution network itself. If there is a subsidy program, the surplus can be sold to the electricity distribution system and some profit can be made. Additionally, the delivered and/or withdrawn energy can be compensated, and thus a smaller electricity bill will be obtained. The transmitted and withdrawn energy from the distribution network is registered and monitored through the two-way energy meters that are installed in the network system.

The disadvantage of the on-grid PV systems is that when the power supply from the electrical grid is disconnected due to some problems in the grid, this system will be turned off at the same time. The inverters are automatically disconnected from the grid and to protect people who try to eliminate the problem of the grid. This means that you cannot have a power supply during a power outage. Thus, in return, you cannot store energy for later use, and you cannot use the energy generated by the photovoltaic system until the problem in the distribution network is overcome and reconnected. This is the so-called anti-islanding protection [1], [3], [4].

Hybrid photovoltaic system

A hybrid photovoltaic system (HPV) is a system that combines the best of both above-described systems, the stand-alone and grid-tied PV systems. Descriptively speaking, these systems are PV systems with auxiliary (backup) power supply (one or more) or grid-tied PV systems with a battery storage system that provide the uninterrupted continuous power supply.

The HPV battery system connected to the power grid ensures maximum autonomy in terms of power supply. The system uses solar energy at the same time and allows the storage of the excess energy generated in the batteries of the battery energy storage system, except if there is an extra surplus of generated energy that should be delivered to the EE network. The consumers connected to such HPV battery system primarily use the energy generated by the PV modules. In case more energy is required than the energy currently generated by PV modules, this excess energy is provided from the electrical grid and/or from the energy previously stored in the batteries. When the batteries are depleted due to higher demand or when the production of electricity from the PV modules is not sufficient, then the system supplies the load needs with electricity from the electrical distribution network.

This hybrid type of system not only provides greater security in the delivery of the required electricity to consumers, but by being connected to the electrical grid reduces the need for large capacities of the battery system, extends the life of existing batteries, and reduce the costs for battery maintenance and replacements. If due to some technical problems, there are interruptions of power supply from the electrical grid, during sunny hours, the system enters the mode of operation disconnected from the grid. In this case, the loads will demand and receive energy directly from the PV modules. However, if there is a shortage of energy generated by the PV modules, the equilibrium energy will be extracted from the battery system.

As recapitulation, we can see that the hybrid system could be pre-programmed to optimize the three energy sources, the PV modules, batteries, and electrical grid, and to deliver continuous quality power to the consumers. In some hybrid systems that have critical consumers, the system could be programmed to power these critical consumers first, disconnecting the less important ones. Also, for other non-sunny hours, it can be programmed to draw power from either the grid or the battery, as desired, or even by setting a percentage shared supply from both.

The basic parts of this hybrid system are PV modules, hybrid inverter, and batteries (Figure 1).

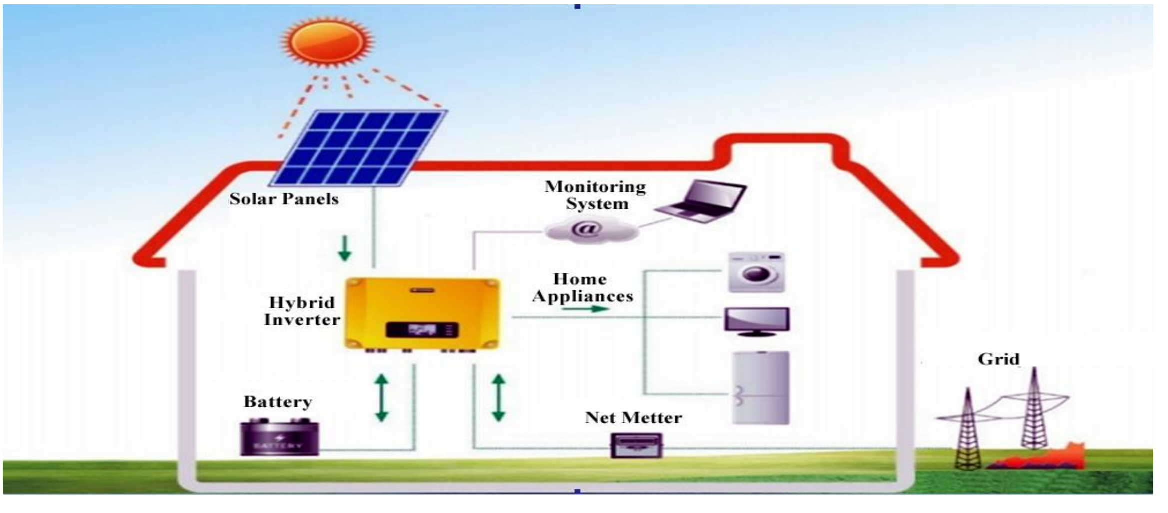


Figure 1. The HPV battery system connected to the power grid.

Nowadays, so-called intelligent hybrid inverters have been used that combine the functions of grid-tied, autonomous inverters, and MPPT controllers. They are real-time programmed to automatically monitoring and analyzing the supply and demand of energy to their customers and to properly synchronize the energy sources in the system and thus contribute to energy savings. The inverters give priority to the use of solar energy and the electrical grid is used only in case of power shortage, and the use of batteries is somewhere in between, thus extending their lifespan. Most modern hybrid inverters have a built-in battery charger and connector that makes it easy to add batteries in the future. There are also hybrid systems with an integrated or suitable battery.

Some of the advantages of hybrid systems are:

- they are cheaper than stand-alone PV systems, and do not need an additional generator and a large battery backup system,
- they provide storage of excess electricity in the battery system which can later cover energy requirements at peak energy demand,
- they provide greater autonomy and security of electricity supply. During periods of insufficient sunlight (non-sunny days, at night, or when the electrical grid becomes unstable), the system will automatically switch to battery power and continue to operate independently of the grid (usually in just a few seconds),
- they have reduced energy demand from the grid and could deliver the excess energy from the system to the electrical grid which would later be compensated or subsidized accordingly.

The major disadvantages of hybrid systems are:

- higher initial costs from network systems due to battery system installation,
- longer payback period of the initial investments, and
- there might be a limit to how many devices can be started simultaneously depending on the type of hybrid inverter and its capabilities [1], [3], [4].

2. Topologies of HPV-battery system connected to the power grid

The HPV battery system itself could be highly versatile, automated, and programmable, providing possibilities for energy sources and energy consumers to be prioritized and optimized accordingly. As already mentioned, in this system in case the energy generated by the PV modules is not sufficient for the supply of consumers, the differential energy can be drawn from the electrical grid or the batteries as previously programmed. If the grid is available, it can be extracted from it or it can be extracted from the battery if the grid is not available. On other occasions, the system can be programmed to take part of the needed energy from the battery and the rest from the electrical grid. In other words, this is a very versatile and very configurable power generation system.

To better understand the characteristics of such a system we will consider a configuration of a simple HPV battery system with an installed power of 1000 W and connected to the power grid and batteries. In total, eight common cases (topologies) are investigated.

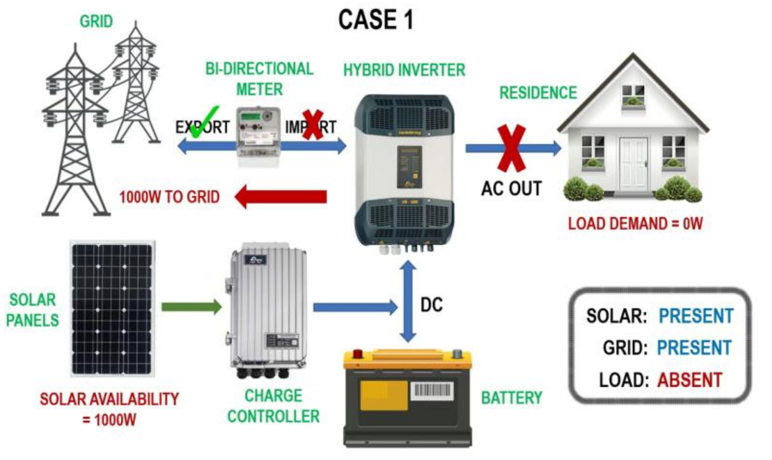


Figure 2. Case #1.

In the first case (Figure 2), we do not have consumers who demand energy, and the entire energy generated from the PV modules in the amount of 1000W is delivered to the electrical grid (as pre-programmed).

Delivered energy to the grid is registered on the bi-directional energy meter.

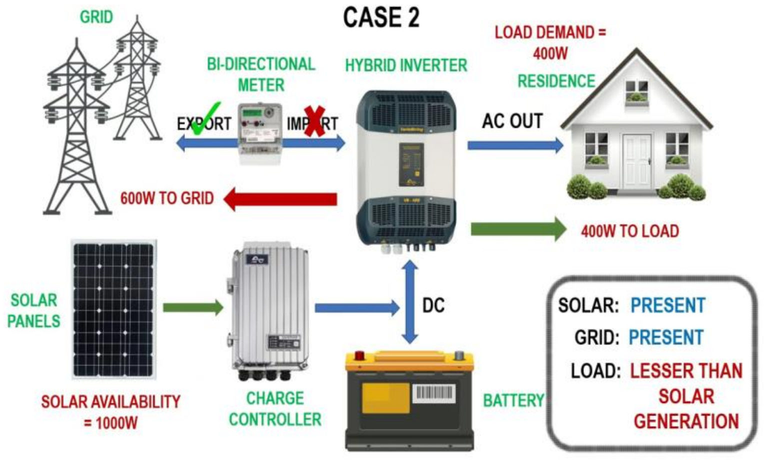


Figure 3. Case #2.

In this case (Figure 3), we have active consumers who demand part of the energy in the amount of 400W generated by the PV modules. Since PV modules generate 1000W, the excess generated energy again is delivered to the electrical grid, however this time in the amount of only the remaining 600W.

Again, delivered energy to the grid is registered on the bi-directional energy meter.

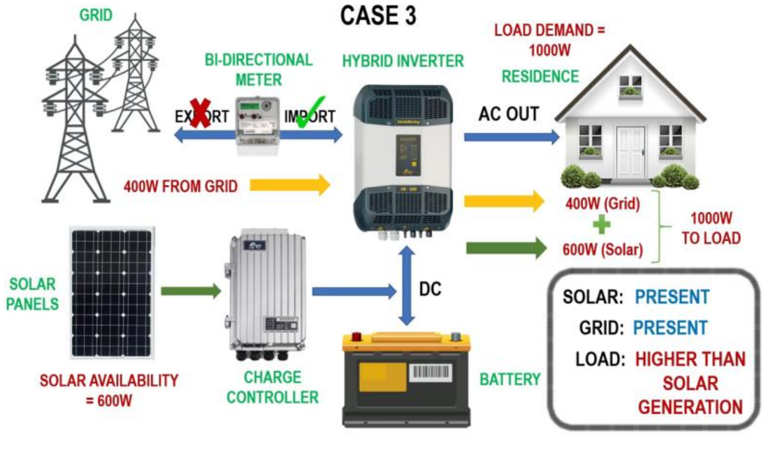


Figure 4. Case #3.

In this case #3 (Figure 4), compared to the previous two cases we have reduced energy production from PV modules, only 600W. Since consumers demand 1000W, more energy than produced by PV modules, the energy disbalance is covered by drawing energy from the electrical grid in the amount of 400W and thus the needs of consumers are met. Again, the bi-directional energy meter is used.

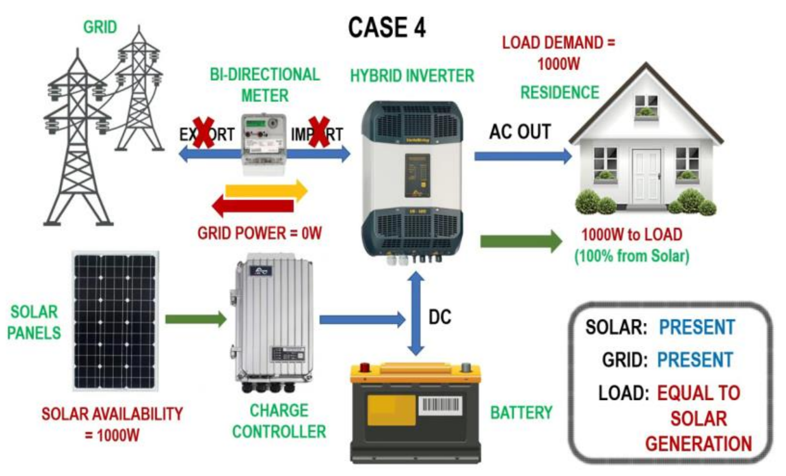


Figure 5. Case #4.

Case #4 (Figure 5) shows a case where the PV modules generate 1000W, and the consumers demand the same amount of energy, 1000W, thus that whole demand energy is completely satisfied with the generated energy from the PV modules. No excess of generated energy exists.

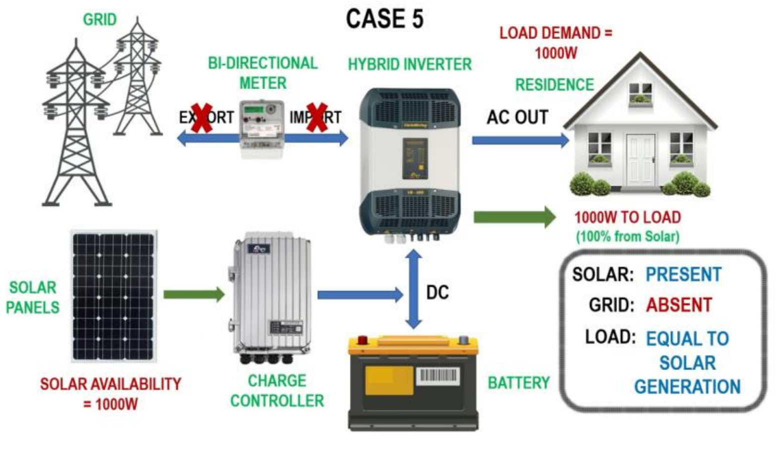


Figure 6. Case #5.

In case #5 (Figure 6), the power supply from the electrical grid due to some technical problems in the grid is fully interrupted, thus the grid in such case is absent. The PV modules generate 1000W, and the consumers' demand hopefully is the same as the PV generation (1000W), thus the existing demand is fully met by the energy from the PV modules.

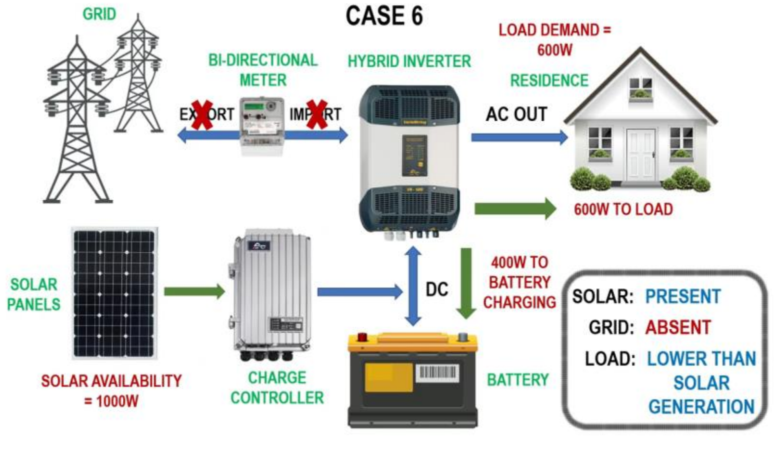
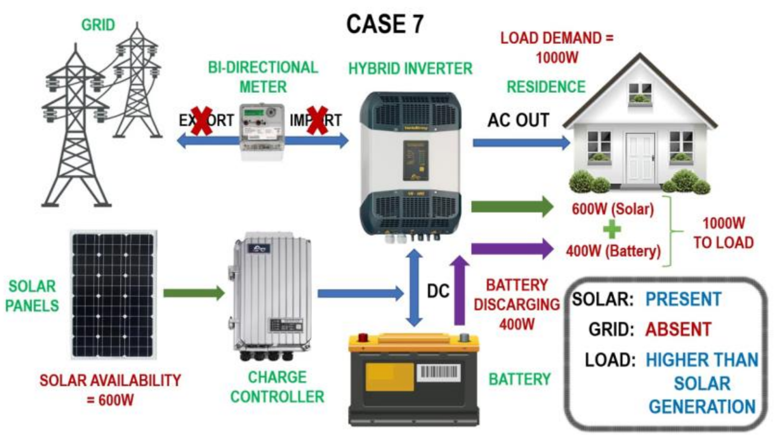


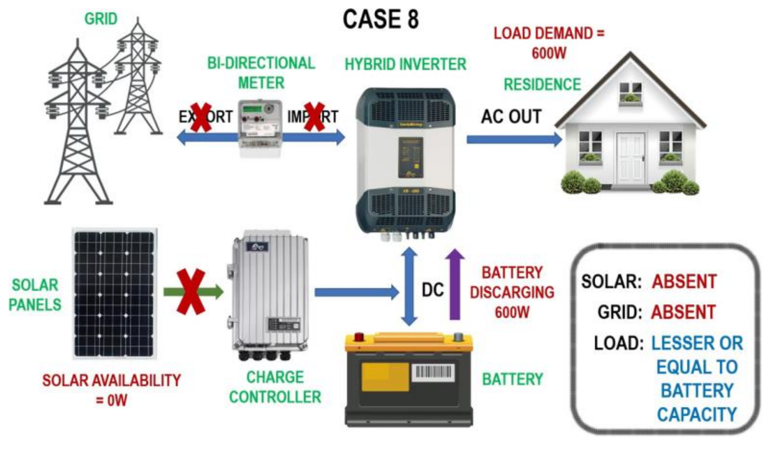
Figure 7. Case #6.

In case #6 (Figure 7) again the power supply from the electrical grid is interrupted due to certain technical reasons, thus the grid is absent. The energy generated by the PV modules (1000W) is partially delivered to meet the needs of consumers which now amounts to 600W and the rest is used to charge the batteries of the battery storage system with the remaining 400W.



Even in this case #7 (Figure 8), the power supply from the electrical grid is absent, i.e. interrupted due to certain technical reasons. In this case, we have reduced energy production from PV modules (600W), and increased energy demand by the consumers (1000W). The difference in power for consumers will be provided by the battery system (400W).

Figure 8. Case #7.



Finally, in case #8 (Figure 9), the power supply from the electrical grid is interrupted due to some technical problems in it and the PV modules do not generate energy (non-sunny hours or nighttime). In this case, the overall energy demand of the consumers will be covered only and if possible by the energy from the battery system (600W).

Figure 9. Case #8.

These eight cases or topologies of the HPV-battery system gave us a simplified pictorial illustration of how the energy could flow in the HPV system made of *„Power Grid – PV modules – Battery – Consumers"could* be pre-programmed to enable reliable and stable power supply under various network and weather conditions [5]. This system also provides bi-directional power measurements between the generation facilities (PV modules), power grid, and the consumers, which from a financial viewpoint could be highly beneficial in case this kind of subsidy is enabled.

Conclusions

Properly sized and controlled photovoltaic systems significantly can increase the quality of energy supply to the consumers who use the energy from those photovoltaic systems. Such a system is the grid-connected hybrid photovoltaic system with battery storage.

This system compared to the stand-alone and on-grid system provides maximum autonomy in terms of power supply and continuous and quality energy supply to the consumers who use the energy generated by its photovoltaic modules. This system at the same time uses solar energy and allows storage of excess generated energy in the battery energy storage system. In cases when batteries are already fully charged, this excess of generated energy is delivered to the electrical grid for other customers. The hybrid system could be pre-programmed to optimize the three energy sources, the PV modules, batteries, and power grid network, enabling continuous and reliable delivery of electric power to connected consumers.

During the process of design and sizing of the PV systems, the performance of the system can be predicted through appropriate simulation software. The most important point during this process is to determine the exact geographical location of the location where the photovoltaic modules would be placed.

The computer program HOMER (Hybrid Optimization Model for Electric Renewables) is used to analyze and simulate several variants and select the optimal solution for designing and operating a hybrid power generation system that uses renewable energy sources. Our next planned activity is the simulation of the operation of a hybrid photovoltaic system in real conditions in the HOMER program package.

References:

[1] Neel Kamal Saini and Vineet Shekher (2011). Grid Connected Hybrid PV / Battery Distributed System, VSRD International Journal of Electrical, Electronics & Comm. Eng. Vol. 1 (7), 420-428

[2] Vlatko Cingoski, "Basics of renewable energy sources", lectures, Faculty of Electrical Engineering, University "Goce Delchev", Shtip, 2018.

[3] https://www.solarreviews.com/blog

[4] https://www.cleanenergyreviews.info/blog/

[5] Topologies of Hybrid Solar PV System, https://www.youtube.com/watch?v=iWnSV5FCyrg