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Controlling Hybrid Renewable Energy Sources for Rural Use

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Abstract

This project aimed at studying the automatic control of more than one renewable energy sources, combined in order to meet the energy needs of an average household in a rural area that the connection to grid is difficult or impossible. On the following pages, a significant part of the renewable energy sources, which are widespread and suitable for the afore-mentioned purpose, are presented, along with innovative alternative energy systems that can replace or supplement existing technologies in areas with different criteria than usual (sunshine, wind supply, etc.). Although this topic is conventionally perceived as a problem of electrical engineering, the combination of different energy sources can be successfully achieved through electronics engineering applications and microprocessor-based programming for the automated control of such a demanding energy system.

Keywords

Renewable Energy Sources, Microprocessor-Based Control, Rural Power Systems

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1. Introduction

Renewable energy is defined as the energy that is produced from the sunlight (solar), wind, biomass, waves and tides, hydroelectric (depends on dams and rainfalls) and geothermal [1]. *Renewable energy sources* (RES) are continuously available as opposed to non-renewable, which will eventually disappear. A simple comparison could be a coal-mine and a forest. While a forest could be eliminated, under the proper management it could be a constant source of energy (biomass energy) compared to a coal-mine that has finite supply ability. Most of the available energy sources of Earth are renewable. For example, RES account for more than 93% of total US energy stocks [2]. In other words, if all non-renewable sources uniformly exhausts then they would represent only 7% of the annually available energy resources, provided that all available RES would have been fully developed. Such a development of RES is essential for dealing with energy security (the uninterrupted energy supply under most circumstances) and especially global warming.

RES energy capacity is still higher than traditional fossil fuels and in theory can easily meet the global energy needs. Although it is not possible to collect all or even a major proportion of the solar energy falling on the planet's surface every year, less than 0.02% of this energy would be enough to meet the current global energy needs. Another example is wind energy. Only 5% of the annually available wind energy could satisfy the current global needs. Most of this wind energy is available in the open oceans. The oceans cover 71% of the planet and winds tend to be stronger in open waters, where there are fewer obstacles [3].

This study focuses on the satisfaction of the energy needs of a resident in a rural area, where the connection to grid is either very difficult or even impossible. It was motivated by

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the case of Greece, the native country of the authors, a land that is 80% mountainous along with 227 inhabited islands [4]. In such an environment, the power supply of remote residences, situated either in inaccessible mountainous areas or in very small islands that are frequently isolated during the winter's sea-storms, is a true engineering, as well as financial, challenge. Of course, such a study can be useful in any case of isolated residences, anywhere in the world. Thus, the most suitable RES for this purpose will be presented, along with their advantages and disadvantages, and some innovative alternative energy systems that can supplement the existing technologies. The combination of more than one RES in a hybrid energy system may maximize the advantages and minimize the disadvantages of the participating systems. Although this topic is conventionally perceived as a problem of electrical engineering, this combination of different energy sources can be successfully achieved through electronics engineering applications and microprocessor-based programming for the automated control of such a demanding system.

2. The Features of RES

This section will deal with these technologies of RES that are currently more prevalent worldwide. The reasons for their wide acceptance are mostly economic and the easy installation of the required equipment. Additionally most of the time, the climate of each country plays an important role to implement these technologies. From the different RES, the most common that can be everywhere available for rural residential use, in an uninterrupted and unsupervised manner (e.g., unlike biomass energy), are the solar and wind power. Their main features will be presented in the two following subsections.

2.1. Solar Power

The interest in *solar power* has been intensified thanks to the photovoltaic effect, ever since the practical possibility of easy, direct and efficient production of electricity by photovoltaic (PV) generators was demonstrated. The advantages of the PV conversion of solar energy to electricity are the following:

- Renewable and freely available energy source.
- Good conversion efficiency.
- Relatively easy manufacturing process of solar cells from raw materials.
- Very long lifetime of solar modules (at least 25 years).
- The solar modules have no moving parts and are virtually free of the need for inspection and maintenance. Even in case of damage, the restoring operation is easy because of the modular form of the PV array.
- The PV conversion does not cause environmental pollution or noise or other nuisance and does not generate waste or waste products.
- It enables independence from centralized electricity distribution networks, making it an affordable supply of energy facilities remote from the main electricity distribution network (grid).
- The PV stations can operate with as little power as available.
- The ratio of power output to the weight of the device is large enough, about 100W per kg, which is an important attribute for roof installations.
- The development of semiconducting materials technology and the continuous reduction of production cost are leading to a gradual reduction of the purchasing cost of PV modules.

The major disadvantage of a PV generator is the failure to continuously produce electricity during the 24 hours of the day. The peak power production is observed between 10.00 and 16.00 hours, while it cannot produce electricity at night, which is a particular problem in countries that are in quite high northern and southern latitudes [5]. Another related disadvantage is the dependence on weather conditions to produce energy, since the energy demand is high in winter (for heating) while the availability of solar energy is minimal. Finally, the conversion of solar energy into electricity in the PV cells cannot be the total solar radiation being received on their surface. A portion of the solar radiation is reflected on the surface of the PV elements and diffuses back to the environment, while from the radiation that penetrates, only a portion contributes to the PV effect.

Nevertheless globally, solar power is the most rapidly growing energy source, representing an annual average growth of 35% over the last years. Japan, Europe, China, the US and India are the major investors in the development of solar power. Progress in technology and economy, together with the demand for solutions to global warming, have led PVs to become the most likely candidate to replace nuclear and fossil fuels [3].

2.2. Wind Power

Generally, the energy generated from the operation of wind is called *wind power* [6]. This action is included in the "clean" sources, as they are usually called, the energy sources that do not emit or cause pollution. The earliest forms of exploitation of wind power were the sails of the first sailing ships and much later the windmills on land. Wind power is nowadays an attractive solution to the power problem. The "fuel" is abundant, decentralized and free. No greenhouse gases are emitted and other pollutants, and the environmental impact is small compared to the power plants from fossil fuels. Also, the economic benefits for an area because of the development of wind industry are remarkable. The kinetic energy of wind is converted into electricity through the *wind generators* or *turbines* (WT) that are electromechanical machines. Depending on the technology that distinguishes them, they are classified in four types:

- The horizontal axis WT, where the blades move around a horizontal axis and the plane of rotation is approximately perpendicular to the direction of the wind flow. A control system is required for turning the WT towards the direction of the wind. This type is regarded as the most conventional one.
- The vertical axis WT, where the blades rotate around a vertical axis perpendicular to the ground and perpendicular to the wind flow. They do not need a control system for turning the WT towards the direction of the wind. It is claimed that they cannot take advantage of the velocity of wind in higher altitude, because of their short profile. Yet, novel versions [7] can be elevated as high as any conventional WT.
- The bladeless WT, which make use of the vorticity effect, are less efficient but much simpler and cheaper than the conventional ones [8, 9].

The funnel-type WT that are designed in at least two versions. Firstly, the Invelox system that can operate in a wide variety of conditions and it is claimed to be up to 600% more efficient than conventional WTs [10]. Secondly, the Perimetric system that is coupled to a Tesla Turbine and can additionally cope with stormy winds and rainfalls [11].

Advances in technology, the increased reliability of WT and their environmental friendliness foreshadow a bright future for wind power globally. In 2011, the total capacity of the installed wind power worldwide grew to around 241,000 MW [12]. The growth rate for the period 2011 to 2015 was predicted to 7% annually, nowadays covering 3% of the total electrical needs of humanity. The European Union is leading the development of new WTs that will contribute to an energy future with less dependence on fossil fuels.

3. Hybrid RES Systems for Rural Use

The purpose of using various RES in a hybrid system is a solution that aims at stabilizing the power in a facility, which is entirely powered by them and not by the stable power grid. As mentioned above, RES depend on the weather conditions of each area, so each of them is suitable for a different time of day or year, because their performance will vary depending on the seasonal weather changes. For example, it was previously presented that the PVs efficiency is minimal in winter (see subsection *2.1 Solar Power*), while the WT efficiency is maximum at the same season [13]. Thus by combining the two systems, we may achieve a more stable result in potential energy and a more reliable method of energy production, because each system counterbalances the daily or seasonal disadvantages of the other. The hybrid RES systems are much more efficient, economical and environmentally friendly. Therefore, they are increasingly becoming more popular.

3.1. Popular Hybrid RES Systems

Two of the most popular hybrid RES systems are the combinations of:

- biomass fuel cells with WTs and
- PVs with WTs that was mentioned previously.

The first hybrid system is a combination of 60% biomass energy, 20% of wind energy and energy stored in fuel cells that is utilized mostly by farmers in their irrigation systems. The biomass module cannot be regarded as a continuous and unsupervised one, because it requires a constant resupply of biofuels. The second hybrid system combines PV panels and usually one WT, capable of producing energy to power a house or even a small plant. Each module is attached to a common battery bank, which in turn is connected to an inverter that transforms the direct current (DC) of the batteries to an alternate current (AC) output, for the proper function of the household appliances. We will focus our study on the second hybrid system because it can provide electric power to a residence in a continuous and unsupervised manner.

The average residence requires an electricity power installation of about 8 kW capacity. Considering that the average cost of solar and wind power generation equipment is 1.12 USD per Watt [14, 15], a hybrid system for a rural residence costs about 9,000 USD, excluding the very expensive storage, control and transforming devices. Such a system though can be also supplemented by an innovative alternative energy production system, as a third module, the *Pyramidal Electric Transducer* [16, 17].

3.2. The Pyramidal Electric Transducer

The Pyramidal Electric Transducer (PET), instead of converting energy from mechanical to electrical, collects electrostatic energy from the atmosphere. The atmospheric electricity is manifested as a build-up of electrostatic energy, a phenomenon that constantly electrifies our environment. In the global atmospheric electro-circuit, the Earth's surface is negatively charged while the atmosphere is positively charged. The differential voltage between the Earth's surface and the ionosphere is estimated that is maintained by the electrical activity of the troposphere and the solar wind magnetosphere.

This particular collector (PET) has the shape of a pyramid and was demonstrated that in the dimensions of the Great Pyramid of Giza, its proportions express both the fundamental proportions of a sinusoidal signal and the proportions of Fibonacci numbers. The funnel-shaped antennas of the pyramid are suitable for detecting small pulse waveforms and for the excitation of the atmospheric electrostatic discharge. It was found that a pyramidal antenna, installed in a scaled down model of the Great Pyramid of Giza, can be connected with the atmosphere and transfer the force of electrostatic charges in an innovative protruding shaped resonance circuit, which converts the random electric discharges in a series of regular exponential-decay sinusoidal waveforms. This electrostatic discharge can be converted into an alternating voltage of prescribed frequency by the relevant circuitry inside the pyramid. Thus, the PET can become a renewable source of electricity by harnessing the power activity of the atmosphere.

From the available information regarding the PET, we know that the surface of the base of the pyramid is proportional to the produced power in Watt. Suppose we want to construct a pyramidal copper-covered roof on a house of 100 m^2 (square meters) surface (i.e., the pyramid's base area), while the other dimensions of the roof are proportional to the dimensions of the Great Pyramid of Giza (e.g., the overall height of the roof is 6.363 meters). Then, such a PET-roof would produce around 3 kW of electric power [18]. The roof on a house is very useful since it has twice as many economic benefits to the cooling and heating of it. Therefore, within the general construction cost of a roof, if the materials of the construction include copper as an outer layer instead of tiles, then this construction can become a PET that will contribute to the power supply of the household. However, it is still considered an expensive and difficult solution to combine two or three RES in a hybrid system.

4. Technical Solutions for Hybrid RES Systems

The basic modules of a usual hybrid RES system include PV and WT energy sources. As suggested in this study, a PET can be also combined. The energy produced by these RES is combined and sent to a battery bank, which is the storage unit that maintains the energy produced by the RES, because the direct supply of energy from each different RES to the final load is not reliable. The battery bank must be under the supervision of a central charge controller that can be connected to a different controller for every RES module (i.e., PV, WT and PET). The DC of the battery bank is then converted to usable energy (AC at 220-240V/50Hz or 110-120V/60Hz) by using an *inverter*, which is imperative to transform electricity into a more useful form (Fig. 1).

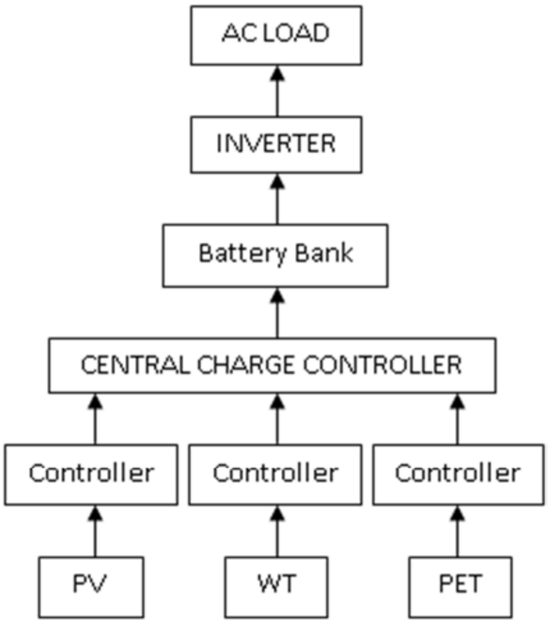

Figure 1. The main diagram of a hybrid RES system.

4.1. Inverters

The inverter is an electronic circuit that converts the DC into AC. It performs the reverse process of a rectifier, as a high-power electronic oscillator. Inverters can be either interconnected to the grid or autonomous (off-grid) that is the herein case of rural use. Their main distinction is between *pure sine wave* (PSW) and *modified sine wave* (MSW) inverters [19].

A PSW inverter generates nearly perfect sine waves (<3% total harmonic distortion) that are substantially the same as the ones of the grid. It is therefore compatible with all AC electronic devices. This is the type used in interconnected systems. Their design is more complex and they cost more per unit of energy, but they achieve higher levels of efficiency and generally have a longer operating life [20]. The output of a MSW inverter is similar to a square wave, where the output is driven to zero volts for a period of time before changing from positive to negative [21]. It is a simple structure at low cost (about 0.10 USD per Watt) and is compatible with most electronic devices, except for particularly sensitive or specific ones like laser printers, fluorescent lighting and sound equipment. Most AC machines will work with this power supply although at a reduced performance of about 20%.

Two alternative solutions to the expensive PSW inverter can be applied, providing electricity of the same high quality. The first one is implemented by the cooperation of an electric motor with an electric generator in order to achieve the same purpose [22]. The electric motor of a somewhat higher output power (to cope with power losses) is connected to the battery bank and coupled to the electric generator that supplies the energy to the final load (household appliances). This pair has increased size and more noise but reduced final cost [23]. The second alternative is implemented by connecting an RLC filter (or a series of them) to the output of a MSW inverter [24]. The result of this pair has been studied by using the Matlab simulation software [25]. As shown below (Fig. 2), the sine wave sequence (middle one), resulting from the conversion of the square wave sequence (top one) passing through the filter, is almost identical to the perfect sine wave sequence (bottom one). Thus, the output voltage is almost the same as that of the current supplied by the grid [26].

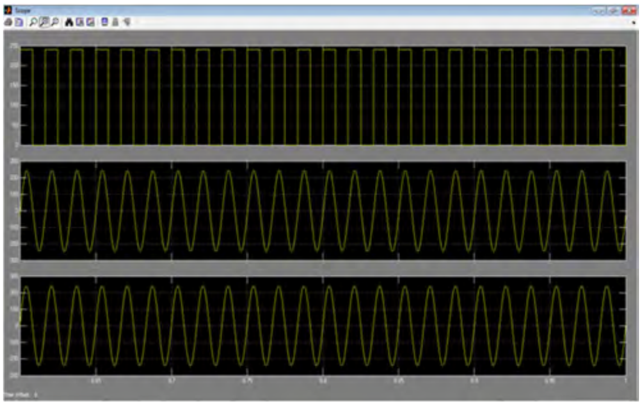

Figure 2. The Matlab simulation of the wave sequences conversion through a filter.

Nevertheless, the most vulnerable module of a hybrid RES system, having the shortest operational life, is the battery bank (Fig. 1). A break down here will interrupt the power supply of the entire system. A technical solution for increased energy security is presented in the next subsection.

4.2. Microprocessor-Based Control of Battery Banks

An alternative technical solution for increased energy security is to double the battery banks, which is a practice already implemented in some remote installations, where the backup battery bank is activated only in case of an emergency. In the herein experiment, the two battery banks are both utilized in normal function, after an original idea of John Bedini and Robert Lee [27]. In the *dual battery bank storage* (DBBS), each battery bank is in *charge-discharge* operation successively. This arrangement can have several advantages for an uninterrupted power supply of a rural residence. During the charging period of one battery bank on the installed RES system, the other bank supplies the AC load through the inverter, if sufficiently charged. By using a suitable controller to monitor the charging amount of each battery bank (via a voltmeter), the system uses the proper bank to supply the load.

A similar simpler controlling process of a DBBS, where the battery banks swap their roles after a fixed period, is described in Fig. 3. The controller consists of two sets of four terminals each, {A-D} & {1-4}, that are connected to the two battery banks (1st BB; 2nd BB), the central charge controller (CCC) and the inverter. At the depicted phase:

- terminal {A} is interconnected to {D} and terminal {1} is interconnected to {4}, thus allowing to the 2nd BB to be in *discharging mode* by supplying the inverter (red route);
- terminal {B} is interconnected to {C} and terminal {2} is interconnected to {3}, thus allowing to the 1st BB to be charged (*charging mode*) by the RES (blue route).

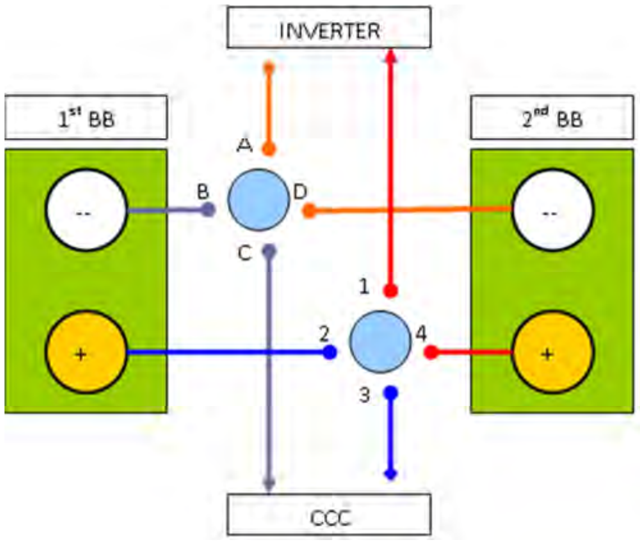

Figure 3. A DBBS with a fixed-period controlling process.

The mode of the two BBs is swapped when terminals {A,B}, {C,D}, {1,2} and {3,4} are interconnected respectively [28].

Although the switching device of the DBBS control (Fig. 3) can be implemented by mechanical means, a switching circuit has been implemented by power electronics (Fig. 4) in a small-scale simulation [29]. On the left of Fig. 4, we can see the {A-D} set of terminals, while on the right is the {1-4} set of the switching device. The terminals are interconnected via power transistors (MOSFETs, IGBTs, etc.) that can be either in *conduction status* (green lines) or not (red lines). When an intermediate between two terminals transistor is in conduction status, then the respective terminals are interconnected, otherwise they are not. The group of terminals that are interconnected in one phase (i.e., when the 1st BB is in discharging mode and the 2nd BB is in charging mode, as depicted in Fig. 4) they are not interconnected in the next phase. The conduction status can be determined by microprocessor-based control. In this particular experiment, a simple Regulating Pulse Width Modulator of the SG1524 series [30] has been used for this purpose (Fig. 4: Oscillator), but more sophisticated electronic components can be utilized, according to the scale and scope of the desired application.

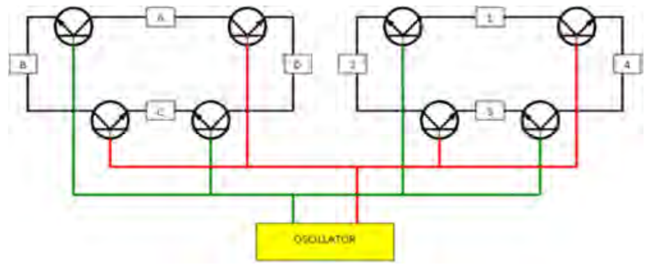

Figure 4. DBBS switching by power electronics.

5. Summary & Conclusions

The RES, since they are continuously available compared to non-renewable that will be eventually eliminated, gain more and more supporters in the field of energy security. Our planet has finite stocks of fossil fuels and several consequences of contamination in our environment, bringing RES nowadays in the spotlight. Even with the claims that RES are insufficient to meet our energy needs due to low energy production, today two or more RES can be coupled in a hybrid system, which is electronically controlled through microprocessor-based programming, by combining solar, wind and electrostatic power for the required supply of a house or even a larger installation. This control regards the storage of energy that is one of the biggest problems in the field of energy production. However, with the cooperation of two battery banks, the desired effect of energy storage can be achieved, with less wear and tear of the equipment, and provide adequate and suitable final power supply to a rural house, in an uninterrupted and unsupervised manner. The produced DC electricity (stored in battery banks) cannot be used as such for powering a rural house, where AC is used for our household appliances. Thus, inverters (or other more conventional ways) have to be used for having the suitable type of electricity. This study indicated that a cost-effective solution can be the RLC filters. With simple and comparatively low-cost solutions, the energy security can be achieved with the required AC of a rural house in remote or isolated areas.

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