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Sustainable electricity generation by solar pv/diesel hybrid system without storage for off grids areas

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Abstract. Access to energy is known as a key issue for poverty reduction. The electrification rate of sub Saharan countries is one of the lowest among the developing countries. However this part of the world has natural energy resources that could help raising its access to energy, then its economic development. An original "flexy energy" concept of hybrid solar pv/diesel/biofuel power plant, without battery storage, is developed in order to not only make access to energy possible for rural and peri-urban populations in Africa (by reducing the electricity generation cost) but also to make the electricity production sustainable in these areas. Some experimental results conducted on this concept prototype show that the sizing of a pv/diesel hybrid system by taking into account the solar radiation and the load/demand profile of a typical area may lead the diesel generator to operate near its optimal point (70-90 % of its nominal power). Results also show that for a reliability of a PV/diesel hybrid system, the rated power of the diesel generator should be equal to the peak load. By the way, it has been verified through this study that the functioning of a pv/Diesel hybrid system is efficient for higher load and higher solar radiation.

1. Introduction

The electrification rate in sub-saharan Africa is lower than in any other region of the world. Indeed, more than 70 % of the populations of this region are excluded from the benefits linked to the access of electricity. The situation is more catastrophic in rural areas where less than 12% of the populations have access to electricity [1]. In order to contribute to the increasing of the electrification rate in this region, an original concept called "flexy energy", which consists of hybrid solar PV/diesel/biofuel power plant without battery storage, has been developed by Azoumah et al [2]. To assess the technical and economical feasibility of this concept, a PV/diesel hybrid system without storage has been set up on the site of the International Institute for Water and Environmental Engineering (2iE) at Kamboinsé (12°22' N and 1°31'W), located at fifteen kilometers in North of Ouagadougou, capital of Burkina Faso. This prototype consists of a 9.2 kW diesel generator coupled with a PV array of 2.85 kW*p* and an inverter rated at 3.3 kW. The peak Watt (W*p*) is an amount of electrical power that a system is expected to deliver in standard test conditions, STC (AM 1.5, solar cell operating temperature of 25°C

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and solar radiation of 1000W/m²); the air mass (AM) is the ratio of the mass of the atmosphere through which the beam radiation passes to the mass of the mass it would pass if the sun were at the zenith.

The concern of this paper is to present the technical performances experimentally obtained for the hybrid system under various operating conditions. Four fixed load/demand profiles corresponding to different percentages of the nominal capacity of the diesel generator have been experimented for different solar radiations and consequently various PV contributions. The obtained raw and calculated performances are presented and discussed in this paper. Also, a comparative analysis for three different systems (diesel and solar PV generators only, and hybrid solar pv/diesel system) for powering a same load profile has been done.

2. Experimental

2.1. *Experimental set up*

Hybrid systems can be broadly classified in series hybrid, switched hybrid and parallel hybrid configurations [3]. The present prototype has a parallel hybrid configuration (figure 1). In this scheme, the PV system is connected to the diesel generator by the mean of a DC-AC converter or inverter. The PV and the diesel generators supply a portion of the load demand directly (since they are operating in parallel).

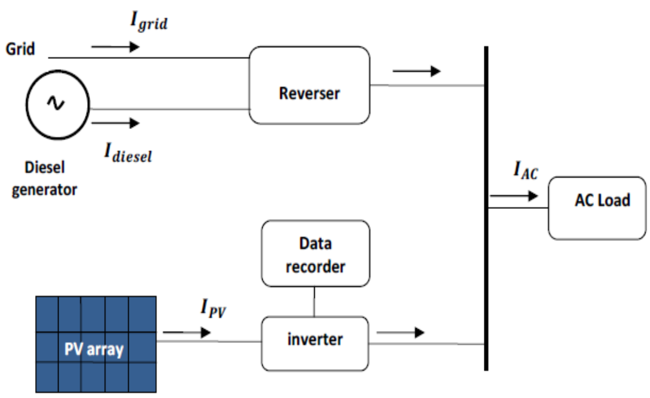

Figure 1. Prototype design

The PV system is composed of 15 modules HIT (Heterojunction with Intrinsic Thin layer), each rated at 190 W*p*, totalling 2.85 kW*p* DC at Standard Testing Conditions. The PV array covers an area of about 18 m² with PV modules distributed in a parallel/series configuration of three strings connected to one inverter rated at 3.3 kW. The diesel generator rated power is 9.2 kW (11.5 kVA) at 1500 rpm.

2.2. *Results and discussion*

In this section, the behavior of a typical hybrid PV/diesel system without storage which characteristics have been presented in the previous sections is studied. The contribution of the PV and the diesel generators, the specific consumption of the diesel generator for a given load (L) profile have been assessed. For four days, we have considered four constant load profiles (3.7 kW, 5.7 kW, 7.6 kW and 9.7 kW) corresponding respectively to 40%, 62%, 82% and 105% of the diesel generator nominal power.

The behaviors of the PV and the diesel generators in the hybrid system are interdependent. It can be observed from fig. 2 to fig. 5 that for the loads in the order mentioned above, the specific fuel consumption of the diesel generator ranges respectively from: 0.45 to 0.51 l/kWh (see fig.2), 0.35 to 0.41 l/kWh (see fig.3), 0.33 to 0.36 l/kWh (see fig.4) and 0.33 to 0.34 l/kWh (see fig.5).

These results show that for small loads (less than 62% of the rated power of the DG), the contribution of the PV generator (P_{AC} / L) which ranges from 4 to 38% for a load values of 3.7 kW and 5.7 kW does not enable an optimal functioning of the diesel generator. In fact, as mentioned by Ashari et al [4] and also verified by results obtained in the present investigation[5], the maximum fuel efficiency of a diesel generator is about 0.33 l/kW, but for these two rated loads, the specific fuel consumptions are far from this optimal value. This is due to the fact that these loads are already far from the optimal functioning point of the diesel generator and therefore the PV generator contributes rather to decrease the performance of the engine.

However, for high loads (see fig. 4 and fig.5), the contribution of the PV array (which ranges from 1.5% to 33% for a load value representing 82 % of the diesel generator nominal power and from 2.5 % to 22% for a load value representing 105 % of the diesel generator nominal value) does not affect considerably the performance of the diesel engine.

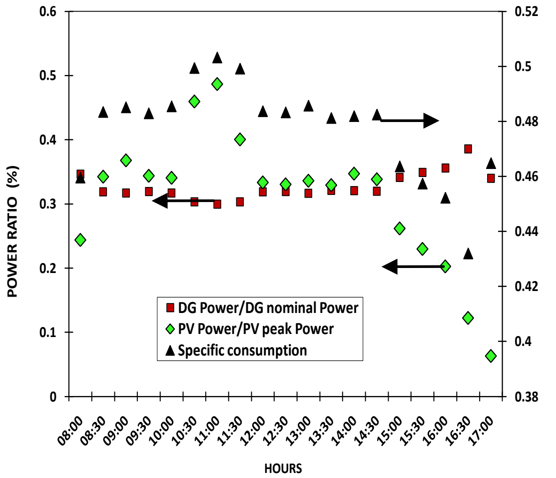

Figure 2. Behaviour of the system for a load equal to 40% of the diesel generator rated power

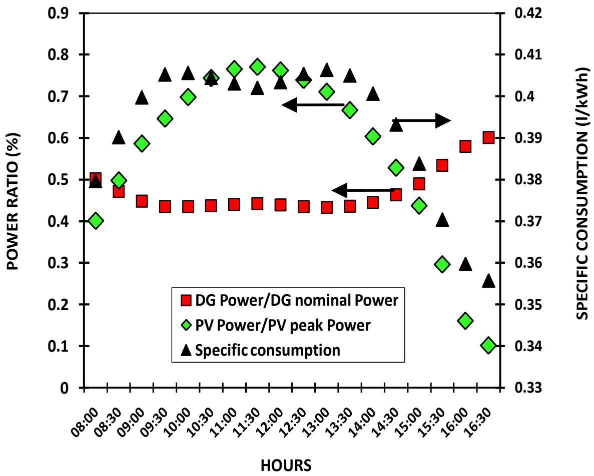

Figure 3. Behaviour of the system for a load equal to 62% of the diesel generator rated power

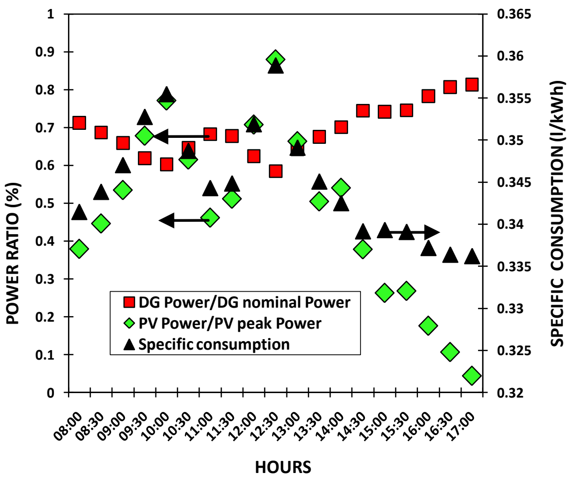

Figure 4. Behaviour of the system for a load equal to 82% of the diesel generator rated power

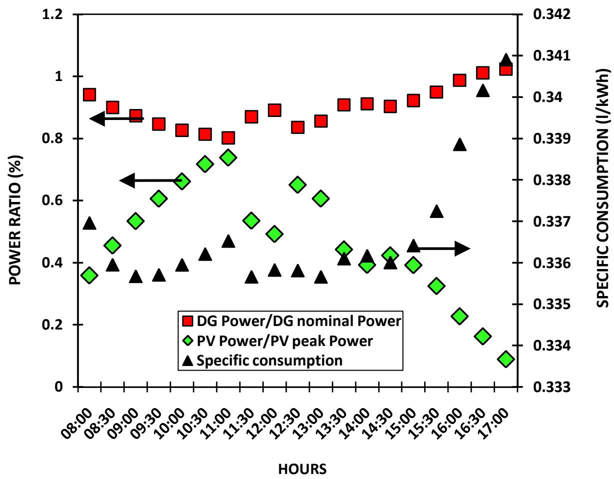

Figure 5. Behaviour of the system for a load equal to 105% of the diesel generator rated power

As a matter of fact, for these loads, the values of the specific fuel consumption vary from 0.33 to 0.36 l/kWh what is close to the optimal functioning point of the diesel generator. As the specific fuel consumption and then the operation cost of the diesel generator increases considerably when the hybrid system operates below the load values representing less than 62% of the diesel generator rated power, the sizing of such a system must be done so that the diesel generator operates near its optimal point (70-90 % of its nominal power).

3. Advantages of using hybrid systems: comparative analysis for three different systems (diesel generator only, solar PV generator only and hybrid solar PV/diesel) for powering a same load profile [2]

3.1. *Economic analysis*

To point out the economic advantages of hybrid systems for remote areas, a comparative analysis is conducted for three types of power generators (DG only, PV generator only and hybrid solar PV/diesel) for powering a same load. For this study a typical daily load of the Sabou village in Burkina Faso is considered (see figure 6). This village has 45,000 inhabitants, thus about 6429 households (if considering seven persons per household).

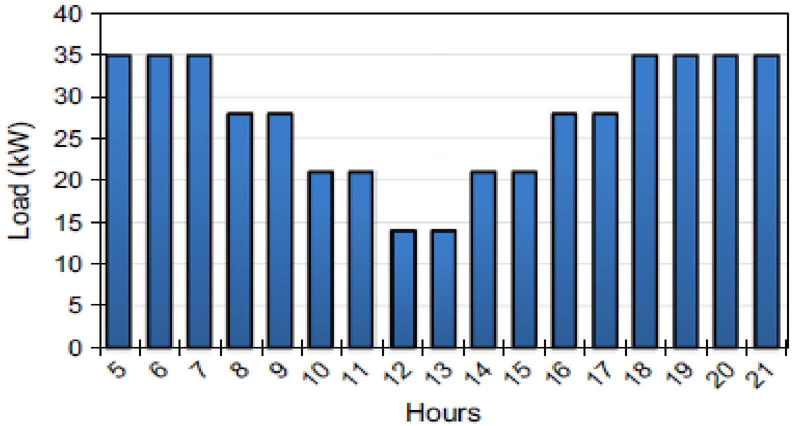

Figure 6. Typical daily load profile of the Sabou village in Burkina Faso.

The economic analysis made in this section is based on the use of the life cycle cost (LCC) method. The life cycle cost is an economic assessment of the cost for a number of alternatives by taking into account all significant costs over the lifetime of each alternative, adding each option's costs for every year and discounting them back to a common base. These costs can be categorized into two types: (i) recurring cost (operation and maintenance costs for the diesel generator, maintenance costs for the PV generator and batteries) and (ii) non-recurring cost (batteries and diesel generator replacement costs).

The life cycle cost is expressed as follows:

$$LCC = C + PW_R + PW_{NR} \tag{1}$$

where C is the initial cost PW_R is the present worth recurring costs and PW_{NR} is the present worth non- recurring costs.

The data of the following table 1 are used for the calculations.

After calculation, one obtained that for the same energy demand estimated at 3,423,700 kWh over 20 years, hybrid solar PV/diesel system Life cycle cost (LCC=983,865 Euros) is lower than the PV generator only (LCC=992,000 Euros) which is at its turn lower than the DG only (LCC=996,000 Euros).

It is important to point out that the hybrid system considered here is not the optimal one in terms of configuration, the load management, and even the whole system management. By considering all these aspects, it is no doubt that the benefits will be more important and it is what we intend to demonstrate through the ‘‘flexy-energy’’ concept [2] .

Table 1[a]. Costing data considered in the present study

	Diesel generator system (38.5 kW)	**PV**	**Battery**
Initial cost	15,400 €	700€/kWp	0.07€/Wh
Annual operation cost	0.9€/l of fuel	0	0
Annual maintenance cost	0.18€*RT	3% of annualized initial cost	15% of annualized initial cost
Salvage value	10% of the diesel generator initial cost	10% of the PV generator initial cost	0
Replacement cost	Equal to the initial cost	0	Equal to the initial cost
Life span (years)	10	20	5
Interest rate, i (%)	8	8	8
Escalation rate, e (%)	4	4	4

[a] In the table 1, RT is the running time of the diesel generator.

3.2. *Environmental analysis*

3.2.1. *Environmental evaluation of the DG only*. Petroleum-based products are one of the main causes of anthropogenic carbon dioxide (CO_2) emissions to the atmosphere. As a matter of fact, the combustion of each liter of diesel produced 2.7 kg of CO_2. During the life cycle of the diesel generator, 1, 244, 286.28 L of diesel oil will be consumed; this will lead to about 3360 tons of CO_2 released in the nature.

3.2.2. *Environmental evaluation of PV generator only*. The mayor drawback with this scenario is the recycling of batteries at the end of their lifetime. In fact, there is no policy concerning recycling of batteries in sub-Saharan African region and this particular aspect represents a considerable environmental concern. In the case studied, over the lifetime of the system, for a total capacity of 41,037.5 Ah, it is 411 batteries of 100 Ah (12 V) which will be probably thrown in the nature.

3.2.3. *Environmental evaluation of PV/diesel hybrid system*. By considering in the first time that the diesel generator in this scenario is fueled by fossil fuels, about 2915 tons of CO_2 are released in the nature. Therefore, it is 445 tons of CO_2 emission which is saved over the life cycle of the hybrid system compared to the diesel generator system only.

From the present case studied, one can conclude on the environmental aspect that, the hybrid system enabled to save CO_2 emission of about 445 tons compared to the diesel generator system only. Furthermore, for the PV system only, more than 411 batteries of 100 Ah (12 V) will be thrown in the nature against zero battery released when considering the hybrid system scenario.

4. Conclusion

First, this paper presents the experimental results of a hybrid pv/diesel system without storage. These results are very useful for the design optimization and the reliability enhancement of PV/Diesel hybrid systems. Second, the economical and environmental advantages of the hybrid system compared to Diesel and PV systems only are displayed and show clearly that the PV/diesel hybrid systems can be an appropriate technological solution for the electrification of remote areas.

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