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Development of thermoelectric generators for electrification of isolated rural homes

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ABSTRACT

This work presents the experimental development of the first two prototypes of thermoelectric generators intended for initial electrification of rural isolated homes. The microcontroller system designed for these devices is oriented to develop a ‘‘plug and play’’ generator that is able to work on firewood home stoves without specialized supervision.

1. Introduction

At present, photovoltaic (PV) solar systems are mostly selected to provide electric power to isolated rural homes. In comparison to other renewable technologies, the principal advantage of PV systems is the universality of the solar resource, its simple operation and low maintenance (O&M costs). On the other hand, high costs limit the massive application of PV panels in low-income homes. The cost of PV panels are about 6000 $/kW, but the costs for complete electrical systems can go over 100,000 $/kW.

There are several concomitant causes for this apparent low performance of PVs [1,2].

1. Worldwide PV load factors are low (down to 20%) and lowest in winter, when the demand is highest.
2. The concentration of the PV generation is during the diurnal cycle; meanwhile the home demand is mainly nocturnal.
3. The high cost of batteries (300 $/kWh) and their short life (≈800 cycles). For example, a deep-cycle Trojan L16RE-A battery (6 V, 325 Ah) can be bought at about $360, that is 185 $/kW. But it could be discharged down to 20% of its nominal charge, and also efficiencies of around 80% should be considered for discharge periods of 5 h. This gives an effective cost of approximately 300 $/kW delivered.
4. The random characteristic of this resource that requires larger batteries when it is applied to continuous loads.

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Thus, for example, if a certain constant power is required during 24 h and the PV load factor is about 10%, the installed PV power must be multiplied by 10. However, considering the most unfavorable (winter) conditions, the previous values could easily be twice. Thus, multiplying the installed PV power by 20, a specific cost of about 120,000 USD/kW is achieved, considering only the PV modules. This very high cost can explain the generalized choice of commercial thermoelectric generators (TE) for cathodic protection of oil pipelines. Recently some hybrid PV-hydrogen system are been proposed for overcome these PV drawbacks related to stand-alone applications, but at present the economical competitiveness of these schemes are worse than the isolated PV options [3,4].

TE generators, which can transform heat directly into DC electricity, have been applied worldwide for generation of small continuous loads in remote areas in the oil industry for at least 40 years [5], and recently in self-powered hydrogen sensors [6]. Commercial TE generators are manufactured by Global Thermoelectric almost exclusively for this niche market, having sold more than 20,000 units at approximately 100,000 $/kW per unit [7]. Nonetheless, this price range is not affordable for the isolated homes market, especially in developing countries.

Nevertheless, in recent years TEs have arisen as a feasible option within the portfolio of new sustainable energies [8–13], due to the irruption in the open market of independent TE modules manufacturers from the US, such as Hi-Z and Tellurex, and from China as well. Being that the specific costs of American TE panels are similar to those of PV's (6000 $/kW), their main advantage is the possibility of generating power continuously using a moderate temperature heat source. This last condition is often available in rural homes, where a firewood stove is usually used for heating and cooking. Prototypes of low cost stove-top [9–12] and chimney [13] TE generators are being successfully tested.

Chinese manufacturers of TE panels have recently produced marked cost reductions, as low as 1500 $/kW [13]. This cost reduction was a result of an increase in production using the same technology (BiTe) of American manufacturers. The significant cost reduction of TE modules shows that this technology has not completed its development curve yet; and, further cost reductions could be expected in the future.

In this work the technological development of two different TE generators is presented. They are oriented to facilitate their utilization by non-technicians users, becoming a plug and play option for the generation of small-scale electric power generators.

1.1. *Thermoelectric power*

The thermoelectric effect was first found by Seebeck in 1822. But until the discovery of semiconductors the power generated was neglected; renewed interest began around the middle of the 20th century.

It can be shown that the power produced by a thermoelectric module to be approximately given by [14]

$$W = 2\frac{m}{(1+m)^2}\frac{\alpha^2}{\rho}N\frac{A}{L}\Delta T^2 \tag{1}$$

Fig. 1 – Full assembly of the experimental set-up.

where $\Delta T = T_H - T_L$ is the temperature difference between the hot-side temperature and the cold-side of the thermoelectric module of area A, length L and electrical resistivity ρ, α is the thermoelectric material Seebeck coefficient, N the number of couples in the module, and m the electrical load ratio [15]. It could be assumed that α and ρ are not temperature dependent. Hence, Eq. (1) demonstrates an obvious optimization that occurs at $m = 1$ (matched load). In practice one would operate just above $m = 1$, because it is known that resistivity tends to increase with operation. Also Eq. (1) shows the strong parabolic dependence of power on the across-module temperature difference. For these reasons, the overall efficiency of any thermoelectric generator is markedly relates to the power managing provided, which should considerer the T_H and T_L under every operational state. So, smart temperature controlling devices are strong recommended for non-controlled thermal sources, like firewood stoves are, in order to obtain better generator performances.

2. Analysis of experimental set-up

An experimental set-up, which is depicted in Fig. 1, was assembled in the laboratory in order to characterize two TE modules, from Hi-Z and Tellurex. The assembly consists of a great heat drain (aluminum tank with 25 l of water), and on one side is assembled one or two TE modules compressed by a mechanical system between two aluminum plates, which allow equalizing the temperatures in all the points of each side. On the front plate, it is placed an electric heater as source of heat, which is properly thermally protected, in such a way that losses of heat to the outside are diminished. In this way, practically all the power provided crosses almost uniformly the thermoelectric assembly, facilitating to calculate its efficiency, defined as the quotient between the generated electric power and the provided thermal power. The power exchanged with the thermoelectric generator is controlled through an auto-transformer and is measured with a DC Amp current clip (using the Hall Effect).

The thermoelectric module is electrically connected to an ohmic load composed of an adjustable power resistance, and

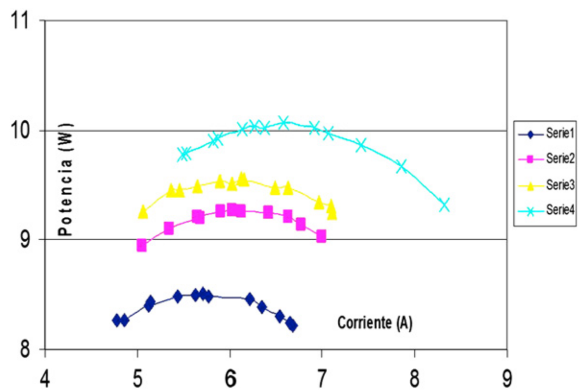

Fig. 2 – Hi-Z TE output power versus current for various Th and Tc; Series N°1: 260/60 °C, N°2: 240/40 °C, N°3: 230/30 °C and N°4: 220/20 °C.

the generated voltage and current are measured. The temperatures imposed on both sides of the thermoelectric module are measured by means of thermocouples placed on the aluminum plates. The temperature of the cold source is manually controlled by regulating the flow of cold water that is redrawn from a faucet. The relative large volume of water employed allows obtaining a high thermal inertia (variations of around 0.5 °C/min) that simplifies this control, being at the same time appropriate the proposed system.

In the case of the Hi-Z modules, ceramic buffers must be placed (provided by the same manufacturer) between both sides of the module and the aluminum conductive plate. These buffers introduce a thermal contact resistance on both faces, which should be considered when the actual temperature of each side of the module is estimated from the values measured on the aluminum plates. Approximate values for these contact resistances are available in the literature, and range from 0.1 to 0.3 °C/W [10]. The thermal resistance of the module (R_{te}) is calculated from its conductivity k_{te} and thickness L_{te} (provided by the manufacturer) as: $R_{te} = L_{te}/k_{te}$; the temperature gap in the module (ΔT_{te}) is obtained then as $\Delta T_{te} = q^* R_{te}$. From this, the temperature gap in each global interface may be estimated, assuming the symmetry among the assemblies (module + buffer + Aluminum plate) in both faces, as half of the difference among the temperature gap measured between both aluminum plates and the temperature gap in the module.

3. Analysis of experimental results

Maintaining roughly constant the temperature of the source and the drain of heat, the power generated was measured as a function of the resistance of the load imposed, always operating under steady-state conditions. The results obtained models qualitatively the behavior claimed by the manufacturer, but with a significantly smaller power (almost 1/3) of the one declared by the manufacturer. Consulted this, it was suggested to improve the mechanical assembly, in such a way of assuring that the surfaces in contact have uniform pressures in all their points. Since the module expands when it warms, and contracts when it cools down, it is necessary to mount a system of springs that allow assuring an almost uniform contact pressure, being preferable using only a single axis of central compression. This system lastly was not adopted by limitations of time, but the contact pressure during operation was verified, using a torque meter in order to adjust the pressure exercised by the two lateral guides of the mechanical system.

It is observed that the module gives the maximum power when the load resistance equals to the value of the TE internal resistance, calculated from the voltage and current generated.

The effect of the variation of the operating temperatures was studied (maintaining constant the temperature gap between both sides of the TE module in 200 °C). Thus, Fig. 2 was build, in which it is clearly appreciated that the smaller the average temperature $(T_h + T_c)/2$ is, the bigger the power generated, following an inversely proportional relationship, just as was predicted in the theory [1,7].

In order to study the effect of the contact pressure (translated as a smaller thermal contact resistance to more pressure, in the thermal modeling of the TE), curves of Fig. 2 was repeated for different contact pressures, observing variations of almost 100% in the generated power. In this way, it was reached a maximum power of 12.3 W, for a temperature gap of 200 °C, which is still 35% below of the one claimed by the manufacturer (19 W). Since the mechanical assembly implemented in the laboratory did not allow assuring the uniformity of the contact pressure, it is not clear if the efficiency of Hi-Z modules was harmed by this reason. Anyway, comparing with the simple assembly of the Tellurex modules, which do not require more than modest contact pressures, and that they demonstrated an analogous efficiency to the nominal one, these thermoelectric modules were preferred for the final prototype. Another advantage of the Tellurex TE modules, resides in that provides a higher voltage, which simplifies the electric power conversion system, thinking of a prototype composed of a single TE module.

It can be observed from previous figure that the internal resistance of the TE slightly varies with the average operating temperature [1,7]. Although the electric equivalent of the TE module is a voltage source (as can be derived from voltage vs. current curve in Fig. 3, which is a straight line with negative slope), the condition of varying the resistance with temperature implies that for optimizing the efficiency of the TE system that operates with a variable thermal source (like is the case from a stove) a DC/DC converter that always allows to equal the effective resistance of the load (the one that the TE module sees) to the internal resistance of the TE will be required. In this respect, it is useful to appeal to the wide experience that exists in the development of intelligent converters for photovoltaic solar systems. In this sense, different methods of maximum power point tracking of photovoltaic solar systems have been studied under changes in the parameters of the modules and climatic conditions, and various efficient converter topologies have been proposed, which are of direct application for the proposal presented in this work [16].

After having experimentally characterized TE modules from Hi-Z and Tellurex manufacturers, it was chosen for the first prototype presented in Fig. 4, the Tellurex TE model G1-1.4, which is nominally able to generate a power of 5.7 W,

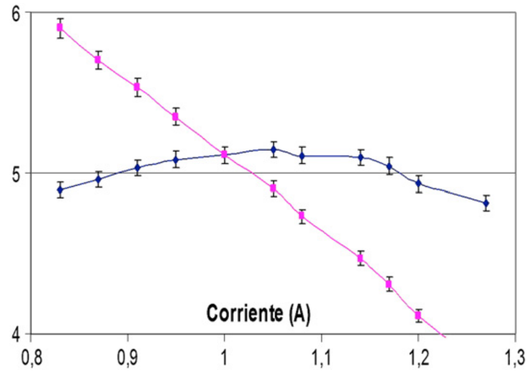

Fig. 3 – Voltage, current and power characteristic curves for the selected TE Module from Tellurex.

delivering a current of 1.2 A with a voltage of 4.8 V, when a temperature gap settled down between its both sides is 150 °C and 50 °C (see Fig. 3). Since this TE module is manufactured with two ceramic buffers welded to its faces, its mechanical assembly is extremely simple, because all the involved contact thermal resistances are reduced, and they are as low as 0.1 °C/W due to the employment of flat plane surfaces, contrary to those of Hi-Z that require a more sophisticated assembly.

In the daily use of the thermoelectric generator (with variable sources of heat) the temperature of the hot side cannot be assured that will not exceed the limit of security (avoiding the deterioration of the TE module); therefore it is imperative to implement a temperature control system. It is not feasible to propose a servomechanism that acts on the source of heat, but it is simple to control the temperature of the heat drain by means of the control of the flow of air that cools the heat sink system.

Two thermocouples type K are used to sense magnitudes of temperature in both sides of the TE module, and a pulse width modulation technique (PWM) is employed to control the speed of operation of the fan and thus to maintain the temperature of the TE cold side in appropriate values to maximize the useful power generated. In addition to this auto-management energy system, the interface with the user is designed, by using a security system with various alert signals that indicate the TE module operation state and permits to the own user to take preventive actions of control. The light interface is composed of three Leds (yellow, green and red) that indicate the user whether the source of heat provides to the TE generator an insufficient, enough or in excess power, respectively. The sound interface emits an alarm (piezoelectric buzzer) that in the case of overcoming the maximum allowed temperature, notifies to the user that should carry out an immediate action to reduce this temperature, such as taken away the unit from the source of heat. All these systems are controlled and implemented by means of a microcontroller Atmel (ATMega168), using an original software specially developed for this application.

It is significant to keep in mind that the system is self-powered; reason why the used electronics and the load are subjected to normal voltage variations that the TE module provides. For example, when starting up at low temperature, the TE generator cannot reach the enough voltage so as to feed the electronics and the fan. Since the fan cannot run, the temperature of the cold side increases, thus reducing even more the temperature gap between both TE faces and consequently, the power and voltage provided, entering in a cycle of negative feedback.

From first experiences, it could be verified than the module was not able to start up the system for its own, so that the DC/DC converter was crucial for this operation. Thus, this switching device allows obtaining a near constant output voltage over a great range of input voltages of the TE module. This converter was implemented through a simple integrated circuit (M34063L) and an additional electronics that assures an output voltage of 5 V when the input voltage is in the range of 2 V to 6 V. It is to be noted that this electronic module is usually included in most of mobile chargers, reason why is very cheap. On the other hand, more sophisticated DC/DC converters have been developed, in order to improve the overall efficiency by means of adapting the load impedance to the internal impedance, which is a function of the thermoelectric temperature. This feature will be fully described in another paper [17].

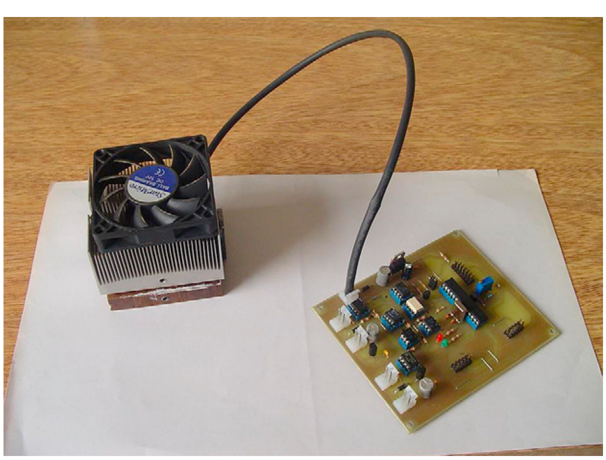

Fig. 4 – Prototype of TE generator with its electronic system.

4. Conclusion

This work studied experimentally the technical feasibility of a novel technology of electric power generation that uses thermoelectric generators for electrification of rural homes. Attached to a main source of heat (firewood home stoves), the proposed prototype takes advantage of the residual heat thrown away by this source of heat. Furthermore, it was verified experimentally by means of the development of a prototype, the great simplicity and potentiality of local development of this technology. In this sense, it would constitute an option of sustainable electric generation (being that residual heat is used otherwise wasted) that could be developed in the own regional economies where it is used. This characteristic, jointly with its simple installation and operation for the own users, would give TE modules some comparative advantages respect to conventional PV solar arrays. In addition, its low operating cost, feature shared with PV systems, becomes TE an attractive option for low-income rural homes.

Although the development of low-cost commercial thermoelectric generator systems is still incipient, its extreme simplicity would allow replying the developments proposed in all Latin America. Much of the experience and systems used with PVs can be used here, since both technologies share the characteristic of generating in DC current and low voltage.

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