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Parameter analysis of thermoelectric generator/dc-dc converter system with maximum power point tracking

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ABSTRACT

The power generated from TEG is relatively unstable owing to temperature variations at its hot and cold side terminals. The dc-dc converters can provide more stable power output thereby improving the overall efficiency of TEG system. However, to facilitate better performance improvement, maximum power point tracking (MPPT) algorithm can be applied to extract maximum power from TEG system. Therefore, parameter analysis of a TEG/dc-dc converter system in different modes is being carried out. A TEG-dc-dc boost converter model is analysed in both MPPT and direct pulse width modulation (PWM) modes subjected to a variable load. To further study the capability of dc-dc converters to stabilise the TEG power output, increasing ramp and random hot side temperature is applied to the MPPT and direct PWM based modes so that the effect on output parameters i.e. voltage and power, can be analysed. It is noted that even for the random temperature input to the TEG, the output voltage resulting from the converter is almost constant. Therefore dc-dc converters are able to stabilise the power generated from TEG. It is also observed that dc-dc converter with MPPT based model is able to effectively extract the maximum power without having to adjust any component from the MPPT algorithm as it is the case with direct PWM based model. From the study, it has been established that proper selection of converter components is necessary to reduce converter losses as well interferences on the load connected to TEG-dc-dc converter system.

Introduction

Energy-harvesting systems which convert heat into electricity with the use of thermoelectric energy generation (TEG) devices are being constantly developed and manufactured (Liu et al., 2015; Noori et al., 2015).A number of currently available and applicable low-grade waste heat recovery methods adopt thermoelectric (TE) modules including plant/district/water heating, direct power generation and others (Ebrahimi et al., 2014). TE modules offer low cost electricity without moving parts or production of environmentally deleterious wastes (Seetawan et al., 2014). TEG devices can also be applied in harvesting heat energy from biomass, especially in tropical countries (Twaha et al., 2016a). This will facilitate the sustainability of scarce energy resources, especially the fossil fuels which are almost near exhaustion. Biomass cooking stoves which are commonly applied in developing countries with limited access to electricity, can be operated with TEG devices to generate low level electricity for home use, such as for mobile phone charging (Najjar and Kseibi, 2017; Yap et al., 2017). In this regard, a TEG based biomass cooking stove was developed and deployed for electricity generation, in the off grid areas (Mal et al., 2016). Apart from clean cooking, the TEG based stove has the ability to provide lighting and battery charging (or mobile phone battery charging) based on the user's preference as well as price sensitivity. These TEG applications are steps forward for energy and sustainable development in rural and remote areas, geared towards reducing energy poverty or scarcity in underdeveloped countries. However, the optimal performance of TE modules depends on several factors like material properties and operation strategy (Twaha et al., 2016b).

Various research efforts are underway to improve the performance of TE conversion system. The integrated thermoelectric devices are also developed by restructuring them to allow more heat to enter the p–n junctions, thereby producing more power output (Barry et al., 2015). Product development for TEG devices requires solving a couple of challenges in material and system construction aspects for numerous TEG system applications (Leblanc, 2014).Accuracy of mathematical models used in thermoelectric simulation is assessed with special reference to thermal influence of insulated air zone and radiation heat (Gao et al., 2015). Heat transfer analysis between TEG cold and hot plates reveals that the developed model is of theoretical significance in guiding TEG design for high-power or large-temperature-difference application. Different TEG structures including rotated and coaxial leg configurations (Erturun and Mossi, 2015), rectangular prism and cylindrical legs (Erturun et al., 2014), have been evaluated with regards to power output, temperature distribution, conversion efficiency and thermal stresses in the legs. Not forgetting to mention the concentric

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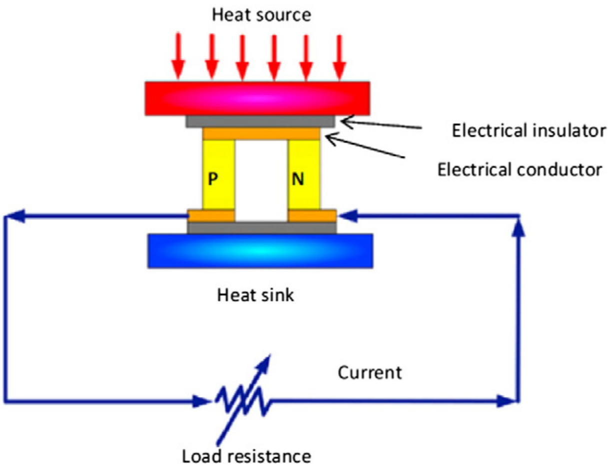

Fig. 1. A single p-n pair of the TEG module (Najjar and Kseibi, 2016).

cylindrical design which is also applied to TEG system with improved power output (Huang Kuo et al., 2016). With all these efforts, it is still necessary to do more research work on the performance improvement for TEG systems.

Maximum power point tracking (MPPT)methods for a long time have been applied to improve the performance of photovoltaic (PV) system in both normal and partial shading conditions (Ramli et al., 2016). In order to fully utilize the energy generated from TEG systems, dc-dc converters with MPPT are being adopted to stabilise the output voltage generated from TEG as well as to ensure maximum power extraction from TEG system (Yusop et al., 2016; Paraskevas and Koutroulis, 2016; Molina et al., 2010; Liu et al., 2016a, 2016b; Molina et al., 2012). In (Yusop et al., 2016), an analysis is carried out on an MPPT control strategy for thermoelectric-solar hybrid energy harvesting system. The hot side temperature is set between 40 °C and 50 °C while single supercapacitor is used as the load to the system purposely to increase the tracking response. The authors in (Paraskevas and Koutroulis, 2016) presented a simple MPPT method for TEG which is based on controlling a power converter such that it operates on a pre-programmed locus of operating points close to the MPPs of the power–voltage curves. In their work, a single battery is used as the load. In (Liu et al., 2016a), Yi-Hua et al. presented a novel MPPT for TEG system which combines the benefits of perturb and observe (P&O) method and the fast tracking ability of open circuit voltage (OCV) method with batteries used as the load to the system. In reality, temperature profiles are random in nature, especially in vehicles. As well, some loads are never constant, making it a necessity to analysis the TEG-converter systems when they are subjected to different loads. In our previous study (Twaha et al., 2017), an IC-based MPPT method is presented with a ramp step temperature on the hot side and a constant temperature on the cold side whereas the converter is subjected to a constant resistive load. Therefore, it is necessary to test the TEG-converter system with a random temperature because temperature profiles are random in most of the real applications. Moreover, it is necessary to analyse the system with a variable load to identify the optimal load for the TEG-converter system to perform near its maximum potential. The objective of this work is to investigate the parameters of TEG-dc-dc converter system enabled by incremental conductance (IC) based MPPT and direct PWM signals. The converter performance is analysed with reference to the temperature variation at the hot side of TEG in addition to varying the external converter load. The study is aimed to test the TEG output power conditioning model for application in the waste heat recovery in low carbon vehicle.

Thermoelectric module

A Single p-n pair of the TEG module is shown in Fig. 1. A TEG is a solid-state device that can convert heat directly into electrical energy when a temperature difference is placed across it (Yu et al., 2015). Electric power can be converted to cooling or heating by reversing the current direction (Zheng et al., 2014). In a thermoelectric material there are free electrons or holes which carry both charge and heat. The electric potential (Voltage) produced by a temperature difference is known as the Seebeck effect and the proportionality constant is called the Seebeck coefficient. If the free charges are positive (the material is p-type), positive charge will build up on the cold end which will have a positive potential. Similarly, negative free charges (n-type material) will produce a negative potential at the cold end (Najjar and Kseibi, 2016).

While choosing TEGs for application in varying conditions, it is necessary to select an appropriate semiconductor with acceptable performance in the temperature range of that condition (Niu et al., 2015).The figure of merit (Z) is a parameter generally used to gauge the performance of a TE material:

$$Z = \frac{S_{p,n}^2 \sigma_{p,n}}{\lambda_{p,n}} \tag{1}$$

where $S_{p,n}$ is the Seebeck coefficient of n-type or p-type material;$\sigma_{p,n}$ is the electrical conductivity of the material in p-type or n-type in Siemens per meter whereas $\lambda_{p,n}$ is the thermal conductivity (Niu et al., 2015).

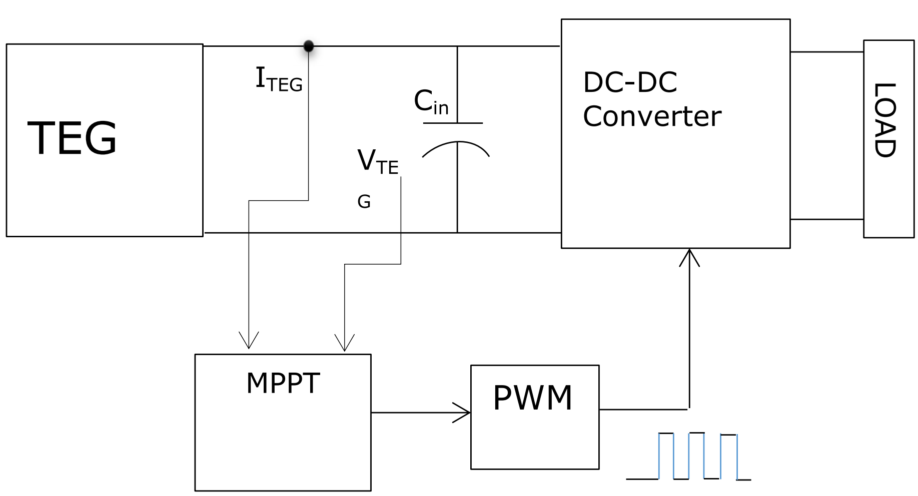

Fig. 2. The TEG-converter simulation model.