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Theoretical, experimental and numerical diagnose of critical power point of thermoelectric generators

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ABSTRACT

When a number of TEMs (thermoelectric modules) are connected in a series–parallel matrix and under mismatched temperature gradients, the overall maximum output power of the thermoelectric generator (TEG) may be lowered by certain TEMs with relatively smaller temperature difference. It is possible to avoid such a performance decrease by the disconnection of these low temperature TEMs, provided that the critical power point can be accurately determined. In this paper, firstly a rigorous and universal formulation is fully detailed to mathematically determine the conceptions and conditions of the critical power point in the series and parallel TEM arrays. Secondly, experiments of a series–parallel hybrid interconnected TEG are presented to clearly quantify the theoretical analyses. Finally, the hierarchical simulation, based on the SPICE (simulation program with integrated circuit emphasis) platform, is applied to estimate the critical power point. By numerically modeling the nonlinear physical processes of the TEG, the simulation can be used as an enabling technique in any model-based controller to dynamically minimize the mismatch power loss within the TEM matrix of any configuration. In experimental and numerical results, a number of critical power points are disclosed for a 2×4 parallel–serial hybrid TEM matrix, where the hot temperature mostly ranges from 120 °C to 60 °C.

1. Introduction

TEGs (Semiconductor thermoelectric generators) have the merits of high durability, great environmental harmony, and pure DC (direct current) power source. As they can recover the huge amount of low grade waste heat into electricity in a simple manner, TEG systems have been of great interest to energy applications in recent years. Representative examples of TEGs include fuel fired combustors and thermal fluid tubes in industrial power plants and private sectors [1–7], as well as the exhaust pipes in fuel cells [8–11], aircrafts [12] and vehicles [13–19], where thermoelectric modules (TEMs) can be mounted on heat sources to operate as an array of thermal batteries that supplies power to the load.

In composing a battery pack, ordinary voltage sources such as alkaline batteries usually prefer the series connection. This is because, if the batteries are mismatched, then those with higher voltage may charge others when the batteries are connected in parallel. In this case, the batteries with lower voltage cannot work normally to output power and may be overheated by the great current as the resistance of most batteries is very small. The thermal runaway may even be aroused for lithium-ion batteries by short circuit, that both heat and temperature are kept increased to ultimately lead battery packs to explode. In general, a lot of voltage sources, e.g., battery charger, backup power source, and grid-connected generators, can only be paralleled after special protection design to prevent such mismatch damages. Different from these voltage sources, mismatched TEMs do not have the charging and security risks in the case of parallel connection. Consequently, series and parallel connection are of equal importance in composing TEM arrays to satisfy the technical tradeoff between the reliability and the power generation specifications imposed by the practical load voltage and current.

Yet a well recognized rule in designing such a series/parallel hybrid battery pack as TEM arrays is that every cell should have close electric parameters in order to make the power loss caused by the mismatch minimal [20]. The electric parameters refer to the open-circuit voltage and the internal resistance for Thevenin's voltage sources. As the TEMs connected together are usually represented by Thevenin's voltage source model, they should ideally be of similar voltage and resistance characteristics to each other so that no degraded battery limits the string current or the total voltage. However, both theoretical [1–4,6,7,9,11,12,16,18] and

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experimental [5,8,10,13–15,17,19] investigations clearly show that the variance of the temperature difference applying to different TEMs in most thermal systems can be as much as a few hundred degrees. Since the voltage as well as the internal resistance of a TEM are nonlinearly determined by its hot and cold temperatures, the TEM mismatch power loss is inherently associated with most TEM arrays.

As can be proven in terms of the fundamental circuit theory and shown by means of numerical calculation [3,7,11] and experiment test [21], the maximum power capability of a TEM array, measured by the ratio between its equivalent open-circuit voltage and equivalent internal resistance, may be lowered by the inclusion of some TEMs with smaller temperature difference due to the mismatch power loss. In this case, however, the possibility to optimize the array output power by the removal of the TEMs operating with lower heat source temperature, implemented by replacing the traditionally fixed hardwire interconnections between the TEMs with controllable switches, has only received some attention recently [22]. Once the array is spitted into two sub-arrays, and one can be assumed as the original array whilst the other is composed of the removed TEMs, it is also possible to configure each of the sub-arrays with an individual power electronics stage and MPPT (maximum power point tracking) controller [23]. In this way, not only the mismatch power loss caused by the temperature nonuniformity is recovered, but more power may also be produced than the original TEM array with uniform temperature distribution and zero power loss.

From the practical viewpoint, it is thus important to both qualitatively and quantitatively evaluate how small the temperature difference of certain TEMs is enough that their disconnection from the array would be beneficial. The issue has not been thoroughly covered by the previous works focusing on the controller design and implementation [22,23], but can be identified in an alternative way to find out the extremum of the maximum output power for a TEM array with various temperature distribution patterns. Such a power maximum determines the best occasion to optimally remove TEMs/split the array, and is corresponding to the so-defined critical power point. The main objective of this paper is to carry out the qualitative and quantitative evaluation mentioned above, and the diagnoses of the critical power point will be realized by means of the analytical, experimental, and numerical approaches, respectively, aiming for the feasible design assistance and guide in building practical TEG systems. The main contribution of the analytical study is to rigorously analyze the mismatch power loss in TEGs and formulate the critical power point to optimally split TEM arrays in terms of both series connection and parallel connection (Section 2). The main contribution of the experiments, taken from a practical TEG consisting of eight independently controlled TEMs, is to confirm the theories of critical power point and provide concrete figures on the magnitude of thermal imbalance to arise such critical power points (Section 3). The main contribution of the thermo-electro coupled simulation, using the hierarchical TEG modeling in the circuit simulator SPICE as the ideal solution, is to accurately predict TEG behaviors at the system level, where multiple TEMs can be both electrically connected and thermally combined arbitrarily (Section 4).

2. Mismatch power loss and critical power point

A common configuration to create the temperature difference for a TEG is the fluid-to-fluid heat transfer, where a number of TEMs are placed in the heat exchanger interface separating a hot fluid stream and a cold fluid stream, and generate power as the heat flows through them [1–4,7,10–14,19]. Each TEM is electrically described as a voltage source serially connected with a resistor [24], and when all TEMs are connected in series, the total voltage and resistance of the TEG in the quasi-one dimensional (1D) configuration [25] can be described as.

$$V=\sum_{i=1}^{L_f/w} N\left(\int_{T_c(i)}^{T_h(i)} \alpha_p \mathrm{d}T_p - \int_{T_c(i)}^{T_h(i)} \alpha_n \mathrm{d}T_n\right), \tag{1}$$

$$R=\sum_{i=1}^{L_f/w} N\left(\int_{0(i)}^{L(i)} \frac{\rho_p}{S_p}\mathrm{d}x + \int_{0(i)}^{L(i)} \frac{\rho_n}{S_n}\mathrm{d}x\right). \tag{2}$$

As shown in Eqs. (1) and (2), the local power generation of any TEM in the TEG system can be developed by the nonlinear integral functions within the local temperature difference, i.e., from $T_c(i)/0(i)$ to $T_h(i)/L(i)$, where heat source temperatures T_h and T_c can be assumed same for all thermocouples of each individual TEM. The power capability of the TEG with all TEMs connected together is described as.

$$P=\frac{V^2R_l}{(R+R_l)^2}, \tag{3}$$

which is maximized when $R_l = R$, i.e.,

$$P_{max}=\frac{V^2}{4R}. \tag{4}$$

Similarly, when all TEMs are connected in parallel, V and R of the TEG can be described as.

$$V=\frac{\sum_{i=1}^{L_f/w}\frac{N\left(\int_{T_c(i)}^{T_h(i)} \alpha_p dT_p - \int_{T_c(i)}^{T_h(i)} \alpha_n \mathrm{d}T_n\right)}{N\left(\int_{0(i)}^{L(i)} \frac{\rho_p}{S_p}\mathrm{d}x + \int_{0(i)}^{L(i)} \frac{\rho_n}{S_n}\mathrm{d}x\right)}}{\sum_{i=1}^{L_f/w}\frac{1}{N\left(\int_{0(i)}^{L(i)} \frac{\rho_p}{S_p}\mathrm{d}x + \int_{0(i)}^{L(i)} \frac{\rho_n}{S_n}\mathrm{d}x\right)}}, \tag{5}$$

$$R=\frac{1}{\sum_{i=1}^{L_f/w}\frac{1}{N\left(\int_{0(i)}^{L(i)} \frac{\rho_p}{S_p}\mathrm{d}x + \int_{0(i)}^{L(i)} \frac{\rho_n}{S_n}\mathrm{d}x\right)}}. \tag{6}$$

According to Kirchhoff circuit laws, the numerator of Eq. (5) represents the sum of the ratios between the voltage and the resistance of all TEMs, i.e., $\sum V_i/R_i$, and the denominator of Eqs. (5) and (6) represents the sum of the reciprocals of the resistance of all TEMs, i.e., $\sum 1/R_i$. Although all TEMs are connected in parallel, the N pairs of thermoelements within each TEM are usually connected in series, as shown in (5) and (6).

Other instances of TEG heat source include various waste-heat recovery applications in the outer walls of exhaust pipes or combustors [5,6,8,15–18]. When all TEMs are connected in series, the total voltage and resistance of the TEG in the two-dimensional (2D) configuration can be similarly described as.

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