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Abstract:

Thermoelectric generators (TEGs) can harvest thermal energy from waste heat sources to supply various power levels due to the Seebeck effect. The power generated by a TEG is dependent not only on the temperature difference across them but also on the electrical load applied. Typically, waste heat sources have variable operating conditions which means maximum power point tracking (MPPT) must be employed through the use of power converters to produce the desired operating point of the system and thus increase the system efficiency. This paper presents a new MPPT scheme which has not been previously applied to thermoelectric generators, the high frequency injection (HFI) scheme to achieve a fast and accurate tracking of the maximum power operation point for TEGs. The proposed MPPT scheme is implemented with a power converter, and the tracking scheme performance is experimentally evaluated on a commercial TEG module through three different experiments. The proposed scheme is also compared to the most commonly used MPPT scheme for TEGs, Perturb & Observe. The experimental results show that the tracking efficiency of the proposed MPPT scheme is 99.73% at steady-state compared to the 90% tracking efficiency achieved by the Perturb & Observe scheme, as well as a 3 times faster dynamic response compared to the fastest method recorded in literature.

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High Frequency Injection Maximum Power Point Tracking for Thermoelectric Generators

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7 Abstract

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Thermoelectric generators (TEGs) can harvest thermal energy from waste heat sources to 8 supply various power levels due to the Seebeck effect. The power generated by a TEG is 9 dependent not only on the temperature difference across them but also on the electrical load 10 applied. Typically, waste heat sources have variable operating conditions which means max-11 imum power point tracking (MPPT) must be employed through the use of power converters 12 to produce the desired operating point of the system and thus increase the system efficiency. 13 This paper presents a new MPPT scheme which has not been previously applied to thermo-14 electric generators, the high frequency injection (HFI) scheme to achieve a fast and accurate 15 tracking of the maximum power operation point for TEGs. The proposed MPPT scheme is 16 implemented with a power converter, and the tracking scheme performance is experimentally 17 evaluated on a commercial TEG module through three different experiments. The proposed 18 scheme is also compared to the most commonly used MPPT scheme for TEGs, Perturb & 19 Observe. The experimental results show that the tracking efficiency of the proposed MPPT 20 scheme is 99.73% at steady-state compared to the $\sim 90\%$ tracking efficiency achieved by the 21 Perturb & Observe scheme, as well as a 3 times faster dynamic response compared to the 22 fastest method recorded in literature. 23

²⁴ Keywords: DC-DC power converter, energy harvesting, high frequency injection (HFI),

²⁵ maximum power point tracking (MPPT), perturb & observe (P&O), thermoelectric

²⁶ generator (TEG)

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27 1. Introduction

Harvesting energy from waste heat is a method by which the overall system efficiency may 28 be increased [1]. In the past decades, thermoelectric generators (TEGs) have gained interest 29 as a viable technology for recovering energy that is lost to the environment in applications that 30 range from medical [2, 3, 4] to automotive [5, 6, 7, 8, 9]. Thermoelectric generators are solid 31 state devices that convert thermal energy directly into electrical energy. This phenomenon 32 known as the Seebeck effect is observed when a voltage is generated across the junction of 33 two conductors due to a temperature difference. The direct energy conversion is a major 34 advantage of TEGs and other advantages include their small size, low system complexity, 35 quiet operation and little to no maintenance [10]. 36

The power produced by a TEG is not only dependent on the thermal operating conditions 37 but also on the electrical load applied. Therefore, a power converter is usually interfaced with 38 the TEGs that are connected either in series or parallel, depending on the desired voltage 39 output of the system. To ensure that the maximum power is produced by the TEG during 40 operation, a Maximum Power Point Tracking (MPPT) scheme is programmed to control 41 the power converter. In waste heat recovery applications such as automotive, geothermal, 42 industrial plants, etc., the waste heat sources are dynamic in operation, i.e. the exhaust fluids 43 have variable temperature and mass flow rates which determine the amount of heat energy 44 available for harvesting. Unlike other waste heat recovery technologies such as Rankine cycles 45 (i.e. turbo-lag) [11], TEGs can operate robustly in these dynamic environments to recover 46 energy. Consequently, MPPT algorithms need to be employed that can quickly adapt to 47 these variable operating conditions. 48

The most commonly used MPPT scheme for TEGs in the literature is the Perturb & 49 Observe (P&O) scheme which works by altering the TEG operation setpoint, observing if the 50 output power increased or decreased and making a decision based on this information [12, 13, 51 14, 15]. The main disadvantage with this method is that the maximum power point (MPP) 52 is not reached, but instead the power output of the TEG oscillates around the MPP. The 53 Incremental Conductance (IncCond) method considers the derivative of the power (derivative 54 is zero at MPP) and changes the setpoint based on this feedback [16, 17, 18]. In comparison 55 to P&O, IncCond offers a more robust quantifier on the location of the operation point. 56

Similarly to P&O, IncCond requires a sufficiently large step and keeps moving around the MPP. The fractional open-circuit voltage scheme is another commonly used MPPT method in the literature. It is implemented by setting the current to 0A, measuring the open-circuit voltage of the TEG, and then setting the electrical load to half this value [19, 20, 21]. One drawback with this scheme is that the TEG needs to be disconnected from the load to measure the open circuit voltage and hence the dynamics, i.e. the operating condition of the TEG is affected.

Although other schemes are presented in the literature, the majority of the MPPT al-64 gorithms' performance is evaluated at steady-state which is not indicative of what occurs 65 during the operation of TEGs in waste heat recovery applications. The location and mount-66 ing of the thermocouples in the MPPT method proposed by [22] adds complexity to the TEG 67 harvesting system and introduce possible errors when finding the accurate MPP of a larger 68 TEG system (more than one TEG module), since it depends on accurate measurements of 69 the temperature differences. Although, [23] proposed a simpler method to find the MPP of 70 a TEG, a setback is that the TEG system needs to be characterized prior to implementation 71 since a pre-programed setpoint of MPPs is used by the algorithm. As the operating condi-72 tions change rapidly in waste heat recovery application such as those in the exhaust system 73 of a vehicle [24], calibrating the system for every possible setpoint would be cumbersome. 74

In this paper, a new MPPT scheme is proposed, the High Frequency Injection (HFI) 75 scheme, where a high frequency signal is injected into the system and the perturbation ob-76 served is used as feedback to control the operating condition of the TEG and arrive at the 77 MPP, without inducing oscillations to the system. The HFI scheme requires only measure-78 ment of the TEG power, hence no additional sensors are needed such as thermocouples and 79 the MPPT can quickly adapt to changes in the system without prior characterization. The 80 proposed scheme is experimentally implemented and the performance is evaluated through 81 three different experiments, including transient operation. The scheme is also experimentally 82 compared to the most commonly used MPPT scheme, P&O. 83

The paper is organized as follows: Section 2 explains the physics of TEGs as well as how they were experimentally characterized. Section 3 explains the theory behind the HFI MPPT scheme and goes over the P&O scheme. Next, the experimental validation procedure ⁸⁷ is explained and the experimental results are discussed in Section 4 and 5.

Non	nenclature		
		η efficiency, %	
ΔT	temperature difference, K	ω angular frequency, rad/s	
A	cross-sectional area, m^2	Abbreviations	
В	amplitude	HFI High Frequency Injection	
D	duty cycle	MP Maximum Power	
f	frequency, Hz	MPPT Maximum Power Point Tra	cking
Ι	current, A	P&O Perturb & Observe	
K	thermal conductance, W/K	TEG Thermoelectric Generator	
k	thermal conductivity, W/m-K	Subscripts	
L	length, m	C cold side	
P	electrical power, W	H hot side	
Q	heat flux, W	int internal	
R	electrical resistance, Ω	l load	
T	temperature, K	max maximum	
V	voltage, V	o out	
Gree	ek Symbols	oc open circuit	
α	seebeck coefficient, V/K	sw switching	

88 2. TEG Energy Harvesting

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The following sections describe the working principle of TEGs and demonstrate the electro-thermal characterization of a TEG module to experimentally evaluate the performance of MPPT schemes.

92 2.1. Working Principle

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Figure 1: (a) TE p-n couple schematic (b) Many p-n couples form a TEG module.

⁹³ Thermoelectric generators operate due to the Seebeck effect. This effect was observed ⁹⁴ when two dissimilar conductors were connected and an electromotive force (emf) was gen-⁹⁵ erated due to the junctions being maintained at different temperatures [25]. The Seebeck ⁹⁶ coefficient, α , is defined by the emf or open circuit voltage, V_{oc} , generated and the tempera-⁹⁷ ture difference, ΔT , across the thermoelectric junctions

(

$$\alpha = \frac{V_{oc}}{\Delta T}.$$
(1)

Semiconductors generate a higher V_{oc} compared to metals, hence they are used to manu-99 facture TEGs. A positive-doped (p-type) semiconductor is connected via a metal contactor 100 to a negative-doped (n-type) semiconductor to create a thermoelectric (TE) junction, con-101 sidered a p-n couple as shown in Fig. 1(a). When a temperature difference is applied across 102 the TE junction, V_{oc} is generated and if an electrical load is connected, current is allowed to 103 flow, thus generating power. At steady-state, a TEG may be modeled as a voltage source in 104 series with an electrical internal resistance, R_{int} , as presented in Fig. 2(b). Hence, V_{oc} can be 105 increased by joining many p-n couples in series. Thus, A TEG module consists of many p-n 106 couples connected electrically in series and thermally in parallel as seen in Fig. 1(b). 107

¹⁰⁸ A temperature difference is created by allowing heat to flow across the TEG module (heat ¹⁰⁹ source and heat sink required), therefore electrical insulation from the heat source is necessary ¹¹⁰ (usually a ceramic). As heat, Q_H , flows through the TEG, the thermal conductance of the ¹¹¹ TEG, K_{TEG} , will cause a temperature difference across the TEG: T_H and T_C , the hot side ¹¹² and cold side, respectively. When electrical current flows through the TEG module, heat will ¹¹³ be transferred from T_H to T_C due to the Peltier effect [25]. In general, this will cause the ¹¹⁴ temperature difference to decrease which is seen as a negative effect. Finally, there are also ¹¹⁵ Joule losses that are generated when current flows through the TEG.

Taking into account all these thermoelectric effects, Q_H and the heat exiting the TEG, Q_C is defined as [26]

$$Q_{H} = \alpha T_{H}I + K_{TEG} \left(T_{H} - T_{C} \right) - \frac{1}{2} I^{2} R_{int}$$
(2a)

$$Q_{C} = \alpha T_{C}I + K_{TEG} \left(T_{H} - T_{C}\right) + \frac{1}{2}I^{2}R_{int}$$
(2b)

where I is the current flowing through the TEG. An electrical diagram of the heat flows in the TEG and its equivalent circuit are shown in Fig. 2(a) and (b), respectively. The power generated by the TEG is then the difference between Q_H and Q_C and defined as

$$P = Q_H - Q_C \tag{3a}$$

$$= \alpha \Delta T I - I^2 R_{int}.$$
 (3b)

¹²⁷ Therefore, the power produced is not only dependent on the temperature difference across ¹²⁸ the TEG, but also on the current, *I*. The power output can be predicted with (3b), as a ¹²⁹ function of current, if α and R_{int} are known for any temperature difference.



Figure 2: (a) Equivalent electro-thermal model of TEG (b) Electrical TEG model.

Consider the electrical circuit of a TEG as shown in Fig. 2(b). The power produced from
the TEG may also be described as

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$$P = I^2 R_l \tag{4}$$

where R_l is the electrical load resistance connected to the TEG terminals. The TEG current, 134 I, is therefore equal to

$$I = \frac{V_{oc}}{R_{int} + R_l} \tag{5}$$

 $_{136}$ and (4) can be rewritten as

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$$P = \frac{V_{oc}^2}{(R_{int} + R_l)^2} R_l.$$
 (6)

¹³⁸ The maximum power may now be found by taking the derivative with respect to R_l

$$\frac{dP}{dR_l} = \frac{V_{oc}^2 \left(R_{int} - R_l\right)}{\left(R_{int} + R_l\right)^3} = 0.$$
(7)

140 Thus, $R_l = R_{int}$ when the TEG power is maximized and results in

$$V_{TEG} = \frac{1}{2} V_{oc}.$$
(8)

At maximum power, the load resistance will equal the internal resistance of the TEG, thus (6) becomes

$$P_{max} = \frac{V_{oc}^2}{\left(R_{int} + R_{int}\right)^2} R_{int} = \frac{V_{oc}^2}{4R_{int}} = \frac{\alpha^2 \Delta T^2}{4R_{int}}.$$
(9)

The theoretical maximum power for a TEG module can now be calculated with (9) if α , R_{int} and the temperature difference across the TEG are known.

147 2.2. Experimental Characterization Setup

As explained in the previous section, a temperature difference must be imposed across 148 the TEG and an electrical load connected to observe the power generated. The experimental 149 test rig designed for characterization of a TEG module is seen in Fig. 3. A TEG module is 150 compressed between two copper blocks with equal cross-sectional area. The hot block has 151 heaters that are controlled to maintain the TEG hot side at a specified temperature. Fins 152 were machined into the cold block and are cooled by a chiller. A force is applied to a bolt 153 that is screwed into the cold block to maintain a fixed pressure on the TEG module. A load 154 cell is used to measure the pressure applied to the TEG module. All the tests were completed 155 at 530kPa which is recommended by the TEG module datasheet. 156

The TEG module and copper blocks, which sandwich the module, are placed in a vacuum chamber to ensure there are no convective heat losses from the blocks to the environment. Since the hot block experiences high temperatures, a radiation shield is placed around the block to reduce thermal losses in vacuum. Thermocouples (TCs) are placed along the axial direction (y-axis in Fig. 3) of both copper blocks to record the temperature gradient. A TC is not placed between the blocks and the TEG module to directly measure T_H and T_C as



Figure 3: Schematic of experimental setup for electro-thermal characterization (not drawn-to-scale).

this creates a hot spot and incorrect temperature measurement results. At steady-state, a temperature distribution exists only in the axial direction and T_H is derived from

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$$T_H = T - \frac{L}{kA}Q\tag{10}$$

where T is the temperature reading of the closest TC to the TEG module, L is the distance 166 between the TC and the TEG, k is the thermal conductivity of the copper block, and A is 167 the cross-sectional area of the block which is equal to that of the TEG module. Q is the 168 heat flux through the block which is calculated from the other TC readings at steady-state. 169 The same calculation is done to calculate the TEG cold side, T_C . When there is no current 170 flowing through the TEG, Q_H should be equal to Q_C or similarly the heat flux through the 171 hot copper block should be equal to the heat flux through the cold copper block. Experiments 172 performed in this test rig showed that this is true within 2% error. 173

A DC load is connected to the TEG module to vary the current for the characterization. A DAQ interfaced with LabView is used to control the current imposed on the TEG, as well as the temperature difference across the TEG. The experimental characterization was performed as follows: 1) Set current, 2) PID control of heaters to fix T_H , 3) chiller setpoint is changed to achieve desired T_C , 4) wait until steady-state is achieved and record data. The results of the characterization for various temperature differences is presented in the next
 section.

181 2.3. Electro-Thermal Characterization

A TEG module, TEG1-12610-5.1 from TECTEG MFR was experimentally characterized for various T_H , while maintaining T_C at 35°C. The characterization results are shown in Fig. 4. As can be observed from the graph, there exists one maximum power point (MPP) per curve and it occurs at $V_{oc}/2$. The parameters, V_{oc} , R_{int} and α are tabulated in Table 1.



Figure 4: Experimental electrical characterization of commercial TEG module for $T_C=35^{\circ}C$.

Table 1: TEG module parameters						
ΔT	$V_{oc}[V]$	R_{int} [Ohm]	$\alpha~[{\rm V/K}]$			
140	5.33	2.35	0.0381			
165	6.17	2.40	0.0374			
190	6.97	2.46	0.0367			
215	7.72	2.51	0.0359			

Taking the parameters from Table 1, (3b) was used to generate the power profiles in Fig. 5. The maximum error between the experimental data in Fig. 4 and the model in Fig. 5 is 1.7%,



Figure 5: TEG power output model results for various T_H with $T_C=35^{\circ}C$.

¹⁸⁸ but the maximum error only considering the MPP is 0.2%. Hence the parameters from Table
¹⁸⁹ 1 can be used to predict the maximum power as a function of temperature difference.

¹⁹⁰ 3. Maximum Power Point Tracking

Two MPPT schemes were implemented to evaluate the tracking performance on the 191 characterized TEG module. The first scheme is the commonly used Perturb & Observe 192 scheme and the second scheme is the proposed High Frequency Injection scheme that has not 193 been previously experimentally demonstrated. The TEG module can be electrically modeled 194 as shown in Fig. 2(b). The power output is maximized when the load resistance is equal 195 to the TEG internal resistance as presented by (4)-(8). The MPPT configuration for both 196 schemes is presented in Fig. 6, where a DC/DC converter is programmed to be interfaced 197 between the TEG module and DC load, to control the TEG power output. 198



Figure 6: TEG MPPT configuration.

199 3.1. Perturb & Observe

The Perturb & Observe (P&O) scheme works by observing how the power output of the TEG shifts once a perturbation or setpoint change is made to the operating conditions. The sampling period, T_s , must be much larger than the electro-thermal time constants to ensure electro-thermal dynamics do not distort the power measurement. A flowchart explaining how the algorithm works is in Fig. 7.



Figure 7: Perturb & Observe MPPT algorithm.

Initially, the current reference for the converter is set to some initial value, I_{ref} , then every T_s the power is measured (the TEG power as shown in Fig. 6) and the current reference is either increased or decreased by ΔI according to either an increase or decrease in power. For the experimental validation, ΔI was chosen as 0.08A and T_s was 10ms. Although there exists adaptive P&O schemes such that ΔI varies as the MPP is approached [27], in this work a constant ΔI was chosen for simplicity and to have a baseline reference scheme for comparison.

212 3.2. Proposed MPPT

Simulations for the proposed MPPT scheme were presented in IECON'15 [28]. The following paragraphs describe the mathematical formulation behind the method. The High Frequency Injection (HFI) MPPT method adds a high frequency sinusoidal signal to the operating condition of the TEG which results in a perturbation that can be controlled directly,
thus choosing the operation point of the TEG. A schematic of the operation for the HFI
scheme is shown in Fig. 8.



Figure 8: High Frequency Injection MPPT scheme.

²¹⁹ Consider, a boost converter used in the MPPT configuration of Fig. 6. The TEG output ²²⁰ voltage, V_{TEG} , can be described as function of the DC load voltage, V_o , as

$$V_{TEG} = V_o(1-D) \tag{11}$$

where D is the duty cycle of the switch in the power converter [29]. The output power of the TEG is then

$$P = IV_{TEG} \tag{12}$$

 $_{225}$ and I can be written as

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$$I = \frac{V_{oc} - V_{TEG}}{R_{int}}.$$
(13)

227 Substituting (11) and (13) into (12) and simplifying with only known values (D, V_{oc}, V_o)

$$P = IV_o(1 - D)$$
 (14a)

$$= \frac{V_{oc}V_o - V_{oc}V_oD - V_o^2 + 2V_o^2D - V_o^2D^2}{R_{int}}.$$
 (14b)

Assume a sine signal with angular frequency ω and amplitude *B* is injected into the duty cycle such that $d = D + Bsin(\omega t)$. Substitute *d* into (14a), the power output of the TEG, and the derivation is the same as (14b) except *d* is the new duty cycle. The power output, *p*, due to the duty cycle, *d* is now

TTT/(1)1) 235

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$$p = IV_o(1-d)$$

 $= \frac{V_{oc}V_o - V_{oc}V_oD - V_o^2 + 2V_o^2D - V_o^2D^2}{R_{int}} \\ + \frac{Bsin(\omega t) (2V_o^2 - 2DV_o^2 - V_{oc}V_o)}{R_{int}} \\ - \frac{B^2sin^2(\omega t)V_o^2}{R_{int}}.$ (15)

Rearranging (15), results in 240

$$p = P + \frac{Bsin(\omega t)[V_o(2V_{TEG} - V_{oc})]}{R_{int}} - \frac{B^2 sin^2(\omega t)V_o^2}{R_{int}},$$
(16)

by identifying that the first term is the power, P, from (14b), and the second term is a 242 function of $(2V_{TEG} - V_{oc})$. It is interesting to note that this term has popped up, since the 243 maximum power of a TEG occurs when the load voltage is equal to the internal voltage, i.e. 244 $V_{TEG} = \frac{1}{2} V_{oc}$, as stated in (8). 245

Now consider only observing the high frequency terms, which are the second and third 246 term of (16). A high-pass filter is used on p so that only the last two terms of (16) are left, 247 since P is a low frequency term (does not have a sine term). However, since the last term is 248 a sin^2 function, the high-pass filter will extract an offset since this function has an average 249 value. Refer to this offset, or average value as C, which is defined as 250

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$$C = \frac{1}{\omega t} \int_{0}^{\omega t} \frac{B^2 sin^2(\omega t) V_o^2}{R_{int}} d(\omega t) = \frac{B^2 V_o^2}{2R_{int}}.$$
 (17)

Now (16) is rewritten after a high-pass filter has been applied to p as p_{hp} described by 252

$$p_{hp} = p_1 + p_2 + C$$

$$p_{1} = \frac{Bsin(\omega t)V_{o}(2V_{TEG} - V_{oc})}{R_{int}}$$

$$p_{2} = -\frac{B^{2}sin^{2}(\omega t)V_{o}^{2}}{R_{int}}.$$
(18)

Multiply p_{hp} by $Bsin(\omega t)$ to get p_{sin} to determine whether the term $(2V_{TEG} - V_{oc})$ can be 257 isolated 258

$$p_{sin} = Bsin(\omega t)p_1 + Bsin(\omega t)p_2 + Bsin(\omega t)C,$$
(19)

and apply a low pass filter to p_{sin} , which will again result in an offset, P_{lp} described as 260

$$P_{lp} = \frac{1}{\omega t} \int_0^{\omega t} p_{sin} d(\omega t).$$
(20)

 $_{262}$ By evaluating the average value, (20), P_{lp} is reduced to

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$$P_{lp} = \frac{1}{\omega t} \int_0^{\omega t} Bsin(\omega t) p_1 d(\omega t) = \frac{B^2 V_o (2V_{TEG} - V_{oc})}{2R_{int}}$$
(21)

since the average value of sin^3 and sin is always zero over an entire number of periods. The offset, (21), can be negative or zero depending only on the sign of $(2V_{TEG} - V_{oc})$ since the constants $\frac{B^2V_o}{R_{int}}$ are always positive.

By observing the offset from the power after the low pass filter, P_{lp} (21), three different cases arise. Case 1: $V_{TEG} = V_{oc}/2$, which makes P_{lp} zero and indicates that the MPP is reached. Case 2: $V_{TEG} > V_{oc}/2$ which signifies that the load voltage is higher than $V_{oc}/2$ and results in a positive offset. Case 3: $V_{TEG} < V_{oc}/2$ due to the load voltage being lower than $V_{oc}/2$ and equates to a negative offset. The offset, can now be controlled to zero using a PI controller and hence P_{lp} is used as feedback for a proportional integral controller to correct the duty cycle D of the power converter.

The injection frequency is chosen such that it can be resolved well in presence of the 274 power electronic sampling times, e.g. one order of magnitude slower. The high and low pass 275 filter are designed to operate on signals at injection frequency. Hence their bandwidth is 276 chosen at least one order of magnitude lower than the injection frequency. When the HFI 277 scheme is implemented, the power electronic sampling frequency is chosen as $f_{sw}=200$ kHz, 278 the injection frequency is 1kHz, the bandwidth of the high pass filter is 100Hz, and the 279 bandwidth of the low pass filter is 10Hz. The injection amplitude, B, is .05V which is 1.25%280 of the operating TEG voltage. The losses in the converter are estimated to be negligible due 281 to the low magnitude and frequency of the injection signal. 282

283 4. MPPT Experimental Setup

The converter utilized for the experiments was an off-the-shelf evaluation kit from Texas Instruments and the microcontroller is the C2000 TMS320F28377S. The experimental setup for the MPPT experiments is shown in Fig. 9, which has the same electrical configuration as shown in Fig. 6. The TEG module is in the vacuum testing chamber described in Section 2.2 during the MPPT tests performed. For the Perturb & Observe scheme, the closed loop parameters for the current control were $k_p = 0.02$ and $k_i = 7.3 \times 10^{-5}$. For the HFI scheme,



Figure 9: MPPT experimental setup.

Table 2: Converter efficiency.						
$I_{in}\left(A\right)$	$V_{in}\left(V ight)$	$P_{in}\left(W\right)$	$P_{out}\left(W\right)$	$\eta\left(\% ight)$		
0.50	9.01	4.51	3.70	82.2		
1.10	9.01	9.91	8.29	83.7		
1.90	9.01	17.12	14.92	87.2		
0.50	12.0	6.0	4.86	80.9		
0.95	12.0	11.4	10.15	89.0		
1.35	12.0	16.2	14.87	91.7		

the parameters to control the offset, P_{lp} from the low pass filter, to zero were $k_p = 0.05$ and $k_i = 0.01$.

The converter efficiency was also evaluated for various input current and voltages, with the results shown in Table 2.

²⁹⁴ 5. Experimental Results

The following sections present the results from the experiments which were completed to evaluate the performance of the proposed HFI MPPT scheme as well as the most-commonly used P&O MPPT scheme. The MPPT experiments were performed with the TEG module that was characterized in Section 2.3. The experimental setup was previously discussed and is shown in Fig. 9.

The experiments were performed to not only compare the HFI scheme to the P&O scheme, but also to compare the HFI results to other experimental work found in the literature. The

three experiments conducted were similar to those found in [30], which include thermal tran-302 sients. The first experiment is a steady-state test which is commonly used to evaluate how 303 well the MPPT scheme finds the MPP. The second experiment is designed to test the response 304 time of the algorithm. The TEG module is at open-circuit and has a fixed temperature dif-305 ference and suddenly, the tracking scheme is turned-on. This is done to observe how fast the 306 MPPT scheme can find the MPP or half the open circuit voltage. The third experiment is to 307 evaluate how the MPPT scheme performs when the TEG experiences temperature changes 308 $(\Delta T \text{ is not constant})$. This is a more realistic test, as the TEG will experience tempera-309 ture fluctuations when implemented in any waste heat recovery applications as previously 310 discussed in Section 1. 311

312 5.1. Steady-State Performance

The purpose of this steady-state test is to evaluate whether the proposed MPPT scheme-HFI, can accurately track the MPP of the TEG at fixed temperature differences. The MPPs of the TEG module were previously characterized in Section 2.3 for various temperature differences. The P&O scheme was also implemented and tested to have a performance comparison. The steady-state tests were performed as follows: 1) Use the TEG testing facility to reach the desired temperature difference across the TEG, 2) Turn-on the desired tracking scheme (HFI or P&O) and wait for the MPP to be reached while maintaining a fixed temper-

Table 3: Steady-state results: (1) Characterization results for various temperature differences, (2) Experimental MPPT Results for both schemes: V_{MP} , Voltage at max power (MP), P_{MP} power output at MP (3) MPPT performance error compared to characterization.

	Charact. Results		Charact MPPT Results			MPPT Performance				
			Results HFI P&O		zО	HFI		P&O		
ΔT	V_{MP}	P_{MP}	V_{MP}	P_{MP}	V_{MP}	P_{MP}	V_{MP}	P_{MP}	V_{MP} error	P_{MP} error
[C]	[V]	[W]	[V]	[W]	[V]	[W]	[%]	[%]	[%]	[%]
140	2.67	3.02	2.57	3.01	2.92 - 3.24	2.68 - 2.74	3.56	0.27	9.57 - 21.58	9.12 - 11.11
165	3.09	3.95	2.97	3.94	3.35 - 3.68	3.49 - 3.54	3.73	0.26	8.59 - 19.29	10.38 - 11.65
190	3.49	4.94	3.38	4.93	3.89 - 4.19	4.43 - 4.48	3.01	0.17	11.62 - 20.23	9.37 - 10.38
215	3.86	5.93	3.76	5.92	4.14 - 4.86	5.33 - 5.38	2.59	0.15	7.25 - 25.91	9.24 - 10.09

ature difference across the TEG, 3) Wait to reach electro-thermal steady-state and measure
the voltage across the TEG module as well as the current flowing through the TEG.

The results of the steady-state tracking performance for both HFI and P&O are shown in Table 3. The first column tabulates the characterization results. The second column presents the operating TEG voltage and power produced by the TEG module for both schemes. Since the P&O scheme oscillates around the MPP, the operating range is presented. The final column shows the error compared to the expected operating TEG voltage and TEG power output (from characterization). The MPPT scheme errors from Table 3 are also presented in graphical form in Fig. 10.

At steady-state the HFI scheme has a tracking efficiency, defined as operating point of the MPPT scheme (P_{op}) divided by the available max power (MP)

$$\eta_{tracking} = \frac{P_{op}}{MP} \tag{22}$$

of 99.73%. However, the tracking efficiency of the P&O scheme is approximately 90% which 332 has previously been found by other researchers [31]. Although more adaptive P&O schemes 333 can be implemented to achieve higher tracking efficiencies such as variable step sizes when 334 approaching the MPP, the purpose of these experiments was to validate the hypothesis that 335 the proposed HFI scheme can accurately track the MPP. The HFI tracking efficiency for 336 various temperature differences is compared to the P&O tracking efficiency in Fig. 10(c). 337 Further work could be done in designing the DC/DC converter to further reduce losses, 338 however this is out of the scope of this paper. 339

340 5.2. Fast Transient Performance

33

A fast transient test was performed by maintaining the TEG module at a fixed temper-341 ature difference and observing the response when the MPPT scheme was turned on. When 342 the HFI scheme is turned on, as seen in the oscilloscope capture of Fig. 11, the TEG volt-343 age changes from 5.68V and reaches half the open circuit voltage (MPP) of 2.8V in 2.4ms. 344 Compared to similar performance evaluations, [30] completed a similar experiment and their 345 MPPT response time was 8ms, while the researchers [18] had a response of 300ms. To the 346 best of the authors' knowledge, 2.4ms is the fastest settling time that has been reported in 347 the literature. The P&O scheme results are not shown since the sampling time of the scheme 348



Figure 10: Steady-State performance from Table 3 represented in graphical form. (a) Voltage error (%) (b) Power error (%) for various temperature differences (ΔT) (c) Comparison of tracking efficiency for the P&O scheme and HFI scheme.

is 10ms, as previously mentioned. The electro-dynamics need to reach steady-state before
the power is measured for the P&O scheme, hence the settling time would be much higher
than the HFI scheme.

352 5.3. Thermal Transient Performance

The final test to evaluate the performance of the HFI scheme was observing the MPP tracking while the TEG operated under thermal transients. When TEGs harvest energy from waste heat sources such as the exhaust system of a vehicle, they experience variable temperature differences, therefore the MPPT scheme was tested in a transient setting. The test was performed as follows: 1) the TEG module is initially at one temperature difference, 2) the heater power is increased, simultaneously turning on the MPPT scheme, 3) the temperature difference across the TEG is recorded as a function of time, 4) the test is stopped once the



Figure 11: Transient Evaluation: TEG output voltage changes from V_{oc} to $V_{oc}/2$ when HFI MPPT scheme is turned on. Response time is 2.4ms.

temperature stops varying. The temperature difference across the TEG is plotted in green in Fig. 12(b) as a function of time during the tracking of the HFI scheme. The power produced by the HFI scheme is plotted in blue in Fig. 12(b), as well as the theoretical maximum power of the TEG module (red). The theoretical maximum power output of the TEG is calculated from (9) with the parameters from Table 1, since the temperature difference is known every second. The voltage, current, and power generated by the HFI scheme are also shown in the oscilloscope screenshot in Fig. 12(a).

As observed in Fig. 12, the HFI scheme performs well at tracking the MPP over time. The maximum error over the entire time length is 1.3% which makes the tracking efficiency during transient operation 98.7%. The authors in [30] reported the same tracking efficiency during their thermal transient test. Although [32] completed a transient test, their tracking efficiency was not reported and a 0.05W power output difference was presented over 60 mins of tracking.

The P&O scheme was also evaluated during a thermal transient and the results are shown in Fig. 13. As previously discussed, the P&O scheme does not find an exact operating point but instead oscillates around the MPP. Hence, oscillations in the power are observed in Fig. 13(b). The maximum error between the power produced by the P&O MPPT scheme and the expected maximum power is 10%.



Figure 12: Thermal transient: (a) Scope screenshot of TEG voltage and current measurement during HFI tracking (b) Comparison of expected power output as a function of temperature difference (ΔT) of the TEG module versus HFI MPPT power.

378 6. Conclusion

Thermoelectric generators may be implemented for energy harvesting in waste heat recovery applications. However, to improve the efficiency of the system they need to be interfaced with power converters to ensure the maximum power is generated by the TEG. Since waste heat sources such as the exhaust system of a vehicle vary rapidly in their operating conditions, a maximum power point scheme must be employed to track the varying power output by the TEG system.

In this paper, a High Frequency Injection (HFI) maximum power point tracking scheme was proposed and experimentally validated through three different experiments, as well as compared to the most commonly used MPPT scheme in the literature, P&O. The High Frequency Injection scheme works by adding a high frequency signal to the operation of the



Figure 13: Thermal transient: (a) Scope screenshot of TEG voltage and current measurement during P&O tracking (b) Comparison of expected power output as a function of temperature difference (ΔT) of the TEG module versus P&O MPPT power.

TEG, which results in an offset that can be controlled to directly arrive at the TEG's MPP. 389 The experimental results showed that the response time of the proposed MPPT scheme is 390 2.4ms which is 3 times faster than any scheme presented in the literature. An advantage of the 391 proposed scheme is that the algorithm can be implemented into current MPPT hardware, i.e. 392 no additional sensors. The HFI scheme was implemented with an off-the-shelf converter and 393 achieved a tracking efficiency at steady state of 99.73%, comparable to the best steady-state 394 tracking schemes while achieving the fastest recorded dynamics. During thermal transients 395 the HFI MPPT exhibited an efficiency of 98.7%. 396

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