Comparison of control strategies for thermoelectric generator emulator

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ABSTRACT

Thermoelectric generator (TEG) can directly convert heat energy into electrical energy. It improves the power efficiency of the energy generation system by converting the power loss in the form of heat produced during the generation process into additional electrical energy. The TEG emulator (TEGE) is a power converter that produces a similar current-voltage characteristic as the TEG. It is a valuable device used to develop and test the TEG-based energy generation system. Nonetheless, the research on the TEGE is still in the early stage. This paper proposed a proper, low-cost, and high-efficient TEGE design using the buck converter. The contribution of the paper covers the TEG model in the form of an array, the buck converter design tailored to the TEGE, and 4 new control strategies proposed for the TEGE. The control strategies are the direct referencing method (DRM), perturb and observed (PnO) method, resistance comparison method (RCM), and resistance feedback method (RFM). The conventional proportional-integral controller is used to maintain a smooth operation during transient and steady-state periods. The results show the merits or demerits for each proposed control strategy based on the accuracy, transient response, stability, overshoot, and efficiency.

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1. INTRODUCTION

A thermoelectric generator (TEG) or Peltier device is a module that is able to change heat energy to electrical energy directly. The device consists of two sites, the hot and cold sites. The larger the temperature difference between these sites, the higher the output power produced [1]. The current-voltage (I-V) characteristic curve of a TEG module is also not linear, similar to the photovoltaic (PV) module. Nonetheless, the I-V characteristic for the TEG is simpler compared to the PV module. Therefore, the maximum power point tracking (MPPT) algorithm is needed to ensure all the power produced by the TEG module is extracted [2], [3].

During the operation of the PV module, the temperature of the PV module increases resulting in power loss in the form of heat. Several researchers have proposed to hybridize the TEG with the PV module [4]–[6]. This allows the power loss produced to be converted into usable electrical energy. The TEG modules are commonly placed at the back of the PV module, which has a higher temperature compared to the ambient temperature. Due to the temperature difference between the PV module and the air, the power is generated from the TEG. The result from the research shows that there are power increases up to 58% for the
hybrid PV-TEG system when compared to the standard PV system [6]. Besides placing the TEG modules at the back of the PV module, there is also another method that transfer the heat away from the PV module to the TEG modules to further improve the efficiency of the system [7]. Besides PV, the TEG technology is also being implemented in the nuclear auxiliary power and biogas [8]. Therefore, the TEG module is a useful technology that can convert the power loss in the form of heat into useful electrical energy.

In the power electronics field, an emulator is a power supply that generate a specific I-V characteristic. The conventional power supply commonly produces a constant voltage or constant current. However, an emulator voltage and current is not constant and commonly depends on the load. The emulator is commonly used during the development of a product or the testing of the system. The advantages of using the emulator instead of actual components are commonly small in size, highly efficient, lower in cost, safer alternative, easy to configure, and able to repeat the condition of the test. These emulators include the PV emulator [9], [10], wind turbine emulator [11], battery emulator [12], and load emulator (also known as electronic load) [13]. Nonetheless, the research conducted on the TEG emulator (TEGE) is still in the early stage. The current TEGE uses a commercial PV emulator to emulate the I-V characteristic curve of a TEG [14]. Although this approach is applicable, the cost for the conventional PV emulator is high. A proper, low-cost, and high-efficient TEGE design is needed to allow a more convenient development and testing process of the TEG generation system. Therefore, the control strategies from PV emulator is adopted into the TEGE since both PV emulator and TEGE produce same DC output.

The first control strategy available from the PV emulator is the direct referencing method (DRM) [15], [16]. This control strategy is common due to the simple implementation process. It uses the transient response of the closed-loop controller and power converter to determine the operating point of an emulator. Nonetheless, it is susceptible to the changes in the transient response. Since the load change affects the transient response, it can lead to oscillating problem. The perturb and observe (PnO) control strategy for the emulator is based on the common MPPT algorithm [17]. It is based on a fixed step size to determine the operating point of an emulator. As a result, it produces large oscillation similar to the MPPT if the step size is not properly tuned. The resistance comparison method (RCM) is another control strategy available in emulator [18], [19]. Instead of using continuously calculating the operating point like the DRM and PnO, the RCM calculating the operating point first before producing the reference input. It allows a more stable emulation. However, the processing burden is high. The resistance feedback method (RFM) is similar to RCM, with lower computation burden [9], [20]. Nevertheless, the model needs to be mathematically modified.

This paper proposed the TEGEs using the buck converter. There are four control strategies proposed for the TEGE (adopted from the PV emulator) and the control strategies are simulated individually. The array TEG model has been proposed for a higher power application in the TEGE. The modified design of the buck converter is also proposed to fit the TEGE application for maintaining the continuous current mode operation and at a specific output voltage ripple. The standard proportional-integral (PI) controller is applied for the TEGE. The paper is based on the simulation using MATLAB/Simulink. The simulation results are designed to prove the derivation of the buck converter and the performance of the proposed control strategies. The next section proposed the design of the TEGE. Section 3 shows the results and discussions. The latter section deduces the finding from the simulation.

2. PROPOSED DESIGN FOR THERMOELECTRIC GENERATOR EMULATOR

The TEGE consists of four main components, which is the TEG model, power converter, closed-loop controller for the power converter, and control strategy. The power converter used for the TEGE is the buck converter. While the closed-loop controller used for the TEGE is the PI controller.

2.1. Thermoelectric generator array model

The TEG mathematical model for a single module is shown in (1) [1], [21]. The power produced for a single TEG module is low and it is not suitable for power generation. Therefore, the modules need to be connected in the series and parallel connection, as shown in Figure 1. Assume each TEG receive the same temperature and has the same $S_{teg(u)}$, $\Delta T$, and $R_{int(u)}$. Using thevenin theorem, the thevenin resistance, $R_{th}$, is derived and shown in (2). By applying the Kirchhoff current law at the $V_{teg}$, the derivation becomes in (3). The thevenin voltage, $V_{th}$, which is also the open-circuit voltage, $Voc$, is derived from in (4) to become (4). By applying the Kirchhoff voltage law, $V_{teg}$ becomes in (5). By substituting in (2) and (4) into (5), the TEG model array is shown in (6).

$$V_{teg(u)} = S_{teg(u)}\Delta T - I_{teg(u)}R_{int(u)}$$  \hspace{1cm} (1)

$$R_{th} = R_{int} = \frac{N_{ser}R_{int(u)}}{N_{par}}$$  \hspace{1cm} (2)
\[
\frac{N_{par}(V_{th}-N_{ser}S_{teg(u)}\Delta T)}{N_{ser}R_{int(u)}} = 0
\]  
(3)

\[V_{th} = V_{oc} = N_{ser}S_{teg(u)}\Delta T
\]  
(4)

\[V_{teg} = V_{th} - I_{teg}R_{th}
\]  
(5)

\[V_{teg} = N_{ser}S_{teg(u)}\Delta T - \frac{N_{ser}I_{teg}R_{int(u)}}{N_{par}}
\]  
(6)

Where \(V_{teg(u)}\) is the voltage of a TEG module, \(S_{teg(u)}\) is the seebeck coefficient of a TEG module, \(\Delta T\) is the temperature difference between the hot and cold sites (\(\Delta T = T_h - T_c\)), \(T_h\) is the temperature at hot site, \(T_c\) is the temperature at cold site, \(I_{teg(u)}\) is the current of a TEG module, \(R_{int(u)}\) is the internal resistance of a TEG module, and \(N_{ser}\) is the number of TEGs in series and \(N_{par}\) is the number of TEGs in parallel.

![Figure 1](https://example.com/f1.png)

**Figure 1.** The equivalent circuit of the TEGs connected in series and parallel

### 2.2. Buck converter design

When it comes to emulator applications, the buck converter shines as it can handle various tasks effectively while maintaining a minimal component count. These components are the power switch, diode, inductor, and capacitor, as presented in Figure 2. When designing a buck converter, three parameters need to be considered, which are the duty cycle (\(D\)), continuous current mode operation, and the output voltage ripple. The design for the buck converter is widely known [22]. Nonetheless, these designs not consider the dynamic operation of an emulator. Therefore, the conventional buck converter is modified to suit the TEGE.

![Figure 2](https://example.com/f2.png)

**Figure 2.** The equivalent circuit of the buck converter

The input voltage, \(V_i\), is based on the \(V_{oc}\) of the PV array at the highest temperate difference of the TEG, \(\Delta T_{max}\). Therefore, the \(V_i\) is calculated using (7). Since the \(D\) relates to \(R_o\) for the TEGE, the minimum
and maximum $R_o$ ($R_o\text{(min)}$ and $R_o\text{(max)}$, respectively) need to be calculated based on the minimum and maximum $D$ ($D_{\text{min}}$ and $D_{\text{max}}$, respectively). For MPPT application, the $R_o\text{(min)}$ and $R_o\text{(max)}$ is consistent based on the maximum power point theory, which is shown in (8).

$$V_i = N_{\text{ser}}S_{\text{teg}}(\Delta T)_{\text{max}} \tag{7}$$

$$R_o\text{(max)} = R_o\text{(min)} = \frac{N_{\text{ser}}R_{\text{int}}(u)}{N_{\text{par}}} \tag{8}$$

For emulation purposes, the range of emulation is based on $D_{\text{min}}$ and $D_{\text{max}}$. To relate the $D$ with $R_o$, the TEG model is modified. In (9) is substituted into (6) and produces (10). Since the $R_o\text{(max)}$ occurs at $D_{\text{max}}$, (10) is modified to become (11), which the assumption is the requirement of the $R_o\text{(max)}$ occur when the $\Delta T$ is at maximum. The $D_{\text{max}}$ is calculated based on (12). Therefore, the $R_o\text{(max)}$ is calculated using (13). Using the same approach, the $R_o\text{(min)}$ is calculated using (14).

$$I_{\text{teg}} = \frac{V_{\text{teg}}}{R_{\text{teg}}} \tag{9}$$

$$R_o = \frac{N_{\text{ser}}R_{\text{int}}(u)V_{\text{teg}}}{N_{\text{par}}(N_{\text{ser}}S_{\text{teg}}(\Delta T)V_{\text{teg}})} \tag{10}$$

$$R_o\text{(max)} = \frac{N_{\text{ser}}R_{\text{int}}(u)V_{\text{teg}}(\Delta T)}{N_{\text{par}}(N_{\text{ser}}S_{\text{teg}}(\Delta T)\Delta TV_{\text{teg}}(\Delta T))} \tag{11}$$

$$V_{\text{teg}}(\Delta T) = D_{\text{max}}N_{\text{ser}}S_{\text{teg}}(\Delta T)_{\text{max}} \tag{12}$$

$$R_o\text{(max)} = \frac{N_{\text{ser}}R_{\text{int}}(u)\Delta T_{\text{max}}}{N_{\text{par}}(1 - D_{\text{max}})} \tag{13}$$

$$R_o\text{(min)} = \frac{N_{\text{ser}}R_{\text{int}}(u)\Delta T_{\text{min}}}{N_{\text{par}}(1 - D_{\text{min}})} \tag{14}$$

Maintaining the continuous current mode hinges on the precise choice of inductance, $L$. Based on the conventional buck converter design, the $L$ required to maintain the continuous current mode is shown in (15). The output voltage ripple is maintained by choosing the right capacitance, $C$. Based on the conventional buck converter design, the $C$ required to maintain the output voltage ripple is shown in (16).

$$L \geq \frac{(1 - D_{\text{max}})R_o\text{(max)}}{2f_s} \tag{15}$$

$$C \geq \frac{(1 - D_{\text{min}})}{8L\gamma_{\text{Vo}}f_s} \tag{16}$$

Where $f_s$ is the switching frequency and $\gamma_{\text{Vo}}$ is the output voltage ripple factor.

### 2.3. Proportional integral controller

Commonly, an emulator requires a closed-loop controller for the power converter used within the emulator. This applies to the TEGE. Due to its prevalent usage in emulator applications, the PI controller is selected as the preferred option. This is due to the simplicity of the PI controller ($G_p$), as shown in (17), and the availability of the transfer function for the buck converter ($G_{\text{buck}}$), as shown in (18) [23, 24]. The arrangement of the $G_p$ and $G_{\text{buck}}$ is shown in Figure 3. The proportional and integral gains, $K_p$ and $K_i$, respectively, are tuned automatically using the single input single output (SISO) tool available in MATLAB.

$$G_p(s) = K_p + \frac{K_i}{s} \tag{17}$$

$$G_{\text{buck}}(s) = \frac{\frac{V_i}{L}}{s^2 + \frac{1}{R_oC} + \frac{1}{LC}} \tag{18}$$
2.4. Control strategies

The main purpose of the control strategy is to pinpoint the appropriate operating point for the TEGE. Four control strategies are proposed, which are the DRM, PnO, RCM, and RFM. The TEG model, PI controller, and buck converter is kept constant for all control strategies.

2.4.1. Direct referencing method

The DRM is a simple control strategy that uses the transient response of the TEGE to determine the operating point. This control strategy is adopted from the common control strategy used in the PV emulator [15], [16]. The $I_o$ is measured and fed into the TEG model, as shown in Figure 4. The TEG model produces the reference voltage, $V_{ref}$, and it is compared with the $V_o$ before going to the PI controller. The PI controller determines the $D$ for the buck converter. The process is repeated until the $V_{ref}$ is equal to $V_o$.

![Figure 4. The block diagram of the DRM](image)

2.4.2. Perturb and observe method

The PnO uses fixed step sizes instead of relying fully on the transient response of the TEGE. This is expected to be a more robust control strategy when compared to the DRM while maintaining its simplicity. The PnO is adopted from the common MPPT algorithm used in the PV generation application [25]. The $I_o$ is measured and fed into the PnO, as shown in Figure 5(a). The $I_o$ is used to determine the $V_{teg}$, as shown in Figure 5(b). The $V_{teg}$ is compared with the $V_o$. If $V_{teg}$ is larger than $V_o$, the $V_{ref}$ is increased with a fixed step size called the perturbation voltage, $V_{per}$. If $V_{teg}$ is smaller than $V_o$, the $V_{ref}$ is decreased with a fixed step size of $V_{per}$. The $V_{ref}$ is compared with the $V_o$ and the difference is fed into the PI controller. The PI controller determines the $D$ for the buck converter. The process is repeated until the $V_{ref}$ is equal to $V_o$. The $V_{per}$ and perturbation time ($t_{per}$) are 0.1 V and 30 µs, respectively.

![Figure 5. The PnO: (a) block diagram and (b) flowchart](image)

2.4.3. Resistance comparison method

The RCM uses both $V_o$ and $I_o$ to determine the operating point. As a result, the $V_{ref}$ produced is expected to be more stable compared to the DRM and PnO. The RCM is modified from the RCM obtained from the PV emulator that uses an integral controller to determine the operating point [19], [26], [27]. The process starts by measuring the $V_o$ and $I_o$. Then the $R_o$ is digitally calculated by dividing $V_o$ with the $I_o$. As the
result, the $R_o$ is determined instantaneously. However, the TEG model only has current and not resistance as the input. Therefore, the integral controller is used to convert the resistance input into the current input. The $R_o$ is compared with the TEG resistance, $R_{teg}$, by dividing the $V_{teg}$ with the $I_{teg}$, as shown in Figure 6. The difference is fed into an integral controller with RCM gain, $K_{rcm}$. The $K_{rcm}$ is adjusted based on the response of the TEG using the try and error method. The $V_{ref}$ is obtained from the $V_{teg}$ at a much faster rate. Therefore, the operating point is produced before the transient period of the TEGE ended. This is expected to produce a more robust control strategy.

![Figure 6. The block diagram of the RCM](image)

### 2.4.4. Resistance feedback method

The RFM uses both $V_o$ and $I_o$ as the feedback, similar to the RCM. Nevertheless, the RFM has the simplicity of the DRM. Unfortunately, it requires a modification of the TEG model. The control strategy is adopted from the PV emulator [20]. The process starts by changing the $I_{teg}$ input of the TEG model using Ohm’s Law, as shown in (9). In (9) is substituted into (6) and produces (19). This new TEG model has $R_{teg}$ as the input. Referring to Figure 7, the $V_o$ and $I_o$ are measured and the $R_o$ is digitally calculated. Using the modified TEG model, the $V_{ref}$ is instantaneously calculated. The $V_{ref}$ is compared with the $V_o$ and the difference is fed into the PI controller. The PI controller determines the $D$ for the buck converter. The process is repeated until the $V_{ref}$ is equal to $V_o$.

\[
V_{teg} = \frac{N_{par} N_{ser}(u) \Delta T}{N_{par} N_{int}(u) + 1}
\]

(19)

![Figure 7. The block diagram of the RFM](image)

### 3. RESULTS AND DISCUSSIONS

The results and discussions consist of two parts that cover two proposed designs. The first analysis is conducted to determine the accuracy of the buck converter design for the TEGE application. While the second part analyses the performance of the control strategies. The control strategies are simulated with various $R_o$ ranging from 1 Ω to 85 Ω. The $T_h$ and $T_l$ are kept at 100 °C and 30 °C, respectively. The temperature changes are not analyzed for this paper.

#### 3.1. Design analysis of buck converter for thermoelectric generator emulator

The analysis of the buck converter for the TEGE focuses on the duty cycle, continuous current mode operation, and output voltage ripple factor. If the derivation is accurate, the simulation follows the design specification of the buck converter for the TEGE. This means that the duty cycle is between the minimum and maximum value. While the current at the inductor don’t become zero during steady state condition. Lastly, the output voltage ripple factor doesn’t go above the desired value.
3.1.1. Duty cycle

When designing the emulator, the $R_o$ relates to the $D$. If the $R_o$ is not properly calculated, the $D$ can be out of the range between $D_{\text{min}}$ and $D_{\text{max}}$. Therefore, it is essential to calculate the $R_{o(\text{min})}$ and $R_{o(\text{max})}$. The design specification for the $D_{\text{min}}$ and $D_{\text{max}}$ is 0.1 and 0.9, respectively. Based on this specification, the $R_{o(\text{min})}$ and $R_{o(\text{max})}$ are 1 $\Omega$ to 85 $\Omega$, respectively. The simulated $D$ is shown in Figure 8. The result shows that all the TEGEs maintain its operation within the boundary of the $D$. Therefore, the derived (13) and (14) is accurate. Note that the $D$ is slightly higher for $R_{o(\text{min})}$ and $R_{o(\text{max})}$ due to the effect of the nonideality of various components in the buck converter.

3.1.2. Continuous current mode

Ensuring continuous current mode operation is crucial in the design of the buck converter. If the buck converter switches to discontinuous current mode, it alters the transfer function, necessitating a distinct type of PI controller. Consequently, to ensure proper design of the PI controller, it is imperative to maintain continuous current mode in the buck converter consistently. This is done by a proper design of $L$ using (15).

The continuous current mode operation in the simulation is observed using the minimum inductor current, $I_{L(\text{min})}$, which never goes to zero. Based on the result in Figure 9, the $I_{L(\text{min})}$ never goes to zero. This indicates that the derived (15) is accurate. The $I_{L(\text{min})}$ becomes smaller as $R_o$ increases.

3.1.3. Output voltage ripple

The output voltage ripple is controlled by choosing the right $C$. The $C$ is calculated using (16). The output voltage ripple is measured using the $\gamma_{V_o}$, and is calculated using (20). Based on the derived (16), the highest $\gamma_{V_o}$ should occur when the $R_{o(\text{min})}$ is connected, which the TEGE operates at $D_{\text{min}}$. However, the simulation result does not follow the design, as shown in Figure 10. The maximum $\gamma_{V_o}$ should be 1%, yet it is only 0.41% only. This shows that the derived equation produces an overdesign buck converter for the TEGE. Although this considers following the design parameter, the overdesign results in slower transient response. Therefore, a more accurate design is needed for the $C$ of the buck converter used in the TEGE application.

$$\gamma_{V_o} = \frac{(V_{o(\text{max})}-V_{o(\text{min})})}{V_o} \times 100\%$$  \hspace{1cm} (20)

Where $V_{o(\text{max})}$ is the maximum output voltage and $V_{o(\text{min})}$ is the minimum output voltage.

![Figure 8. The $D$ against $R_o$](image)

![Figure 9. The $I_{L(\text{min})}$ against $R_o$](image)

![Figure 10. The $\gamma_{V_o}$ against $R_o$](image)
3.2. Performance analysis for control strategies

The performance analysis of the proposed control strategies for the TEGE focuses on the accuracy, transient response, operating point stability, percentage overshoot, and efficiency. This analysis shows the advantages and disadvantages of the proposed control strategies. A good control strategy should have high accuracy, fast transient response, stable operating point, low or no overshoot, and high efficiency.

3.2.1. Accuracy

Accuracy plays a pivotal role in emulator applications, and it encompasses three types of analysis: emulator accuracy, model accuracy, and control strategy accuracy. In the case of the TEGE, the emulator accuracy assesses the conformity between the TEGE's output and the TEG array's output. The model accuracy evaluates the alignment between the TEG model and the TEG array. Lastly, the control strategy accuracy compares the TEGE's output with the TEG model. As the paper's main focus revolves around control strategies, the accuracy of the control strategy is utilized to evaluate the precision of the proposed TEGE. The accuracy of the TEGE is analysed using the percentage voltage error, $e_{\%v}$, which is calculated based on the TEGE voltage ($V_{\text{tege}}$) and the voltage of the TEG model ($V_{\text{tegm}}$), as shown in (21). The lower the $e_{\%v}$, the higher the accuracy.

$$e_{\%v} = \frac{|V_{\text{tege}} - V_{\text{tegm}}|}{V_{\text{tegm}}} \times 100\%$$  \hspace{1cm} (21)

The results in Figure 11 show that the accuracy of the DRM is higher compared to other control strategies. However, the accuracy of the DRM changes with $R_o$. The $e_{\%v}$ is low around 0.0004% when the load is 31 Ω and 68 Ω. However, the accuracy becomes lower when the $R_o$ is at the minimum and maximum limit, which the $e_{\%v}$ is around 0.5%. This irregular change inaccuracy is due to the dependency of the DRM on the other components in the TEGE, such as the buck converter, PI controller, and TEG model. For this particular design specification, the accuracy produced is high. Nevertheless, the accuracy changes with the different design specifications. The PnO, RCM, and RFM don't depend on external components like the DRM. Therefore, the accuracy is almost similar even the $R_o$ changes, which is around 0.02% to 0.04%. In conclusion, the PnO, RCM, and RFM have consistent accuracy. While the accuracy of the DRM depends on the parameters of the components used in the TEG.

![Figure 11: The $e_{\%v}$ against $R_o$](image)

3.2.2. Transient response

The transient response is an important aspect of the TEGE. The TEG array has a fast response. However, this fast response cannot be emulated since the buck converter is used. This is because both converters contain $L$ and $C$ that result in a slow transient response. The response can be improved by choosing a higher $f_s$. Still, the computation time for the digital controller in the TEGE may not be compatible if the buck converter is too fast. Therefore, a suitable $f_s$ needs to be chosen if the hardware is implemented. For this paper, this relationship is not considered. The transient response of the TEGE is measured using the settling time, $T_s$. The $T_s$ is the time taken for the $V_o$ to be within 2% of its final values. The $T_s$ during start-up is simulated and recorded in Figure 12.

The results show that the DRM and PnO has similar $T_s$ at various $R_o$. While the RCM and RFM show similar almost similar $T_s$ at various $R_o$. The DRM and PnO have faster responses compared to the RCM and RFM. This is due to the characteristic of the $V_{\text{ref}}$ during the transient period. For the DRM and PnO, when the TEGE starts, the $I_o$ is low. The $I_o$ is fed into the TEG model. When the TEG model receives a low $I_o$ during the transient period, the TEG model produces a high $V_{\text{ref}}$, as shown in Figure 13(a). This high $V_{\text{ref}}$
produces a fast response by the PI controller, which result in a lower \( T_s \). As the TEGE comes closer to the steady-state, the \( I_o \) increases, and the \( V_{\text{ref}} \) decreases. This characteristic of the \( V_{\text{ref}} \) allows for a faster transient response. However, this characteristic also affects the performance of the PI controller. The properly tuned PI controller may become unstable. The design of the PI controller is also affected by this characteristic. Although the RCM and RFM have a slower response compared to the DRM and PnO, the \( V_{\text{ref}} \) produces is consistent, as shown in Figure 13(b), and it does not affect the design of the PI controller. In conclusion, DRM and PnO are faster compared to RCM and RFM, but affect the design of the PI controller. The RCM and RFM don’t affect the design of the PI controller.

![Figure 12. The \( T_s \) against \( R_o \)](image)

![Figure 13. The \( V_o \) and \( V_{\text{ref}} \) against time at \( R_o \) of 5 \( \Omega \), (a) DRM and (b) RFM](image)

### 3.2.3. Operating point stability

The stability of the operating point is the ability of the control strategy to maintain a stable reference input for the TEGE. The stability of the operating point is analyzed using the reference voltage ripple factor, \( \gamma_{V_{\text{ref}}} \), which is calculated using (22). The higher the \( \gamma_{V_{\text{ref}}} \), the more unstable the operating point, which leads to unstable TEGE. A good control strategy has \( \gamma_{V_{\text{ref}}} \) equal to 0%, which can be considered as a robust control strategy.

\[
\gamma_{V_{\text{ref}}} = \frac{|V_{\text{ref}}(\text{max}) - V_{\text{ref}}(\text{min})|}{V_{\text{ref}}} \times 100%
\]

(22)

Where \( V_{\text{ref}}(\text{max}) \) is the maximum reference voltage and \( V_{\text{ref}}(\text{min}) \) is the minimum reference voltage in one period of the buck converter switching operation.

The advantage of using both \( V_o \) and \( I_o \) as the feedback for the TEG is that the operating point can be determined instantaneously, which result in 0% \( \gamma_{V_{\text{ref}}} \) displayed in Figure 14. Therefore, the operating point is stable. This means that there is no need to focus on the other component affecting the performance of the TEGE. On the other hand, the DRM and PnO have high \( \gamma_{V_{\text{ref}}} \), especially when the \( R_o \) is low (1.36% \( \gamma_{V_{\text{ref}}} \)). The DRM determines the operating point of the TEGE by measuring the \( I_o \) only. Based on the \( I_o \), the \( V_{\text{ref}} \) is calculated based on the TEG model. Since the buck converter is used, the \( I_o \) contain ripples. These ripples result in unstable operating points. Since the ripple is higher at lower \( R_o \) for buck converter, the \( \gamma_{V_{\text{ref}}} \) becomes higher at low \( R_o \). The PnO also produce a high \( \gamma_{V_{\text{ref}}} \) Since it also used the \( I_o \) as the feedback. The \( \gamma_{V_{\text{ref}}} \) is higher when compared to the DRM since the PnO uses a fixed step size. Nonetheless, the PnO algorithm response is slower compared to DRM, which does not result in an unstable emulation. In conclusion, the RCM and RFM produce a stable operating point. While, the operating point for the DRM and PnO has high \( \gamma_{V_{\text{ref}}} \), especially when the \( \gamma_{V_{\text{ref}}} \) is low.
3.2.4. Percentage overshoot

The PI controller for the TEGE is designed to operate in optimally damped conditions. This means that the transient response of the buck converter is the fastest without any $V_o$ overshoot occurring during start-up. Some of the control strategies disturb the PI controller design that causes the overshoot to occur. Therefore, this analysis is essential to determine the robustness of the control strategies. The overshoot is measured using the percentage overshoot, %OS, and it is calculated using (23).

$\%OS = \frac{|V_{o(max)}-V_o|}{V_o} \times 100\%$ (23)

The results presented in Figure 15 shows that the RCM and RFM do not produce any overshoot. This shows that these control strategies do not disturb the PI controller operation, thus, making these control strategies a more robust choice. The DRM produce a high %OS of 0.08% when the $R_o$ is 1 $\Omega$. Nevertheless, the %OS decreases as the $R_o$ increases. This effect is caused by the significant increases in the $V_{ref}$ during the start-up, which results the overshoot. The effect is less as the $R_o$ increases because there is no significant increase in $V_{ref}$ as the $R_o$ increases. The overshoot in the PnO is around 0.03% and it is nearly consistent for all $R_o$. The overshoot is caused by the fixed step size used in the PnO. This can be improved by using a smaller step size. However, this leads to slower transient response.

![Figure 14: The $\gamma_{V_{ref}}$ against $R_o$](image)

![Figure 15: The %OS against $R_o$](image)

3.2.5. Efficiency

The efficiency is one of the performances that need to be analyzed for the TEGE. A good TEGE should have high efficiency. The efficiency of the TEGE, $\eta$, is calculated using (24). The $\eta$ for various control strategies and at various $R_o$ is shown in Figure 16. The results show that the control strategies do not affect the $\eta$. This is because all four control strategies show similar $\eta$. Based on the results, the $\eta$ is low when the $R_o$ is low. As the $R_o$ increases, the $\eta$ increases up to 96%. The $\eta$ is low when the $R_o$ is low because the $I_o$ is high during that condition. As the result, the $I_i$ and the inductor current ($I_L$) is also high. Since there is resistance at the MOSFET and inductor, power loss occurs at these components. Since the current is high, the power loss is significant, thus producing a lower $\eta$:

$\eta = \frac{V_oI_o}{V_iI_i} \times 100\%$ (24)

where $I_i$ is the input current.

![Figure 16: The $\eta$ against $R_o$](image)
3.2.6. Performance summary

The performance of the control strategy is summarized in Table 1. If an accurate TEGE is needed, the DRM should be implemented. The high accuracy is caused by the variable step sizes produce by the DRM. The DRM and P&O has faster response compared to the RCM and RFM, even though the PI controller used is the same. However, the DRM and P&O produce oscillating operating point and high overshoot. While the RCM and RFM produce a stable operating point and a no overshoot. The result shows that the efficiency remain the same for all control strategies. This means that the efficiency does not affect by the control strategies. However, it is shown that the efficiency is low when the $R_e$ is low. At this condition, the current passing through the components in the buck converter is high, which result in a high-power loss.

<table>
<thead>
<tr>
<th>Control strategy</th>
<th>DRM</th>
<th>P&amp;O</th>
<th>RCM</th>
<th>RFM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accuracy</td>
<td>High</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>Transient response</td>
<td>Fast</td>
<td>Fast</td>
<td>Slow</td>
<td>Slow</td>
</tr>
<tr>
<td>Operating point stability</td>
<td>Oscillate</td>
<td>Oscillate at low $R_e$</td>
<td>Stable</td>
<td>Stable</td>
</tr>
<tr>
<td>Percentage overshoot</td>
<td>High at low $R_e$</td>
<td>High</td>
<td>No overshoot</td>
<td>No overshoot</td>
</tr>
<tr>
<td>Efficiency</td>
<td>Low at low $R_e$</td>
<td>Low at low $R_e$</td>
<td>Low at low $R_e$</td>
<td>Low at low $R_e$</td>
</tr>
</tbody>
</table>

4. CONCLUSION

This research aim is to propose a proper, low-cost, and high-efficient design of a TEGE using the buck converter. The objectives of the research include the TEG model in the form of an array, the buck converter design specific to the TEGE application, and the control strategies. The TEG array has been derived using the Thevenin Theory. The buck converter design has been proved to operate within the duty cycle limit and in the continuous current model. Nonetheless, the derivation of the capacitance required to maintain the output voltage ripple needs to be improved. For accuracy, the proposed DRM has high accuracy. However, the accuracy is inconsistent. The proposed DRM and P&O has a faster transient response when compared to the proposed RCM and RFM. Nevertheless, the RCM and RFM has better operating point stability and has no overshoot compared to the DRM and P&O. The research also concludes that the control strategy does not affect the efficiency of the TEGE. In conclusion, a proper, low-cost, and high-efficient design of a TEGE using the buck converter has been proposed together with four new control strategies for the TEGE.

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