Synergetic Control Based Fast-Converging MPPT Technique for Thermoelectric Generator Energy System

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Abstract

Recently, waste heat energy recovery has attracted the attention of many researchers. The power conversion efficiency of Thermoelectric Generator (TEG) system is enhanced by designing suitable MPPT controller. In this study a robust nonlinear control technique based on synergetic control theory is designed to extract maximum power from Thermoelectric Generator system (TEG). The designed synergetic control law ensures the fast convergence towards maximum power operating point without any oscillations under the presence of system uncertainties and variable temperature conditions. The TEG system comprises of a Thermoelectric Generator module, power converter, maximum power point tracking algorithm and load. The simulation results show viability of proposed strategy in comparison with Perturb and Observe (P&O) method under variable temperature.

Keywords: *Synergetic control, Maximum power point, DC-DC converter,Thermoelectric Generator.*

1. Introduction

Generally, in the transport and industrial segments, a considerable amount of thermal energy is lost as heat. To utilize a portion of this waste heat, thermoelectric generator (TEG) based systems are best choice. The TEG is a solid-state device which converts thermal energy into electrical energy using the seebeck effect. The other type of thermoelectric devices also transforms the electric current into temperature gradient through peltier effect, that can be used for heating or cooling. Some of the advantages offered by TEGs are no pollution, long lifetime, compact in size, light in weight, noise free operation due to non presence of moving parts, autonomous on weather conditions, low maintenance cost and renewable energy resource. However, they suffer from a significant disadvantage of low conversion efficiency, which is usually lower than 10%. The applications of TEG based systems are electric power production in harsh and severe conditions such as, space industry, radioactive environments, remote areas etc., disperse heat recovery in industrial plants and transport like automobile, airplane, ships etc, domestic applications, micro-TEGs for sensors and microelectronics and the use of hybrid combined heat power solar systems[1].

To enhance the efficiency of the TEG system by exploiting the maximum power harvested. To achieve this, a power converter equipped with a suitable algorithm for MPPT is essential, which anticipates developing the most extreme power that is harvested by TEG. The MPPT system is a static DC/DC converter is combined with TEG to drive it to operate at its maximum power point (MPP).

The open circuit voltage method, short circuit current method, Ripple Correlation Control (RCC), Perturb and Observe (P & O), Incremental Conductance (INC) and sliding mode control methods [2] are the existing MPPT techniques for TEG systems. Traditional hill climbing approach is simple and flexible to adapt. However, it has a few difficulties like fluctuations of operating point nearby MPPT, entails long duration to estimate MPP, rapidly changing weather conditions and ineffective operation under Partial Shading Circumstances (PSC); it decreases the complete system efficiency. Open circuit voltage (V_{oc}) based MPPT is basic and easy to implement, yet it is

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essential to estimate the Voc intermittently by commutating the converter instantly, results in a momentary loss of power [3]. The MPPT is working with the short circuit current approach of TEG module is a prerequisite to estimate the short circuit current (I_{sc}). The SMC is used for MPP tracking in photovoltaic systems suffers from the drawback of chattering phenomenon which causes high frequency oscillations around MPP [4].

Synergetic control (SC) is a non-linear control strategy similar to sliding mode control utilizes the advantage of variable structure nature of the system and achieves the objective using switching control by changing structure form one state to another state continuously [5]. Compared to SMC the SC is more robust to load changes and parameter variations and improving the control performance with reduced chattering, finite time convergence and less steady state error.

In this paper design and analysis of a nonlinear control scheme based on synergetic control theory is carried out to extract maximum power of TEG using boost converter as MPPT system. This robust controller performs well for the systems with modeling uncertainties and external disturbances, and overcomes the disadvantage of conventional MPPT methods which only can be applied to systems with negligible external disturbances.

The organization of the work is as per the following, the Section 2, presents TEG module and TEG modeling, operation of MPPT system, boost converter. Section 3 explains the design of synergetic control (SC) technique. In Section 4, simulation results are analyzed to validate the effectiveness of synergetic control (SC) in comparison to P&O technique. The conclusions are given in the last section.

2. Thermoelectric Generator System

Using the seebeck effect, a thermocouple can convert a temperature difference between its two plates to electricity. Thermocouples are reversible devices used to change thermal energy into electricity (TEGs) and vice versa, electricity into thermal energy (cooling apparatus). However, the energy delivered by one thermocouple is not enough to feed the majority of applications why an assemblage of many thermocouples is required.

Fig.1 presents a typical structure of a Thermoelectric Generator. A voltage is produced when a temperature difference is created between two different metals; T_H and T_C are respectively the hot side and the cold side temperature of the thermoelectric element.

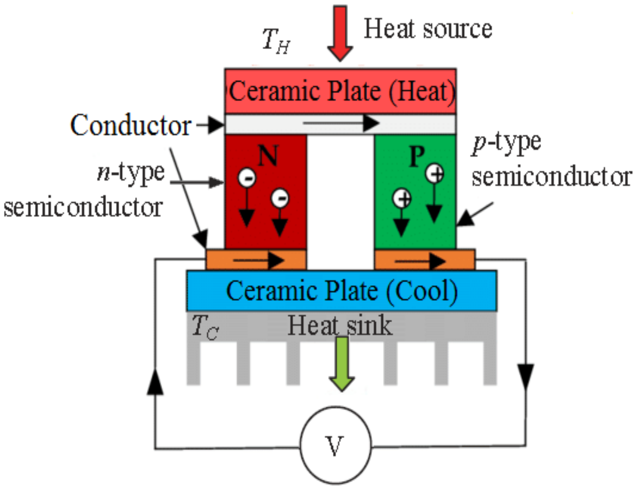

Fig.1. Structure of Thermoelectric Generator

The electrical model of the TEG, shown in Fig. 2 consists of a voltage source with open circuit voltage $V_{oc,TEG}$ and a resistance R_{TEG} in series representing equivalent internal resistance

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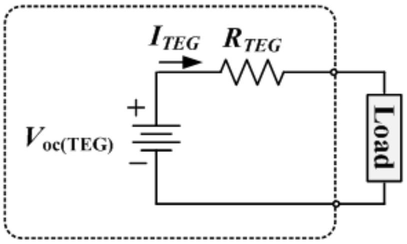

Fig. 2. Model of a Thermoelectric Generator

The output voltage of TEG, which is a function of the generated current I_{TEG} is obtained as,

$$V_{TEG} = V_{oc,TEG} - R_{TEG}\ I_{TEG} \tag{1}$$

$$V_{oc,TEG} = n\,\alpha(T_H - T_C) \tag{2}$$

$$R_{TEG} = n\,R_{th} \tag{3}$$

Where n is the number of thermocouples; α is the Seebeck coefficient; T_H and T_C are hot and cold temperatures; and R_{th} is the elementary resistance.

The ratings of the TEG (HZ-20) considered: material: Bismuth Telluride, Weight = 115 g, Module dimensions = 7.5 x 7.5 x 0.5 cm, Number of thermocouples = 71, Max. continuous temperature = 250°C, Hot and Cold side temperatures (Design) T_H = 230 °C and T_C =30 °C, Thermal Conductivity, λ =0.024 W/cm.K, $P_{max\ (TEG)}$ =19 W, Voltage across Load = 2.38 V, R_{TEG} = 0.3 Ω, $I_{sc\ (TEG)}$ = 8 A, $V_{oc\ (TEG)}$ =5 V, Efficiency = 4.5 %.

Fig. 3 demonstrates the impact of temperature on the MPP locations in P-V and I-V curves of a single TEG unit. Figure 3(a) demonstrates the variation between terminal voltage and the TEG power generated when there is increase in the temperature. It is can be understood that the generated power increases when there is increase in the temperature. As shown in the Fig. 3(b), the increase in the temperature forces the generated current to increase

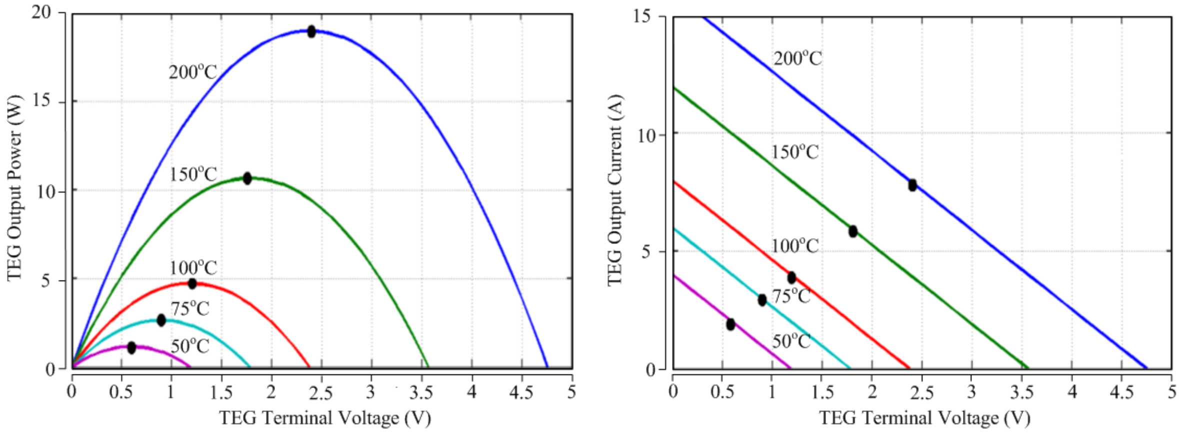

Fig. 3. Impact of temperature on TEG (a) output power (b) output current

The block diagram shown in fig.4 shows the represents the TEG system with MPPT, consist of TEG module of three TEGs (HZ-20) connected in series, DC-DC converter, load and the designed synergetic controller to ensure the maximum power form TEG source. The operation of TEG system is desired always at or close to maximum power point, which is ensured by MPPT controller.

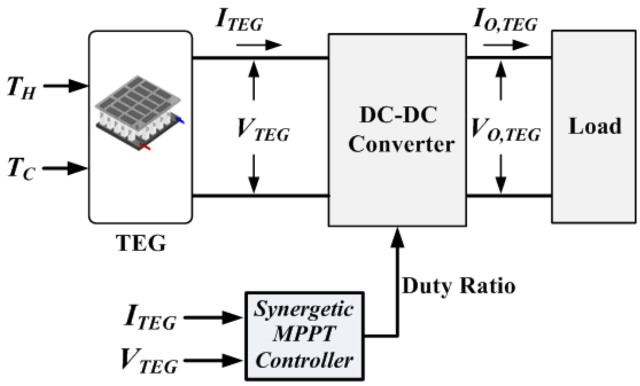

Fig. 4. Schematic diagram of TEG system with synergetic controlled MPPT

The continuous extraction of maximum power is accomplished through continuous switching of the boost converter by controlling the duty cycle, shown in fig. 5. The output ($V_{0,TEG}$) which is the voltage across load is always greater than or equal to the input $V_{IN} = V_{TEG}$ which is generated TEG voltage. The voltage level conversion is controlled by switching on and off of the switch S at a high frequency [6-7].

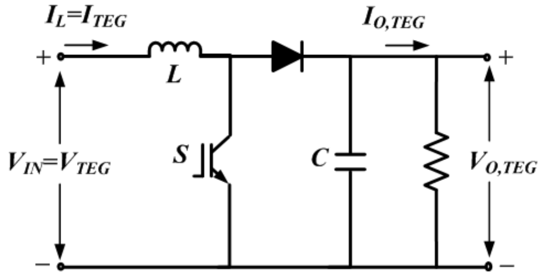

Fig. 5. Circuit model of boost converter

The dynamic equations when the duty cycle D = 1, switch (S) is ON are given as,

$$\frac{dI_L}{dt} = \frac{1}{L} V_{TEG} \quad \& \quad \frac{dV_{o,TEG}}{dt} = -\frac{1}{RC} V_{o,TEG} \tag{4}$$

The dynamic equations when the duty cycle D = 0, switch (S) is OFF are given as

$$\frac{dI_L}{dt} = \frac{1}{L} V_{TEG} - \frac{1}{L} V_{o,TEG} \quad \& \quad \frac{dV_{o,TEG}}{dt} = \frac{1}{C} I_L - \frac{1}{RC} V_{o,TEG} \tag{5}$$

The complete model of the converter becomes,

$$\frac{\mathrm{dI_L}}{\mathrm{dt}} = \frac{1}{\mathrm{L}} V_{TEG} - \frac{1}{\mathrm{L}}(1-\mathrm{D})V_{o,TEG} = \frac{1}{\mathrm{L}}\left(V_{TEG} - V_{o,TEG}\right) + \frac{V_{o,TEG}}{\mathrm{L}}\mathrm{D} \tag{6}$$

$$\frac{dV_{o,TEG}}{dt} = \frac{(1-D)}{C} I_L - \frac{V_{o,TEG}}{RC} = \frac{1}{C}\left(I_L - \frac{V_{o,TEG}}{R}\right) - \frac{I_L}{C} D \tag{7}$$

Let the three state variables are $x_1 = I_L; x_2 = V_{o,TEG}$, then the state vector x becomes,

$$\mathrm{x} = \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} I_L \\ V_{o,TEG} \end{bmatrix} \tag{8}$$

The state space model is represented as,

$$\dot{\mathrm{x}} = \frac{dx}{dt} = f(\mathrm{x}, t) + g(\mathrm{x}, t)\mathrm{D} \tag{9}$$

Where

$$f(x,t) = \begin{bmatrix} \frac{1}{L}\left(V_{TEG} - V_{o,TEG}\right) \\ \frac{1}{C}\left(I_L - \frac{V_{o,TEG}}{R}\right) \end{bmatrix}; g(x,t) = \begin{bmatrix} \frac{V_{o,TEG}}{L} \\ -\frac{I_L}{C} \end{bmatrix} \tag{10}$$

Table 1. Parameters of the boost converter

Parameters	**TEG System**
Inductance (L)	4.32.mH
Capacitance (C)	20 µF
Switching frequency (f_{sw})	10 KHz
Input Voltage (V_{IN})	1.8 to 7.2 V
Output Voltage(V_o)	24 V

3. Synergetic MPPT controller

The nonlinear system dynamics are expressed by the differential equation as follows,

$$\dot{\mathrm{x}} = \frac{dx}{dt} = f(\mathrm{x}, \mathrm{S}, t) \tag{11}$$

Where x is the *n* x *1*state vector, *S* is the *m* x 1 control input and *t* is time.

The design procedure of synergetic control for the nonlinear system involves the following steps

Step 1: Selection of a macro variable which is a nonlinear function of state variables as,

$$\Psi = \Psi(\mathrm{x}, t) \tag{12}$$

The synergetic control will drive the system to converge to the surface ($\Psi = 0$).

The selection of macro-variable is based on the specifications for example the settling time, the steady state error and constraints on control output [7].

Step 2: Selection of the desired dynamics of the macro-variable as

$$T_s\dot{\Psi} + \Psi = 0, T_s > 0 \tag{13}$$

Where T_s is the time constant which specifies the speed of the convergence to the surface $\Psi = 0$. The order of system on the specified manifold is *n-m*.

The solution of this differential equation gives the following function for ψ:

$$\Psi(t) = \Psi_0 \ e^{-\frac{t}{T_s}} \tag{14}$$

From the above equation, for any initial condition Ψ_0, as *t* increases $\psi(t)$ approaches to $\Psi = 0$ i.e attracted to the surface $\Psi = 0$. The parameter T_s determines the rate of convergence, smaller the value greater the rate of the transition processes.

Applying the chain rule of differentiation the derivative of ψ becomes,

$$\dot{\Psi} = \frac{d\Psi}{dt} = \frac{d\Psi}{d\mathrm{x}}\frac{d\mathrm{x}}{dt} = \frac{d\Psi}{d\mathrm{x}}\dot{\mathrm{x}} \tag{15}$$

From equations 12 and 15,

$$T_s\frac{d\Psi}{d\mathrm{x}}f(\mathrm{x}, \mathrm{S}, t) + \Psi = 0 \tag{16}$$

Solving the equation 16 for *S*, the derived control law is expressed as,

$$S = g[\mathrm{x}, t, \Psi(\mathrm{x}, t), T_s] = 0 \tag{17}$$

From the equation 17, it can be observed that the control *S* depends on the state variables as well as on the time constant T_s and the macro variable Ψ.

Similar to other MPPT techniques, the design of the synergetic MPPT controller depends on condition that at the MPP the ratio of change in generated TEG power to the change in current should be zero. Accordingly, the selected manifold

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Ψ is expressed as a function of I_L,

$$\Psi = \frac{\partial P}{\partial I_L} \tag{18}$$

The manifold in terms of TEG variables,

$$\Psi = \frac{\partial P_{TEG}}{\partial I_L} = \frac{\partial (V_{TEG} I_L)}{\partial I_L} = I_L \frac{\partial V_{TEG}}{\partial I_L} + V_{TEG} \tag{19}$$

For the considered boost converter, the manifold Ψ is a function of I_L only, which is the state variable x_1, the inductor current. Hence using the chain rule of differentiation

$$\dot{\Psi} = \frac{d\Psi}{dt} = \frac{d\Psi}{dx_1}\frac{dx_1}{dt} = \frac{d\Psi}{dI_L}\dot{I}_L = \left[2\frac{\partial V_{TEG}}{\partial I_L} + \frac{\partial^2 V_{TEG}}{\partial I_L^2} I_L\right]\dot{I}_L \tag{20}$$

From state space model

$$\dot{\Psi} = \left[2\frac{\partial V_{TEG}}{\partial I_L} + \frac{\partial^2 V_{TEG}}{\partial I_L^2} I_L\right]\left[\frac{1}{L}V_{TEG} - \frac{1}{L}(1 - D)V_{o,TEG}\right] \tag{21}$$

From the desired dynamic equation of the macro-variable,

$$\dot{\Psi} = -\frac{1}{T_s}\Psi \tag{22}$$

$$\left[2\frac{\partial V_{TEG}}{\partial I_L} + \frac{\partial^2 V_{TEG}}{\partial I_L^2} I_L\right]\left[\frac{1}{L}V_{TEG} - \frac{1}{L}(1 - D)V_{o,TEG}\right] = -\frac{1}{T_s}\left[I_L\frac{\partial V_{TEG}}{\partial I_L} + V_{IN}\right] \tag{23}$$

$$D_{SC} = 1 - \frac{V_{TEG}}{V_{o,TEG}} - \frac{I_L\frac{\partial V_{TEG}}{\partial I_L} + V_{TEG}}{T_s\ \frac{V_{o,TEG}}{L}\left[2\frac{\partial V_{TEG}}{\partial I_L} + \frac{\partial^2 V_{TEG}}{\partial I_L^2} I_L\right]} \tag{24}$$

Asymptotic stability is obtained using a positive definite Lyapounov function given as,

$$V_{Lia} = \frac{1}{2}\Psi^2 \tag{25}$$

The derivative of V_{Lia} becomes,

$$\frac{dV_{Lia}}{dt} = \Psi\left(\frac{d\Psi}{dt}\right) = \Psi\left[\left(-\frac{1}{T_s}\right)\Psi\right] = \left(-\frac{1}{T_s}\right)\Psi^2 \leq 0 \tag{26}$$

4. Result Analysis

The effectiveness of the proposed synergetic MPPT controller is verified through the simulations using Matlab software considering temperature gradients change. The cold temperature is fixed at reference value of 30°C and the hot temperature is varied according to square signal as shown in fig.6.

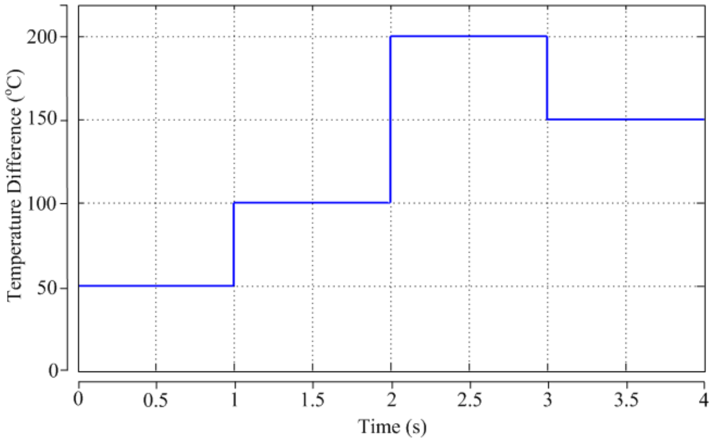


Fig.6. Temperature difference profile

The fig. 6 and 7 demonstrates the simulation results of TEG output power variation and corresponding change in duty cycle of designed boost converter for the considered TEG system using the two MPPT controllers at different temperature differences (T_H-T_C =50°C, 100°C, 150°C,200°C). Clearly, it very well may be reasoned with the Synergetic controller, the generated TEG power reaches the maximum value quicker than the P&O controller. The duty cycle variation with Synergetic method is much smoother with less oscillations in the steady state i.e when the power reaches maximum value.

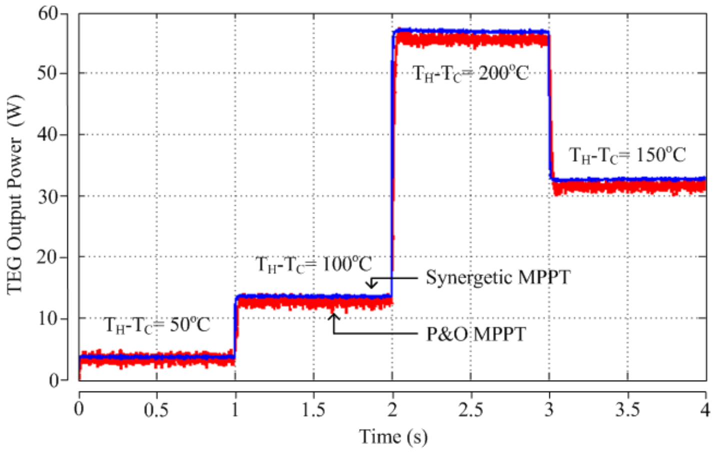


Fig. 6. The TEG power under variable temperatures

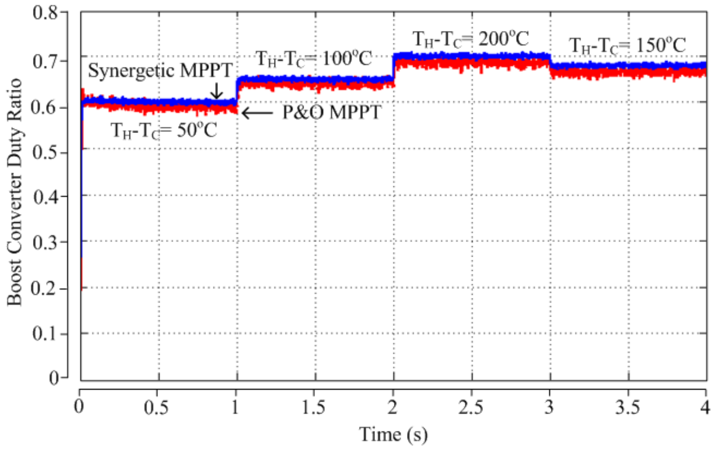
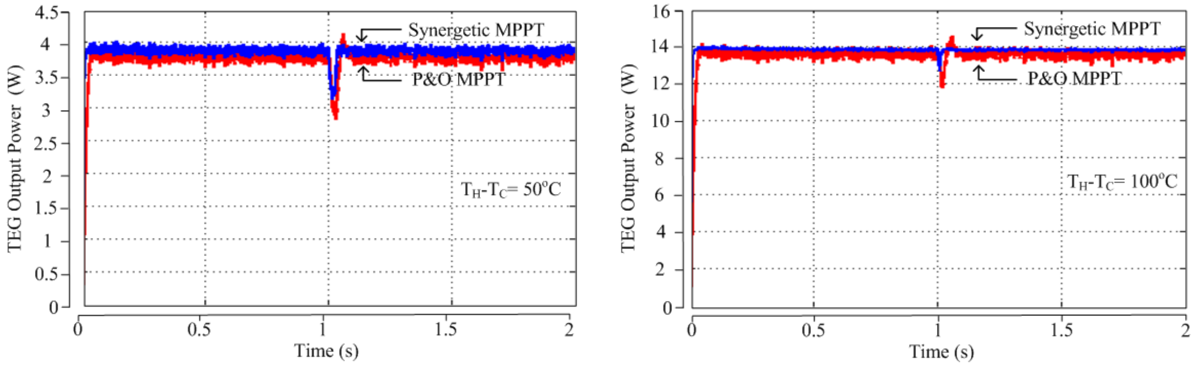


Fig. 7. The duty cycle of boost converter under variable temperatures

The fig. 8 shows variation in the generated TEG power under different temperature differences (T_H-T_C =50°C, 100°C, 150°C, 200°C) with variable load conditions i.e the load resistance is abruptly varied from 50 to 100 Ω at 1 sec in each case. The synergetic controller maintains the generated TEG power at maximum value without any interruption when compared to P&O algorithm..



(a) (b)

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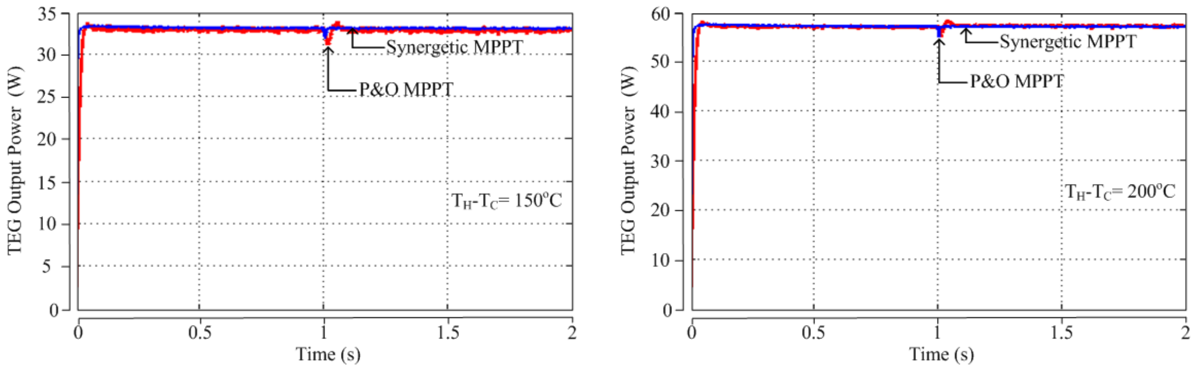

(c) (d)

Fig. 10. The generated TEG power under load change

5. Conclusions

The design and analysis of a nonlinear MPPT controller based on synergetic control theory for the thermoelectric generator (TEG) system presented in this paper. The synergetic control sustains the TEG output power at its the maximum under different temperature differences (T_H-T_C =50°C, 100°C, 150°C, 200°C) and disturbance conditions such as sudden change in load when compared to the conventional P&O algorithm. The variation in duty cycle is also less using synergetic controller. The superiority of proposed controller is shown by comparing the simulation results with standard P&O MPPT algorithm.

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