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Fuzzy Logic Based Temperature Control of Thermoelectric Cooler (TEC) for Single Photon Avalanche Diode (SPAD) Application

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***Abstract*—Single photon avalanche diode (SPAD) is a temperature sensitive device. Even a slight variation of temperature can cause unstable performance in quantum efficiency, responsitivity and dark counts. Due to these reasons, unstable temperature could cause overall poor performance of SPAD. It is common for thermoelectric cooler (TEC) to be used as cooling of photodetectors. SPAD was mounted onto the TEC where it needs to be maintained at a constant low temperature under variation of ambient temperature. The system is simulated using Fuzzy Logic Toolbox in MATLAB Simulink. Simulated using P-type fuzzy logic with the set point temperature of -20˚C and ambient temperature of 16˚C, produce a result of -19.44˚C. The P-type fuzzy logic control design has shown a good overall performance where the steady state error is ±0.56˚C, which is equivalent to ±2.8% and the settling time for the output simulation, *ts*, is 35.91s.**

Keywords: Single Photon Avalanche Diode (SPAD), Thermoelectric cooler (TEC), temperature control, P-type fuzzy logic control, Fuzzy Logic Toolbox in MATLAB Simulink

I. INTRODUCTION

Recent developments in avalanche photodiodes have led to many significant applications such as Light Detection and Ranging (LIDAR), laser range finder, small-signal fluorescence and photon counting. Specifically, Silicon Single Photon Avalanche Diodes (Si SPAD) has many favorable factors such as small size, light weight, long lifetime, high quantum efficiency, high responsibility, fast time response, wide spectral response range, wide operating temperature range and low noise for many applications [1-3]. However, SPAD decreases in performance when operating in unsteady temperature. Therefore, maintaining the operating temperature of this SPAD is crucially important [3][4].

TEC is used as a refrigeration device to cool down the temperature of SPAD. Due to complex and nonlinear mathematical model of TEC, researchers use fuzzy logic, self-adaptive PID and NN-PID to simulate the controller system. According to a research done using fuzzy logic [5], with the linearization mathematical model showed that the cold-end temperature can be maintained at the fixed value within ±0.0045˚C irrespective of the variation of the cooling load and the ambient temperature. Meanwhile, a research using adaptive NN-PID [6] for temperature control of thermoelectric cooler results in response time of 10˚C in 70s with satisfying dynamic and steady performance. A research using fuzzy self-adaptive PID control [7] of temperature control for semiconductor laser results in improved dynamic response and rises in steady state precision. The overshoot is less than 1.6% and regulation time reduced to 2.5s when the environment temperature is 16˚C, with a control accuracy of ±0.005˚C.

In this paper, a P-type fuzzy logic control is designed in MATLAB Simulink. The result simulation shows an overall performance of -19.44˚C when the set point temperature is -20˚C and the ambient temperature is 16˚C. The steady state error is ±0.56˚C, which is equivalent to ±2.80% and the settling time for the output simulation, *ts*, is 35.91s.

II. THERMOELECTRIC COOLER (TEC) OPERATING PRINCIPLE

Thermoelectric cooler, TEC is the most significant component for cooling of SPAD. TEC is a solid state heat pump that works based on the Peltier effect. Peltier effect is the phenomenon whereby the passage of an electrical current through a junction consisting of two dissimilar semiconductors resulting in a cooling effect [8]. When the direction of the current flow is reversed, heating will occur.

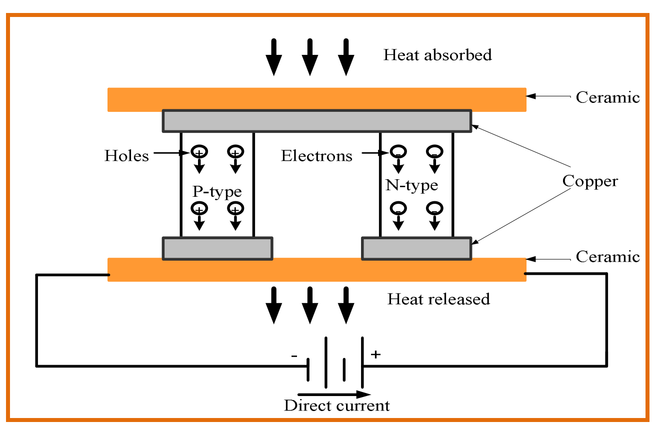

Fig. 1 Schematic diagram of a thermoelectric cooler

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Fig. 1 shows a TEC consist of p-type and n-type semiconductor, usually made of bismuth-telluride material [8]. A pair of p-type and n-type semiconductor in TEC is referred as a "couple". Hundreds of couples are arranged in arrays in order to maximize the cooling effects. The p-type and n-type semiconductors are connected electrically series and thermally parallel [9]. The TEC is affixed with a ceramic substrate on top and at the bottom as it is good for housing rigidity, electrical insulation and thermal conduction [9].

The p-type material has a deficit of electrons and therefore an excess of holes, while n-type material has a deficit of holes and therefore an excess of electrons.

Supplying direct current will cause electrons to flow through the interconnecting conductor from lower energy level in the p-type material to a higher energy level in the n-type material, thus, absorbing heat on the cold side. Meanwhile, the electrons from n-type of the higher energy level go to the lower energy level in the p-type through the interconnecting conductor, thus releasing heat on the hot side [8].

When there is a temperature difference between the hot side and cold sides of TEC, a voltage is generated called the Seeback Voltage [2].

$$Q_C = S_M T_C I - \frac{1}{2} I^2 R_M - K_M \Delta T \quad (1)$$

$$V = S_M \Delta T + I R_M \quad (2)$$

Eq. (1) shows that Q_C is the amount of heat absorbed at cold junction in Watts (W), S_M is the device Seeback voltage in Voltage/Kelvin (V/K), T_C is the cold side temperature in Kelvin (K), I is the current value in Ampere (A), R_M is the electrical resistivity in Ohm (Ω), K_M is the thermal conductance in Watt/Kelvin (W/K) and ΔT is the temperature difference between the hot and cold sides in Kelvin (K). Eq. (2) shows the voltage generated where V is the Seeback Voltage in Voltage (V). For multistage TEC of PK2-15828NC from Multicomp, the value of S_M = 0.048 V/K, K_M = 0.1412 W/K and R_M = 3.78Ω.

A. TEC Modeling

Cooling using TEC consists of an attached cooling load component on the cold side of the TEC, and a heatsink attached on the hot side of the TEC. The heat load, Q_L is absorbed by the cooling load to the TEC and the heat produces on the hot side of the TEC is pumped away using a heatsink.

Assumption is made that the temperature distributions inside the cold side TEC plate and the cooling load exchanger are uniform. The energy balance gives an equation of [8][9][10]:

$$(M_L C_L + M_C C_C)\frac{dT_L}{dt} = Q_L - Q_k - I\alpha_{pn} T_L \quad (3)$$

M_L is the mass of the heat load, C_L, is the specific heat of the heat load, M_C is the mass of the cool side of TEC, C_C is the specific heat of the cool side, T_L is the temperature of cool side, I is the average current of the TEC.

$$Q_k = -kA\frac{\partial T(x,t)}{dt}\bigg|_{x=o} \quad (4)$$

Q_k is the heat conduction at the cold side boundary of the TEC, k is the mean thermal conductivity of the p-n material; A is the cross-section area of the thermoelectric material, $T(x,t)$ is the temperature distribution of the TEC.

The average energy balance of the thermoelectric material can be derived as below.

$$C\gamma\frac{\partial T(x,t)}{\partial t} = k\frac{\partial^2 T(x,t)}{\partial x^2} - \frac{\tau}{A} I \frac{\partial T(x,t)}{\partial x} + \frac{\rho}{A^2} I^2 \quad (5)$$

C is the average specific heat of the TEC, γ is the average consistency of the TEC, τ is the Thomson coefficient and ρ is the resistance ratio of the TEC.

Likewise, the energy balance from the heatsink and the hot side is:

$$(M_F C_F + M_H C_H)\frac{dT_L}{dt} = I\alpha_{pn} T_H + Q_o - hA_F(T_H - T_a) \quad (6)$$

M_F is the mass of the heat sink, C_F is the average specific heat of the heat sink, M_H is the mass of hot side, C_H is average specific heat of the hot side, T_H is temperature of hot side and A_F is the total area of heat radiation and T_a is environment temperature and Q_o is the heat conductivity of hot side boundary of the TEC.

$$Q_o = -kA\frac{\partial T(x,t)}{dt}\bigg|_{x=L} \quad (7)$$

Eqs. (5),(6) and (7) are the equations for TEC, showing that it is a highly nonlinear.

B.Linearization

In order to model the TEC, it needs to be linearized using small-signal linearization method [10]. Assume that the steady state values and some fluctuation quantities:

$T(x,t)=\overline{T}(x)+\widetilde{T}(x,t);$

$T_L(t)=\overline{T}_L+\widetilde{T}_L(t);$

$T_H(t)=\overline{T}_H+\widetilde{T}_H(t);$

$T_a(t)=\overline{T}_a+\widetilde{T}_a(t);$

$Q_L(t)=\overline{Q}_L+\widetilde{Q}_L(t);$

$I(t)=\overline{I}+\widetilde{I}(t);$ (8)

Also, the Seeback coefficient can be expanded from the Taylor series as below.

$\alpha_{pn}(T)=\alpha_L+\frac{\tau}{\overline{T}_L}=\alpha_H+\frac{\tau}{\overline{T}_H}\widetilde{T}_H$

(9)

Where $\alpha_L=\alpha_{pn}(\overline{T}_L);\alpha_H=\alpha_{pn}(\overline{T}_H)$. Substitute (8) and (9) into (5), (6) and (7), we will get:

$$k\frac{\partial^2\widetilde{T}}{\partial x^2}-\frac{\tau\overline{I}}{A}\frac{\partial\widetilde{T}}{\partial x}+\left[\frac{2\rho\overline{I}}{A^2}-\frac{\tau(\overline{T}_H-\overline{T}_L)}{AL}\right]\widetilde{I}=C\gamma\frac{\partial\widetilde{T}}{\partial x} \quad (10)$$

$$\widetilde{Q}_L-(\alpha_L+\tau)\overline{I}\widetilde{T}_L-\alpha_L\overline{T}_L\widetilde{I}+kA\left.\frac{\partial\widetilde{T}}{\partial x}\right|_{x=0}= \cdots(M_LC_L+M_CC_C)\frac{d\widetilde{T}_L}{dt} \quad (11)$$

$$(\alpha_H+\tau)\overline{I}\widetilde{T}_H+\alpha_H\overline{\overline{T}}_H\widetilde{I}-kA\left.\frac{\partial\widetilde{T}}{\partial x}\right|_{x=L} \cdots-hA_F(\widetilde{T}_H-\widetilde{T}_a)= \cdots(M_FC_F+M_HC_H)\frac{d\widetilde{T}_H}{dt} \quad (12)$$

C.Dynamic model of the TEC

Solving Eq. (10),(11) and (12) by Laplace transform, the transfer functions of the cold side temperature and its fluctuations are:

$$\widetilde{T}_L(s)=G_I(s)\widetilde{I}(s)+G_Q(s)\widetilde{Q}_L(s)+G_a(s)\widetilde{T}_a(s) \quad (13)$$

where

$$G_I(s)=\frac{N(s)}{sD(s)} \quad (14)$$

$$G_Q(s)=\frac{E_H\sinh(qL)+Akq\cosh(qL)}{D(s)} \quad (15)$$

$$G_a(s)=\frac{AA_Fhkq}{D(s)} \quad (16)$$

$$N(s)=\left\{\begin{matrix}Akq\left[\alpha_L\overline{T}_L\cosh(qL)-\alpha_H\overline{T}_H\right]+\\ \alpha_L\overline{T}_LE_H\sinh(qL)\end{matrix}\right\}s \cdots+\frac{Akq\beta}{C\gamma}\left[E_H(1-\cosh pL)-Akp\sinh pL\right] \quad (17)$$

$$D(s)=AkqE_L\cosh(qL)+E_HE_L\sinh(qL) \cdots+AkqE_H\cosh(pL) \cdots+A^2k^2pq\sinh(pL) \quad (18)$$

$$p(s)=\frac{\frac{\tau\overline{I}}{A}+\sqrt{\frac{\tau^2\overline{I}^2}{A^2}+4kC\gamma s}}{2k} \quad (19)$$

$$q(s)=\frac{\frac{\tau\overline{I}}{A}-\sqrt{\frac{\tau^2\overline{I}^2}{A^2}+4kC\gamma s}}{2k} \quad (20)$$

$$E_L(s)=(M_LC_L+M_CC_C)s+(\tau+\alpha_L)\overline{I} \quad (21)$$

$$E_H(s)=(M_FC_F+M_HC_H)s+hA_F-(\tau+\alpha_L)\overline{I} \quad (22)$$

$$\beta=\frac{2\rho\overline{I}}{A^2}-\frac{\tau(\overline{T}_H-\overline{T}_L)}{AL} \quad (23)$$

Eq. (13) shows that the cold side, T_L of the TEC is fluctuated by the cooling load, Q_L and the ambient temperature, T_a. $G_I(s)$, $G_Q(s)$ and $G_a(s)$ are the transfer functions of current, cooling load and ambient temperature. The system dynamic model of TEC at constant cooling load and fixed ambient temperature is:

$$G_I(s) = \frac{\widetilde{T}_L(s)}{\widetilde{I}(s)} = \frac{N(s)}{sD(s)} \tag{24}$$

D. Model Reduction

For simplicity, the infinite-order system in Eq. (24) can be further reduced. An approximation is made that the Thomson effect in TEC is small as compared to the Seeback effect.

$$\alpha_H = \alpha_L = \alpha_{pn}$$

$$p(s) = q(s) = \lambda(s) = \sqrt{\frac{C\gamma s}{k}}$$

$$\sinh(\lambda L) \approx \lambda L$$

$$\cosh(\lambda L) \approx 1 + \frac{\lambda^2 L^2}{2} \tag{25}$$

The simplified model of TEC is:

$$G_I(s) = \frac{\widetilde{T}_L(s)}{\widetilde{I}(s)} = -K \frac{\frac{s}{z}+1}{\left[\frac{s}{p_1}+1\right]\left[\frac{s}{p_2}+1\right]} \tag{26}$$

$$K = \frac{\left\{ \begin{array}{l} Ak\alpha_{pn}(\bar{T}_H - \bar{T}_L) + L\alpha^2_{pn}\bar{I}\bar{T}_L \left(\begin{array}{c} \frac{\rho L^2 h A_F}{A} \\ +2\rho L k \end{array} \right) \bar{I} \\ + \frac{\rho L^2 \alpha_{pn} \bar{I}^2}{A} + L\alpha_{pn} h A_F \bar{T}_L \end{array} \right\}}{A A_F hk + LhA_F\alpha_{pn}\bar{I} - L\alpha^2_{pn}\bar{I}^2} \tag{27}$$

$$z = \frac{A A_F hk + LhA_F\alpha_{pn}\bar{I} - L\alpha^2_{pn}\bar{I}^2}{\left[\begin{array}{l} \frac{1}{2} A\alpha_{pn} L^2 C\gamma + L\alpha_{pn}(M_F C_F + M_H C_H)\bar{T}_L \\ \quad \ldots - \frac{\rho L^2}{A}(M_F C_F + M_C C_C)\bar{I} \end{array} \right]} \tag{28}$$

$$p_{1,2} = a \pm \sqrt{\alpha^2 - b^2} \tag{29}$$

$$a = \frac{\left\{ \begin{array}{l} Ak(M_F C_F + M_L C_L + M_C C_C + M_H C_H) \\ + LhA_F(M_L C_L + M_C C_C) + AC\gamma L\left(Ak + \frac{1}{2} hA_F L \right) \\ + L\alpha_{pn}(M_F C_F + M_L C_L)\bar{I} \end{array} \right\}}{\begin{array}{l} AL^2 C\gamma(M_F C_F + M_L C_L + M_C C_C + M_H C_H) + \\ 2L(M_F C_F + M_H C_H)(M_L C_L + M_C C_C) \end{array}} \tag{30}$$

$$b = \frac{\begin{array}{c} AA_F hk + LhA_F \alpha pn\bar{I} \\ - L\alpha^2 pn\bar{I}^2 \end{array}}{\begin{array}{l} \frac{1}{2} AL^2 C\gamma(M_F C_F + M_L C_L + M_C C_C + M_H C_H) \\ + L(M_F C_F + M_H C_H)(M_L C_L + M_C C_C) \end{array}} \tag{31}$$

From an experiment done by [10], the average value of k is -6.4061, z is 0.1323, p_1 is 0.0147 and p_2 is 0.5817.

III. HARDWARE DESIGN AND DEVELOPMENT

A. Design Principle of Temperature Control

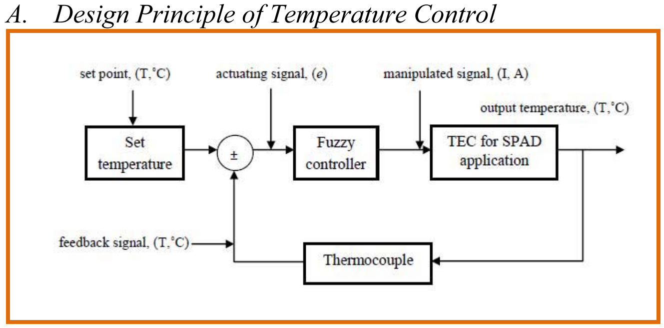

Fig 2. Temperature feedback control of thermoelectric cooler (TEC) for single photon avalanche diode (SPAD) application

Fig. 2 shows a block diagram of a fuzzy logic based temperature control of TEC for SPAD application. The user inserts a set point temperature value. A thermocouple sensor is used to sense the current reading of the ambient temperature. The comparator will compare the set point signal with the feedback signal, resulting in actuating error signal. The fuzzy system is used as the controller to reduce the actuating error signal. The TEC cools the SPAD to the user set point temperature according to the amount of current supplied by the fuzzy system.

B. Design Mounting of TEC and SPAD

The SPAD is custom designed to mount onto the TEC where it needs to be maintained at a constant temperature to achieve an improved overall performance. For temperature control application, the SPAD, TEC, heatsink, fan and thermocouple requires special design of mounting as in Fig. 3 below.

A copper holder is designed so that the dimensions tightly holds the SPAD of C309021EH to ensure that the heat generated from it will thermally conducted to the multistage TEC. From the multistage TEC, heat is absorbed and pumped away to heatsink. Attached to the hot side of the multistage TEC is the 241214B92200G heatsink from Aavid Thermalloy. This heatsink is selected because it provides a suitable low thermal resistance, appropriate density and geometry of fins for better heat transfer and system airflow. Fan of 109P06125702 from Sanyo Denki is attached to the bottom of the heatsink. It is chosen because it provides good air flow and static pressure characteristics. The temperature sensor used is thermocouple from Epcos, embedded in the custom designed copper SPAD holder. It is used because of its fast response to detect current temperature and has suitable dimensions.

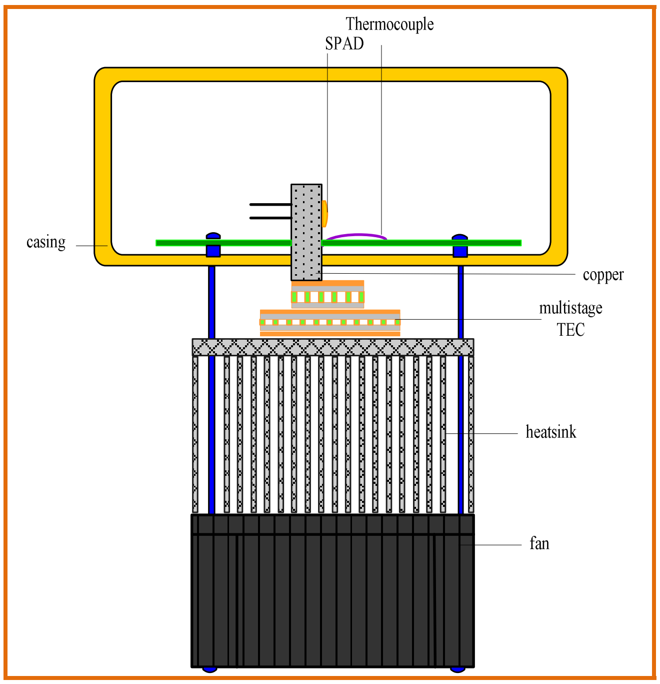

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Fig. 3 Cross section design mounting of TEC and SPAD

It is important to have an arrangement that is good in heat propagation among SPAD, TEC and heatsink. On the microscopic level, all surfaces must be flat and smooth, free from dirt particles. This is because non-smooth or dirty surfaces may contribute to air pockets, which leads to very poor thermal conducting surface. To improve the thermal resistance, the gaps are filled with a high thermal conductivity grease of 10-8108 from GC Electronics. The temperature control electronic components are insulated from surrounding in a thermally isolated box to diminish thermal through radiation and convection.

IV. P-TYPE FUZZY LOGIC TEMPERATURE CONTROL DESIGN

Fig. 4 shows a P-type fuzzy logic temperature control of TEC for SPAD application that provides a solution for nonlinear and complex TEC mathematical model. P-type is used as a test platform and can be compared to the standard conventional proportional controller. In fuzzy system, the fuzzifier functions to map the input value according to the number, shape and range of the membership function. Meanwhile, the defuzzifier functions to map the fuzzy consequent into crisp output current values.

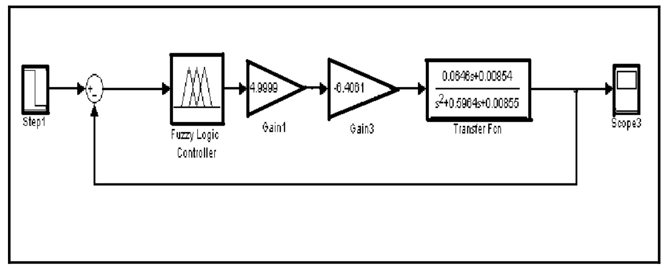

Fig 4 P-type fuzzy logic temperature control of thermoelectric cooler (TEC) for single photon avalanche diode (SPAD) application

There is one linguistic functions for input insert by the user; error in temperature, *e* in the range of -52.5˚C to +52.5˚C. Corresponding to the input is one linguistic variable for output; current to the TEC, in the range of -2.8A to +2.8A. Linguistic terms are variables that are describe in words for input and output of a fuzzy logic. The linguistic variables for the system input and output are Negative Large (NL), Negative Medium (NM), Negative Small (NS), Zero (Z), Positive Small (PS), Positive Medium (PM) and Positive Large (PL). From Eq. (26), the transfer function of output cold side temperature to input current to a TEC, modeled from an experiment by [10]:

$$G_I(s) = \frac{\widetilde{T}_L(s)}{\widetilde{I}(s)} = -6.4061\frac{0.0646s + 0.00854}{s^2 + 0.5964s + 0.00855} \qquad (32)$$

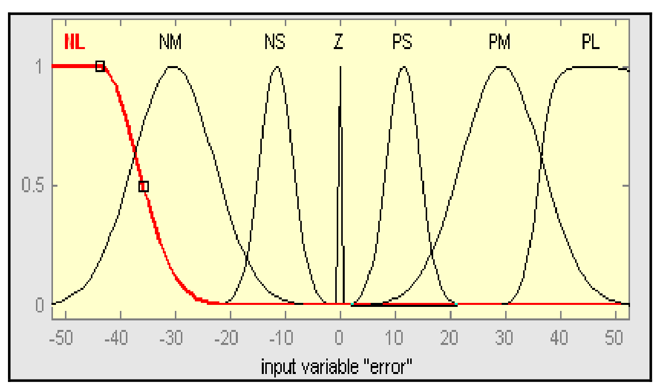

Fig. 5 The linguistic terms and membership functions for input.

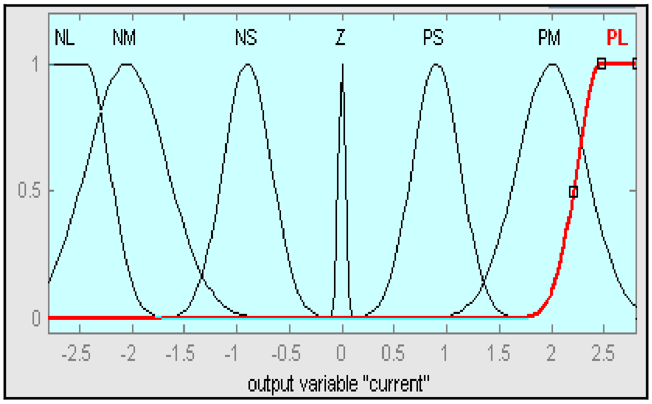

Fig. 6 The linguistic terms and membership functions for output.

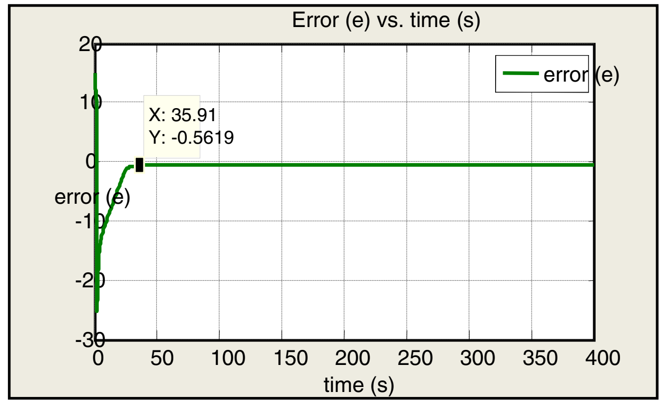

Fig 8. The output error of P-type fuzzy logic control of thermoelectric cooler (TEC) for single photon avalanche diode (SPAD) application

Fig. 5 shows the linguistic terms and membership functions for input into the P-type fuzzy logic temperature control of TEC for SPAD application. Fig. 6 shows the linguistic terms and membership functions for output from the controller to the TEC system dynamic. Rules are used to describe in words the relationship between the linguistic variables of inputs and output based on their linguistic terms. Rule base is the all-combined rules for fuzzy system. It determines how the system interprets the fuzzy linguistics.

V. RESULT & DISCUSSION

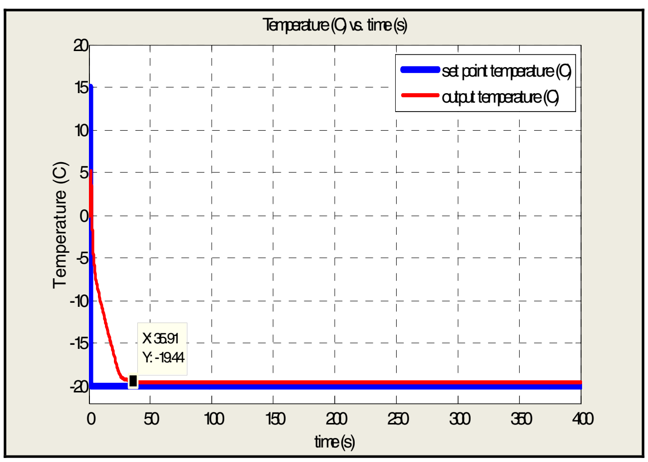

Fig. 7 The output simulation of P-type fuzzy logic of TEC

Fig. 7 shows the output simulation using the P-type fuzzy logic temperature control of TEC for SPAD application. The data is simulated from 0 to 400s. When a user insert a set point temperature of -20˚C to cool down the SPAD from an ambient temperature of 16˚C, the P-type fuzzy logic control shows that it can go down as low as -19.44˚C. The steady state error is ±0.56˚C which is equivalent to ±2.80%. The settling time for the output simulation, *ts*, is 35.91s.

Fig. 8 shows the output error from P-type fuzzy logic control that is fed into the TEC transfer function. The data is tested for 400s. The simulation shows that the error, *e* settles down to -0.5619˚C. The time taken for the system to settle is 35.91s.

Comparing to NN-PID control [6], the settling time for an output temperature of 10˚C takes 70s. The P-type fuzzy logic has better settling time of 35.91s. Comparing to fuzzy self-adaptive PID control [7], it has an overshoot of 1.6%. The output from the P-type fuzzy logic provides improved dynamic response and results in no overshoot. However, compared to fuzzy logic [5] and fuzzy self-adaptive PID control [7], they have faster response and very small steady state error.

The transfer function of a TEC is highly nonlinear [8-10]. The nonlinearity is due to the addition of the heatsink on the hot side and the cooling load at the cool side of the TEC. The P-type fuzzy logic control was used to simulate the TEC for SPAD application as a platform test of temperature control. PI, PD and PID-type of fuzzy logic control would perform better due to its successful performance in many systems. Therefore, the controller can be further improved to satisfy better system performance.

VI. CONCLUSION

When a user insert a set point temperature of -20˚C to cool down the SPAD from an ambient temperature of 16˚C, the P-type fuzzy logic control shows that it can go down as low as -19.44˚C. The steady state error is ±0.56˚C which is equivalent to ±2.8%. The settling time for the output simulation, *ts*, is 35.91s.

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