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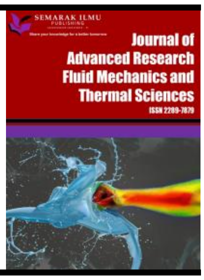

Review of Control Strategies for Improving the Photovoltaic Electrical Efficiency by Hybrid Active Cooling

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ABSTRACT

Photovoltaic (PV) cooling systems are used widely in order to increase the PV efficiency. Most review paper was published for the role, design and cooling techniques of PV applications, there is a lack of collected and organised information regarding the latest and the newest updates on control strategies for PV cooling control systems. Hence, this paper presents a comprehensive review of PV cooling control strategies discussing the latest research works during the years from 2010 to 2022. PV/T hybrid cooling types are highlighted, followed by the main focus of this paper an extensive review of the control schemes for diverse types of PV cooling systems that have been carried out. This paper summarises most of the related work and also pays a special focus on research trends regarding the control of PV cooling systems that have been previously published in the literature. This review paper will be helpful to new researchers when identifying research directions for this particular area of interest.

1. Introduction

Solar energy is a constituent part of technology in renewable energies besides than wind energy, biomass energy, hydropower energy and geothermal energy. Solar energy is preferred due to its abundance source of sunlight. Photovoltaic (PV) system is the known conventional system in order to transform the energy of solar irradiance to electrical energy. This system does not involve any moving parts or environmental releases through the process [1].

However, during the solar insolation process the percentage of energy conversion into electrical energy is in the range of 10–20% while the remaining solar radiation is either transformed into heat or is reflected back [1,2]. The heat or thermal energy which were absorbed in PV causes decrement in electrical efficiency [3]. If the ambient temperature rises, the PV operating temperature will rise as well, which causes heat build-up in PV and thus give effect to the drop of PV electrical efficiency.

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The drop of PV electrical efficiency depends to the PV type and cell material used with rate of decrease ranges 0.25-0.5% per degree Celsius [4]. Hence to overcome this issue, there are numerous of cooling technologies that has been studied from previous researchers to eliminate heat due to temperature rises in PV using two types of cooling technologies of; (i) hybrid passive cooling and (ii) hybrid active cooling.

Hybrid passive cooling does not involve any actuator or any mechanism to move or actuate the PV cooling system. The heat transfer process in PV module is conductive in nature. These hybrid passive cooling technologies are the liquid immersion, phase change material system, concentrating photovoltaic/thermal system and heat pipe. While hybrid active cooling usually involves actuator or any mechanisms to move or actuate the PV cooling system. The heat transfer process is driven by other input source and consume power to cool the PV module. These hybrid active cooling technologies are the water, air, microchannel heat sink, thermophotovoltaic system, and etc. These two cooling technologies of hybrid passive and hybrid active cooling have been examined, compared and reviewed by Grubišić-Čabo *et al.,* [4], Siecker *et al.,* [5], Makki *et al.,* [6], and Abdelrazik *et al.,* [7]. Siecker *et al.,* [5] reviewed nine types of technologies which involve the hybrid active and hybrid passive cooling system. They classified the type of technology used based on the focus and contribution to increase the PV efficiency. The type of hybrid passive cooling reviewed in the paper are the water immersion cooling, phase change materials, photonic crystal and heat sink while the type of hybrid active cooling examined in the paper are the floating tracking, water spraying, forced water circulation, forced air circulation and thermoelectric cooling. They concluded that any cooling technologies of passive and active cooling used to keep the PV operating temperature in low and extracted thermal heat in PV cells. However, each different technology has the advantages, disadvantages and justifications according to application and purposes. Grubišić-Čabo *et al.,* [4] concluded that the hybrid active cooling provides higher electrical efficiency compared to hybrid passive cooling. This type of cooling technique gives most additional power. Makki *et al.,* [6] and Abdelrazik *et al.,* [7] concluded that the traditional technique of hybrid passive cooling provides a simple technique to thermally regulate the temperature of PV cells with low operating costs. However, the hybrid active cooling with forced resulting in further improved performance of PV/T systems in electrical and thermal energy production.

This article presents a review of recent hybrid active PV cooling technologies and control strategy in PV cooling applications. The hybrid active cooling technologies are preferred since it contributes better electrical efficiency performance for the PV system compared to passive cooling. Although, there is abundance of literature available for cooling techniques and technology which relate with the PV electrical efficiency is presented with the merits and drawback of each cooling technique [1,5,6,8]. However, none of these reviews discussed and documented the control strategy for PV cooling applications. The PV cooling control approached discussed in this works are limited for hybrid active PV cooling.

2. Description of Control Approaches for PV Cooling Technologies

When regulating PV cooling conditions, there are typically few parameters which are controlled: PV temperature, water flowrate, air flowrate and etc. The development of automated control solutions for regulating these parameters has been on-going problem for a few decades now. A specific system basically requires a set of control strategies to manage the cooling of PV in a manner which is vigorous and efficient in any situations especially in climate or temperature changes. A preferred control approaches in PV cooling system will have to give benefit to the system which able to reduce temperature variability about an operating point. Hence, the PV cooling system is in controlled, stable manner and provide feedback to any disturbances occurred.

In a control perspective, the PV cooling system is integrated with other parts of the system such as the actuator of the system such as the pump control, blower, control valve and etc. The main objective of the controller in PV cooling system is to provide a minimum deviation of temperature operating point and to achieve the desired temperature operating point at Standard Test Condition (STC). In order to meet the control objective, therefore a suitable controller, the control design and the type of controller are crucial to provide a high electrical efficiency of output.

The control design techniques developed and proposed from the researchers in a PV cooling control system generally can be viewed from two control schemes of: Open-loop control and Closed-loop control. The other control scheme that has been commonly designed for PV cooling control system has been a feedback-loop control or close-loop control. This type of control technique enabled the PV cooling system to adjust its performance based upon the desired output response. The close-loop control techniques in PV cooling system can be categorized into three paradigms [9]

i. Classical control

This design approach is suitable for low-order systems and simple to use. This type of control able to give information to the users the effect of varying the controller parameters of the classical Proportional (P), Proportional-Integral (PI), Batch control and ON-OFF controllers.

ii. Modern control

This design approach is applicable for high-order and complex systems. Certain type of this control unable to provide information to the users the consequences of varying the controller parameters. The techniques are optimal control, robust control and batch control. However, in PV cooling control system, only optimal control applied by the researcher.

iii. Artificial intelligence (AI) control approach

This design approach implies the intelligent techniques such as the fuzzy logic, neural networks and metaheuristics. This technique involves problem determination which mimics the method of human and nature adapting life and processes in nature. Most of these techniques are often used to augment with the PID controllers. Some control strategies also utilized a combination of the techniques e.g. Neuro-Fuzzy controllers and adaptive Fuzzy controllers. In PV cooling control system, only one type of control strategies using metaheuristics applied.

Figure 1 illustrates the controllers reviewed and discussed based upon the categories and were divided into various control techniques.

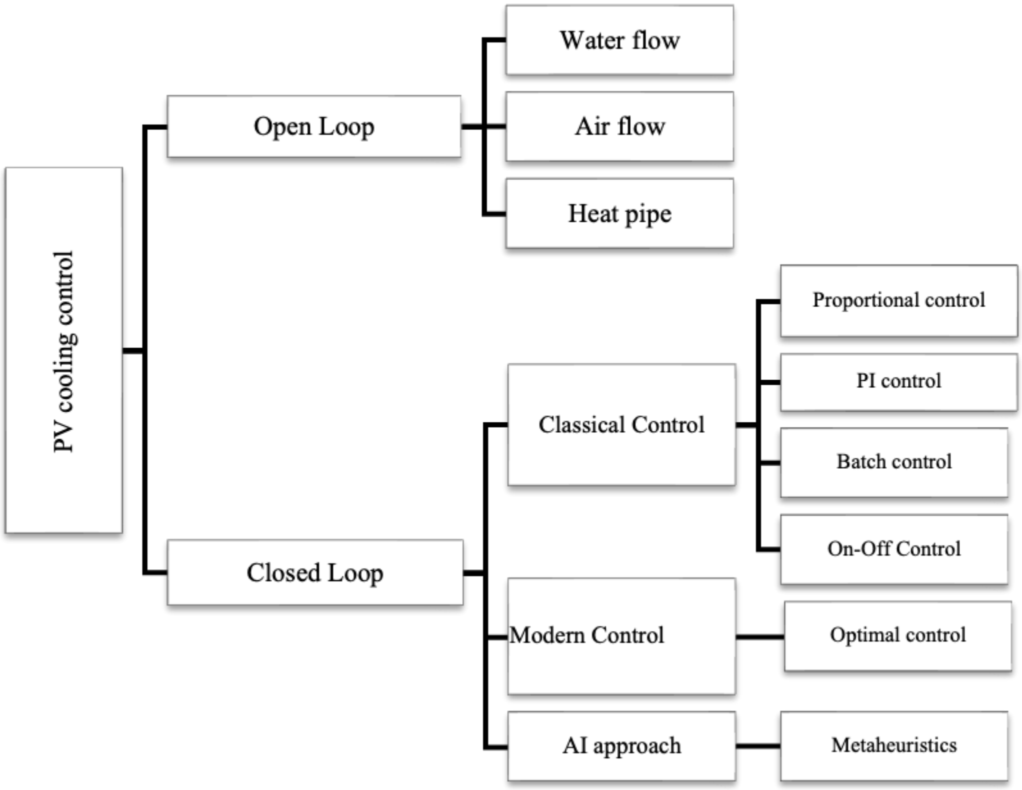

Fig. 1. Control schemes for PV cooling control system

2.1 Open-loop Control

The open-loop control had been widely used by numerous researchers and engineers, included for control of the PV temperature for the PV cooling system. It is preferable due to its easy to implement and handling with no requirement for additional sensors in order to measure the temperature, and this certainly saves in terms of the cost. However, the main drawback of this type of technique is that it is sensitive to external disturbances if it is carried out in the outdoor condition. The types of open loop control in PV/T cooling control are the water, air and heat pipe system. The open loop control in PV/T cooling for water, air and heat pipe is detailed in Figure 2 shown a block diagram for open loop control in PV cooling control system.

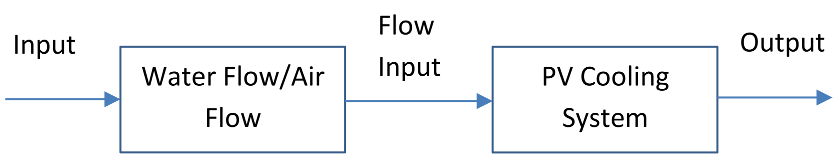

Fig. 2. A block diagram of open loop control strategies for a PV cooling control system

2.1.1 Water flow

Water flow technique has been utilised pervasively by many researchers for an effective feed-forward control of minimising the PV temperature. The water flow implies the technology of active hybrid PV cooling system. A hybrid active water cooling comprises of a solar panel and cooling system. The cooling technologies or configuration for water cooling can be categorized into: a) sheet and tube collectors; b) water free flow/ spraying collectors; c) channel collectors and d) two absorber collectors. The water flow discussed in this work is limited to water free flow or spraying collectors. This active water-cooling technique or active Photovoltaic/Thermal (PV/T) cooling usually are driven by a centrifugal pump to allow water suction through the pipe or collector.

Moharram *et al.,* [10] designed a PV power plant to study the effect of cooling by water on the performance of PV panels. The cooling system had the element of water pump, to suck the water from the middle of the water tank then passes through the water filter and it is sprayed over the PV modules for cooling. Water is sprayed using water nozzles, which are installed at the upper side of the modules. Results shows that that the cooling system that operated for 5 min results had decreased in the solar cells temperature by 10°C, and an increase in the solar cell efficiency by 12.5%. They used a controlled and constant value of water flow rate in the study. The flow rate was controlled manually with the flow rate instrument installed. Abdolzadeh and Ameri [11] and Krauter [12] designed the PV/T water cooling by spraying water on top of PV cell. Through the experiment performed and analysed the configuration of water spraying on top of PV able to decreased the cell's temperature.

Besides that, Dorobanţu and Popescu [13] and Hosseini *et al.,* [14] designed the PV/T water cooling by film water free flowing on top of PV module. Nižetić *et al.,* [15] performed and analysed PV water cooling on front and backside of PV. The circumstances of simultaneous front and backside PV panel cooling resulted maximal relative increase in panel power output. Variation of flow rate conducted by Nižetić *et al.,* [15] proved that as the water spray flow magnitude becomes higher means higher electrical efficiency produced. The configuration of free flow water on top of PV and water spraying able to reduce greater amount of PV operating temperature.

Irwan *et al.,* [16] designed the PV/T water cooling by water flow at front of the PV using solar simulator. The solar simulator was fabricated because of the experiment can be carried out any chosen time, continued for 24 hours a day and in indoor test. Variation of flow rate conducted by Nižetić *et al.,* [15] proved that as the water spray flow magnitude becomes higher means higher electrical efficiency produced. The water spraying on top and bottom of PV module shown in Figure 3(a) and Figure 3(b) has the best results with highest percentage of electrical efficiency increase and highest PV panel temperature decrease. This cooling technique is viable and exhibits the potential to be applied since it contributes to the preeminent percentage figure of electrical efficiency.

(a) (b)

Fig. 3. The PV model (a) front, and (b) backside [15]

A study conducted by Bevilacqua *et al.,* [17] designed four different cooling systems operating on the back surface of PV modules which then compared with a reference module. The cooling units was developed to increase the module's efficiency and limit the required auxiliary energy. They are based on spray cooling and forced convection phenomena. Based from the experimental results from August 2016 to March 2017, they have concluded the most cost-effective solutions appears to be the use of spray-cooling which guaranteed a consistent increment of the electric performance of the PV module.

A comprehensive comparison of the water flow cooling method via water film and water spraying applied from researchers discussed previously were tabulated in Table 1. The results have shown that the water spraying method was more effective in reducing the temperatures and increasing the electrical efficiency, rather than the free flow water or water film. Moreover, the spraying methods were shown to be robust to the environmental errors and they were capable in lowering the PV operating temperature faster than the free flow water.

Table 1
Selected parameters for water flow in PV cooling control

Author	Configuration	Electrical efficiency	Temperature
Moharram *et al.,* [10]	Water spraying (Top)	12.5%	30-35°C (Reduce to 10°C)
Abdolzadeh and Ameri [11]	Water spraying (Top)	13.5%	30-38°C (Reduce to 23°C)
Krauter [12]	Water spraying (Top)	9%	- (Reduce to 22°C)
Dorobanţu and Popescu [13]	Free flow water (top)	9.5%	38.5-41.5 ˚C (Reduce to 16°C)
Hosseini *et al.,* [14]	Free flow water (top)	-	- (Reduce to 18.7°C)
Irwan *et al.,* [16]	Free flow water (top)	8-14%	- (Reduce to 13°C)
Nižetić *et al.,* [15]	Water spraying (both sides of PV)	14.4%	30-38 ˚C (Reduce to 22°C)
Bevilacqua *et al.,* [17]	Water spraying (back surface of PV)	14.7%-16.9%	-

2.1.2 Air flow

The use of air flow technique in order to minimise the PV temperature has been studied and applied from many researchers. The air flow implies the technology of active hybrid PV cooling system. A hybrid active air cooling comprises of a solar panel and active cooling system. Hybrid active air cooling or active Photovoltaic/Thermal (PV/T) cooling usually are driven by a fan, blower or so called the forced convection. The forced air will be channel at the back surface of the panel at certain velocity.

A solar simulator was designed and fabricated by Irwan *et al.,* [16] to analyse the air cooling mechanism for PV. The simulator was designed due to constantly weather changes that makes it difficult for the researchers to performed the measurement outdoor. An experimental setup was carried out with two PV module: one with the DC brushless fans at the back surface of the panel and one without fan with different solar radiation. Results show that the air-cooling mechanism able to decrease the operating temperature hence increase the power output. Joshi and Tiwari [18] has carried out an experimental study of hybrid PV/T air collector with a schematic diagram in Figure 4. From the energy analysis, it is proven to have increment of 2-3% of exergy due to thermal energy. Besides that, they revealed that as the flow rate increase, the energy and exergy increase.

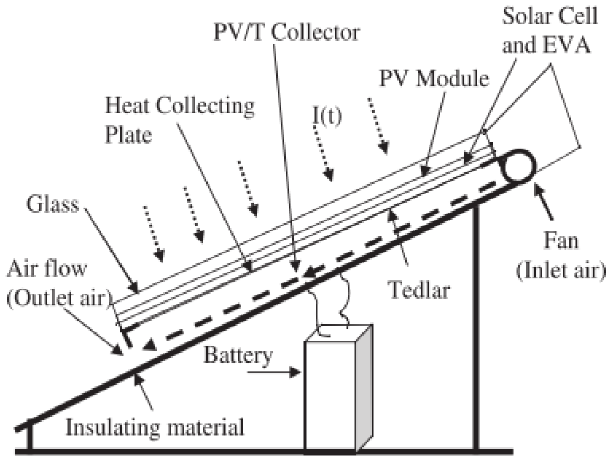

Fig. 4. Schematic diagram of integrated PV/T system (IPVTS) when air is used as the medium to collect thermal energy [18]

Tonui and Tripanagnostopoulos [19] demonstrated PV/T air collector in natural airflow in PV channel and forced convection. The used of fin and thin metallic sheet (TMS) were adopted in forced convection with flow rate of 60m^3/h. The fins yield a better and higher thermal efficiency compared to TMS. For the natural flow, the temperature rise could reach up to about 12 °C in the early afternoon during sunny days and could induce sufficient airflow rate to effect adequate ventilation. The PV modifications are more effective in ventilating the PV module for forced flow.

Joshi *et al.,* [20] then carried out a study to compare the performance of unglazed hybrid PV/T glass-to-glass system with glass-to-tedlar PV/T system. Joshi *et al.,* [20] discovered that the glass-to-glass PV/T air collector gives better results in terms of the thermal efficiency as compared to glass-to-tedlar PV/T air collector. The thermal efficiency increases with the increase in the velocity of duct air and saturates after a certain velocity. The schematic diagram of the PV/T air collector is shown in Figure 5.

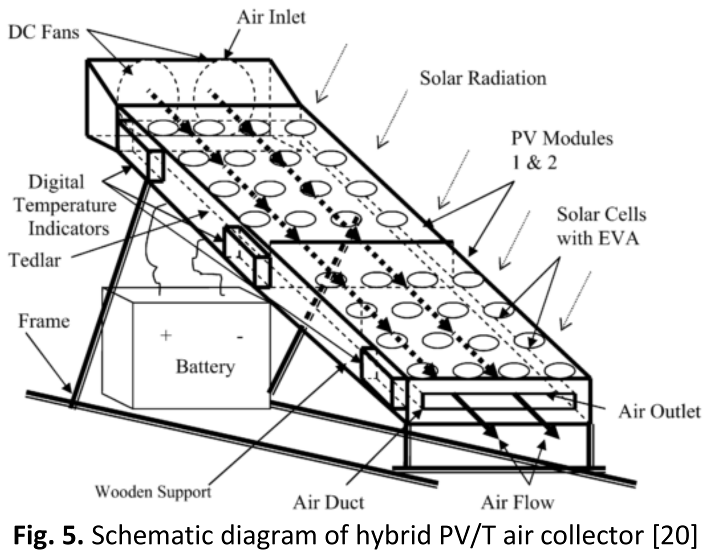

Fig. 5. Schematic diagram of hybrid PV/T air collector [20]

Teo *et al.,* [21] cooled four polycrystalline PV cells with a parallel array of ducts inlet or outlet manifold attached to the back of the PV. The main purpose for such designed is to provide uniform airflow distribution. The cooling mechanism of a direct and alternate current blower were used to cool the modules. With the aid of the blower, the PV temperature attained at 38°C with the electrical efficiency at 12.5%.

Four difference experimental setup of cooling system which involved the two forced convection phenomena system and the two system of spray cooling water were designed by Bevilacqua *et al.,* [17]. The two forced convection were equipped with a ventilation system on the module back surface of PV module. A suitably thin metallic cover fitted on the module's backside provides a closed cavity in which a small mechanical fan functions, expelling an air flow rate that has previously taken thermal energy from the backside. A number of small peripheral apertures on the metallic structure ensure air renewal by inducing the same air flow extracted by the fan inside the cavity. The other PV module was equipped with the same ventilation system as above with additional of four spray nozzles installed at the four external corners of the metallic closed cavity. The overall effect of air temperature on PV electrical efficiency was noticeably between 14.0% to 16.4%.

Fatoni *et al.,* [22] conducted an experimental setup of a PV cooling system consists of aluminium heatsink attached at the back surface of PV module and a fan to accelerate the disposal of heat circulation. With the aid of the fan attached, the PV temperature established at the range of 36.65°C to 39.60°C.

A comprehensive comparison of the air flow cooling method was tabulated in Table 2. The results have shown that the water or fluid cooling method was more effective in reducing the temperatures and increasing the electrical efficiency. The airflow method required significantly high speed of airflow to absorb heat from the PV module. Moreover, the high speed of airflow inside cooling duct consumes high electrical usage of fan or blower [23].

Table 2
Selected parameters for air flow in PV cooling control

Author	Configuration	Electrical efficiency	Thermal efficiency	Temperature
Irwan *et al.,* [16]	Brushless Fan (Back)	6-14%	-	(Reduce to 2-3°C)
Joshi and Tiwari [18]	Inlet air (fan) through the duct (Back)	14-15%	-	-
Tonui and Tripanagnostopoulos [19]	Forced convection (Fin & TMS)	-	12-20%	- (Reduce to 5-10°C)
Joshi *et al.,* [20]	Inlet air (fan)	9.5-11%	26.4-30.5%	38.5-41.5 ˚C (Reduce to 16°C)
Teo *et al.,* [21]	Parallel ducts inlet/outlet manifold (back)	12.5%	-	-
Bevilacqua *et al.,* [17]	Forced convection (fan & spray nozzles)	14%-16.4%	-	-
Fatoni *et al.,* [22]	Forced convection (fan and aluminium heatsink)	-	28.65%	55.50-39.60 ˚C (Reduce to 15.9°C)

2.1.3 Heat pipe cooling

Heat pipes are considered efficient heat transfer devices that combine the principles of both thermal conductivity and phase transition [6]. At one side of pipe, cooling medium evaporates and expands taking up heat while on the other side the medium condensates and releases the heat into surrounding. The medium travels back as liquid via capillary tubes and evaporates, thus completing the cycle [4].

Anderson *et al.,* [24] designed a copper/water heat pipe, aluminium fins with a copper sadle for the CPV cell. The fin dimensions and pitch were determined through computational fluid dynamics (CFD) software analysis with 24 number of fins. With input heat flux of 40 W/cm^2, the heat pipe rejected the heat to the environment by natural convection, with a ΔT of only 43°C [24].

Tang *et al.,* [25] investigated the performance of PV module of air and water by utilizing micro heat pipe arrays. Both systems were compared to the ordinary PV module without cooling. Results indicated that by using air cooling, the temperature reduces by 4.7°C with efficiency difference of 2.6% compared to PV without cooling (In that day the maximal air temperature and wind speed are 36℃ and 5.32 m/s). Whereas the temperatures of that water cooling reduce by 8°C with efficiency difference of 3% compared to PV without cooling (the maximal air temperature and wind speed are 35℃ and 4.72 m/s) [25].

Wu *et al.,* [26] and Gang *et al.,* [27] designed a heat pipe PV/T hybrid system collector to absorb the excessive heat from PV module. Wu *et al.,* [26] carried out investigation of relevant parameters and proven that the thermal efficiency can be improved by lowering the inlet water temperature and increasing the water mass flow rate. When there is a decrease in PV temperature, the flow rate increase. The higher mass flow rate at 0.07kg/s able to obtain the minimum value of temperature at 46.31 and 47.63 ◦C.

A comprehensive comparison of the heat pipe cooling method was tabulated in Table 3. The results have shown that the heat pipe PV/T hybrid system collector of water was more promising in reducing the temperatures and increasing the electrical efficiency compared to air. The parameter of inlet water temperature and water mass flow rate revealed to be dependent with PV performance improvement.

Table 3
Selected parameters for heat pipe cooling in PV cooling control

Author	Configuration	Electrical efficiency	Thermal efficiency
Anderson *et al.,* [24]	Copper aluminium fins design (Natural convection)	-	-
Tang *et al.,* [25]	Microheat pipe arrays		
	-Water pipe	3%	13.9%
	-Air pipe	2.6%	8.4%
Gang *et al.,* [27]	HP-PV/T solar collector	9.4%	41.9%
Wu *et al.,* [26]	Wick heat pipe	8.45%	63.65%

2.2 Close Loop Control

Close loop control or also known as a feedback-loop control has been designed for a PV cooling control system. This control scheme enabled the PV cooling control system to adjust its performance based upon the desired output response. Feedback control loop in PV cooling control system applied the measurement and estimation of the system states to reduce the nominal operating cell temperature by controlling the actuator. Sensors were required in the feedback control systems to determine the PV operating temperature. Sensors that mostly used from most of the researchers are the mounting temperature sensors and the air thermal meters. In this application of PV cooling control system, the closed-loop control strategies reviewed are divided into classical control, modern control and AI approach.

2.2.1 Classical control

This type of control strategies has been applied vastly for the PV/T cooling control system. It involves simple design and effective response for the lower order systems with stable behaviour. Classical control technique usually deals with solving differential equations using the frequency domain such as Laplace, Fourier and Z-Transform. The control design of Proportional (P) control, Proportional and Integral (PI) control and On-Off control, involved frequency response are preferred for the PV cooling control system.

A research work by Choi *et al.,* [28] proposed a PV cooling system using thermoelectric elements. A classical control of a micro-controller with Proportional Integral, PI control was introduced to independently control the temperature of thermoelectric elements. The PV output performance is increased since it can be operated around the nominal operating cell temperature of a PV module through an algorithm for temperature control. The BIPV cooling system is consists of an irradiation meter, a module thermal meter, an air thermal meter and a thermoelectric element attached to the rear of the PV module. A micro-controller (Atmega128) is used as a controller to control the module temperature to maintain at nominal operating cell temperature. The real-time temperature data used the monitoring system of a DAQ board (60164U of National Instrument (NI) company). Results for the experimental work proven that when the proposed method of cooling control system is installed the electrical efficiency is greatly improved. The configuration of thermoelectric cooling control system is shown in Figure 6.

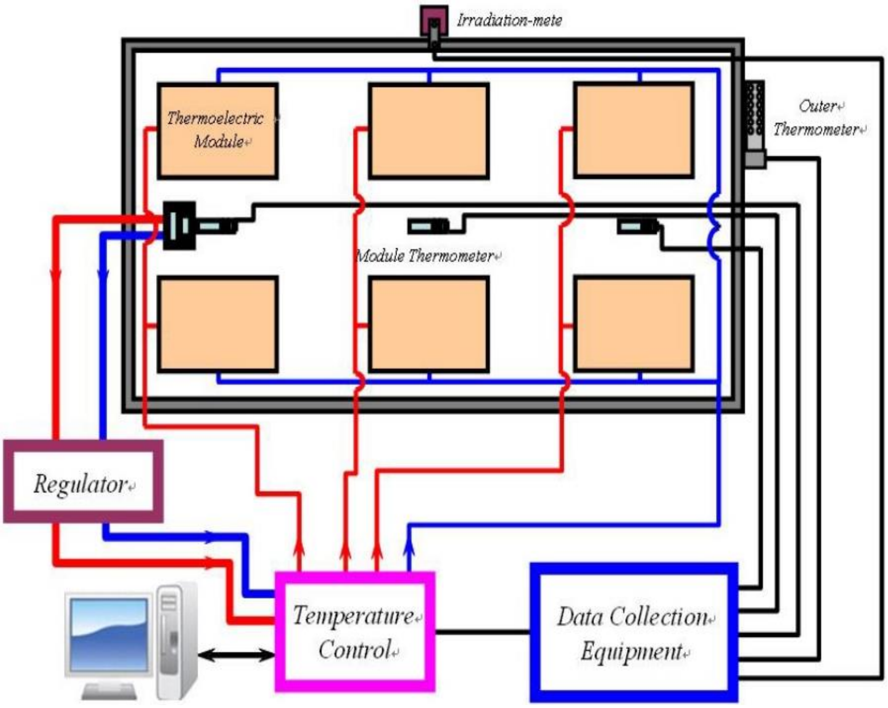

Fig. 6. Configuration of thermoelectric cooling control system (BIPV) [28]

Furthermore, a research work of automated micro-controller using Proportional control was progressing with the research work from Alboteanu *et al.,* [29]. The control cooling system composed of two microcontroller modules of (i) slave and (ii) master, three temperature sensors mounted on the PV, PV module, solar collector, water tank and electrical equipment of PV module. Both of the micro-controller modules were developed with ATMEGA128 microcontroller. The experimental results for this control approaches were the monitoring of temperature values from three temperature sensors mounted on the PV panel. The temperature oscillates within ±1°C from 0-15 minutes of experimental work. This allows the work of pump to start and stop abruptly in order to satisfied the desired temperature of the PV module. The schematic diagram of the automated micro-controller PV cooling control system as shown in Figure 7. The results for the experimental revealed that the PV panel temperature values evolved around the PV nominal operating temperature values.

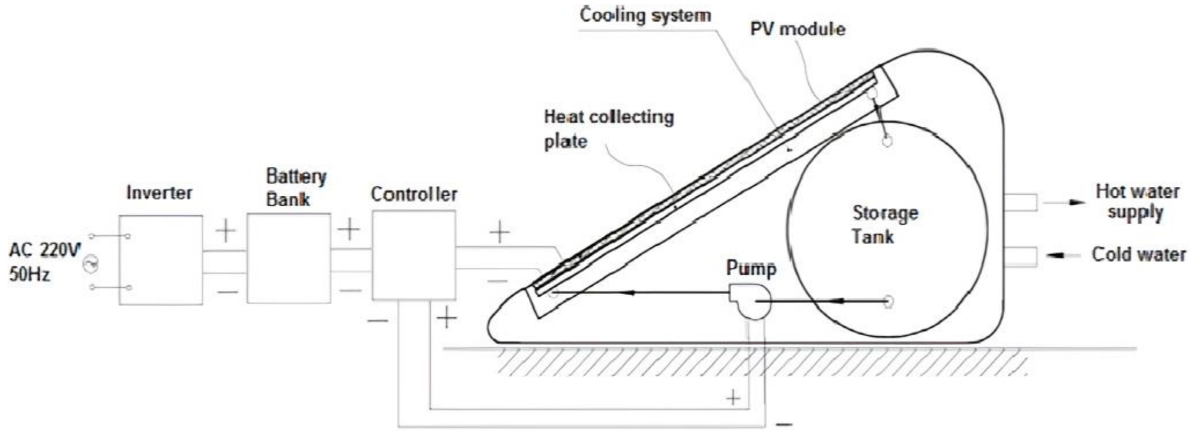

Fig. 7. The PV cooling system [29]

The classical control design of ON-OFF controllers using the micro-controller was then further investigated by Leow *et al.,* [30]. The cooling control system composed of a DC brushless fan and a water pump with inlet/outlet manifold, temperature sensors and PIC 18F4550 micro-controller. The micro-controller was utilized to automatically manipulate the DC fans and DC water pump either to switch ON and OFF based on temperature PV module. Results shows that the cooling control system of DC hybrid increase the output of voltage, current and power with 4.99%, 39.90% and 42.65% respectively.

Ceylan *et al.,* [31] introduced the batch control design in PV cooling control system. This type of control will work in flows and accordingly. The work procedure for Figure 8 began when the cold water flowing into the system passes through cooling system at the rear of the PV module. If the process control equipment (PCE) reaches the set temperature, it will open the solenoid valve which is normally off. The temperature sensor of the process control equipment is attached to the collector output. If the water temperature passes the solar collector decreases and below the set temperature, hence the solenoid valve close. The block diagram of the batch control process is shown in Figure 8. Result shows that the efficiency of the PV module was increased to 3%. The process can be control by work sequence and proven that as the solar radiation increased, the module temperature decreased in the cooling control system.

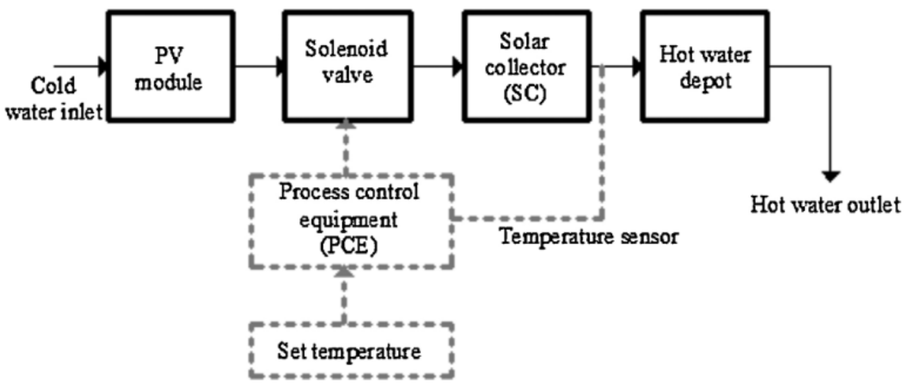

Fig. 8. The batch control process of PV/T system [31]

Abdeelhameed *et al.,* [32] carried out an experimental study of PV cooling control system by controlling the water flow rate of the system. The control of opening and closing of water valve was actuated by a solenoid valve using pulse width modulation (PWM). The opening duration of the solenoid valve varied from the duty cycle of a square wave generated by LabView. The temperature sensor or feedback of the system of LM 35 was used to measure the PV operating temperature. This temperature signal acquired to the Lab view through the National Instrument Data Acquisition (NI DAQ) to be calibrated.

The control of flow by using the classical control of proportional, proportional and integral control have shown the increase of efficiency in PV performances. The promising results from batch control of Ceylan *et al.,* [31] and PI control of Alboteanu *et al.,* [29] had shown that the PV panel temperature values evolved fastly around the PV nominal operating temperature values. However, this classical control method involves the abrupt changes of open and close of a valve which create tendency to damage the valve or the system itself.

2.2.2 Modern control

Modern control strategies were introduced to overcome the difficulties in classical control technique. It can handle non-linear and time invariant systems. These control strategies involved input, output and internal states of the system described by phase or state variables which represent the internal behaviour of the underlying control system. From the literature reading, only the control design of optimal control has been used by Alhammad *et al.,* [33] and Kane *et al.,* [34] involved mathematical model or derivation for the PV cooling control system.

Alhammad *et al.,* [33] proposed designs of combination thermoelectric cooler (TEC) and thermoelectric generator (TEG) modules to cool down PV module in hybrid cars. In order to obtain the optimal current, a mathematical model (controller) was derived. The mathematical derivation was used as control unit for the system while the feedback for the systems were from four sensors that measure temperature for hot point and cold point heat sink. Result validation was carried out with the simulation work of MATLAB. The proposed design of TEC and TEG is shown in Figure 9. This optimal control approach provides the best output efficiency for the PV module and applicable for the application in hybrid cars when adding a PV module. Kane *et al.,* [34] proposed a cooling control approach using temperature based maximum power point tracking (MPPT) scheme in order to operate Thermoelectric module (TEM) at optimal temperature of PV system. TEM is attached at the back side of PV module for absorption of the heat generated in PV module by infrared spectrum. Mathematical model for TEM is developed by consideration of temperature dependence of material properties.

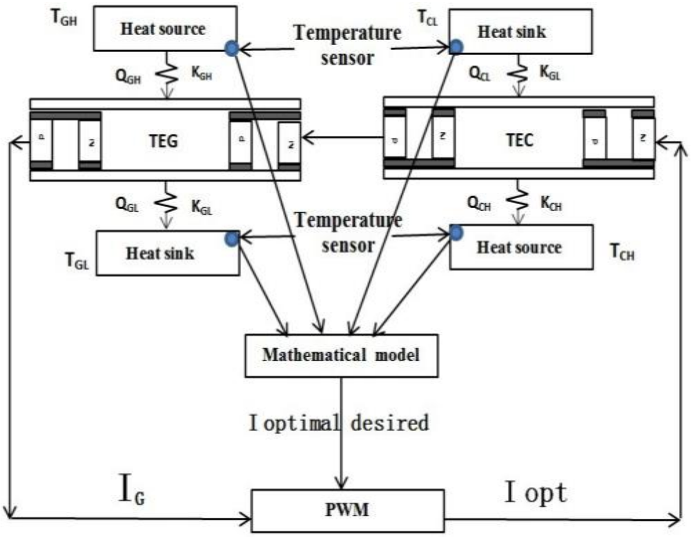

Fig. 9. Proposed model design [33]

The proposed model of PV-TEC hybrid system was developed with fast MPPT controller for PV and temperature-based controller for TEC system which is shown in Figure 10. Result shows that there was improvement in electrical efficiency of PV module in the range of 1 until 18% with temperature range of 25-45°C.

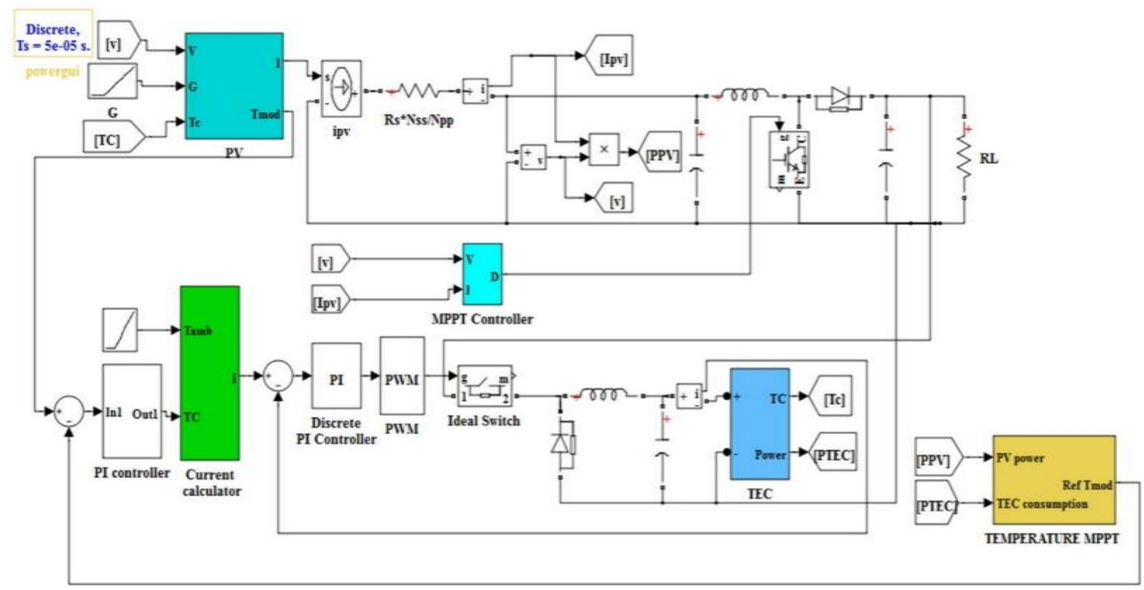

Fig. 10. Schematic of proposed PV-TEC hybrid system [34]

2.2.3 Artificial intelligence control

Artificial intelligence control strategies involved computing approaches such as neural network, metaheuristics, fuzzy logic and etc. These control strategies were introduced since able to offer tools in automatic control at two decision points of input and control [35]. It involves algorithm that able to deal with complicated problems and other capabilities. In PV applications the used of artificial intelligence control in controlling the efficiency of PV performance can be categorized into three categories of maximum power point tracking, inverter control, and sun tracking control [36]. The PV applications of cooling control system of PV surface has not been widely used from most of the researcher. From the literature reading, the control design of metaheuristic control has been used by Najafi and Woodbury [37], Musunuri [38], Sobhnamayan *et al.,* [39], Yousefnejad *et al.,* [40], Abd Elaziz *et al.,* [41], Bassam *et al.,* [42], Zhou *et al.,* [43] and Naceur *et al.,* [44].

Najafi and Woodbury [35] investigated a cooling control system by proposing a cooling method of using Peltier effect. The objectives of the cooling control approaches were (i) to control the PV operating temperature within the desired temperature, (ii) to determine the optimal value of supplied electrical current for the thermoelectric cooling module which leads to the maximum generated power by applying the genetic algorithm. Results shows that it able to satisfy the first and the second objective with the highest net output power by applying an optimization via genetic algorithm, (GA). They implied the control design of metaheuristic by applying an algorithm from a mathematical model of the cooling control system. In addition to the metaheuristics control introduced by Najafi and Woodbury [37], an optimization research of PV/T collector based on exergy concept were studied by Sobhnamayan *et al.,* [39]. By considering energy balance for different components of PV/T collector, the analytical expressions for thermal parameters such as PV temperature, outlet water temperature, useful absorbed heat rate, average water temperature, thermal efficiency and etc can be obtained. The optimization of the exergy efficiency of PV/T collector was carried out by applying the GA algorithm. Results shows that the energy optimization gives optimum points in start or end of optimization parameters ranges.

Musunuri [38] carried out the research of PV cooling control system by modelling the wind and PV energy systems, identifying the appropriate conversion technology and control architecture for the PV hybrid system. An algorithm of Hill Climb is developed to extract maximum power from both the wind and PV energy systems, and it was seen that the proposed algorithms have a better performance when compared to the conventional architectures.

Yousefnejad *et al.,* [40] carried out a PV cooling system with use of heat in a Rankine cycle to power a turbine and generate electricity. To achieve the goal of harvesting low-grade waste heat from PV panels to cool down the panels, Yousefnejad *et al.,* [40] developed an analytical solution (algorithm) for designing a cooling system to find important design parameters of the hardware. The algorithm produced then were validated with the Computational Fluid Dynamics (CFD) simulations to ensure the accuracy of the algorithm is acceptable. The results of the algorithm were further validated by applying the real data from an experiment. The results were sufficiently accurate and the established algorithm were useful in designing PV cooling system.

Abd Elaziz *et al.,* [41] developed an optimization artificial intelligence method to evaluate the performance of photovoltaic/thermal collectors (PVTCs) integrated into electrolytic hydrogen production (EHP) systems in terms of photovoltaic power output, photovoltaic surface cell temperature prediction, and coolant initial temperature performance. A new metaheuristic algorithm called Mayfly-based optimization (MO) was implemented using Random Vector Functional Linking (RVFL) networks to maximize the prediction accuracy. The experimental results of this work show that the hybrid PVTC-EHP system can be considered as a two-sided production system that can produce hydrogen and generate electricity simultaneously with various coolants for low temperature real domestic and industrial applications.

An adaptive neuro-fuzzy inference system technology is being developed by Bassam *et al.,* [42] to estimate the temperature variations of photovoltaic systems. During the learning process, experimental measurements consisting of six environmental variables (temperature, irradiance, wind speed, wind direction, relative humidity and air pressure) and one operating variable (photovoltaic power output) were used as training parameters. The proposed predictive model consists of a zero-order Sugeno neuro-fuzzy system with two generalized bell-shaped membership functions and 128 fuzzy rules for each input. The model is validated with experimental information from an instrumented photovoltaic system. The obtained results show that the proposed method provides a reliable tool for estimating module temperature based on environmental variables.

A phase change material integrated hybrid system with advanced energy conversions and multi-diversified energy forms, such as solar-to-electricity conversion, active water-based and air-based cooling and distributed storages was demonstrated in a research work of Zhou *et al.,* [43]. By combining supervised machine learning and heuristic optimisation methods, a generic optimisation methodology was created. To characterise the optimisation function, an artificial neural network (ANN) was created using an advanced learning method. Multivariable optimisations were carried out systematically in five different climatic areas for widespread application purposes. With a correlation coefficient more than 0.99, the created ANN-based model is accurate and computationally efficient for the correct optimisation function.

A study by Naceur *et al.,* [44] contributes to compare three artificial intelligence approaches of Fuzzy Logic (FL), Artificial Neural Network (ANN) and Deep Learning (DL) based on a solar, wind, and energy consumption database, demonstrating the performance of each method. The system's performance under various conditions was tested using Matlab or Simulink simulations with real energy consumption and weather data. According to the results gained, DL outperforms the other two prediction techniques which produce better outcomes and deliver the nearest result compared to genuine data.

A comprehensive comparison of the control approaches in PV cooling control system from different researchers were tabulated in Table 4. In order to find the best design and operating parameters for PV module, several optimization techniques have been developed. However recently, the trend of researchers from 2014 onwards were diverted to new control approaches of AI control. AI system have been applied since AI has greater abilities and advantages as a prediction tool to assess and predict the performance of the PV and able to explore the optimum operating parameters that maximize the electrical and thermal efficiencies of PV module. Moreover, the overall efficiency of the PV systems shows higher accuracy and produce better outcome by applying techniques or methods of hybridization. Hybridization developed from new artificial intelligence models that are coupled with metaheuristic optimization approaches. The hybridization anticipates the performance of PV systems effectively.

Table 4
Selected parameters for control approaches in PV cooling control system that different researchers reported

Author	Configuration	Control design	Technique (Experimental/ Simulation)	Electrical efficiency	Control approach	Remark
Choi *et al.,* [28]	Thermoelectric element	Classical control	Experimental	-	PI controller	-ATMEGA128 micro-controller -NI (monitoring)
Alboteanu *et al.,* [29]	Heat pipe (water)	Classical control	Experimental	-	Proportional control	ATMEGA8 micro-controller
Najafi and Woodbury [37]	Thermoelectric element	AI control	Simulation	-	Metaheuristics	GA algorithm
Sobhnamayan *et al.,* [39]	PV/T water collector	AI control	Simulation & Experimental	-	Metaheuristics	-Exergy analysis and optimal -Exergy increase 11.4-13% -GA algorithm
Leow *et al.,* [30]	Hybrid air and water cooling	Classical control	Experimental	4.99%	ON-OFF	-Temperature reduce by 6.79°C -PIC 18F4550 micro-controller
Ceylan *et al.,* [31]	PV/T water cooling	Classical control	Experimental	12-16%	Batch control	Δ3% efficiency of cooling & non-cooling
Alhammad *et al.,* [33]	Thermoelectric element	Modern control	Simulation	-	Optimal control	-mathematical modelling formulation
Kane *et al.,* [34]	Thermoelectric element	Modern control	Simulation	1-18%	Optimal control	-GA algorithm (MPPT) -Mathematical modelling formulation (TEM)
Musunuri [38]	Wind PV system	AI control	Experimental & Simulation	-	Metaheuristics	Hill Climb algorithm
Abdelhameed *et al.,* [32]	PV/T water collector	Classical control	Experimental	-	PID control	Pulse width modulation- NI DAQ
Yousefnejad *et al.,* [40]	Hybrid water cooling	AI control	Simulation	-	Metaheuristics	MATLAB algorithm & CFD simulation
Abd Elaziz *et al.,* [41]	Hybrid air and water cooling	AI control	Experimental & Simulation	8.5% (water) 8.0% (air)	Metaheuristics	MO-RVFL
Bassam *et al.,* [42]	Hybrid air cooling	AI control	Experimental & Simulation	-	Metaheuristics	Adaptive Neuro-Fuzzy Inference System
Zhou *et al.,* [43]	Phase change material (water & air cooling)	AI control	Experimental & Simulation	-	Metaheuristics	Overall output energy increase from 1.1-7.4% in 5 different regions.
Naceur *et al.,* [44]	Hybrid air cooling	AI control	Simulation	-	Metaheuristics	Fuzzy Logic, Artificial Neural Network, Deep Learning

3. Conclusions

With only a few of control strategies proposed over the years for PV cooling control system, the determination to choose which one is best suited for an application is a challenge. Table 1 gives the main aspects that could be considered for selecting a particular control strategy. It can be seen that a majority of the methods and configuration design of the system proposed need to have prior knowledge of the system characteristics, controller and sensors used as feedback loop.

It has been discerned that recent research works are lacking on the considerations of PV efficiency in cooling control system applications. Most of the researchers regards with PV cooling preferred the open loop type control strategies which usually affected by external disturbances such as wind and etc. A close loop control system which involved controller and sensors able to contribute a robust, stable and insensitive to uncertainties and external disturbances in a system. Thus, the close loop control system seems to be effective to solve the issues.

It was also discovered in the literature, the numbers of publications related to modern and AI control strategies was quite low compared to classical control. Most of the researchers preferred the use these control strategies since it able to provide information on the effect of varying the controller parameters. Besides that, this may due to the controller design of Single Input Single Output (SISO) for most of their applications which was suitable for simple and low order system of classical control. In this research area, further investigation can be conducted by using the modern and AI control in PV cooling control system, since previous researchers had shown promising result in the system [35-37]. The system robustness may be improved and the closed-loop stability can be proven. The various type of control strategies that have been reviewed in this article might not cover all the PV/T cooling control methods that are available in the literature.

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