Lithium Ion Battery Thermal Management System Using Optimized Fuzzy Controller

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***Abstract* -- Lithium ion battery is an important energy storage device especially, in electric vehicles due to its large capacity. However, heat generated from this battery during the high rate of charging and discharging process might lead to irreversible capacity loss and degrade the battery performance. This paper presents a thermal management system for a lithium ion battery to maintain a regulated thermal process in the battery pack. A robust control algorithm is proposed using particle swarm optimization (PSO) based fuzzy logic controller to the battery thermal management system. The system performance is evaluated by the overshoot, undershoot and settling time, and compared with the PID and simple fuzzy system to validate the results. From the performance results and comparisons, the proposed PSO based fuzzy system is able to yield the least overshoot of 0.497 % and settling time of 32 min 13 s during the heating subroutine, and undershoot of 0.975 % and settling time of 28 min 46 s during the cooling subroutine. Moreover, it is also capable of maintaining a uniform temperature among the battery modules in the pack. These results prove that the PSO based fuzzy system is a robust control system which enhances the performance of the lithium ion battery temperature regulating system efficiently.**

***Index Terms*-- particle swarm optimization, control algorithm, fuzzy controller, heating and cooling system, thermal management, lithium ion battery**

I. Introduction

Renewable energies have been becoming popular worldwide over the last few decades due to the increasing attention on the environmental pollution issue caused by the usage of conventional energies. However, due to the natural, economical and technical issues, the renewable energies is becoming more difficult to be implemented into the electrical grid [1]. To overcome this problem, battery energy storage system (BESS) is looking as a big solution for incorporate renewable energies into the grid [2]. Lithium ion batteries have the potential to remain competitive in the world market due to the superior characteristic and performance of high energy efficiency and density, wide range of the safe operating temperature, higher rate of charging capability, longer cycle life and lower self-discharge rate [3-5].

Lithium ion battery is a power source with lots of electrochemical reactions during the process of charging and discharging. For a large scale of battery pack, the accumulation of the heat generated during the charging and discharging processes might lead to the rise in the overall temperature in the battery pack and thus causing the faster acceleration of electrochemical reaction. This can reduce the battery lifespan and seriously affect the battery charging capability and safety. Besides, the mechanical abuse, overcharging and the short circuit issue in high thermal condition of battery pack may cause battery damage [6]. At low ambient temperature, the lithium ion diffusion capacity inside the battery may decline [7]. Furthermore, at different ambient temperature, cells and modules in a battery pack behave differently and this causes the imbalance of the electrochemical over time, the difference in the rate charging and discharging, a difference in the state of charge (SOC) between adjacent cells, and the capacity loss [8]. Thus, a battery thermal management system (BTMS) is essential to maximize the battery performance by maintaining optimum operating temperature range [9].

In BTMS, the heating system provides the specific temperature in the battery storage system at cold climate and the cooling system ensures the operation in the battery storage system at optimum temperature during the heat release from charging and discharging in battery pack. Many research works have been conducted and developed on battery thermal management system. In an air based cooling system, ambient air circulation is used to carry out the heat transfer process in the battery pack [6,9]. The isolation between the coolant media and the cells is not required and the air based temperature control system is easily setup [10]. However, it requires installing an additional filter into the system to block and filter out the dust from the environment as this cooling system uses the outside air for cooling purposes. Moreover, this air based system has a smaller heat capacity when it compared to other cooling methods. Liquid based cooling systems are configured with a liquid based passive, active moderate and active system for the battery thermal management system. In passive system, heat transfer process is carried out at the heat exchanger through the temperature difference between the liquid coolant and ambient air until the equilibrium temperature is achieved. As the cooling effect depends mainly on the surrounding air temperature, if the temperature of the ambient air is cool enough, the cooling effect is great and sufficient and vice versa. In active system, two heat exchangers are used for the battery cooling process. Thus, the battery coolant used for the battery pack is always maintain at cool condition and is not affected by the ambient temperature. However, its maintenance is difficult due to the complicated in the system structure and it have the tendency of liquid leaking out [10,11]. Refrigerant based cooling system overcomes the disadvantages for both the air based and liquid based cooling system which has been recently applied in most of the hybrid electric vehicles. Here, the battery pack is directly integrating into an existing refrigerant cycle. However, it is not suitable for the applications of a high charge and discharge rate due to the lesser heat capacity of refrigerant when it compared to liquid. Besides, the design structure is complex, the cost of this system is usually high, and it has safety issue concern especially for R134a that is highly flammable [11,12].

For an efficient BTMS, a robust controller is essential that is able to maintain an even temperature during the operation of battery pack with long charge-discharge cycle. Many research and developments have been done on temperature monitoring and control system in the thermal management system as the thermal effects might vary the kinetic movement and transport phenomena of the electrochemical system of lithium battery [13-15]. PID (Proportional-Integral-Derivative) controller recovers and improves the transient and steady state response, thus providing solution to the real application control problems in industries [16]. Many methods such as the Ziegler-Nichole frequency response method, the thumb rules method, the software tools, Cohen-Coon method for tuning the PID controller parameters are applied, however, these involve some cost and training, and require some math [17]. Model predictive control and impedance based battery thermal management system have been developed for thermal monitoring and SOC balancing [18,19]. In many complex control system, Fuzzy Logic controller (FLC) has been introduced to solve the imprecise control issue by computer. Thus, the flexibility have greatly increased and the precision for designing a complex and nonlinear control system is improved. FLC is more often used in temperature and machine control due to its capability to provide a fast response and enhances the system stability and reliability [20,21]. Nevertheless, FLC requires optimally fixing its parameter values. Optimization techniques such as Genetic Algorithm (GA), Particle Swarm Optimization (PSO) and Backtracking Search Algorithm (BSA), are incorporated to optimize fuzzy system for robust control in many applications especially in renewable energy system for improving the system performance such as power optimization, temperature control and variable speed control [16,22].

The PSO algorithm is applied to solve many of the power flow and power system issues in a complex system. The threshold parameters of the power management strategy in the HEV have been optimized using the PSO algorithm [23,24] and the optimal sizing for the hybrid photovoltaic system, wind energy and battery storage system have been determined with the implementation of PSO algorithm [25]. However, PSO algorithm is easily trapped in a local minima and unable to select the control parameters in a proper way that will leads to a poor solution condition [22,24].

In order to achieve the optimum performance of the lithium ion battery storage system, proper thermal management system with robust and optimal control is required. Thermal management system must be able to monitor the temperature in the battery pack and ensure the safe range of the temperature operation by driving the heating and cooling system [26,27]. This paper proposed an optimal fuzzy based lithium ion battery thermal management system for monitoring and maintaining the temperature of the battery pack. This control concept uses PSO algorithm to tune the fuzzy parameters that in turn controls the temperature of the battery pack efficiently.

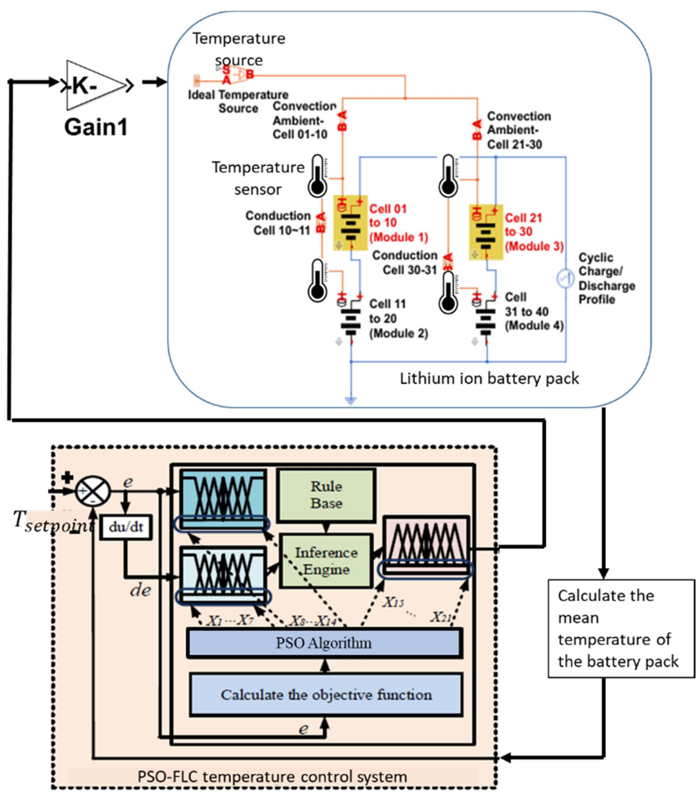

Fig. 1. Lithium ion battery pack thermal management system using PSO based fuzzy algorithm

II. OVERVIEW OF LITHIUM ION BATTERY THERMAL MANAGEMENT SYSTEM

The overview of the lithium ion battery pack thermal management system in block using optimal fuzzy algorithm is shown in Fig. 1. The proposed system mainly focuses on the efficient thermal management system for lithium ion battery pack. This thermal management system is developed by means of PSO based optimal FLC system. The BTMS entails designing lithium ion battery pack, thermal management system, FLC system and PSO algorithm. This section presents the design model of proposed BTMS to achieve an efficient temperature regulation for lithium ion battery pack with system stability and reliability.

A. Template Thermal Model of Lithium Ion Battery

The general equivalent circuit modelling (ECM) with n-RC block is simplified into an ECM with single RC block as it is sufficient to account most of the cell dynamic characteristic such as inner cell temperature, average current discharge and the open circuit voltage [28]. Fig. 2 presents the single RC block model of lithium ion battery where every elements presented in the Fig. 2 are the function of the SOC and temperature as in (1), (2), (3) and (4). The parameter values are estimated at different temperatures in many discharge experiments and presented in the two dimensional look-up tables.

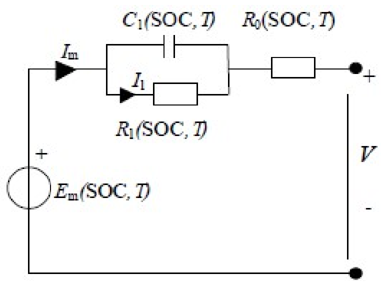

Fig. 2. Single *RC* block model of lithium ion battery cell

$$R_0 = R_0\ (SOC, T) \tag{1}$$

$$R_1 = R_1\ (SOC, T) \tag{2}$$

$$C_1 = C_1\ (SOC, T) \tag{3}$$

$$E_m = E_m\ (SOC, T) \tag{4}$$

ECM components value is mainly depend on two factors, which are the inner cell temperature and the SOC. For this model, it is assumed that the inner cell is always have a uniform temperature and the inner cell temperature is taken as the average temperature of all the cells in a module. By solving the heat equation of the heat exchanging between a homogeneous body and environment, the temperature of the cell can be computed as (5) and the transformation as (6) [29,30]. The capacity, C_Q of a cell is affected by the inner cell temperature, average cell discharging current and the time of discharging. at time, t = 0, the cell is in fully charged condition, the extracted charge, Q_e is assumed initially the cell fully charged. Thus the SOC can be defined as (7) [30,31].

$$C_T\ \frac{dT}{dt} = -\ \frac{T - T_a}{R_T} + P_S \tag{5}$$

$$T(s) = \frac{P_S\, R_T + T_a}{1 + R_T\, C_T\, s} \tag{6}$$

$$\text{SOC} = 1 - \frac{Q_e}{C_Q} = 1 - \frac{\int_0^t I_m(\tau)\, d\tau}{C_Q\ (I, T)} \tag{7}$$

where, C_T is Heat Capacitance (Jm^{-3}K^{-1}), T is Inner cell temperature (K), T_a is Ambient temperature (K), *dT/dt* is Rate of change of inner cell temperature (Ksec^{-1}), R_T is Convection resistance (Wm^{-2}K^{-1}), P_S is Power dissipated inside the cell (W), *s* is Laplace transform variable.

The battery pack consists of four modules that are connected in series and in parallel to each other. Each module is consists of 10 series-connected cells with specific heat of 810.5328 Jkg^{-1}K^{-1} in each cell. The purpose of constructing a series-parallel configuration of the battery pack is to verify the temperature uniformity in each module and to investigate the thermal behavior of each single module during heating and cooling process.

B. Thermal Management System Design

Temperature monitoring and control system is essential in the battery thermal management system as lithium ion batteries perform its best at its optimum temperature ranges. Indirect liquid temperature regulating system is used to maintain the battery pack at desired temperature ranges. In this design, an ideal temperature source with a built-in heater and coolant reservoir inside is to provide heating and cooling effect to the battery pack. The lithium ion battery temperature regulating system with an ideal temperature source is shown in Fig. 3.

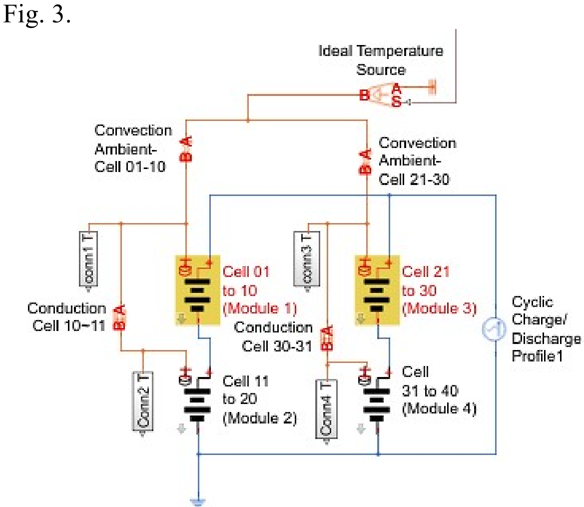

Fig. 3. Lithium ion battery pack configuration with temperature source

In Fig. 3, the ideal temperature source block represents an ideal thermal energy source that is powerful enough to maintain specified temperature at its outlet regardless of the heat flow consumed by the system. Block connections A and B refers to the thermal conserving inlet and outlet ports respectively and the block connection S represents a physical signal port. The temperature differential across the source, T_B-T_A is directly proportional to the control signal provided by the design controller. The heat transfer process among the battery modules is considered through conduction and convection. However, the radiation effect has negligible value compared to conduction and convection cooling in this thermal management. The heat transfer block in Fig. 3 represents the transfer of energy by convection between two bodies by means of fluid motion and by conduction through a layer of material. The block connections A' and B' are thermal conserving ports associated with the points for convection and with material layers for conduction. The heat flows from A' to B' the heat flow is assumed positive. The area, thickness, heat transfer coefficient and thermal conductivity of a cell in the module are 1×10^{-4} m^2, 0.1 m, 20 $Wm^{-2}K^{-1}$ and 401 $Wm^{-1}K^{-1}$, respectively.

C. FLC System Design

Fig. 4 presents the design structure of a temperature control system using the fuzzy controller. Fuzzy based control system analyzes input of the analogue values in terms of logical variables. The logical variables receives on a continuous value between 0 and 1 that is different from a digital logic which only operates on discrete value such as 0 and 1 [20,21]. Fuzzy based system is a rule-based system which is characterized by sets of rules. The rule based system is essential as it is the reference and backbone of the whole temperature regulating system. The rule table of the fuzzy design in this development is prepared based on the knowledge of the experts [17,20] as shown in Table I. The rule table in this design consists of two fuzzy input sets, which is error, *e* and change in error, *de* and each fuzzy input sets is consists of seven membership function. Thus, there are a total of 49 rules statements in the rule-based system.

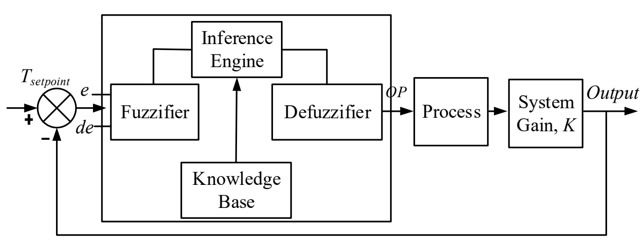

Fig. 4. Structure of Fuzzy based control system

TABLE I
RULE TABLE FOR FUZZY DESIGN

CE \ E	NL	NM	NS	ZE	PS	PM	PL
NL	VL	VL	VL	VL	VL	VL	LOW
NM	VL	VL	VL	VL	VL	LOW	LOW
NS	VL	VL	MED	LOW	LOW	VL	VL
ZE	VL	LOW	LOW	MOD	MED	MED	MOD
PS	MED	MED	MOD	MOD	HIG	HIG	VH
PM	HIG	HIG	HIG	VH	VH	FUL	FUL
PL	VH	VH	FUL	FUL	FUL	FUL	FUL

NL - Negative Large, NM - Negative Medium, NS - Negative Small, ZE - Zero, PS - Positive Small, PM - Positive Medium, PL - Positive Large, VL - Very Large, LOW - Low, MED - Medium, MOD - Moderate, HIG - High, VH - Very High, FUL - Full.

D. Particle Swarm Optimization (PSO) Algorithm

PSO algorithm is a population-based optimization method that is applied to optimize the candidate solution iteratively as a particle of a problem. In general, PSO algorithm is able to search the optimal solution of the swarm particles via the movement of the particles in the search space by finding its optimized velocity and position. The optimization process can be done by obtain the minimum value in an objective function via an iteration process. The first step in the PSO algorithm is to producing the initial populations. Fitness function is the performance index of a population and the higher the fitness value, the better the performance it will be. Fitness function is defined as (8) [22,24].

$$MAE = \frac{1}{M}\sum_{i=1}^{M}\left|Y_r - Y_i\right| \quad (8)$$

where, M is the total number of samples, Y_r is Reference value and Y_i is True value.

The best values of the positions and velocities in the search-space are *Pbest*. The modified velocity and position of each particle can be determined by (9) and (10). The best particle among all the particles in the population is *Gbest* [22-24].

$$v^{k+1} = wv^k + c_1 {r_1}^k(Pbest^k - x^k) + c_2 {r_2}^k(Gbest^k - x^k) \quad (9)$$

$$x^{k+1} = x^k + v^{k+1} \quad (10)$$

where, v^{k+1} is New velocity of the particle, v^k is Present velocity of particle, x^k is Present swarm position, x^{k+1} is Updated swarm position, c_1 & c_2 are Learning factors, w is Weight factor and r_1 & r_2 are Random numbers between (0, 1).

The calculated fitness value will determined whether the number of maximum iteration is reached. Meanwhile, *Pbest* of each particle and *Gbest* of the population are calculated so that the velocity, position, *Pbest* and *Gbest* of the particles can be updated and the best position can be determined. Hence the optimal values are obtained corresponding to the minimum fitness value.

III. OPTIMAL FLC BASED TEMPERATURE CONTROL ALGORITHM

To develop an optimal fuzzy logic controller, PSO algorithm is applied to search the globally optimal parameters of the fuzzy logic system as shown in Fig. 5. The whole process of the PSO-FLC begins by setting the PSO parameters such as N, T, D and the space range qualities. By using the parameters' boundary range, the swarm positions are randomly generated and the initial *Pbest* is set. Next, each particle's fitness value are calculated by using the objective function such as Mean Absolute Error (MAE) as (8) [16,24]. During iteration, the best fitness value is computed to obtain the best *Pbest* among the entire particle's *Pbest* and to assign it as *Gbest.* Next, the velocities of the particles are calculated and the swarm positions are updated by referring to (9) and (10). The verification of the swarm position is essential to determine whether the particles are remaining within the search space. The fitness value of each particle is then recalculated using the objective function in (8). The calculated fitness value will be compared to the previous fitness values. Meanwhile, the *Pbest* is constantly updated until the maximum iteration number is reached. Finally, the minimum fitness value (best fitness value) of the objective function is selected with the best swarm position. The optimal parameter values of error, *e* and change in error, *de* output to the fuzzy logic cooling controller [16,17]. The overall process in the PSO based fuzzy implementation for BTMS is illustrated in the flowchart as shown in Fig. 6.

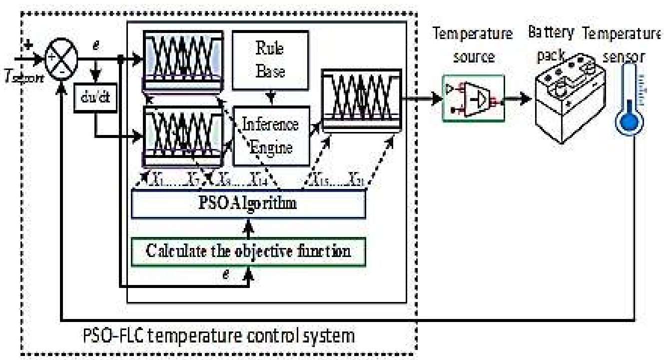

Fig. 5. PSO based FLC implementation

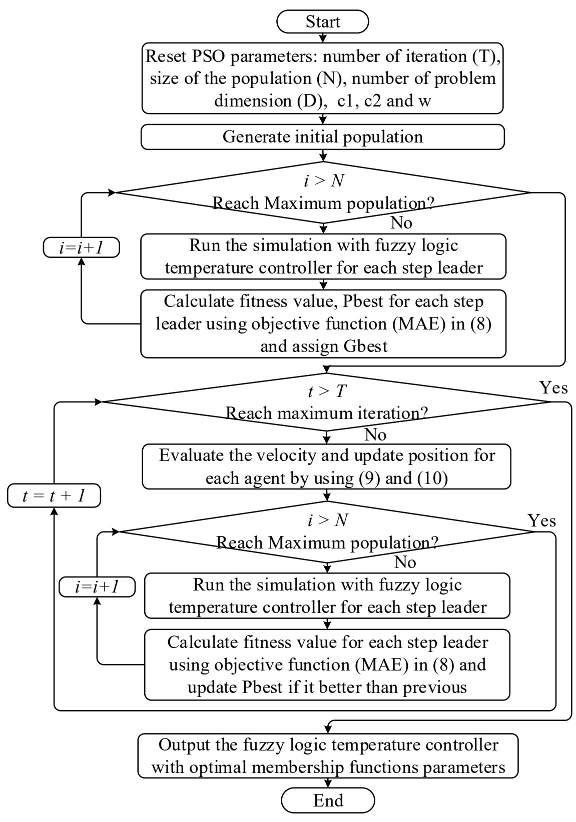

Fig. 6. Flowchart of the PSO based fuzzy implementation

IV. BATTERY THERMAL MANAGEMENT SYSTEM IMPLEMENTATION

The temperature regulating system is carried out by the PSO based fuzzy controller. The set point temperature of this system is assumed 300 K as this temperature is the optimum working temperature of the lithium ion batteries. In order to evaluate the performance of the controllers, the battery pack is initially set to a temperature of 273 K so that the heating subroutine is performed. The battery pack is set to a temperature of 323 K so that the cooling subroutine is performed. The whole proposed BTMS model for a lithium ion battery pack with four modules in series-parallel configuration is implemented in MATLAB/Simulink by configuring all model blocks with their optimum parameter values as shown in Fig. 7.

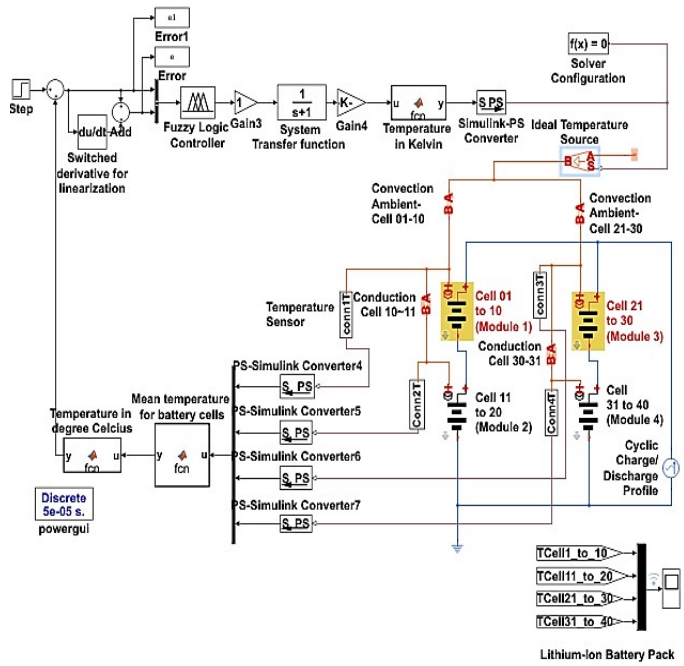

Fig. 7. Simulation model for battery temperature control system

The temperature regulating system is executed with several procedures to maintain the temperature of the lithium ion battery pack at 300 K. First, temperature sensors measure the temperature of each module in the battery pack. Then, the average temperature from these measurements is calculated and is fed back to the system and the controller. If the temperature of the battery pack is below the set point temperature, heating subroutine is carried out by the temperature source to heat up the battery pack. Conversely, if the temperature of the battery pack is above the set point temperature, cooling subroutine is carried out by the temperature source to cool down the battery pack. The overall temperature regulation process of the lithium ion battery pack is described in the flowchart as Fig. 8.

V. RESULTS AND DISCUSSIONS

The lithium battery pack and thermal management system is implemented on the fuzzy based control system incorporating the PSO technique and the obtained results are compared with those of BTMS using PID and simple FLC system in terms of rise time, fall time, overshoot, undershoot and settling time. To evaluate the performance of the control systems on heating and cooling subroutine, the initial temperature of the battery pack is fixed at two different temperature, which is 273 K and 300 K at different times.

The output responses of the PID, simple fuzzy and PSO based fuzzy system are presented and compared accordingly to validate the proposed BTMS.

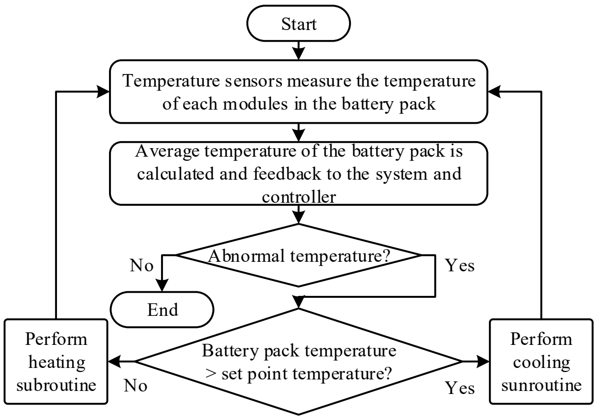

Fig. 8. Temperature regulation scheme of the lithium ion battery pack

VI. Results and Discussions

The lithium battery pack and thermal management system is implemented on the fuzzy based control system incorporating the PSO technique and the obtained results are compared with those of BTMS using PID and simple FLC system in terms of rise time, fall time, overshoot, undershoot and settling time. To evaluate the performance of the control systems on heating and cooling subroutine, the initial temperature of the battery pack is fixed at two different temperature, which is 273 K and 300 K at different times. The output responses of the PID, simple fuzzy and PSO based fuzzy system are presented and compared accordingly to validate the proposed BTMS.

A. Heating Subroutine of the Temperature Regulating System

To evaluate the performance of the different controllers on the heating subroutine, the set point temperature is fixed at 300 K that is the optimum temperature of the lithium ion battery, and the initial temperature of the battery pack is fixed at 273 K. The output response of the PID, fuzzy and PSO based fuzzy system on the heating subroutine is shown in Fig. 9. The performance of the PID, fuzzy and PSO based fuzzy system on the heating subroutine is presented in Table II. From the results of heating subroutine, the rise time, settling time, overshoot are the best values for Module-1, 21 min 14 s, 32 min 13 s and 0.497 %, for Module-2, 21 min 15 s, 32 min 13 s and 0.497 %, for Module-3, 21 min 14 s, 32 min 13 s and 0.497 %, and for Module-4 21 min 15 s, 32 min 13 s and 0.497 %, respectively. Thus, the proposed PSO based fuzzy logic heating system produces significantly the best value as compared to PID and simple fuzzy system. Besides, the proposed optimal controller is capable of maintaining uniform temperature in the 4 modules of the battery pack during heating subroutine as shown in Fig. 10.

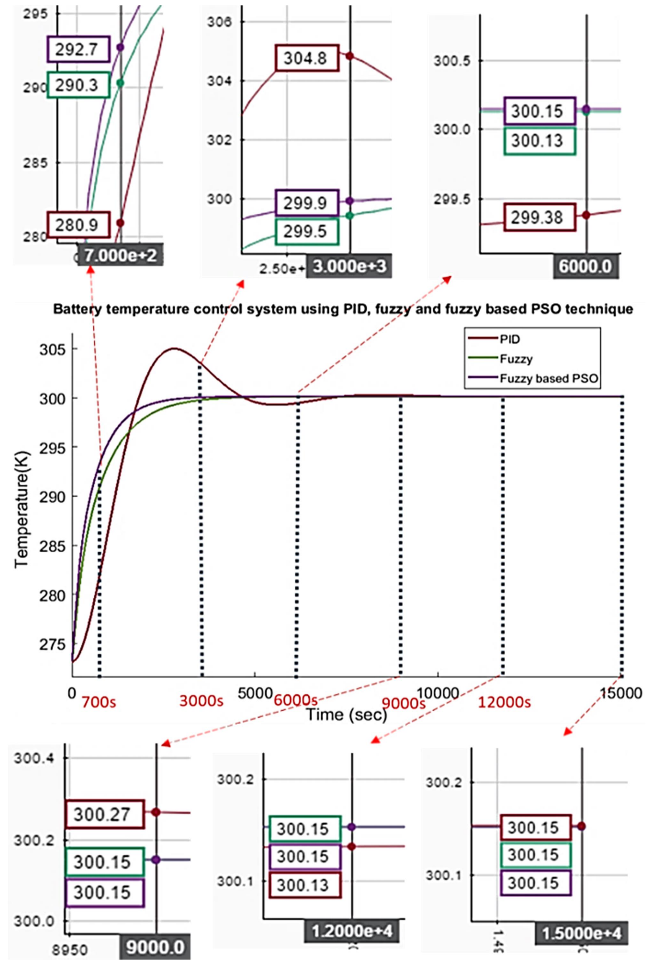

Fig. 9. Output response of the PID, fuzzy and PSO based fuzzy system during heating subroutine

TABLE II
PERFORMANCE OF PID, FUZZY AND PSO BASED FUZZY SYSTEM DURING HEATING SUBROUTINE

Module in battery pack		Time Domain Specifications		
		Rise time	*Settling time*	*Overshoot*
Module 1 (Cell 1 to 10)	PID	20 min 31 s	87 min 46 s	18.452 %
	Fuzzy	29 min 49 s	41 min 42 s	0.788 %
	Fuzzy + PSO	21 min 14 s	32 min 13 s	0.497 %
Module 2 (Cell 11 to 20)	PID	20 min 31 s	87 min 46 s	18.452 %
	Fuzzy	30 min	41 min 16 s	0.888 %
	Fuzzy + PSO	21 min 15 s	32 min 13 s	0.497 %
Module 3 (Cell 21 to 30)	PID	20 min 31 s	87 min 46 s	18.452 %
	Fuzzy	29 min 49 s	41 min 42 s	0.788 %
	Fuzzy + PSO	21 min 14 s	32 min 13 s	0.497 %
Module 4 (Cell 31 to 40)	PID	20 min 31 s	87 min 46 s	18.452 %
	Fuzzy	30 min	41 min 16 s	0.888 %
	Fuzzy + PSO	21 min 15 s	32 min 13 s	0.497 %

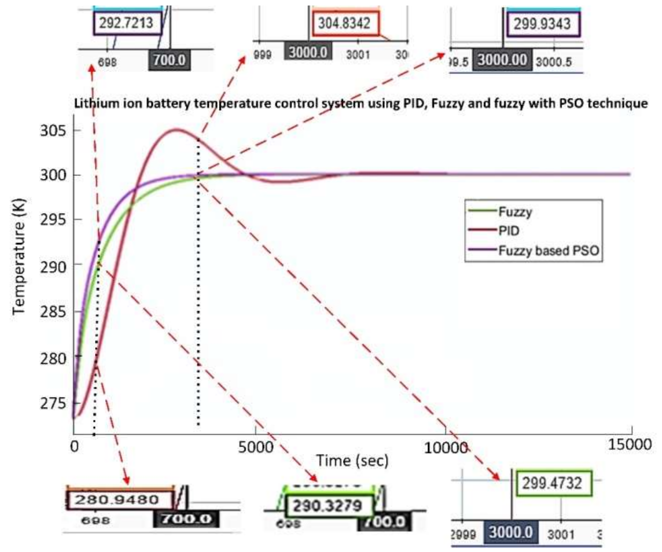

Fig. 10. Temperature control of battery modules during heating subroutine

B. Cooling Subroutine of the Temperature Regulating System

To evaluate the performance of the different controllers on the cooling subroutine, the set point temperature is fixed at 300 K that is the optimum temperature of the lithium ion battery and the initial temperature of the battery pack is fixed at 323 K. The output response of the PID, fuzzy and PSO based fuzzy system on the cooling subroutine is shown in Fig. 11. The performance of the PID, fuzzy and PSO based fuzzy system on the cooling subroutine is presented in Table III. From the results of cooling subroutine, the fall time, settling time, undershoot are the best values for Module-1, 21 min 26 s, 28 min 46 s and 0.975 %, for Module-2, 21 min 26 s, 28 min 46 s and 0.975 %, for Module-3, 21 min 26 s, 28 min 46 s and 0.975 %, and for Module-4, 21 min 26 s, 28 min 46 s and 0.975 %, respectively. Thus, the proposed PSO based fuzzy logic cooling heating system produces significantly the best value as compared to PID and simple fuzzy system.

TABLE III
PERFORMANCE OF PID, FUZZY AND PSO BASED FUZZY SYSTEMS ON COOLING SUBROUTINE

Module in battery pack		Time Domain Specifications		
		Fall time	*Settling time*	*Undershoot*
Module 1 (Cell 1 to 10)	PID	11 min 15 s	112 min 22 s	105.738 %
	Fuzzy	28 min 25 s	38 min	1.015 %
	Fuzzy + PSO	21 min 26 s	28 min 46 s	0.975 %
Module 2 (Cell 11 to 20)	PID	11 min 15 s	112 min 18 s	104.745%
	Fuzzy	28 min 26 s	38 min 6 s	0.995 %
	Fuzzy + PSO	21 min 26 s	28 min 46 s	0.975 %
Module 3 (Cell 21 to 30)	PID	11 min 15 s	112 min 22 s	105.738 %
	Fuzzy	28 min 25 s	38 min	1.015 %
	Fuzzy + PSO	21 min 26 s	28 min 46 s	0.975 %
Module 4 (Cell 31 to 40)	PID	11 min 15 s	112 min 18 s	104.745%
	Fuzzy	28 min 26 s	38 min 6 s	0.995 %
	Fuzzy + PSO	21 min 26 s	28 min 46 s	0.975 %

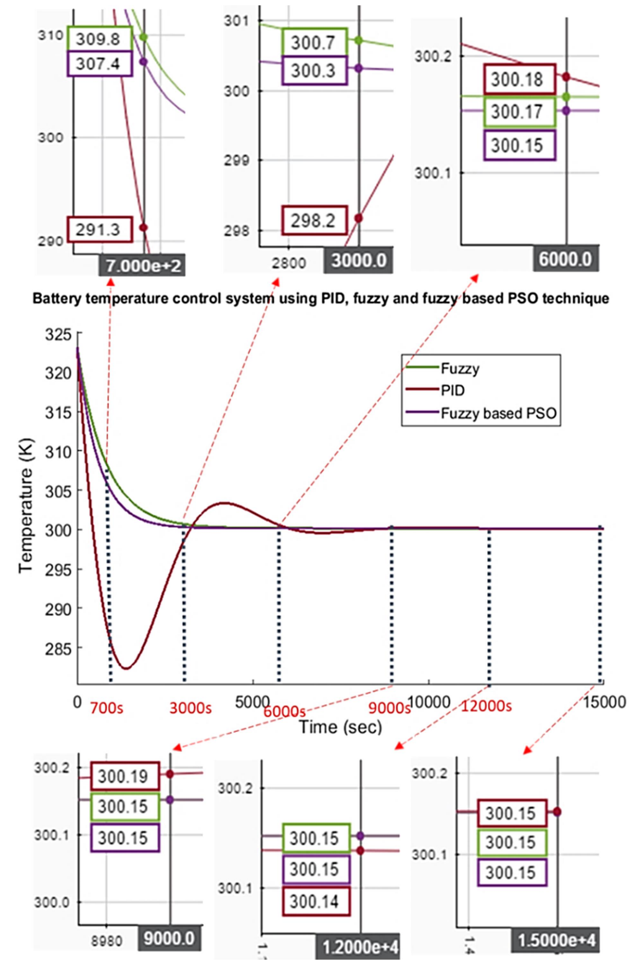

Fig. 11. Output response of the PID, fuzzy and PSO based fuzzy systems on cooling subroutine

The proposed PSO based fuzzy logic cooling system yields considerably the best output as compared to PID and simple fuzzy system. Moreover, the proposed optimal FLC system is capable of maintaining uniform temperature in the all 4 modules of the battery pack during cooling subroutine as shown in Fig. 12. Since the system performance is mainly evaluated by the overshoot, undershoot and settling time and the PSO based fuzzy system is able to yield the least overshoot, undershoot and settling time during the heating and cooling subroutine. Thus, the proposed PSO based fuzzy system is found as the best among the three types of control system when dealing in the temperature regulating process for lithium ion battery storage pack. Besides, the functionality of the PSO algorithm to optimize the system performance is verified.

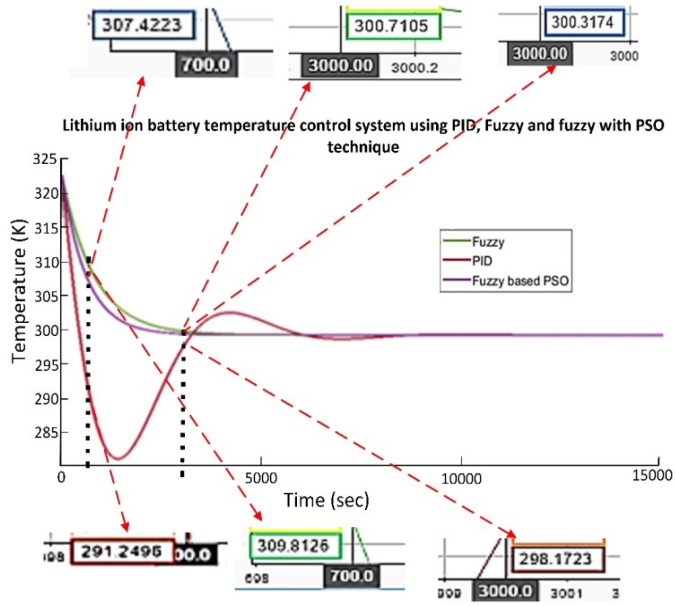

Fig. 12. Temperature control of battery modules during cooling subroutine

VII. Conclusion

In this paper, a PSO based FLC system for a lithium ion battery pack with four modules in series-parallel configuration is developed in MATLAB/Simulink. The methodology for the thermal model of lithium ion battery, thermal management system design, FLC system and PSO algorithm are explained. The proposed optimal FLC based temperature control algorithm and its implementation are described. The results of the proposed PSO based fuzzy system for heating and cooling subroutines are presented along with the results of PID and simple fuzzy based BTMS. Based on the simulation results on the heating and cooling subroutine, it is found that during the heating subroutine, the PSO based fuzzy system yields the least settling time (32 min 13 s) and overshoot (0.497%) whereas during the cooling subroutine, the PSO based fuzzy system yields the least settling time (28 min 46 s) and undershoot (0.975%). Thus, it can be conclude that the performance of the fuzzy based PSO system is the best, followed by the fuzzy based system and PID based system when dealing with the temperature control. Besides, the temperature of the lithium battery pack is even and uniform among the battery modules. This proposed FLC-PSO controller based BTMS will be developed in prototype for testing and validation to apply in real lithium ion battery storage system.

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