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On Thermal and State-of-Charge Balancing using Cascaded Multi-level Converters

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Abstract

In this study, the simultaneous use of a multi-level converter (MLC) as a DC-motor drive and as an active battery cell balancer is investigated. MLCs allow each battery cell in a battery pack to be independently switched on and off, thereby enabling the potential non-uniform use of battery cells. By exploiting this property and the brake regeneration phases in the drive cycle, MLCs can balance both the state of charge (SoC) and temperature differences between cells, which are two known causes of battery wear, even without reciprocating the coolant flow inside the pack. The optimal control policy (OP) that considers both battery pack temperature and SoC dynamics is studied in detail based on the assumption that information on the state of each cell, the schedule of reciprocating air flow and the future driving profile are perfectly known. Results show that OP provides significant reductions in temperature and in SoC deviations compared with the uniform use of all cells even with uni-directional coolant flow. Thus, reciprocating coolant flow is a redundant function for a MLC-based cell balancer. A specific contribution of this paper is the derivation of a state-space electro-thermal model of a battery submodule for both uni-directional and reciprocating coolant flows under the switching action of MLC, resulting in OP being derived by the solution of a convex optimization problem.

Key words: Hybrid electric vehicles, Multi-level converter, Batteries, Cell balancing, Thermal balancing, Convex optimization

I. INTRODUCTION

Although battery technology has evolved significantly during the last decade, batteries of both plug-in hybrid electric vehicles (PHEVs) and electric vehicles (EVs) contribute a large percentage of the total vehicle cost. Consequently, the success of PHEVs and of EVs depends on the development of a battery that will not wear out prematurely to avoid additional battery replacement during the expected lifespan of the vehicle. The battery pack (BP) of EVs/HEVs/PHEVs is built from a large number of small cells connected in series and parallel to meet both the traction power demand and the electric range requirement. Depth of discharge (DoD) is one of the most important factors that determine degradation of battery cells, such as battery operation at higher DoD shorten the cycle life and vice versa [1]-[4]. Therefore, the cycle life of a battery is significantly short when it undergoes full charge-discharge cycles, whereas the cycle life becomes significantly longer when it only undergoes partial charge-discharge cycles [5]. In a

pack with state of charge (SoC) and capacity deviations among its cells, some of the cells undergo charge-discharge cycles at higher DoD than others. Consequently, these cells may reach their end-of-life (EOL) sooner. Thus, maintaining a perfect balance between SoC and DoD of each cell in the battery pack is crucial in prolonging battery life. This balance can be achieved by either passive or active balancing schemes based on various topologies of switched capacitive and resistive circuits, as illustrated in [6]-[9]. The main principle of all active balancing schemes is to transfer the charge from cells with higher SoC to cells with lower SoC by using switched capacitors that act as intermediate storage banks. Passive balancing schemes typically utilize differences in cell voltage to burn excess charge in resistor banks.

Aside from DoD, cell temperature is known to have a strong effect on battery wear, such as hotter cells degrade more quickly than colder cells [10]-[13]. More importantly, the presence of a few overheated cells can wear out the entire battery prematurely. The temperature imbalance between cells is due to variation in internal resistances, in the temperature gradient in the coolant due to convective heat transfer inside the battery pack, and the non-uniform external local thermal disturbances [13], [14]. The lifespan of a Li-Ion cell is reportedly reduced by two months for each degree increase in operating temperature from 30 °C to

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40 °C [15]. However, when temperature increases beyond 40 °C, the cycle life of a battery decreases drastically.

Forced convection cooling is typically used to maintain batteries within the recommended temperature range. However, this method cannot compensate for the temperature gradient along the coolant fluid stream. Cells that are closer to the air inlet will be cooler than those further down the coolant stream. Reciprocating air flow (RF) was proposed in [10] and in [14] as a mean to reduce the effects of the temperature gradient in the coolant stream. However, in the present study, it is shown that cells continue to suffer from non-uniform local heated spots in the presence of parameter variation and local disturbances.

Considering the aforementioned causes of battery wear, the battery management unit (BMU) should balance both SoC and temperature differences between cells. Therefore, this paper investigates the MLC-based active cell balancing scheme that allows hot cells to be bypassed, consequently balancing both SoC and temperature without the need for RF.

Cascaded MLCs [16], [17] had been investigated for electric drives in HEVs and in EVs in [18], [19]. MLC consists of n cascaded H-bridges (HBs) with an isolated battery cell for each HB. In this paper, the combination of HB and a battery cell is referred to as a power cell (PC). MLCs in EV/HEV/PHEV application are intended to reduce inverter losses and total harmonic distortion in the generated waveform for the electric machine. The usual switching strategy in motor drive applications of MLCs is the phase-shifted pulse width modulation (PS-PWM) technique that achieves the uniform use of cascaded cells [16], [17].

However, MLC presents an additional advantage as the cells need not be uniformly used over a time window of one or several voltage waveforms. By non-uniformly using the cells and by exploiting the brake regeneration phases in the drive cycle, an MLC cell balancer can balance both SoC and temperature differences. In this study, the PS-PWM scheme is referred to as the uniform duty cycle operation (UDCO), whereas the optimal scheme that controls the duty cycle of each PC to balance both SoC and temperature is referred to as optimal control policy (OP). The potential benefit of using MLC to balance both SoC and temperature of battery cells under a uni-directional flow (UF) has been thoroughly investigated and compared with that of UDCO [20]. Thus, the main contribution of the current study is to investigate OP under RF, and then to compare the results in detail with those of OP under UF. OP is calculated based on the assumption of perfect information of the SoC and the temperature of each cell, as well as of the future driving. This paper examines whether OP provides more significant improvements compared with UDCO under UF and RF and whether RF presents any potential benefits for OP-based active cell balancing.

For simplicity, this study employs a DC machine as the electric machine and models the cells by resistive circuits. Moreover, the simulation study focuses on an air-cooled battery

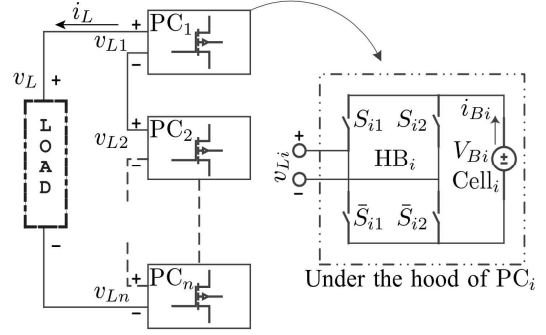


Fig. 1. Block diagram of a single-phase cascaded HB MLC.

sub-module (BSM) with a string of five series-connected cells. The coolant flow is assumed to be laminar with known inlet temperature and speed. In [21], only one configuration of the five-cell string was studied to evaluate the performance of the MLC-based cell balancer. A similar method was adopted in the present study. However, a more thorough analysis was conducted to carefully assess the performance of the cell balancer. For purpose of evaluation, two different variants of the five-cell string were studied. In the first variant, the higher resistance cell is located at the end of the string in the downstream of the coolant fluid. In the second variant, the higher resistance cell is located in the middle of the string. The resistance of the thermally exposed cell was assumed to be almost 50% higher than that of others cells when comparing the performance of UDCO and OP under both UF and RF.

Besides the simulation results and the evaluation of MLC as a cell balancer, another important contribution of this paper is the detailed derivation of a state-space electro-thermal model of BSM under the switching action of MLC under UF and RF. The model was formulated in such a way that a convex optimization problem yields OP under a perfectly known future driving. This model can be used in future research in deciding the duty cycle in a receding horizon model predictive control scheme [22] based on the best available prediction of future driving.

The paper is organized as follows. Section II introduces the basic function of MLC. Section III presents the detailed electro-thermal modeling of BSM under the switching action of MLC. The optimization problem and the numerical solution method are described in Section IV. Section V presents the simulation results and the comparison between OP and the UDCO schemes under both UF and RF. A detailed discussion on the simulation results is provided in Section VI. The conclusions are given in Section VII.

II. MULTI-LEVEL CONVERTERS OVERVIEW

This section provides a short introduction on single-phase MLC. In contrast to two-level converters that consist of a single large battery connected with a single HB, MLC as shown in Fig. 1 has several series-connected PCs in which each PC contains an HB and the independent battery cell.

HB, which consists of two half-bridges, is a switch mode

dc-dc power converter [23] that produces a four-quadrant controllable dc output using four switches, namely, s_{i1} , s_{i2} , \bar{s}_{i1} , and \bar{s}_{i2} , as shown in Fig. 1. The MoSFETs are normally used for these switches. To avoid a shoot-through problem, only one of the switch pairs, (s_{i1}, \bar{s}_{i2}) , (s_{i2}, \bar{s}_{i1}) , (s_{i1}, s_{i2}) , or $(\bar{s}_{i1}, \bar{s}_{i2})$, is switched on at a time. (s_{i1}, \bar{s}_{i2}) generates a positive output voltage v_{Li} from PC_i , (s_{i2}, \bar{s}_{i1}) generates a negative v_{Li} , and both (s_{i1}, s_{i2}) and $(\bar{s}_{i1}, \bar{s}_{i2})$ generate $v_{Li} = 0$. Therefore, the following three modes of operation can be defined for each PC_i depending on the switch pair that is switched on: *Mode-1* ($v_{Li} > 0$), *Mode-2* ($v_{Li} < 0$), and *Mode-3* ($v_{Li} = 0$). To model these three modes of operation, $s_{ij}(t) = 1$ is defined as the ON-State and $s_{ij}(t) = 0$ is defined as the OFF-State of the switch S_{ij} , where 'i' corresponds to PC_i and $j \in \{1, 2\}$ denotes one of the two half-bridges in HB. Therefore, the switching function $s_i(t)$ for Cell_i can be defined as

$$s_i(t) = s_{i1}(t) - s_{i2}(t) = \begin{cases} 1, & \text{Mode-1} \\ -1, & \text{Mode-2} \\ 0, & \text{Mode-3} \end{cases} \quad (1)$$

Thus, all three modes of HB can be defined in terms of $s_i(t)$.

The switching vector $s(t) = [s_1(t) \ \cdots \ s_n(t)]^T$ contains the switching functions for all n PCs inside MLC. With the assumption of an ideal switch behavior, the ohmic and the switching losses can be ignored. Therefore, the input and the output of HB are related through the switching function $s_i(t)$, as shown in Fig. 2. Thus, the current in Cell_i is given by

$$i_{Bi}(t) = i_L(t)s_i(t) \quad (2)$$

As a result of the series connection, the same load current i_L passes through each PC. However, the direction of the current passing through Cell_i depends on the selection of switches and on the direction of load current i_L . Similarly, the voltage output from each PC_i is defined by $v_{Li}(t) = V_{Bi}(t)s_i(t)$. Hence, the total voltage output from MLC can be written as the sum of the voltage output from each PC_i as given below.

$$v_L = \sum_{i=1}^n v_{Li} = \sum_{i=1}^n V_{Bi}(t)s_i(t) \quad (3)$$

The number of voltage levels that MLC generates depends on the number of PCs and on the terminal voltage V_{Bi} of Cell_i. If the terminal voltage of all cells is the same, MLC can then generate $L = 2n + 1$ different voltage levels (v_L).

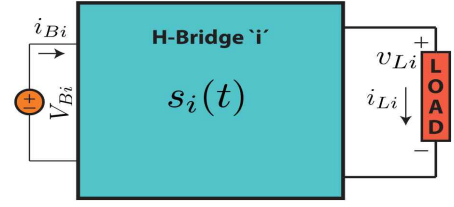


Fig. 2. Switching model of HB.

III. MODELING OF THE CELL BALANCING SYSTEM WITH RF

The block diagram of the cell balancing system for RF and for UF is shown in Fig. 3. MLC is capable of generating the same output voltage level v_L in several ways by using different combinations of the three modes for various PCs, providing redundancy in generating the same load voltage through numerous possible switch combinations. This redundancy adds an extra degree of freedom (DoF) that is utilized in this paper to design the optimal control signal u_i for Cell_i. Consequently, SoC and temperature differences between cells are kept within a certain zone, while satisfying all other operating requirements. In this section, a switching model and an averaged state-space model of a PC is derived based on the assumption that the load is a DC machine. Finally, the complete state-space model for n PCs is developed.

A. Switching Model of a Power Cell

In this subsection, the electro-thermal model of a switched battery cell under RF is derived. Each PC_i is assumed to contain only one Cell_i. The dynamics of cell temperature depends on several factors such as coolant properties, cell material properties, cell placement, and battery pack configuration. In [14], the forced-convection cooled battery pack was modeled by the *lumped capacitance thermal model* and by the *flow network model* (FNM). In the said study, the battery pack was configured as $n_s S n_p P$ that represents n_p parallel strings, with each string, called a battery module, containing n_s cells connected in a series. A sufficient amount of free space is present between the cells to allow streams of laminar flow of the coolant (air). A configuration of the battery pack, Li-Ion cells, and the air properties adopted in the present paper are similar to those in [14]. Various coefficients for the thermal and the physical properties of the cell and of the air used in this study are listed in Table I. Details are provided in [14]. $C_{Ni}[Ah]$ represents the nominal capacity of Cell_i, and $R_{ui}[KW^{-1}]$ represents the convection thermal resistance for Cell_i that depends on the geometry of the battery cell, on the coolant fluid properties, and on the

TABLE I
DEFINITION OF BATTERY PARAMETERS

Parameters	Expression	Parameters	Expression
$a_{si} [\frac{1}{s}]$	$\left(\frac{1}{C_{si}R_{ui}}\right)$	$b_{ri} [\Omega]$	R_{si}
$a_{ei1} [\frac{1}{s}]$	$\left(\frac{1}{R_{i1}C_{i1}}\right)$	α_i [Unitless]	$R_{ui}C_f$
$a_{ei2} [\frac{1}{s}]$	$\left(\frac{1}{R_{i2}C_{i2}}\right)$	β_i [Unitless]	$-1 + \alpha_i$
$b_{si} [\frac{\Omega K}{W s}]$	$\left(\frac{R_{si}}{C_{si}}\right)$	$b_{ei2} [\frac{V}{s A}]$	$\left(\frac{1}{C_{i2}}\right)$
$b_{ei1} [\frac{V}{s A}]$	$\left(\frac{1}{C_{i1}}\right)$	$b_{ei3} [\frac{1}{A s}]$	$\left(\frac{1}{3600C_{Ni}}\right)$

Nusselt number, which, in turn, depends on the Reynolds number.

The coefficient $C_{si} = \rho_{si}c_{psi}V_{si}[JK^{-1}]$ represents *heat capacity* (amount of heat energy required to raise the temperature of Cell_i by 1 Kelvin), where ρ_{si} is the density, c_{psi} is the *specific heat capacity* (heat capacity per unit mass of battery), and $V_{si}[m^3]$ is the volume of Cell_i. The coefficient $c_f = \rho_f c_{pf} \dot{V}_f [WK^{-1}]$ is *thermal conductance* of the coolant fluid. All other quantities are shown in Fig. 4.

In this paper, only one submodule (of the battery module) that consists of n series-connected battery cells is studied. First, the thermal model is derived separately for the coolant flow in each direction. The two models are then combined to create the model for RF. In this study, both RF and UF are examined and compared. Hence, the case of *forward flow* (i.e., from lower to higher cell index) is designated as UF for ease of reference. The thermal model proposed in [14] does not consider any power electronic switching of the battery cells. Thus, power electronic switching must be incorporated into the current framework. The previous model was modified by embedding the switching function $s_i(t)$ and subsequently combining it with the enhanced Thevenin equivalent electrical model, shown in Fig. 4, to derive the switching electro-thermal model of PC_i .

For *forward flow*, the dynamics of the surface temperature $T_{si}[K]$ of Cell_i in terms of $i_L(t)$ and $s_i(t)$, after substituting the value of $i_{Bi}(t)$ from equation (2) into the model proposed in [14], is given by

$$\dot{T}_{si} = -a_{si}T_{si} + b_{si}i_L^2 s_i^2 + a_{si}T_{fi-1}, \quad \forall i = \{1, \dots, n\} \quad (4)$$

where the $i_L^2 s_i^2$ represents the instantaneous ohmic power losses on Cell_i and $T_{fi-1}[K]$ is the temperature of temperature node ' $i-1$ ' (of the fluid element modeled by FNM) attached to Cell_i in an upstream direction. Equation (4) is not that interesting in terms of control design because it explicitly depends on the fluid node temperature T_{fi-1} for

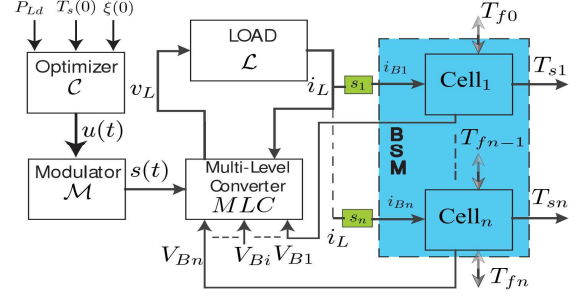


Fig. 3. Conceptual block diagram of a battery cell balancing system with RF. $T_s(0)$ is a vector containing the initial temperature of all cells, $\xi(0)$ is a vector containing the initial SoC of all cells, P_{Ld} is the demanded power for load with the known voltage and current profile, and T_{f0}, \dots, T_{fn} represent temperatures of temperature-nodes of the coolant fluid. The subsystem inside the blue box represents BSM being balanced and the green boxes contain the switching functions for the corresponding cell.

Cell_i that is not directly known. Therefore, this equation must be modified to remove this explicit dependency. For control design purpose, the temperature dynamics of each cell can be more appropriately modeled in terms of battery current $i_{Bi} = i_L s_i$ and of the temperature $T_{fi} \in \{T_{f0}, T_{fn}\}$ of the coolant fluid at the inlet. To achieve this, T_{fi-1} is eliminated from equation (4) as follows. According to [14], the temperatures of the nodes ' $i-1$ ' and ' i ' are related by

$$T_{fi} = \frac{(T_{si} + \beta_i T_{fi-1})}{\alpha_i}, \quad \forall i \quad (5)$$

where α_i and β_i are defined in Table I. Given that T_{f0} is a known quantity, then by forward recursion of equation (5), any T_{fi} can be expressed as a function of the inlet fluid temperature T_{f0} and of the temperatures T_{s1} to T_{si} of the battery cells, such as

$$\begin{aligned} T_{f1} &= \left(\frac{1}{\alpha_1}\right)T_{s1} + \left(\frac{\beta_1}{\alpha_1}\right)T_{f0}, \\ T_{f2} &= \left(\frac{\beta_2}{\alpha_1\alpha_2}\right)T_{s1} + \left(\frac{1}{\alpha_2}\right)T_{s2} + \left(\frac{\beta_1\beta_2}{\alpha_1\alpha_2}\right)T_{f0}, \\ T_{f3} &= \left(\frac{\beta_2\beta_3}{\alpha_1\alpha_2\alpha_3}\right)T_{s1} + \left(\frac{\beta_3}{\alpha_2\alpha_3}\right)T_{s2} + \left(\frac{1}{\alpha_3}\right)T_{s3} \\ &\quad + \left(\frac{\beta_1\beta_2\beta_3}{\alpha_1\alpha_2\alpha_3}\right)T_{f0}, \end{aligned} \quad (6)$$

and so on. Therefore, the general equation for any T_{fi} is written as follows:

$$T_{fi} = a_{fi1}^{(1)}T_{s1} + a_{fi2}^{(1)}T_{s2} + \dots + a_{fii}^{(1)}T_{si} + b_{fi}^{(1)}T_{f0} \quad (7)$$

where

$$a_{fii}^{(1)} = \left(\frac{1}{\alpha_i} \right), \quad b_{fi}^{(1)} = \left(\frac{\prod_{k=1}^i \beta_k}{\prod_{k=1}^i \alpha_k} \right), \quad \forall i \geq 1 \quad (8)$$

$$a_{fij}^{(1)} = \left(\frac{\prod_{k=j+1}^i \beta_k}{\prod_{k=j}^i \alpha_k} \right), \quad \forall i > j, \quad a_{fij}^{(1)} = 0, \quad \forall i < j \quad (9)$$

Using equation (7) in (4), the thermal dynamics of the battery cells can be rewritten as follows:

$$\dot{T}_{si} = a_{si}^{(1)} T_{s1} + \dots + a_{sin}^{(1)} T_{sn} + b_{si} i_L^2 s_i^2 + b_{ii}^{(1)} T_{f0} \quad (10)$$

where:

$$a_{iii}^{(1)} = -a_{si}, \quad \forall i \geq 1 \quad (11)$$

$$a_{tij}^{(1)} = \left(\frac{\prod_{k=j+1}^{(i-1)} \beta_k}{\prod_{k=j}^{(i-1)} \alpha_k} \right) a_{si}, \quad \forall i > j, \quad a_{tij}^{(1)} = 0, \quad \forall i < j \quad (12)$$

$$b_{ii}^{(1)} = \left(\frac{\prod_{k=1}^{(i-1)} \beta_k}{\prod_{k=1}^{(i-1)} \alpha_k} \right) a_{si}, \quad \forall i \geq 1 \quad (13)$$

Analogous to the *forward* flow case, the thermal dynamics of Cell_i is derived for the *reverse* coolant flow (i.e., from higher to lower cell index). The result is given below

$$\dot{T}_{si} = a_{si}^{(2)} T_{s1} + \dots + a_{sin}^{(2)} T_{sn} + b_{si} i_L^2 s_i^2 + b_{ii}^{(2)} T_{fn} \quad (14)$$

where T_{fn} is the temperature of the inlet fluid entering BSM from the Cell_n side. The other coefficients are defined as follows:

$$a_{iii}^{(2)} = a_{si}^{(1)}, \quad \forall i \geq 1, \quad b_{ii}^{(2)} = b_{i(n-i+1)}^{(1)}, \quad \forall i \geq 1 \quad (15)$$

$$a_{tij}^{(2)} = a_{tji}^{(1)}, \quad \forall i < j, \quad a_{tij}^{(2)} = 0, \quad \forall i > j \quad (16)$$

The electrical equivalent model of a battery cell is shown in Fig. 4. This model is an enhanced Thevenin model with two time constant behaviors [24]–[26]. The dynamic model for this circuit is given by

$$\dot{V}_{i1} = -a_{ei1} V_{i1} + b_{ei1} i_L s_i, \quad (17)$$

$$\dot{V}_{i2} = -a_{ei2} V_{i2} + b_{ei2} i_L s_i, \quad (18)$$

$$\dot{\xi}_i = -b_{ei3} i_L s_i, \quad (19)$$

$$V_{Bi} = f(\xi_i) - V_{i1} - V_{i2} - b_{ri} i_L s_i \quad (20)$$

where i_{Bi} is the current flowing through Cell_i and ξ_i is the normalized SoC of Cell_i. $\xi_i \in [0, 1]$ is a unit-less quantity. V_{i1} and V_{i2} are the voltages across capacitors C_{i1} and C_{i2} , respectively, and V_{Bi} is the output voltage of Cell_i. The SoC-dependent open circuit voltage is given by $V_{oci} = f(\xi_i)$,

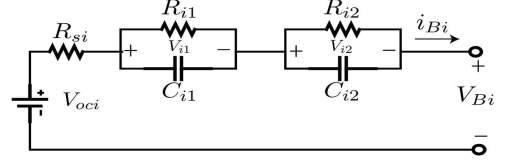


Fig. 4. Electrical model of a battery cell.

where $f: [0, 1] \rightarrow \mathbb{R}_0^+$ is a function of SoC. Equations (10) to (20) describe the switched behavior of the battery under the switching action of MLC, in terms of the load current $i_L(t)$ and of the switching function $s_i(t)$. Therefore, this model can be considered as a switching model of PC_i .

B. Averaged State-Space Model of PC

Cell balancing can be formulated as an optimization problem using two approaches. In the first approach, cell operation is optimized by directly using the switching function $s_i(t)$ as an optimization variable for Cell_i. The switching function $s_i(t)$ in equation (1) can only attain values from the discrete set $\{-1, 0, 1\}$. Hence, the computed optimal control is a discrete-valued signal. In this case, the system is normally modeled as a switched system with various modes of operation, and the optimization problem therefore becomes combinatorial that is normally difficult to solve because of its non-convex nature. However, the aim of this study is to evaluate OP, which necessitates a model with a real-valued control signal because such models are far easier to handle in optimization problems than those with discrete-valued signals. Hence, the second control approach is used instead, wherein the battery duty cycle $u_i \in [-1, 1]$, which is the average of the switching input function $s_i(t)$, is used as optimization variables for Cell_i. The optimizer computes a control vector signal u that contains duty cycles $u_i \in [-1, 1]$ for each PC_i . Note that the negative duty cycle means operation in *Mode-2*. The computed control u is then fed to the modulation block M, which then generates an appropriate switching function $s_i \in s(t)$ for each PC. Given that the switching model (10)–(20) involves discrete-valued signals $s_i(t)$, these signals must be transformed into real-valued averaged signals to modify the system model (10)–(20) accordingly. The use of averaging is justified by the fact that, in most cases, the switching frequency F_s inside the modulator M is significantly higher than the bandwidth f_L of the system. Thus, by assuming that $F_s \gg f_L$ and by employing the two-time scale separation principle [27], the concept of averaging can be employed [28] [29]. In other

words, the system response is assumed to be determined predominantly by the duty cycle $u_i(t) \in [-1, 1]$ or the average of the switching input function $s_i(t)$. In addition, careful derivation is required given that the switching model involves certain bilinear and quadratic terms. In this section, the averaged model is derived in detail by averaging each signal over one switching cycle. The following assumptions are made in deriving the average quantities:

Assumption 1: The switching function can only attain values either from set $\{0, 1\}$ or from $\{0, -1\}$ during any switching cycle of period T_s . This assumption implies that it is not allowed to charge and to discharge the battery cell during the same switching cycle.

Assumption 2: The load current $i_L(t)$ remains fairly constant during any switching cycle. This assumption is justified based on the discussion above.

Assumption 3: All internal electrical states $V_{i1} = \bar{V}_{i1}$, $V_{i2} = \bar{V}_{i2}$, and $\xi_i = \bar{\xi}_i$, as well as terminal voltage V_{Bi} , remain fairly constant during the switching cycle.

Based on these assumptions, the average of the switching function $s_i(t)$, which is also called the duty cycle, is given by

$$u_i(t) = \bar{s}_i(t) = \frac{1}{T_s} \int_{t-T_s}^t s_i(t) dt = \pm \frac{T_{on}}{T_s} \quad (21)$$

where T_{on} is the ON time of a switch during any switching interval. This equations shows that $u_i(t)$ can attain any continuous real value in the interval $[-1, 1]$, depending on the value of T_{on} . All other averaged signals can be defined in terms of $u_i(t)$ and $i_L(t)$ as follows:

$$\bar{i}_{Bi}(t) = u_i i_L, \quad i_{Br_i}^2 = |u_i| i_L^2 \quad (22)$$

$$\bar{v}_{Li} = (f(\bar{\xi}_i) - \bar{V}_{i1} - \bar{V}_{i2})u_i - b_{ri}|u_i|i_L \quad (23)$$

where \bar{i}_{Bi} is the average current flowing through Cell_i during interval T_s , i_{Br_i} is the root mean square (RMS) current that incurs equivalent ohmic loss across Cell_i during one switching cycle, and \bar{v}_{Li} is the average output voltage from PC_i during period T_s of any switching cycle. [20] presents the detailed derivation of all the averaged variables. Using the averaged quantities, the *averaged model* of PC_i is written as follows:

$$\dot{\bar{T}}_{si} = a_{i1}^{(\sigma)} \bar{T}_{s1} + \dots + a_{i(n)}^{(\sigma)} \bar{T}_{sn} + b_{si} i_L^2 |u_i| + b_{ii}^{(\sigma)} T_{fin} \quad (24)$$

$$\dot{\bar{V}}_{i1} = -a_{ei1} \bar{V}_{i1} + b_{ei1} i_L u_i \quad (25)$$

$$\dot{\bar{V}}_{i2} = -a_{ei2} \bar{V}_{i2} + b_{ei2} i_L u_i \quad (26)$$

$$\dot{\bar{\xi}}_i = -b_{ei3} i_L u_i \quad (27)$$

$$\bar{V}_{Bi} = f(\bar{\xi}_i) - \bar{V}_{i1} - \bar{V}_{i2} - b_{ri} i_L u_i \quad (28)$$

where $\sigma=1$ and $\sigma=2$ designate the forward and the reverse coolant flow, respectively and $T_{fin} \in \{T_{f0}, T_{fn}\}$ is the known fluid temperature in one of the two inlets depending on the direction of the coolant flow. Given that $|u_i|$ in (24) is not continuously differentiable, u_i and $|u_i|$ are defined in terms of two new control variables u_{i1} and u_{i2} that are defined as $u_{i1} = \max\{0, u_i\} \in [0, 1]$ and $u_{i2} = \max\{0, -u_i\} \in [0, 1]$, respectively. Thus, $u_i = (u_{i1} - u_{i2}) \in [-1, 1]$ and $|u_i| = (u_{i1} + u_{i2}) \in [0, 1]$. u_{i1} can then be interpreted as the duty cycle for Mode-1, whereas u_{i2} can be interpreted as the duty cycle for Mode-2. In this new context, u_{i1} and u_{i2} cannot be both nonzero simultaneously (cf. Assumption 1) at any time for safety reasons, which if violated can cause a shoot-through problem. Based on this newly defined control signal, the thermal subsystem of battery Cell_i for reciprocating coolant flow is given by

$$\dot{X}_{ti} = a_{i1}^{(\sigma)} X_{t1} + \dots + a_{i(n)}^{(\sigma)} X_{tn} + \hat{g}_{ti}(x_L) \hat{u}_i + b_{ii}^{(\sigma)} T_{fin} \quad (29)$$

where $X_{ti} = \bar{T}_{si} \in \mathfrak{R}$, $\hat{g}_{ti}(x_L) = [b_{si} x_L^2 \quad b_{si} x_L^2]^T$, $\hat{u}_i = [u_{i1} \quad u_{i2}]^T \in \mathfrak{R}^2$, and $x_L = i_L$. Similarly, the electrical subsystem of Cell_i is given by

$$\dot{X}_{ei} = A_{ei} X_{ei} + \hat{g}_{ei}(x_L) \hat{u}_i \quad (30)$$

where $X_{ei} = [X_{ei1} \quad X_{ei2} \quad X_{ei3}]^T \in \mathfrak{R}^3$ with $X_{ei1} = \bar{V}_{i1}$, $X_{ei2} = \bar{V}_{i2}$, and $X_{ei3} = \bar{\xi}_i$, $A_{ei} = \text{diag}(-a_{ei1}, -a_{ei2}, 0) \in \mathfrak{R}^{3 \times 3}$, and $\hat{g}_{ei}(x_L) = [b_{ei} x_L \quad -b_{ei} x_L]^T \in \mathfrak{R}^{3 \times 2}$ with $b_{ei} = [b_{ei1} \quad b_{ei2} \quad -b_{ei3}]^T$.

C. Complete Averaged State-Space Model of n-Cell MLC

An n-cell MLC can be represented in various state-space models depending on the number of cells and on the configuration in which they are connected inside each PC_i. In this model, each PC_i is assumed to contain only one Cell_i. Using equations (29) and (30) as basic building blocks, the state-space system for the thermal subsystem of n cells can be written as follows:

$$\dot{X}_t = A_t^{(\sigma)} X_t + \hat{G}_t(x_L) \hat{u} + W_t^{(\sigma)} T_{fin}, \quad Y = C_t X_t \quad (31)$$

where $A_t^{(\sigma)} \in \mathbb{R}^{n \times n}$ is the system matrix in which $A_t^{(1)}$ is the lower triangular matrix with coefficients $a_{ij}^{(1)}$ defined by equations (11) and (12) for forward coolant flow, $A_t^{(2)} = (A_t^{(1)})^T$ is the upper triangular matrix with coefficients $a_{ij}^{(2)}$ defined by equations (15) and (16) for reverse coolant flow, $\hat{G}_t(x_L) = \text{diag}(\hat{g}_{t1}(x_L), \dots, \hat{g}_{tm}(x_L)) \in \mathbb{R}^{n \times 2n}$ is the load current-dependent input matrix for the thermal subsystem, $W_t^{(\sigma)} = [b_{t1}^{(\sigma)} \dots b_{tm}^{(\sigma)}]^T \in \mathbb{R}^n$ with coefficients $b_{ti}^{(\sigma)}$ defined by equation (13) for $\sigma=1$ and equation (15) for $\sigma=2$ is the scaling vector for the inlet fluid temperature, $C_t = I_n \in \mathbb{R}^{n \times n}$ is the output matrix, $X_t = [X_{t1} \dots X_{tm}]^T \in \mathbb{R}^n$ is the thermal state vector, $\hat{u} = [\hat{u}_1^T \dots \hat{u}_n^T]^T \in \mathbb{R}^{2n}$ is the input vector, $T_{fin} \in \mathbb{R}$ is the known fluid temperature (T_{f0} or T_{fn}) in one of two inlets depending on the direction of the coolant flow, and $Y \in \mathbb{R}^n$ is the output vector. Similarly, the electrical subsystem of the n-cells is given by

$$\dot{X}_e = A_e X_e + \hat{G}_e(x_L) \hat{u} \quad (32)$$

where $A_e = \text{diag}(A_{e1}, \dots, A_{en}) \in \mathbb{R}^{3n \times 3n}$ is the system matrix, $\hat{G}_e(x_L) = \text{diag}(\hat{g}_{e1}(x_L), \dots, \hat{g}_{en}(x_L)) \in \mathbb{R}^{3n \times 2n}$ is the load current-dependent input matrix for the electrical subsystem, $X_e = [X_{e1}^T \dots X_{en}^T]^T \in \mathbb{R}^{3n}$ is the electrical state vector, and $\hat{u} \in \mathbb{R}^{2n}$ is the input vector. Subsequently, the two subsystems can be combined in diagonal form.

$$\begin{bmatrix} \dot{X}_t \\ \dot{X}_e \end{bmatrix} = \underbrace{\begin{bmatrix} A_t^{(\sigma)} & 0 \\ 0 & A_e \end{bmatrix}}_{A^{(\sigma)}} \underbrace{\begin{bmatrix} X_t \\ X_e \end{bmatrix}}_X + \underbrace{\begin{bmatrix} \hat{G}_t(x_L) \\ \hat{G}_e(x_L) \end{bmatrix}}_{\hat{G}(x_L)} \hat{u} + \underbrace{\begin{bmatrix} W_t^{(\sigma)} \\ 0 \end{bmatrix}}_{W^{(\sigma)}} T_{fin} \quad (33)$$

where $A^{(\sigma)} \in \mathbb{R}^{4n \times 4n}$ is the system matrix, $\hat{G}(x_L) \in \mathbb{R}^{4n \times 2n}$ is the load current-dependent input matrix for the complete system, $C = [C_t \ 0] \in \mathbb{R}^{n \times 4n}$ is the output matrix, $X \in \mathbb{R}^{4n}$ is the state vector, $\hat{u} \in \mathbb{R}^{2n}$ is the input vector, and $W^{(\sigma)} \in \mathbb{R}^{4n}$ is the scaling vector for the inlet fluid temperature. The averaged state-space electro-thermal model under RF, as shown in equation (33), is a *piece-wise affine* system.

Remark 1: The control signal u_i can be used to determine the modes of HB_i and $Cell_i$ inside each PC_i at any time 't'. The mode in which HB_i inside any PC_i is operating can be determined by algorithm 1. Similarly, algorithm 2 can be used to determine the mode of $Cell_i$ (i.e., whether it is charging or discharging) inside any PC_i .

Algorithm 1 H-Bridge Mode Determination at any time 't'

```

 $u_i = [1 \ -1] \hat{u}_i$ 
if  $u_i(t) > 0$  then
     $HB_i$  in Mode-1 at time 't'
else if  $u_i(t) < 0$  then
     $HB_i$  in Mode-2 at time 't'
else
     $HB_i$  in Mode-3 at time 't'
end if

```

Algorithm 2 Battery Mode Determination at any time 't'

```

 $u_i = [1 \ -1] \hat{u}_i$ 
if  $x_L(t) u_i(t) > 0$  then
     $Cell_i$  is Discharging at time 't'
else if  $x_L(t) u_i(t) < 0$  then
     $Cell_i$  is Charging at time 't'
else
     $Cell_i$  is Disconnected at time 't'
end if

```

IV. OPTIMIZATION PROBLEM

In this section, an optimization problem is formulated for the OP scheme to achieve cell balancing in terms of both temperature and SoC. The averaged state-space model derived in the previous section is used along with an objective function and certain constraints as described below.

A. Definition of the Objective Function

The objective of this study is to equalize SoC of all cells at the final time and to maintain both SoC and temperature deviations among the cells within a certain zone during the entire drive cycle. These objectives will be specified as constraints in the next subsection. Another aim is to minimize temperature deviations among the battery cells, as specified in the following objective function:

$$J(Y) = \int_0^{t_f} (Y_1 - Y_2)^2 + \dots + (Y_{n-1} - Y_n)^2 dt \quad (34)$$

To transform $J(Y)$ into the quadratic form in X , $Q = C^T \bar{Q}_1 \bar{Q}_1^T C$ is defined with $\bar{Q}_1 = \text{diag}(q_1, \dots, q_{n-1}) \in \mathbb{R}^{n \times (n-1)}$, where $q_i = [1 \ -1]^T$. Therefore, the objective function (34) can be rewritten as the following standard quadratic form:

$$J(X) = \int_0^{t_f} X^T Q X dt \quad (35)$$

B. Definition of Constraints

There are some hard (operational, safety and balancing) constraints that need to be respected by OP. The objective of balancing SoC is defined in terms of the following zone and terminal constraints. During run-time, SoC of all cells must stay within a certain zone from each other, as given by

$$-\Delta \text{SoC} \leq (X_{ei3}(t) - X_{ej3}(t)) \leq \Delta \text{SoC}, \quad \forall t, \forall i, j \in \{1, 2, \dots, n\} \quad (36)$$

and at the final time, SoC of all cells should be equal:

$$X_{ei3}(t_f) = X_{ej3}(t_f) \quad \forall i, j \in \{1, 2, \dots, n\} \quad (37)$$

In addition, SoC of Cell_i must stay within following zone:

$$0 \leq X_{ei3}(t) \leq 1 \quad \forall t, \forall i \in \{1, 2, \dots, n\} \quad (38)$$

To ensure tight thermal balancing, in addition to minimizing the deviations of cell temperatures, a hard constraint maintains temperature deviations among the cells in the following zone:

$$-\Delta T_s \leq (T_{si}(t) - T_{sj}(t)) \leq \Delta T_s \quad \forall t, \forall i, j \in \{1, \dots, n\} \quad (39)$$

Moreover, a safety constraint on the maximum operating temperature of each cell is present.

$$T_{si}(t) \leq T_{s\max} \quad \forall t, \forall i \in \{1, 2, \dots, n\} \quad (40)$$

where $T_{s\max}$ is the maximum operating temperature allowed for Cell_i. The objective to track the demanded load voltage (v_{Ld}) can be written as the following constraint

$$v_{Ld} = \sum_{i=1}^n [(f(X_{ei3}) - X_{ei1} - X_{ei2})u_i - b_{ri}|u_i|x_L] \quad (41)$$

where v_{Ld} is normally provided by the higher supervisory block called energy management system (EMS) in the context of HEVs. $u_i = [1 \quad -1]\hat{u}_i$ represents the duty cycle of Cell_i. In this study, $f(X_{ei3})$ is assumed to be constant, while X_{ei1} and X_{ei2} are negligible, which are normal assumptions in developing EMS for (P)HEVs [30]. These assumptions preserve the convexity of the problem. Moreover, a constraint is identified on the maximum current that each battery cell can supply.

$$x_L u_i \in [\bar{i}_{Bi\min}, \bar{i}_{Bi\max}] \quad (42)$$

where $\bar{i}_{Bi\min}$ and $\bar{i}_{Bi\max}$ are the minimum and the maximum battery current limits, respectively. Certain constraints are also present on the control signal $\hat{u}_i = [u_{i1} \quad u_{i2}]^T \in \mathbb{R}^2$, which are given by

$$u_{i1} \in [0, 1], \quad u_{i2} \in [0, 1], \quad |u_i| = (u_{i1} + u_{i2}) \in [0, 1],$$

$$\text{and } u_i = (u_{i1} - u_{i2}) \in [-1, 1] \quad (43)$$

Based on the definitions of u_{i1} and u_{i2} in the previous section, these values cannot be nonzero simultaneously to avoid a shoot-through problem. Thus, the following constraint is imposed to ensure safety:

$$u_{i1}u_{i2} = 0 \quad (44)$$

However, the last constraint is non-convex and must be removed to preserve convexity of the problem.

C. Definition of the Optimization Problem

The optimization problem can subsequently be written as follows:

$$J^0 = \min_{\hat{u}} \int_0^{t_f} X^T Q X dt \quad \text{subject to} \quad \begin{cases} \dot{X} = A^{(\sigma)} X + \hat{G}(x_L)\hat{u} + W^{(\sigma)}T_{fin}, \\ \text{Constraints (36) - (44)}, \\ x_L(t), T_{fin} \text{ and } \sigma \text{ are known at each time step.} \end{cases} \quad (\text{P-I})$$

The optimization problem (P-I) is non-convex because of the non-convex constraint $u_{i1}u_{i2} = 0$. In the next subsection, certain assumptions are formulated to restore convexity and to simplify the problem.

D. Solving the Optimization Problem Using CVX

The problem (P-I) was solved by CVX, which is a MATLAB-based package for specifying and for solving convex programs [31], [32] and uses a disciplined convex programming ruleset [33]. CVX transforms MATLAB® into a modeling language, allowing constraints and objectives to be specified using standard MATLAB expression syntax.

The non-convex constraint ($u_{i1}u_{i2} = 0$) must be removed prior to establishing the optimization problem (P-I) in CVX. In this study, cell balancing is achieved by assuming that the modes of all PCs belong *either* to set {Mode-1, Mode-3} *or* to {Mode-2, Mode-3} *but not* to {Mode-1, Mode-2} at any time instant. In other words, it is not allowed at any time instant to charge and to discharge cells simultaneously.

Based on this assumption, the sign of u_{i1} can be pre-decided based on the sign of a known demanded load voltage (v_{Ld}).

Therefore, at $v_{Ld} \geq 0$, $u_{i2} = 0$ and $u_i = (u_{i1} - u_{i2}) \geq 0$.

Otherwise $u_{i1} = 0$ and consequently, $u_i \leq 0$. Therefore, the non-convex constraint ($u_{i1}u_{i2} = 0$) need not be specified. The system was discretized using Euler's approximation at sampling time $h = 1$ sec. The simulation parameters are shown in Table II,

TABLE II
SIMULATION PARAMETERS

Parameters	Value	Parameters	Value
n	5	\bar{i}_{Bimin}	$-200\text{ A}, \forall i$
t_f	12 min	\bar{i}_{Bimax}	$200\text{ A}, \forall i$
h	1 sec	ΔT_s	2°C
N	$t_f/h = 720$	ΔSoC	0.1
\bar{R}_s	$6.2770\text{ m}\Omega$	T_{smax}	40°C
R_{s5} or R_{s3}	$1.48\bar{R}_s = 9.29\text{ m}\Omega$	T_{fin}	20°C
$T_{si}(0)$	$25^\circ\text{C}, \forall i$	τ	60 sec

where \bar{R}_s is the nominal value of series resistance R_{si} of any Cell_{*i*}, N is the prediction (or driving) horizon in discrete time, and τ is the reciprocation period or the period in which the coolant completes one cycle of uniform forward and reverse flows.

V. SIMULATION RESULTS

A few variables must be introduced before the simulation results are presented. These variables are illustrated in plots for more clarity. $\bar{X}_{ii} = \frac{1}{N} \sum_{k=0}^N X_{ii}(k)$ is defined as the average temperature of Cell_{*i*} on the entire driving horizon N and $\bar{X}_{tb} = \frac{1}{n} \sum_{i=1}^n \bar{X}_{ii}$ is the average temperature of BSM. Similarly, the *normalized average power loss per unit ohm* across any Cell_{*i*} on the entire driving horizon is given by

$$\bar{I}_i = \frac{\frac{1}{N} \sum_{k=1}^N i_{Br_i}^2(k)}{\max_j \left(\frac{1}{N} \sum_{k=1}^N (i_{Br_j}^{ou}(k))^2 \right)} \quad (45)$$

where $i_{Br_j}^{ou}$ is the RMS current through Cell_{*j*} for OP under UF, as defined by equation (22). The superscripts “o” and “u” distinguish the signals of OP from UDCO, whereas the superscripts “u” and “r” represent UF and RF, respectively. Fig. 5 shows the drive cycle data comprising the demanded power, voltage, and current profiles used in the simulations. In the following sections, the simulation results of two different cell configurations are presented to thoroughly evaluate the effectiveness of the proposed OP. In configuration-1, the cell with 50% higher resistance is assumed to be the last downstream cell (Cell₅) in the five-cell string, whereas in configuration-2, the cell with higher resistance is assumed to be connected in the middle (i.e., at position of Cell₃) of the string. Both string configurations are discussed separately below to show the implications of OP.

A. Configuration-1: Downstream Cell₅ has higher resistance

In this subsection, the performances of UDCO and OP under both UF and RF are evaluated. Cell₅ is assumed to have

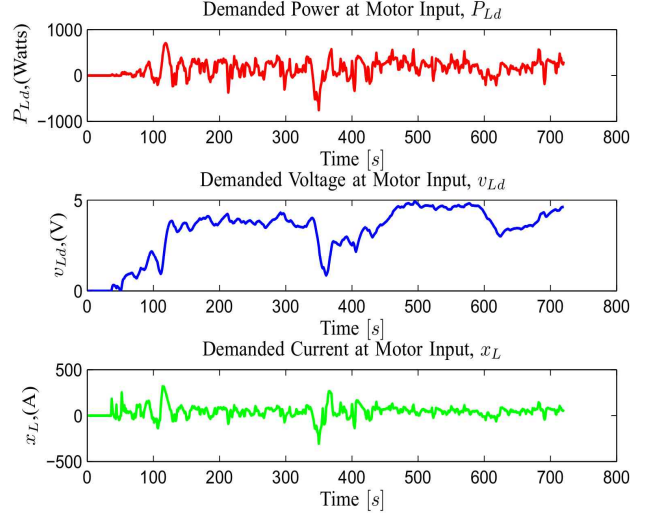


Fig. 5. Drive Cycle: Demanded Power, Voltage, and Current Profile. Two short duration high power peaks exist: (1) around 120 seconds and (2) around 350 seconds.

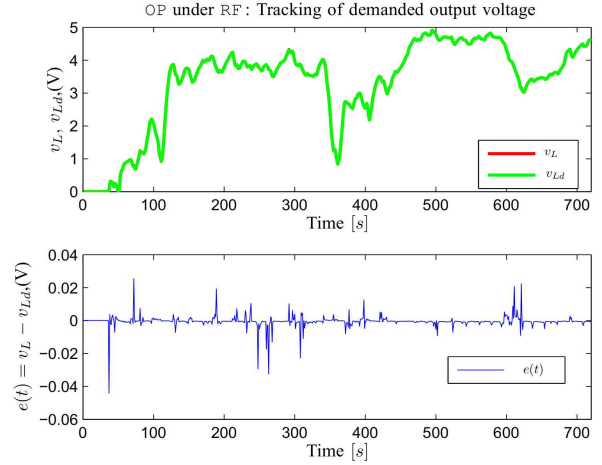
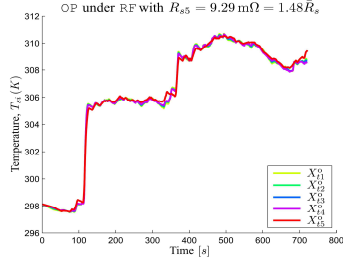


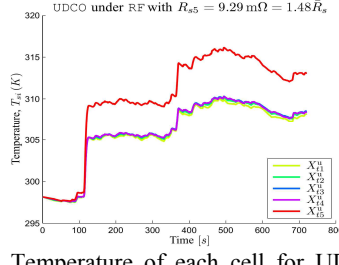
Fig. 6. Tracking of demanded output voltage. The figure shows that OP tracks the demanded output voltage with significantly small error. The tracking performance is the same for string configurations 1 and 2.

almost 50% higher series resistance because of aging or of some other effect. The temperature (X_{ti}), SoC (ξ_i), and the normalized average per unit power loss (\bar{I}_i) are plotted for each cell. Note that the assumption about 50% increase in internal resistance is not unrealistic as according to [34] the battery internal resistance may vary significantly as a function of its cycle-life. The simulation results are shown for both OP and UDCO in Fig. 7 for RF and in Fig. 8 for UF.

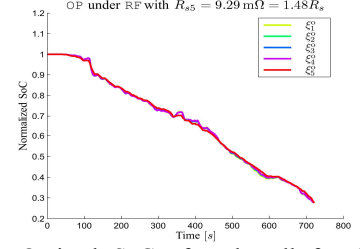
OP versus UDCO under RF: Fig. 6 shows the output voltage generated by MLC and the good tracking performance with a significantly small error for OP. The temperatures of all cells under RF are shown for OP in Fig. 7(a) and for UDCO policy in Fig. 7(b). The temperature of Cell₅ under RF for the UDCO policy is significantly higher than that of OP.



(a) Optimal Temperature of each cell for OP under RF. Despite R_{s5} being 50% higher, OP successfully achieved thermal balancing among all cells.

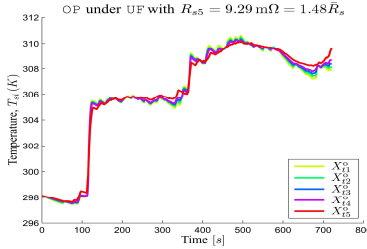


(b) Temperature of each cell for UDCO under RF. Red: *Hottest Cell*, Light Green: *Coldest Cell*. Cell₅ suffers from thermal run away as shown in red.

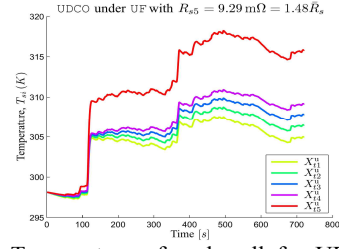


(c) Optimal SoC of each cell for OP under RF. The plot shows that OP has simultaneously achieved SoC and thermal balancing shown in Fig. 7(a).

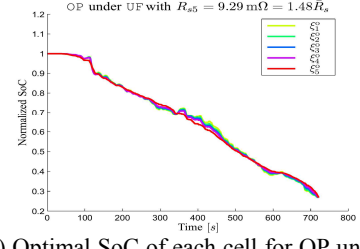
Fig. 7. Configuration-1 under RF: Simulation results and comparison between OP and UDCO for RF with the most downstream Cell₅ having 50% higher resistance. The plots show that OP significantly performs better than UDCO under RF. The uniform use of cells is naturally not optimal in this situation because the resistance (R_{s5}) of Cell₅ is 50% higher than that of the others. The plots also show that using RF is not highly helpful for UDCO under parameter variation. RF only helps to reduce temperature deviation in the cells with nominal resistance, while cells with higher resistance still suffer from thermal run away.



(a) Optimal Temperature of each cell for OP under UF. Despite R_{s5} being 50% higher, OP has successfully achieved thermal balancing among all cells.

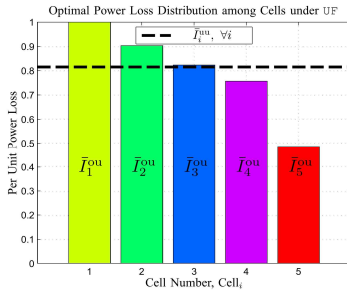


(b) Temperature of each cell for UDCO under UF. Red: *Hottest Cell*, Light Green: *Coldest Cell*. Cell₅ suffers from thermal run away as shown in red.

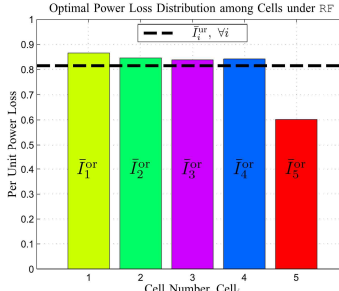


(c) Optimal SoC of each cell for OP under UF. The plot shows that OP has simultaneously achieved SoC and thermal balancing shown in Fig. 8(a).

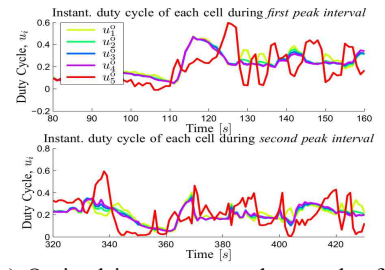
Fig. 8. Configuration-1 under UF: Simulation results and comparison between OP and UDCO for UF with the most downstream Cell₅ having 50% higher resistance. The plots show that OP significantly performs better than UDCO under UF. The uniform use of cells is naturally not optimal in this situation because the resistance (R_{s5}) of the Cell₅ is 50% higher than that of others. Fig. 7 and 8 show that OP exhibits similar performance under UF and RF. Thus, RF is redundant for an MLC-based active cell balancing system when operated using OP.



(a) Optimal normalized average power loss per unit ohm across Cell_i for OP under UF. The dashed horizontal black line shows normalized unit power loss across Cell_i for UDCO.



(b) Optimal normalized average power loss per unit ohm across Cell_i for OP under RF. The dashed horizontal black line shows normalized unit power loss across Cell_i for UDCO.



(c) Optimal instantaneous duty cycles for each cell during high current intervals for OP with RF. The plot shows that during high current intervals, OP least uses Cell₅ compared with other cells.

Fig. 9. Configuration-1 UF versus RF: Optimal power loss distribution under UF and RF. These plots show that during high current intervals, OP least uses Cell₅ compared with other cells. Thus, Cell₅ provides less current during high current intervals and consequently, has less losses, as shown in Fig. 9(b). This is naturally optimal as losses are quadratic in current.

Moreover, OP achieved good thermal balancing while maintaining the temperatures of all cells within $\pm 2^\circ\text{C}$ and SoC within $\pm 10\%$ from each other, as shown in Fig. 7(c). SoC for the UDCO policy is not shown. However, a uniform decay is

assumed for each cell. Fig. 9(b) shows the normalized average unit power loss \bar{I}_i for each cell under RF. The horizontal dashed black line illustrates the average unit power loss \bar{I}_i^{ur}

across each cell for the UDCO policy, whereas the colored vertical bars illustrate the average unit power loss \bar{I}_i^{or} across each cell for the OP scheme. The internal resistance R_{s5} of Cell₅ is almost 50% higher than that of other cells. Thus, as shown in Fig. 9(b), the naturally optimal policy is the least use of Cell₅ compared with others and Cell₁, under best thermal conditions, should be used most.

OP versus UDCO under UF: The temperatures of all cells are shown for OP in Fig. 8(a) and for UDCO policy in Fig. 8(b) under UF. Fig. 9(a) shows the normalized average unit power loss for each cell under UF. OP again performs better than the UDCO policy, as demonstrated in the figure. Similar to the RF case, OP simultaneously achieved good thermal and SoC balancing by using Cell₅, which is the most downstream cell with 50% higher resistance, least compared with the others whereas Cell₁ is used most. [20] presents a more detailed comparison between OP and UDCO under UF.

Optimal Power Loss Distributions for UF and RF: Fig. 9(a) and 9(b) demonstrate the normalized average unit power loss for UF and RF cases, respectively. These figures demonstrate the effect of the coolant flow scheme on optimal decisions of OP. The difference between the average unit power loss in UF and that in RF should be noted, particularly the difference between the optimal power loss distributions for Cell₅ in the two cases. In the RF case the Cell₅, that is no longer a downstream cell, can benefit from coolant reciprocation. Thus, OP decides to use it almost 10% more (in terms of losses) than that of the UF case. Although the optimal power loss distribution is different in both cases, the temperature increase of the cells is the same, as shown in Figures 8(a) and 7(a). This similarity indicates that OP automatically handles the coolant flow scheme and decides on the optimal power loss distribution over each cell accordingly. OP likewise handles thermal imbalances caused by resistance variation and by the temperature gradient in the coolant. Fig. 9(a) shows that in the UF case, optimal power loss distribution between two adjacent cells differs by almost 10% due to the temperature gradient in the coolant. The difference in power loss distribution between two cells is almost 20% because of the resistance variation. This finding indicates that although the power loss difference due to resistance variations is large, power loss due to the coolant temperature gradient is also not negligible. Thus, active thermal balancing is still necessary to compensate for the temperature gradient in the coolant though no resistance variation occurs in the battery string. In recollection, no decision is ad hoc here, everything is handled systematically by solving the model-based optimization problem (P-I).

B. Configuration-2: Middle Cell₃ has higher resistance

In this subsection, the performances of UDCO and OP under both UF and RF are evaluated for configuration-2 of the five-cell string. In this case, the middle Cell₃, instead of Cell₅, is assumed to have almost 50% higher series resistance. The temperature (X_{it}), SoC (ξ_i), and the normalized average per unit power loss (\bar{I}_i) are plotted for each cell. Simulation results are shown for both OP and UDCO in Fig. 10 for RF and in Fig. 11 for UF. The drive cycle data is the same as those presented previously (Fig. 5).

OP versus UDCO under RF: Fig. 10(a) and 10(c) show the temperatures and SOC of all cells for OP under RF. Fig. 10(b) exhibits the temperature for the UDCO policy under RF. The temperature of Cell₃ for the UDCO policy is significantly higher under RF than that of OP in this configuration. Moreover, OP simultaneously achieved good thermal and SoC balancing while satisfying all constraints. Fig. 12(b) shows the normalized average unit power loss \bar{I}_i that is optimally decided by OP for each cell. The internal resistance R_{s3} of Cell₃ is almost 50% higher than that of other cells. Thus, the natural OP least uses Cell₃ compared with other cells, and Cell₁ and Cell₅, under the best thermal conditions for the RF case, are used more.

OP versus UDCO under UF: Fig. 11(a) and 11(b) show the temperatures of all cells for OP and for the UDCO policy, respectively. Fig. 12(a) presents the normalized average unit power loss for each cell under UF. As shown in the figures, OP performs better than UDCO. Similar to that in the RF case, OP simultaneously achieved good thermal and SoC balancing for this cell configuration by using Cell₃ least and Cell₁ the most compared with other cells, as shown in Fig. 12(a).

Optimal Power Loss Distributions for UF and RF: Fig. 12(a) and 12(b) display the normalized average unit power loss for UF and for RF cases, respectively. These figures indicate the effect of the coolant flow scheme on the optimal decisions of OP. The optimal power loss distributions for Cell₃ in this configuration are relatively similar in both UF and RF cases. Given that Cell₃ is the middle cell, reciprocation has a slight influence on the optimal power loss decision of OP for this cell.

VI. DISCUSSION

In this section, some important implications of the simulation results are discussed.

A. Benefits of Reciprocating Air Flow

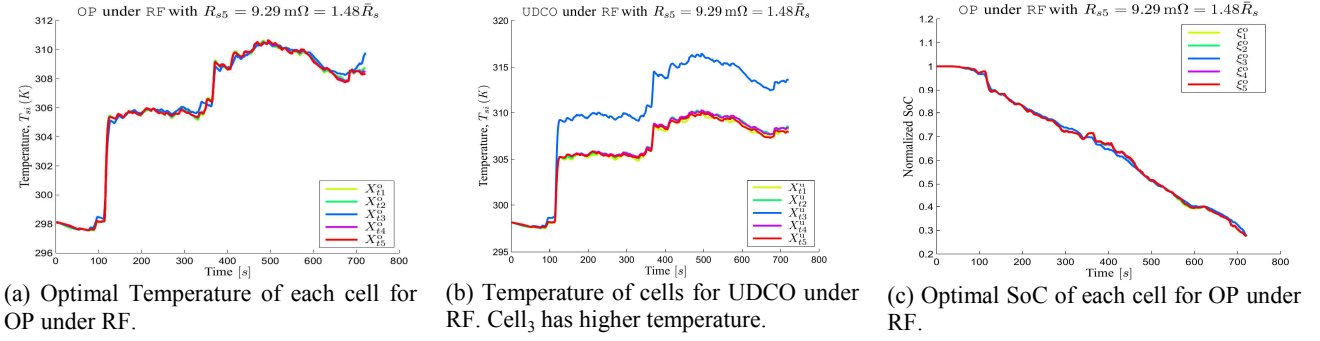


Fig. 10. **Configuration-2 under RF**: Simulation results and comparison between OP and UDCO for RF with middle Cell₃ having 50% higher resistance. The plots show that OP significantly performs better than UDCO under RF. The Fig. 10(b) shows that using RF is not very helpful for UDCO under parameter variations.

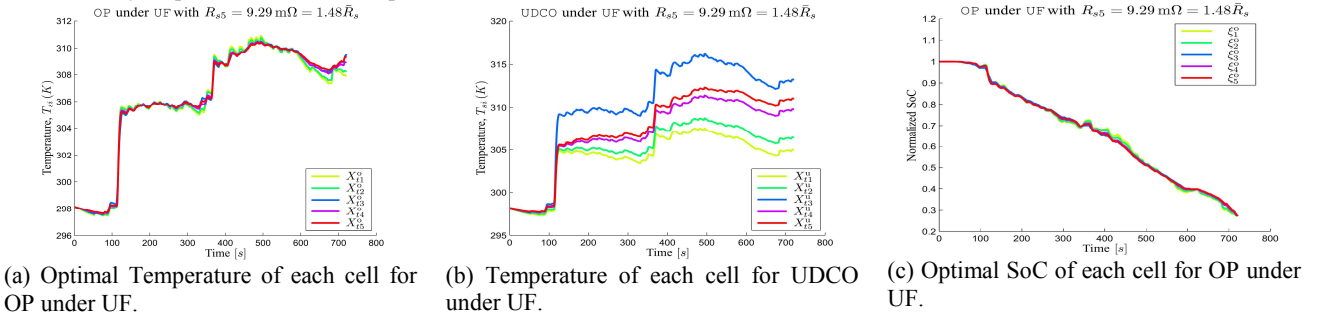


Fig. 11. **Configuration-2 under UF**: Simulation results and comparison between OP and UDCO for UF with middle Cell₃ having 50% higher resistance. The plots show that OP significantly performs better than UDCO under UF as well.

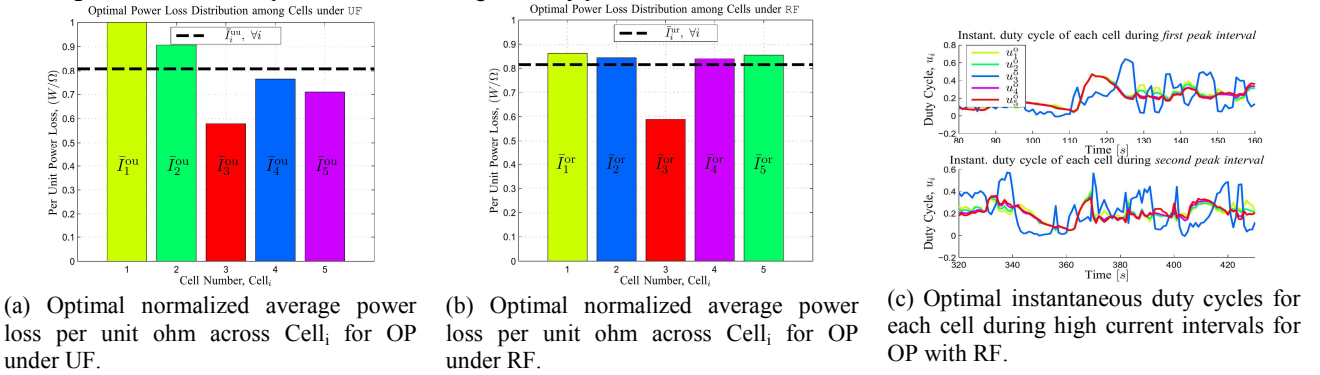


Fig. 12. **Configuration-2 UF versus RF**: Optimal power loss distribution under UF and RF. These plots show that during high current intervals, OP least uses Cell₃ compared with other cells. Thus, Cell₃ sees less current during high current interval and consequently, has less losses, as shown in Fig. 12(b). This is naturally optimal as losses are quadratic in current.

In this section, UF and RF are compared for both OP and UDCO. The temperatures of the cells for the UDCO policy under UF are shown in Fig. 8(b) for configuration-1 and in Fig. 11(b) for configuration-2. The temperatures of the cells for the UDCO policy under RF are exhibited in Fig. 7(b) for configuration-1 and in Fig. 10(b) for configuration-2. Similarly, the temperatures of the cells for OP under UF are shown in Fig. 8(a) for string configuration-1 and in Fig. 11(a) for string configuration-2. The temperatures of the cells for OP under RF are shown in Fig. 7(a) for string configuration-1 and in Fig. 10(a) for string configuration-2. These figures clearly show that OP has no significant gain when using RF, particularly for short series-connected battery string. The main

purpose of RF is merely to achieve temperature uniformity. Using RF with the UDCO policy minimizes temperature deviations among cells with nominal resistance. However, it is not that useful for Cell₅ or Cell₃ that has 50% higher resistance. These figures clearly indicate that RF without OP can bring temperature uniformity only in the string having cells with same resistances. Moreover, the temperature gradient in the coolant under RF is negligible only for short strings of cells. For long strings, RF generally cannot remove this gradient completely. Thus, RF alone cannot solve the temperature non-uniformity problem in battery packs of EV/HEV/PHEV because these battery packs normally have long strings of cells with high possibility of having resistance differences.

However, the temperature uniformity under said conditions can be achieved by *optimally shifting the power losses among the cells* using MLC-based OP even under UF. Thus in the presence of OP, RF is a redundant function.

B. Configuration-1 versus Configuration-2

In this subsection, the optimal power loss distribution for two string configurations is compared. Fig. 9(b) and 12(b) show that changing the position of the higher resistance cell in the string has slight influence on the power loss distribution in the RF case. However, the influence may be more noticeable in longer battery strings. In the case of UF, changing the position of the higher resistance cell always influence optimal decisions on power loss distribution. This finding can be validated by comparing the optimal power loss distributions of Cell₅ and of Cell₃ in Fig. 9(a) and 12(a). The difference in power loss compensates for the temperature gradient in the coolant for the UF case.

A difference can be observed in the temperature dynamics for the two configurations under the UDCO policy, as illustrated in Fig. 11(b) and 8(b). This difference is due to higher resistance Cell₃ in the middle of the string for configuration-2, thereby generating more heat that results in higher temperature differential between Cell₂ and Cell₃. Meanwhile, temperatures of Cell₁ to Cell₄ for configuration-1 are distributed in a staircase fashion because of uniform temperature gradient in the coolant. However, the temperature evolution of the two configurations is almost the same under OP, as shown in Fig. 11(a) and 8(a).

C. Working of OP in a nutshell

OP achieves thermal balancing by least using Cell₅ (or Cell₃) compared with other cells during high current intervals, as shown in Fig. 9(c) (or Fig. 12(c)). Thus, Cell₅ (or Cell₃) has less ohmic losses. This policy is naturally optimal as losses are quadratic in current. In a nutshell, OP achieves thermal balancing by avoiding the use of higher resistance cells during peak power intervals and by using the cell more frequently during low power intervals. Moreover, similarities can be observed between the optimal duty cycles of the switches in two different string configurations, as shown in Fig. 9(c) and 12(c).

VII. SUMMARY AND CONCLUSIONS

This article investigated the potential benefit of optimally using the extra DoF of MLC for simultaneous balancing of SoC and temperature of cells under UF and RF. A complete state-space electro-thermal model was developed and a constrained convex optimization problem was formulated and solved based on the assumption that the state of each cell and the schedule of reciprocating air flow are perfectly known. The simulation results showed that at 50% increase in internal

resistance of any cell, OP optimally uses the extra DoF of MLC, significantly reducing temperature deviation among the cells compared with the ad hoc uniform duty cycle operation. In a nutshell, OP achieves thermal balancing by *optimally shifting the power losses among the cells* depending on their resistance and positions in the string. Thus, OP can also achieve temperature uniformity under parameter variations even with UF, whereas RF cannot maintain temperature uniformity in such circumstances without OP. This study shows that using RF has no significant benefit when using an MLC-based OP. Thus, RF is considered a redundant function when an MLC-based active cell balancing system is operated using OP.

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