Evaluation and Comparative Study of Cell Balancing Methods for Lithium-Ion Batteries Used in Electric Vehicles

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ABSTRACT: Vehicle manufacturers positioned electric vehicles (EVs) and hybrid electric vehicles (HEVs) as reliable, safe and environmental friendly alternative to traditional fuel based vehicles. Charging EVs using renewable energy resources reduce greenhouse emissions. The Lithium-ion (Li-ion) batteries used in EVs are susceptible to failure due to voltage imbalance when connected to form a pack. Hence, it requires a proper balancing system categorised into passive and active systems based on the working principle. It is the prerogative of a battery management system (BMS) designer to choose an appropriate system depending on the application. This study compares and evaluates passive balancing system against widely used inductor based active balancing system in order to select an appropriate balancing scheme addressing battery efficiency and balancing speed for E-vehicle segment (E-bike, E-car and E-truck). The balancing systems are implemented using “top-balancing” algorithm which balance the cells voltages near the end of charge for better accuracy and effective balancing. The most important characteristics of the balancing systems such as degree of imbalance, power loss and temperature variation are determined by their influence on battery performance and cost. To enhance the battery life, Matlab-Simscape simulation-based analysis is performed in order to fine tune the cell balancing system for the optimal usage of the battery pack. For the simulation requirements, the battery model parameters are obtained using least-square fitting algorithm on the data obtained through electro chemical impedance spectroscopy (EIS) test. The achieved balancing time of the passive and active cell balancer for fourteen cells were 48 and 20 min for the voltage deviation of 30 mV. Also, the recorded balancing time was 215 and 42 min for the voltage deviation of 200 mV.

Keywords: Electric vehicle, Lithium-ion battery, Energy efficiency, Temperature behaviour and Cost analysis.

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1. Introduction

A Li-ion battery pack which is used in EVs consists of several cells assembled in series and in parallel to deliver the required voltage and capacity. Any discrepancy in the capacity and voltage of the connected cells affect the efficiency of the whole battery pack (Omariba et al., 2018). This may happen due to various environmental factors or manufacturing differences which introduce variations in the EV cell specifications resulting in a performance degradation (Jonathan et al., 2020).

In order to recover the maximum battery pack energy, a balancing scheme is incorporated using BMS for EVs. The balancing systems which remove excess energy from the over charged cells are categorised into passive and active (Ouyang et al., 2020). Passive system uses a dissipative resistor to bleed excess charge from the highly charged cell and active system uses an energy storing element to transfer excess charge to a low charged cell, thus facilitating support between a strong and a weak cell (Campbell et al., 2019). The cell balancing system used in EVs typically involves three modes of operation as shown in Fig. 1 (Omariba et al., 2019).

Balancing is employed to maximise the energy delivered to or from the cell during the process of charging or discharging. The idle balancing mode operates when the cell is neither charged nor discharged. The balancing algorithms used in the balancer is either voltage (Hoque et al., 2015) or charge based (Ma et al., 2018) which are applicable to both active and passive balancing schemes.

Passive balancing scheme, shown in Fig. 2 is extensively used in EV applications due to its low cost and easy implementation (Koseoglou et al., 2020). Problem consists of excess heat dissipation due to the balancing resistor, long balancing time and low efficiency. Balancing current must be kept low to reduce power loss and manage thermal issues (Stuart et al., 2009). Recently Xu et al. (2019) used MOSFET (metal–oxide–semiconductor field-effect transistor) switch as a variable resistor instead of the balancing resistor to handle the power dissipation optimally. In the passive scheme to tackle huge power loss, a proper thermal management system needs to be implemented in order to control any inadvertent rise in temperature which leads to pack degradation. Currently, active topologies are replacing traditional passive systems.

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to handle power loss and heat dissipation issues (Jonathan et al., 2020).

Active balancing schemes are classified into capacitor, inductor and transformer based (Hemavathi, 2020). Capacitor based scheme offers low implementation cost, but the balancing speed is low (Lee et al., 2016). Transformer based scheme has a high balancing speed and it requires high cost due to the presence of a transformer (Gallardo-Lozano et al., 2014). Inductor scheme gives a better performance with a trade-off between balancing speed and implementation cost (Xie et al., 2011). A next-to-next inductor balancing topology (Phung et al., 2014) consists of (N-1) inductors which transfers energy between adjacent cells, extending the battery discharge time, however the presence of a higher number of components makes it difficult to implement. Single switch per cell with unidirectional balancing (Kim et al., 2014) reduces the number of switches but has drawbacks in the form of voltage stress on the centre-cell switch. Dong et al. (2015) presented a solution to overcome the slow balancing time of the charge equalizer by fixing independent equalizers in different layers. To enhance equalization current and efficiency, any-cell-to-any-cell bidirectional inductor-based topology was introduced by Zhou et al. (2016). However, the presence of a high number of switches lead to higher costs and size.

The topology discussed by Kumar et al. (2017) offers the fastest balancing time using a single switch inductor. The inductor-based system proposed by Moghaddam and Van Den Bossche (2018) exhibits excellent characteristics with reduced complexity and fewer components when compared to traditional inductor based balancing system (Cassani and Williamson, 2009). By using a coupled inductor (Moghaddam and Van Den Bossche, 2019) as shown in Fig.3a instead of a traditional one (Xie et al., 2011) as shown in Fig.3b, can reduce the number of components and the cost further. The traditional scheme uses (N-1) inductors and 2(N-1) switches for N number of cells, coupled scheme needs N/2 inductors and N switches for N number of cells.

In a non-hybrid electric car, such as BMW i3, 96 cells are installed in series which has a total battery voltage of around 360 V. In electrified trucks and passenger electric vehicles, the maximum DC link voltage may reach up to 870 V, and often called as 800 V system (Jung, 2017). These types of high-power electric vehicles need to employ active balancing system for the effective use of power.

Table 1

| Balancing attributes | Passive balancing | Capacitor based balancing | Inductor based balancing | Transformer based balancing |
|----------------------|-------------------|---------------------------|--------------------------|----------------------------|
| Preferred Mode       | Charging          | Charging, discharging     | Charging                 | Charging                   |
| Size                 | Slow              | Slow                      | Fast                     | Faster                     |
| Cost                 | Small             | Medium                    | Medium                   | Bulky                      |
| Modulatorization     | Economical        | Expensive                 | Moderate                 | Very expensive            |
| Efficiency           | > 90%             | 88% to 95%                | > 95%                    | 80% to 95%                |
| Control complexity   | Simple            | Complex                   | Moderate                 | Complex                    |
| Implementation       | Simple            | Complex                   | Complex                  | Complex                    |
| Merits               | Easy to realize   | Simple control, no need for closed-loop control | Faster balancing, good efficiency, relatively cheap filtering capacitors are needed for high switching frequency | Faster balancing, low switch voltage/current stress High cost, size, complex |
| Demerits             | Energy is dissipated as heat, slow balancing | Greater number of switches |                                      | control                   |

Fig. 1 Cell Equalization modes

Fig. 2 Passive balancing

Fig. 3(a) Coupled inductor and (b) Traditional inductor
The necessity of a balancing system is to improve the power and energy stipulations, energy efficiency and life cycle extension of the battery system (Hua et al., 2020). This research work analyses the passive and inductor based active cell balancing characteristics which are explored by Thiruvonasundari and Deepa (2020) with respect to power level, cell balancing mode, thermal characteristics and implementation cost to select a suitable balancing method for battery powered EVs. Table 1 compares the balancing system from the available literature.

This paper is organized as follows: Section 2 discusses the balancing principle and design methodology. Section 3 describes simulation techniques and captures the outcomes of active and passive balancing schemes. In Section 4, simulation results are compared against balancing parameters and the balancing method suitable for different E-vehicle segment, followed by the conclusion in Section 5.

2. Methodology

2.1. Balancing Principle

Passive and active cell balancing algorithms rely on voltage balancing strategies. The algorithms check whether the voltage difference between any two cells is more than the threshold value, the passive system dissipates the excess energy through the balancing resistor whereas in an active system an inductor transfers excess energy to low energy cells. The balancing thresholds could be further fine-tuned by increasing the accuracy of the sampling circuit and based on the system requirements. Table 2 summarizes the cell specifications for the balancing system.

To simulate the balancing system, a proper battery cell model is required. The most widely used equivalent circuit model (ECM) is chosen for the state estimation (Zheng et al., 2018). Li-ion nickel manganese cobalt (NMC) cells have been tested and their parameters were estimated as discussed by Thiruvonasundari and Deepa (2020). A complete battery model is drafted by the 3RC equivalent circuit modelling approach. The cell balancing is performed by using a model-based simulation in a Matlab-Simulink environment as represented in Fig. 4. This model describes open circuit voltage (OCV), state of charge (SOC) and state of health (SOH) variable parameters as a function of temperature and SOC. The 3RC elements are accurately capture the battery system dynamics and the thermal block is used to model the battery temperature. Figures 5 and 6 show the OCV and internal resistance (Rs) of the battery with respect to SOC. The internal resistance of the model reflects the battery SOH. The various drive cycles such as urban dynamometer driving schedule (UDDS), new European drive cycle (NEDC) are studied to perform the cell balancing. In this work, the cell balancing algorithm is set to activate the balancing when all the cell voltages are above 3.9 V (top-balancing) and ∆V > 30 mV. The simulation was performed by varying the cell initial voltages of values from 3.57 V to 4.16 V with a minimum to maximum voltage deviation of the cells between 30 mV to 230 mV. The balancing architecture, working principle, control flow algorithm, modes of operation and simulation outcome of inductor cell balancing schemes are explained in Thiruvonasundari and Deepa (2020).

Table 2

| Li-ion battery pack specifications for 18650-NMC cells |
|-----------------------------------------------|
| **Cell Specifications** | **Value** |
| Number of cells | 14         |
| Pack voltage  | 48V        |
| Capacity      | 3.35Ah     |
| Maximum charge voltage | 4.2V   |
| Minimum discharge voltage | 2.5V |
| Balancing voltage | 3.9V       |
2.2. Cell Balancing Design

Energy efficiency is a major factor to be considered while designing electrical energy storage applications (Chen et al., 2020). Achieving higher energy efficiency during the cell balancing process involves optimal dimensioning of the cell balancing system, thus saving precious energy instead of wasting it in the form of heat. In both passive and active balancing system implementations, several resistors, inductors and MOSFET switch variants may be used in the balancing circuit design. Each minor configuration for a certain balancing current has the potential to alter energy dissipation and volume of the balancing architecture.

The balancing current is not only responsible for energy dissipation, but also determines the speed of the charge transfer process. The passive system uses relatively low balancing current, to drain the excess charge from overcharged cells.

\[ I_B = \frac{V_C}{R_B} \]  

Where,
- \( V_C \) is the cell voltage
- \( R_B \) is the balancing resistor

The cell balancing current of C/100 is sufficient for the system (Amin et al., 2017), a balancing current of 100 mA finds the balancing resistor of 37 Ω. Though higher balancing current reduces the balancing time but it increases the energy loss.

### Table 3

| Properties of MOSFET & Inductor |
|-------------------------------|
| **MOSFET** | **Symbol** | **Inductor** | **Symbol** |
| Max. Current | \( I_{max} \) | Max. Current | \( I_{max} \) |
| Switch resistance | \( R_D \) | Inductance | \( L \) |
| O/P Capacitance | \( C_{out} \) | DC Resistance | \( R_{ind} \) |
| Delay time | \( t_{on}, t_{off} \) | Volume | \( v_{ind} \) |
| Volume | \( v_{in} \) | | |

Energy loss = Power loss \times Balancing time

\[ E_{loss} = \frac{v^2}{R_B} \times t_B \text{ or } \frac{I^2 R_B}{L} \times t_B \]  

The reduction in balancing time mandates, higher current requirement on the MOSFET and high wattage rating on the bleeding resistors. The properties of MOSFET and inductors which influence the balancing parameters of the balancing architecture are listed in Table 3 (Narayanaswamy et al., 2014).

The selection of balancing inductor in a circuit is based on the rated current of the battery. In inductor balancing, the energy stored in the inductor at the first stage (when the switch is closed) is fully transferred to the low voltage cell in the second stage (when the switch is opened and diode works), the duty cycle D should be < 0.5 cycle. So, the balancing inductor works in discontinuous current mode (DCM). The DCM mode of DC-DC converter operation is shown in Fig.7a and b (Wang et al., 2017). When switch S1 is turned on, the cell 1 voltage charges the inductor L1 (Wang et al., 2017).

\[ V_{Lon} = i_{Lon} R_{on} + L \frac{di_{Lon}}{dt} + V_m, \ 0 < t < t_{on} \]  

Where,
- \( V_{Lon} \) is the voltage across L1
- \( i_{Lon} \) is the current through the inductor
- \( R_{on} \) is the total resistance in the current path
- \( V_m \) is the voltage drop across the MOSFET

When switch S1 is turned OFF, the energy stored in the inductor is transferred to cell 2 and voltage across the inductor is denoted by \( V_{loff} \).

\[ V_{loff} = i_{loff} R_{off} + L \frac{di_{loff}}{dt} - V_d, t_{on} < t < t_d \]  

Where,
• $V_d$ is the forward voltage drop across the MOSFET diode,
• $t_d$ is the time when the inductor current drops to zero.

The on and off time of the switch is calculated as below

\[
t_{\text{on}} = \frac{t_{\text{on}}}{(V_{\text{com}}-V_m)} \quad (6)
\]

\[
t_{\text{off}} = \frac{t_{\text{off}}}{(V_{\text{com}}-V_d)} \quad (7)
\]

The peak value of the inductor current is calculated from Eqn. (6)

\[
i_p = \frac{(V_{\text{com}}-V_m)I_{\text{com}}}{I_1} \quad (8)
\]

By ignoring the drop across the switch,

\[
i_p = \frac{(V_{\text{com}}-V_m)D}{2L_1f} \quad (9)
\]

The average value of inductor and battery currents are:

\[
i_{\text{avr}} = \frac{(V_{\text{com}})D}{2L_1f} \quad (10)
\]

\[
i_{\text{max}} = \frac{(V_{\text{com}})D^2}{2L_1f} \quad (11)
\]

The average value of balancing current is inversely proportional to the inductance and switching frequency. Due to the inverse relationship between balancing time and current, the balancing time is dependent on $L$ and $f$. The size of the inductor can be reduced further by increasing the switching frequency.

3. Results

In this simulation, it was found that the passive balancer takes very long time, owing to higher voltage difference between the cells as shown in Fig.8 and 9. This limitation of passive cell balancing is overcome by using active cell balancing, as given in Fig.10 and 11. The power loss across the balancing system could be a major cause for the temperature rise near the battery pack, decreasing the battery life by stimulating the aging mechanisms. Comparison of temperature characteristics is done by evaluating the maximum temperature ($T_{\text{max}}$) and temperature distribution ($\Delta T$) among the cells. The active system reaches lower maximum temperature (24°C) than passive system (27°C) and $\Delta T$ does not exceed 4°C at the time of charging as represented in Fig.12 and 13 where $\Delta V$>30 mV.

| ΔV (mV) | Cells (#) | $P_{\text{loss}}$ (W) | $BT$ (min) | $E_{\text{loss}}$ (Wh) | $\eta$ (%) | Cost ($) |
|---------|----------|------------------------|------------|------------------------|------------|--------|
| 30      | 1        | 0.35                   | 48         | 0.28                   | 99.83      | 0.04   |
|         | 13       | 4.55                   | 48         | 3.64                   | 97.84      | 0.49   |
| 200     | 1        | 0.35                   | 215        | 1.25                   | 99.26      | 0.17   |
|         | 13       | 4.55                   | 215        | 16.30                  | 90.34      | 2.17   |

Table 4: Passive system energy efficiency and cost calculation
4. Discussion

4.1. E-vehicle use cases

In low power E-bikes, the number of series connected cells going out of balance are considerably low. Among fourteen cells, for a single cell balancing, passive balancer took 48 min to bring down the difference to 30 mV (shown in Fig.8).

The power dissipation of 0.35 W is observed across the balancing resistor which is insignificant (shown in Table 4). Since the heat dissipation is minimum in passive balancing, active balancing is not a feasible option due to high cost and circuit complexity. Hence, the passive balancing is suitable for low power E-bikes. If cells are aged (cycled many times), the voltage deviation is maximum and the pack contains a greater number of imbalanced cells and the passive balancer took 215 min to balance with a power loss of 4.55W is observed. This loss is significant (as shown in Table 4), hence the passive balancing is not a feasible option for aged out cells and high-power battery pack (possibility of more imbalanced cells). The active balancer took 15 to 42 min for ΔV is from 30 mV to 200 mV is shown in Table 5. Table 6 illustrates a comparative study of the cell balancing system characteristics of EV variants. It is observed that cost saving from the energy loss is not significant even with passive balancing though power loss is reduced drastically with active balancing. Due to the excess energy loss the passive cell balancing system produce hot spots within the pack which limits the battery state of health and the remaining useful life of the battery (Lipu et al., 2018).

In the recent years, life cycle assessment studies are conducted on next generation Li-ion batteries for EVs, including Si-Nanotube based, molybdenum disulfide Li-ion battery to do environmental impact analysis (Deng et al., 2019).

3.1. Calculation of key parameters from simulation

The simulation result provides many key parameters including balancing time, power loss, energy loss, energy efficiency and the cost of the lost energy. Tables 4 and 5 show the passive and active simulation outcome of a typical 48 V E-bike system. Using passive balancing, it is observed that a considerable energy loss occurs only when the cell imbalance is high. In contrast to passive system, the energy loss is observed to be low in the active topology, irrespective of the number of cells and voltage deviation (ΔV).

### Table 5

| Cells in series | 1 | 13 | 1 | 13 |
|-----------------|---|----|---|----|
| Cells (#)       | 1 | 13 | 1 | 13 |
| Power loss (W)  | 0.07 | 1.05 | 0.4 | 1.16 |
| Balancing time (min) | 15 | 20 | 35 | 42 |
| Energy loss (Wh) | 0.02 | 0.35 | 0.23 | 0.81 |
| Efficiency (%)  | 99.9 | 99.7 | 99.86 | 99.51 |
| Cost ($)        | 0.003 | 0.047 | 0.031 | 0.108 |

### Table 6

| Parameters | E-Bike | E-Car | E-Truck |
|------------|--------|-------|---------|
| PB         | AB     | PB    | AB      |
| Cells in series | 14 | 14 | 96 | 96 | 250 | 250 |
| ΔV (mV)    | 30     | 30    | 30     | 30    | 30   | 30   |
| P_{loss} (W)| 4.55 | 1.05 | 38      | 9.5    | 99.6 | 24.9 |
| BT (Min)   | 48     | 20    | 48      | 20     | 48   | 20   |
| E_{loss} (Wh)| 3.64 | 0.35 | 30.4    | 3.2    | 80   | 8.3  |
| η (%)      | 97.8   | 99.7  | 97      | 99     | 96.7 | 98.5 |
| E_{loss cost} ($) | 0.49 | 0.05 | 4.05    | 0.4    | 10.7 | 1.11 |

PB – Passive Balancing, AB – Active Balancing
balancing redistributes the excess charge and ensures that the cells are balanced even when the EVs are at the beginning of charging, driving or parked. The active balancer took almost same time for minimum to maximum voltage deviations as shown in Table 5. It can balance cell voltages rapidly, with suitable balancing current results at a higher charging efficiency (Chol-Ho et al., 2013). Table 7 illustrates C-rate and time while discharging and charging batteries of 1Ah (Collin et al., 2019).

In most cases, the safely accepted C-rate of the EV batteries is still restricted to 1-1.5 C. Various charging schemes (Tomaszewsk et al., 2019) have been proposed for fast charging of Li-ion batteries as illustrated in Fig. 14. CC-CV plot indicates the constant current charging behavior till the battery voltage reaches up to a cut-off value and followed by a constant voltage until the current falls to prescribed minimum value. In CP-CV constant power in the beginning of charging followed by a CV. Multistage CC-CV (MCC-CV) plot shows three CC stages followed by a CV. Pulse charger feed the charge current in pulses and charging profile in the boost charging scheme is shown in pulse charging plot. High charge current at the beginning of charging followed by a moderate current with CC-CV profile in the boost charging scheme is shown in the Boost Charging plot. VCP plot shows a greater number of variable current profiles for fast charging.

Table 7  
| C-rate(C) | Time (hr) |
|-----------|-----------|
| 5         | 0.2       |
| 2         | 0.5       |
| 1         | 1         |
| 0.5       | 2         |
| 0.2       | 5         |
| 0.1       | 10        |
| 0.05      | 20        |

Source: batteryuniversity.com

Table 8  
| Key element cost comparison |
|-----------------------------|
| Key parts         | PB ($) | AB ($) | Existing PB ($) | Existing AB ($) |
| BMS IC Complex    | 13.3   | 16.00  | 57.4            | 42.36           |
| Resistor/ Inductor| 1.96   | 19.95  | 3.92            | 31.92           |

* Existing scheme cost is for 4S1P, so derived it for 48V

4.3. Energy concerns

The charging efficiency of the passive system is low compared to active system, due to power loss across the balancing resistor and it is further reducing for high power EVs (shown in Table 6). The energy loss incurred in passive system is calculated by measuring the cell voltage, balancing resistor and the balancing time as represented in Eqn. (2 and 3), whereas the active system produces heat due to balancing converter power losses. Sometimes the active system in standby mode, the power wastage leads to greater loss than the passive balancing (Davide Andrea, 2010). Tables 4 and 5 show increase in energy efficiency by 1.86% for the maximum number of unbalanced cells and by 9.17% for the cells with high voltage deviation. This is significantly higher than the results (1% and 6%) discussed by Iosu Aizpuru et al. (2017). So, active balancing is recommended for the application which needs a medium or large battery pack that should be extremely energy efficient. The power handled during balancing is on the range of 0.1 to 10 W then the passive balancing could be a better option (shown in Table 6).

4.4. Temperature behavior

In order to improve the power capacity Ni content in NMC cells are increased in different variants, (from NMC111 to NMC811) but high reactivity of the cathode material with the electrolyte introduces safety issues due to increase in temperature (Ma et al., 2016).

During thermal run-away test, at high temperatures the cylindrical Li-ion cells with NMC cathode showed a poor temperature tolerance (Lei et al., 2017). Packing a set of similar performance cells while manufacturing modules have shown an equalized temperature distribution and lowered rise in temperature (Li et al., 2019). The temperature performance of the battery pack is highly dependent on the balancing system which controls parameters such as temperature deviation (∆T) between the cells and maximum temperature of the battery pack (T_{max}) as per the experiments conducted (shown in Fig.12 and 13). The power loss across each cell is responsible for the temperature rise in the battery pack (Abronzini et al., 2019). The balancing system equalizes the cell voltages so that the ∆T between the cells are reduced and T_{max} is found to be low in the case of active (shown in Fig.13).

4.5. Total cost of the balancing system

Passive systems architecture represented in Fig. 2 require a power MOSFET switch S_n in combination with a
balancing resistor $R_p$ to dissipate the excess energy of the cells. Active systems have complex architecture as represented in Fig. 3a i.e., they need a greater number of active switches and inductors. The total system cost of passive and active systems could be reduced by using a specific battery management system ICs. Table 8 shows that this scheme is more cost effective than the scheme discussed by Dong et al. (2015).

5. Conclusions and Future Research Orientations

For longer life-span and reliable performance of EV battery packs, cell balancing algorithm is a key contributor. Passive balancing finds application in low power systems (E-bike, E-rickshaw, etc.) with cells which are closely matched and charged through conventional charging method. Battery pack for high power applications (E-car, E-truck, etc.) contains greater number of series connected cells which may contribute significant imbalance and hence needs a high current active balancing topology. While balancing, the temperature deviation ($\Delta T$) among the cells is less than 1°C in the active system and around 3°C in the passive system. By using active balancing, the efficiency of the battery system is enhanced; 2% for cells having low $\Delta V$ and about 9% for cells having high $\Delta V$. Passive system is simple and the implementation cost is low, but it involves high investment to have a thermal management system. Though the active system is more complicated and expensive, substituting active system with the passive for high power battery pack applications (e.g., E-truck) reduces thermal issues while providing higher energy efficiency. Future research in cell equalization is considered using wide band gap devices and smart intelligent techniques to improve existing solutions.

According to the international energy agency (IEA) report, the expected growth of renewable energy capacity is around 218 GW in 2021, nearly 10% higher than 2020 (200 GW). Renewable capacity additions are led by solar PV (around 54%) and wind (around 31%) respectively. The strong growth is mainly because of projects delayed in the last year due to COVID-19 pandemic (www.iea.org).

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