A Wireless Battery Temperature Monitoring System for Electric Vehicle Charging

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***Abstract*—Thermal monitoring during charging increases the safety and efficiency of Electric Vehicles (EVs) batteries. Up to now, no thermal sensing solutions are able to perform temperature sensing for each battery cell in the EV due to the cost, deployment complexity, and/or safety reasons. In this paper, a complete wireless thermal monitoring system for EV battery charging surveillance is presented. The designed sensing device is wireless, fully passive, with small feature size, and low-cost thus can be deployed on a large scale for cell-level battery temperature sensing. The maximum reading distance of the device is >5 m in the ambient, with a sensing precision of ±1.5 °C (3σ) from -20 to 80 °C. The whole system is validated in-house using a 18650-36V-4.4A Li-ion battery cell to track its temperature change when being charged at different C-rates.**

***Index Terms*—Electric vehicles battery charging, wireless battery temperature monitoring, RFID sense tag**

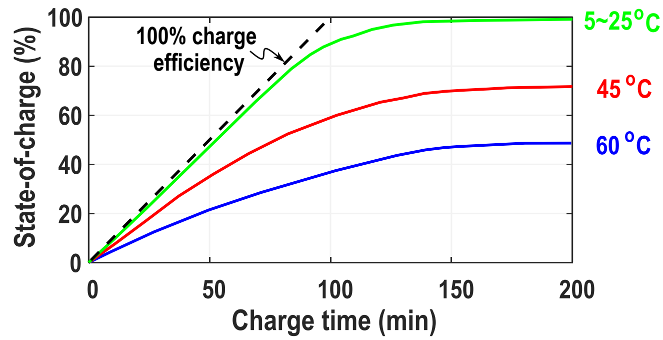

Fig. 1: NiCd charge acceptance as a function of the battery temperature during charging, showing its strong temperature dependency (with a charging rate of 1C) [6].

I. Introduction

Battery refill is a main challenge in the penetration of the electric vehicles (EVs) [1], [2]. For depleted batteries (e.g., Li-ion, lead-acid, NiCd, NiMH, etc.), they can be either swapped with other charged batteries or being recharged in situ while in the EV [3]. Typically, EV battery charging is performed within a narrow temperature range (e.g., 5 $\sim$ 45 °C for Li-ion [4]) to avoid its performance degradation [5]. For example, as shown in Fig. 1, a strong decrease in charge efficiency can be observed when dwelling above 30 °C [6]. At 60 °C, the NiCd battery accepts only 45% of its full capacity. This mandates real-time battery temperature monitoring during charging for accurate state-of-charge (SoC) calculation. More importantly, unbalanced or aged batteries with high internal resistance will be heated up rapidly during charging. To avoid disintegration of these batteries or even catastrophic explosions, the charger should also monitor the battery temperature to halt the charge when the battery gets unduly stressed (thermal runaway). In a word, a temperature monitoring system can be used to keep the battery in its optimum condition, estimate its SoC with high precision, prolong the battery life, dynamically control the charging current/voltage, and avoid hazards inherent to the batteries.

Attaching a thermistor to the EV battery pack is an inexpensive yet reasonably accurate way to monitor its temperature. However, it requires wiring and additional readout circuits to obtain the digitized temperature data. In high-power applications, the charge controller even requires one sensor for each battery cell. This further complicates the deployment and degrades the robustness of the sensing system given the harsh automotive operating environment. Moreover, the obtained temperature data cannot be handily transmitted to the stations for dynamic charge control. Wireless temperature sensors can be used to tackle these problems by mounting a sensor to each battery cell. However, existing products using Cellular network, WiFi, BLE, Zigbee, NFC, etc. are either bulky, costly, require battery/wiring for power, and/or have limited reading distance (e.g., <10 cm [7]) and therefore cannot be deployed on a large scale for in situ EV battery monitoring.

This paper presents a complete wireless thermal monitoring system for EV battery charging surveillance in the stations, particularly for DC fast charging. The designed sensing device is fully passive (battery-less) and utilizes the ultra-high frequency (UHF) radio-frequency identification (RFID) technology for data transmission, which is an improved version of our previous designs [8], [9]. The multi-time programmable (MTP) memory in the device stores the temperature characteristics (look-up table) of the battery, which can be used for the SoC calculation together with the cell voltage read by the charger. Extra information of the battery (e.g., capacity, age, nominal voltage, number of char-discharge cycle experienced, etc.) can also be stored in the MTP to achieve flexible charging control.

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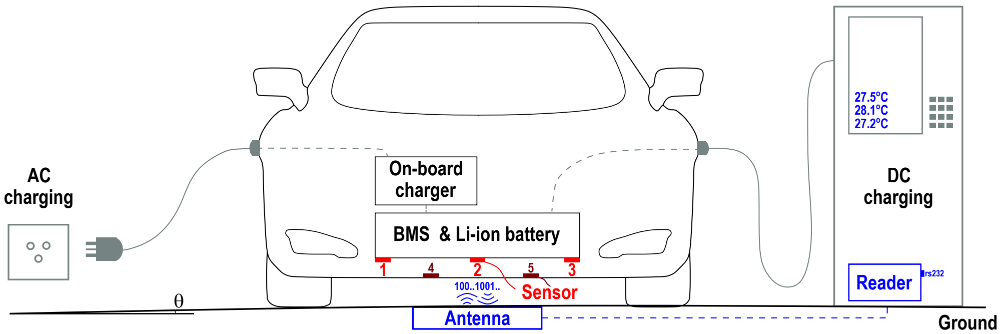

Fig. 2: Illustration of typical EV battery charging in the stations and the deployment of the proposed system in the station (slightly tilted ground to avoid water accumulation on the antenna surface).

The maximum reading distance of the device is >5 m in the ambient, with a sensing precision of ± 1.5 °C (3σ) from -20 to 80 °C. The whole system is validated in-house using a 18650-36V-4.4A Li-ion battery cell to track its temperature change when being charged at different C-rates.

II. System and Device Design

Typically, there are two types (AC and DC) of EV charging schemes in the charging station, as shown in Fig. 2. During charging, the battery cells would be heated up rapidly, especially for DC fast charging (e.g., 400−600 V, up to 300 A [10]) using an off-board battery charger. Our proposed passive wireless sensor device can be mounted to the bottom surface of the battery cells to achieve cell-level thermal monitoring. Thermal paste will be added between the battery and the device to minimize the thermal time constant of the system. Extra devices are also deployed to monitor the ambient temperatures as required by the monitoring equipment in stationary applications standard [11]. Given the material characteristics of the battery and the ambient condition, the core temperature of the battery can be calculated [12]. For wireless temperature data reading, a ceramic antenna is buried underneath the refueling parking area and is electrically connected to the reader using a coaxial cable. The reader can be integrated with the charge controller. The whole system only requires a small cost overhead and a minor infrastructure renovation in order to be applied in the EV's ecosystem.

The sensing device utilizes UHF RFID protocol for data transmission. Compared to our previous design [9], 1) an on-chip averaging scheme is enabled to suppress the device noise; 2) a new ceramic antenna is designed to achieve higher antenna gain. The system diagram of the device is shown in Fig. 3, which consists of a power management unit (PMU) to harvest the incoming RF energy to sustain the tag operation, a digital baseband for system control, an on-chip temperature sensor, and a modulator/demodulator module. For EV battery monitoring, a moderate sensing precision (± 2 °C) and resolution (0.1 °C) suffice while the sampling rate should be high enough (e.g., >20 Sa/s) to capture the transient temperature changes. In this design, the time (including startup, conversion, digital processing and data transmission) required for one temperature sampling is $\sim$11 ms including 2 times' on-chip data averaging. The whole device consumes <10 μW power during full operation, allowing it to be read robustly when being deployed inside the complex EV chassis (strong RF reflection).

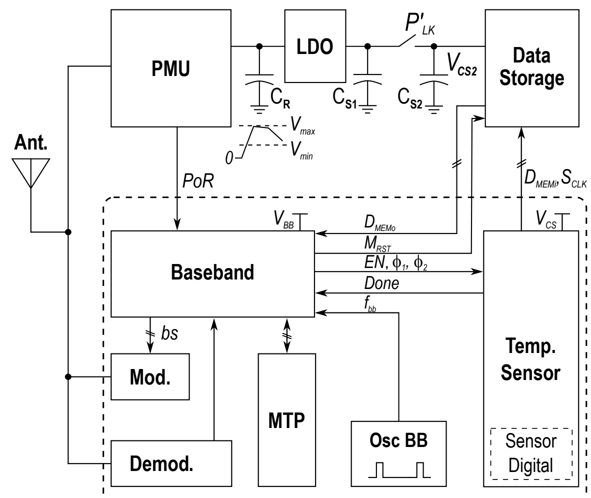

Fig. 3: System diagram of the designed UHF RFID sensing device [9].

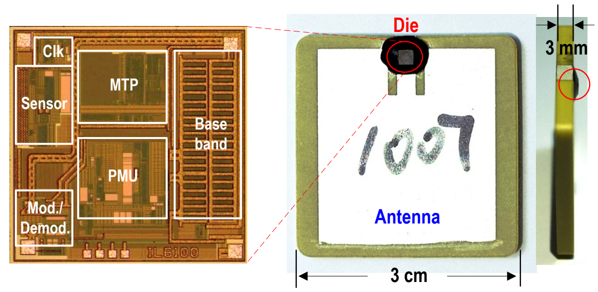

Fig. 4: Die photo and ceramic package of the designed sensing device.

During operation, a rectifier converts the incoming continuous wave from the reader to DC voltages (with large ripple). This voltage will charge up the on-chip storage capacitor to sustain the tag operation. The nominal RF energy harvesting efficiency is optimized to $\sim$35% in this design. To avoid device breakdown when the tag receives strong incident RF power, an on-chip limiter is added, which allows the device to be read at a centimeter-range as well. For temperature sensing, this device utilizes two parasitic PNP bipolar junction transistors (BJT) as the sensing device. By biasing the two BJTs with

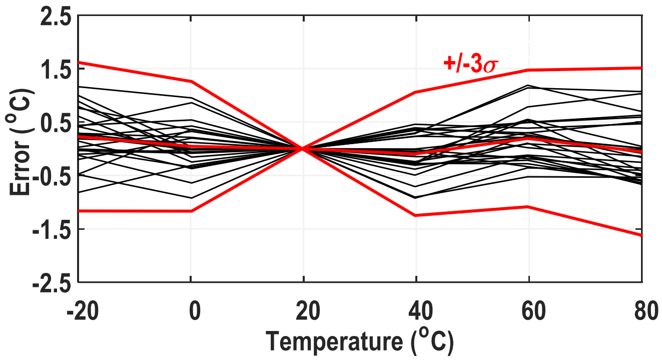

Fig. 5: Inter-device sensing error profile from -20 to 80 °C.

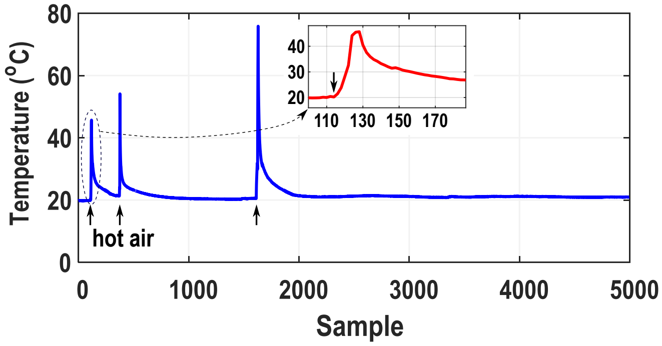

Fig. 6: Continuous reading (1 sample/second) of the sensing device showing its repeatability and transient response.

different collector current densities (with a ratio of 1:p), their base-emitter voltage difference ΔV_{BE} is proportional-to-absolute-temperature. Meanwhile, the base-emitter voltage V_{BE} of the BJT is complementary-to-absolute-temperature. By quantizing $\alpha\Delta V_{BE}/(\alpha\Delta V_{BE}+V_{BE})$ (α is a constant), a digital representation of temperature can be derived [9].

III. Device Characterization

Fig. 4 shows the die photo of the designed chip, together with its packaging on a 3×3 cm^2 ceramic strip antenna (a gain of 2 dBi). The antenna size is scalable based on the reading distance requirement and the actual battery installation conditions in the EV. Since water has a strong RF attenuation effect, the antenna can be sealed with a thin layer of hydrophobic material before deployment.

By benchmarking 26 devices with a PT-100 reference sensor, the inter-die accuracy is ±1.5 °C from -20 to 80 °C (Fig. 5), with a sensing resolution of 0.1 °C, which is enough for the target application. Fig. 6 shows the reading repeatability and the dynamic response of the device with a long-term reading. The device shows fast thermal tracking when being heated up (use hot air gun to heat up the chip). To verify the robustness of the device (aging test), 4 samples were tested for 600 hours at 150 °C in the oven. The resulted drift error is $<$0.2 °C.

Fig. 7 shows the exemplary application setup of the device for battery thermal monitoring together with a DC charger. Finally, the device is attached to a 18650-36V-4.4A Li-ion battery cell to verify its temperature tracking performance during battery charging process. As shown in Fig. 8, the sensor shows a stable response and the battery temperature difference at different C-rates can be observed. The core temperature of the battery can be estimated using its heat transfer property together with the ambient temperatures. For actual car setup, this system must be further optimized in terms of tag installation locations and the antenna reading power to achieve robust sensing.

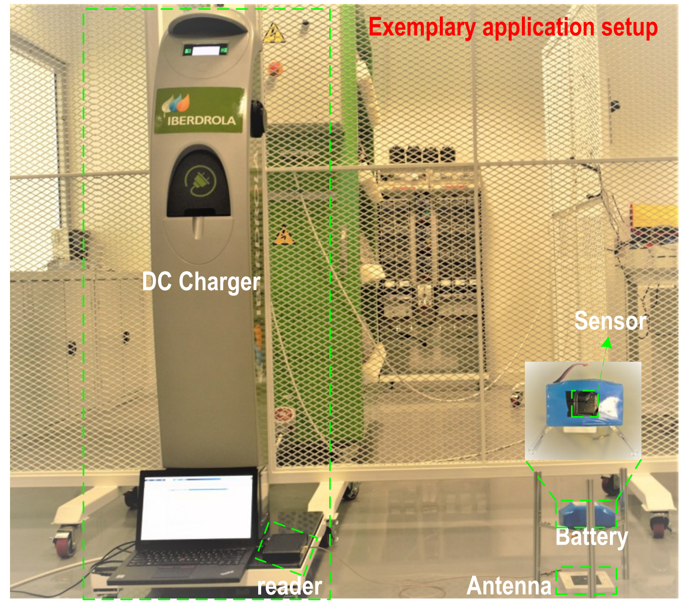

Fig. 7: Exemplary test setup of the sensing device with the reader, antenna, etc. in the DC charging station.

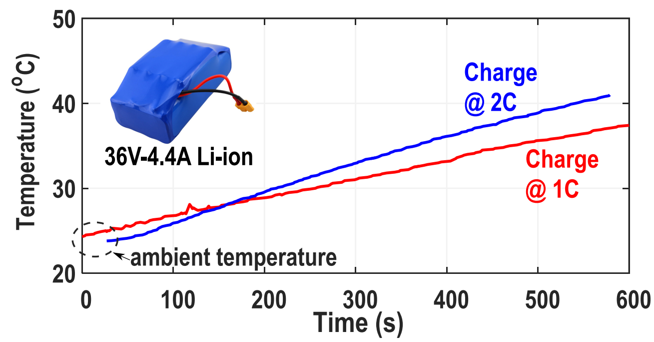

Fig. 8: Measured Li-ion battery temperature behavior during charging (at different C-rate, the initial ambient temperatures are slightly different).

IV. Conclusion

A wireless sensing device utilizing UHF RFID protocol is presented in this paper. It shows potential applicability for future EV battery thermal monitoring during charging, especially for DC fast charging in the stations. The device performance is verified in-house. As compared with existing wireless sensing solutions, the proposed system shows high accuracy, long reading distance, safe deployment, long-term robustness, as well as low cost and minimal infrastructure renovation for massive deployment. Besides battery monitoring, this system can also be customized and be used in other locations in the EV, like engine, bearing, etc., where robust passive sensing is also needed.

V. Acknowledgment

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