DESIGN AND IMPLEMENTATION OF AN EMBEDDED CONTROL PLATFORM FOR AIR AND PCM-BASED BESS COOLING

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Introduction:

Lithium-ion batteries are widely used in Battery energy storage system because of its characteristics such as long cycle life and high energy density. The main challenge while using lithium-ion batteries is Thermal management. Batteries generate heat during operations, if the produced heat is not managed it leads to performance degradation and thermal runaway.
There are various cooling techniques namely Air cooling, Water cooling and Phase Change Material based cooling. Each method has its pros and cons. Air cooling is used in most of the cases because it is simple, easy to maintain and low cost, but it is not suitable for high power applications. Similarly, Phase change material-based cooling absorbs large amount of heat, and changes its form from liquid to solid. This method also has disadvantage of heat accumulation; heat dissipation is delayed if the material is fully melted.
To overcome the disadvantages of individual cooling method, in this project we proposed hybrid thermal management system, which has both active and passive cooling method sin as ingle system which has advantages of air and PCM cooling. Excess heat produced during operation is absorbed by Phase change material, it also limits the rise in temperature. Similarly, air cooling system allows heat dissipation and also removes heat stored in PCM. This hybrid system also has some cons such as selection of Phase change materialis important (it includes characteristics such as melting point, Thermal conductivity, Solidification etc, design and optimization etc.

Objectives:

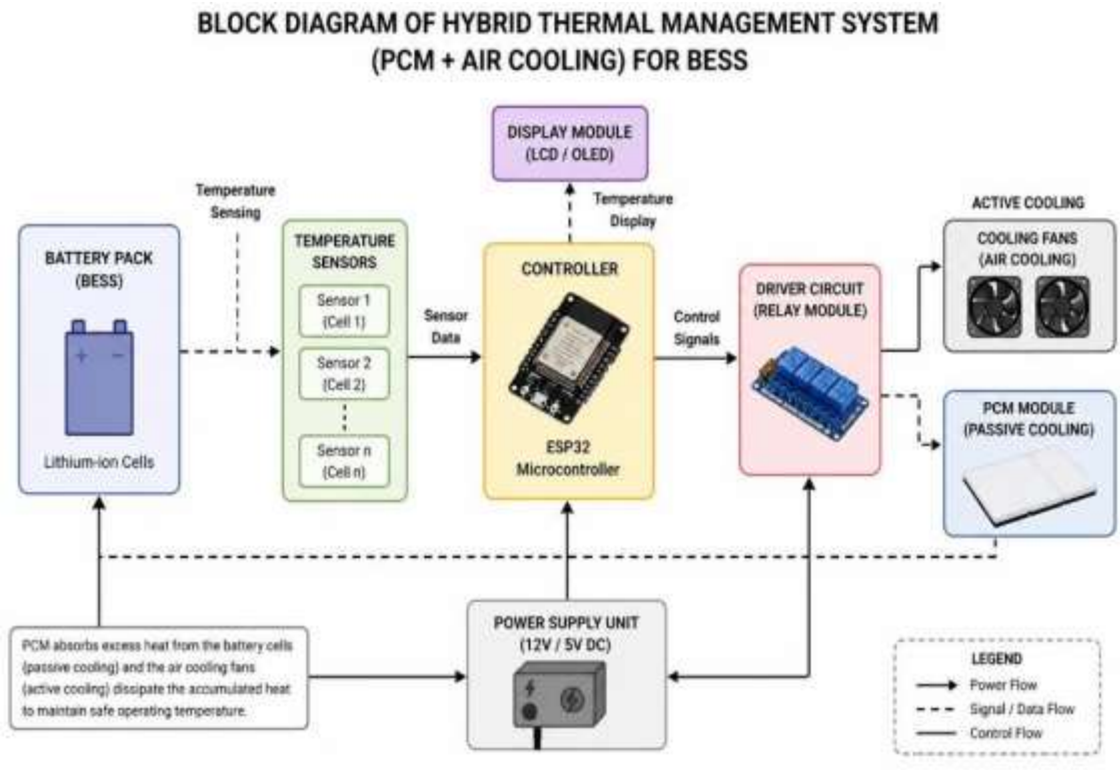
1. To implement hybrid cooling system combining Phase Change material (PCM)and air for lithium-ion batteries in battery energy storage system
2. ThermalregulationusingESP32microcontroller
3. Battery temperature,current and voltage is continuously monitored using temperature sensor, current sensor, voltage sensor respectively.
4. Power consumption is also minimized

Methodology:

Overall architecture can be divided into three layers

1. Sensing layer: It has various sensors such as temperature sensors, current sensors, voltage sensors. These sensors continuously monitor the system.
2. Control layer: Control layer comprises of ESP32 microcontroller. This is considered as brain of the system.
3. Actuation layer: It has 3 mechanisms: air cooling, peltier module, Phase change material. It has closed loop architecture which ensures safe operating conditions.

The block diagram is as follows:



Block diagram of Hybrid Thermal Management system

Result and Conclusion:

1. Battery Energy Storage Systems for Renewable Integration

Stationary BESS units are deployed alongside solar PV and wind installations to store excess generation and dispatch energy during periods of low generation or high demand. These systems typically cycle daily (charging during peak generation and discharging during peak demand), and their operational economics depend heavily on battery longevity. The hybrid BTMS, by maintaining battery temperatures with in the optimal range during cycling, reduces degradation rates and extends the service life of the storage system. Even a 10% extension in battery life can have substantial economic value in commercial-scale deployments.

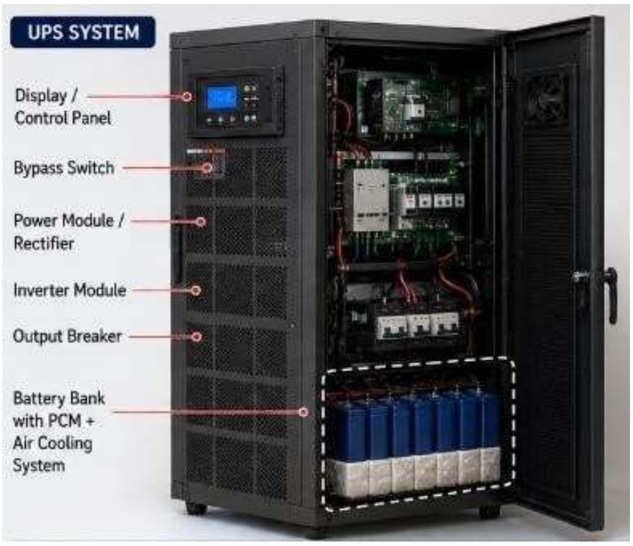
2. **Electric Two-Wheelers and Light Electric Vehicles**

Electric scooters and light electric vehicles (e-bikes, low-speed electric vehicles) typically use battery packs in the48V to72V range with capacities of 20Ah to50Ah.The compact and lightweight nature of the hybrid PCM-air system makes it suitable for integration into such vehicles, where space and weight constraints preclude liquid cooling systems. PCM placed with in the battery enclosure provides passive thermal protection during normal riding, while a small fan activated by a microcontroller handles extraordinary thermal loads during hill climbs or high-speed operation.

Cooling system In EV's

3. **Uninterruptible Power Supply Systems**

UPS systems in data centers and commercial buildings must deliver reliable backup power during Grid outages. The battery packs in the systems may experience high discharge rates during outages following periods of idle standby, creating significant thermal transients. The hybrid BTMS's ability to handle thermal spikes passively (via PCM) before activating active cooling is particularly well suited to this duty profile, where the system must respond immediately to a demand without relying on the fans having already been pre-cooled.



UPS cooling system

4. Portable Power Stations and Field Equipment

Portable power stations used in outdoor, construction, or military field applications are exposed to widely varying ambient temperatures and may experience intensive use cycles. A compact hybrid BTMS integrated into such devices can extend their operational range of ambient conditions and improve reliability in hot environments where passive cooling alone would be insufficient.

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Future Scope:

Integrating metallic fins or conductive fillers with in the PCM can significantly improve heat transfer rates. Expanded graphite(EG)is a particularly promising additive: at 10–15wt% loading, it increases the effective thermal conductivity of paraffin from approximately 0.25 W/m·K to 4–10 W/m·K, dramatically accelerating both the charging (heat absorption) and discharging (heat release) rates of the PCM. Future versions of the prototype should explore EG-paraffin composites, which are commercially available and can be processed into the same pouch packaging format used in the current design.

1. Machine Learning Based Predictive Control

The current control system uses simple threshold-based on/off fan control. A more sophisticated approach would use machine learning algorithms to predict battery temperature trajectories based on current operating conditions (current magnitude, ambient temperature, state of charge, recent thermal history) and activate the fans before the temperature reaches the threshold. This predictive approach could further reduce peak

temperatures and cooling energy consumption.
Recurrent neural networks (RNNs)or longshort-term memory (LSTM) models are particularly well suited to battery thermal prediction because of their ability to model temporal dependencies in the battery's thermal response. Lightweight versions of such models can be deployed directly on the ESP32 using TensorFlow Lite for Microcontrollers, which has been demonstrated torun inference on similar microcontrollers within the computational constraints of an embedded system.

2. IoT Monitoring and Remote Management

The ESP32's built-in Wi-Fi capability, which is not utilized in the current prototype beyond serial data logging,can be leveraged to implement cloud-connected battery monitoring. Real-time temperature, current, and voltage data can be transmitted to a cloud platform (such as AWS IoT, Azure IoT Hub, or a self-hosted MQTT broker) where it can be visualized on dashboards, analyzed for anomalies,and used to trigger maintenance alerts. Historical data accumulated over many cycles can also be used to build thermal models specific to a particular battery pack and duty cycle.

3. Alternative and Advanced PCM Materials

While paraffin wax is an excellent choice for the current prototype, ongoing research is exploring advanced PCM materials with superior properties.In organic PCMs such as salthy drates offer higher thermal conductivity and latent heat density than organic PCMs but present challenges of corrosion and supercooling. Microencapsulated PCMs, in which tiny spheres of PCM (5–50 μm diameter) are enclosed in polymer shells, can be incorporated directly into thermal interface materials or slurries, improving contact with battery surfaces and enabling new form-factor integration strategies.
Nano-enhanced PCMs incorporating graphene nanoplatelets, carbon nanotubes, or metal nanoparticles show promise in laboratory settings, with reported thermal conductivity improvements of 50–200% at low additive loadings. However, these materials currently face challenges of nanoparticle agglomeration and increased cost that must be resolved before practical deployment.