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Evaluasi Performa Pengendali Neural Network Berbasis Imitation Learning pada Sistem Active Cell Balancing Menggunakan Konverter ?uk
Akhmad Mursidan Al Farizi, Prof. Ir. Oyas Wahyunggoro, M.T., Ph.D.; Dr. Eng. Ir. Adha Imam Cahyadi, S.T., M.Eng.,
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ABSTRAK

Sistem baterai lithium-ion seri berpotensi mengalami ketidakseimbangan *State-of-Charge* (SoC) antar sel akibat perbedaan kapasitas, resistansi, dan degradasi. Kondisi ini dapat menurunkan kapasitas efektif *battery pack*, mempercepat degradasi, serta meningkatkan risiko *overcharge* dan *overdischarge*. Oleh karena itu, diperlukan mekanisme *active cell balancing* untuk mendistribusikan energi antar sel secara terkontrol. Penelitian ini bertujuan mengevaluasi performa *Neural Network* berbasis *imitation learning* sebagai pengendali *duty cycle* pada sistem *active cell balancing* berbasis konverter Ćuk.

Metode penelitian meliputi pemodelan empat sel baterai lithium-ion seri, perancangan *PI controller* sebagai pengendali referensi dan *teacher controller*, pengumpulan *dataset* dari keluaran *PI controller*, pelatihan *feedforward Neural Network* dengan variasi neuron pada *hidden layer*, serta pengujian *closed-loop* pada 15 skenario kondisi awal SoC. Konfigurasi yang dievaluasi adalah NN-3, NN-8, dan NN-15. Parameter evaluasi meliputi waktu *balancing*, perubahan $\Delta SoC(t)$, tegangan puncak *output*, arus puncak *output*, *ripple*, kompleksitas komputasi, dan nilai *fitness* multi-kriteria.

Hasil penelitian menunjukkan bahwa seluruh konfigurasi *Neural Network* mampu menghasilkan sinyal *duty cycle* untuk mencapai kondisi *balancing* pada seluruh skenario. Peningkatan jumlah neuron cenderung mempercepat waktu *balancing*, tetapi meningkatkan respons puncak tegangan dan arus. NN-15 menghasilkan waktu *balancing* tercepat, namun disertai *electrical stress* dan kompleksitas komputasi lebih tinggi. Sebaliknya, evaluasi *fitness* dengan pembobotan sama rata menunjukkan bahwa NN-3 memiliki kompromi performa gabungan paling seimbang pada skenario pengujian. Dengan demikian, pemilihan arsitektur *Neural Network* perlu mempertimbangkan waktu *balancing*, *electrical stress*, *ripple*, kompleksitas komputasi, dan nilai *fitness*.

Kata kunci—*active cell balancing*, konverter *Ćuk*, *Neural Network*, *imitation learning*, *electrical stress*.

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ABSTRACT

Series-connected lithium-ion battery systems are prone to cell-to-cell State-of-Charge (SoC) imbalance due to variations in capacity, resistance, and cell degradation. This condition can reduce the effective capacity of the battery pack, accelerate degradation, and increase the risk of overcharge and overdischarge. Therefore, an active cell balancing mechanism is required to redistribute energy among cells in a controlled manner. This study aims to evaluate the performance of an imitation learning-based Neural Network as a duty cycle controller in a Ćuk converter-based active cell balancing system.

The method includes modeling a four-cell series-connected lithium-ion battery system, designing a PI controller as the reference and teacher controller, collecting a dataset from the PI controller output, training a feedforward Neural Network with different numbers of neurons in the hidden layer, and performing closed-loop testing under 15 initial SoC scenarios. The evaluated configurations are NN-3, NN-8, and NN-15. The evaluation parameters include balancing time, $\Delta SoC(t)$, peak output voltage, peak output current, ripple, computational complexity, and multi-criteria fitness.

The results show that all Neural Network configurations can generate duty cycle signals to achieve balancing in all tested scenarios. Increasing the number of neurons tends to reduce the balancing time, but also increases the peak voltage and current responses. NN-15 achieves the fastest balancing time, but with higher electrical stress and computational complexity. Conversely, the equally weighted fitness evaluation shows that NN-3 provides the most balanced overall performance in the tested scenarios. Therefore, selecting a Neural Network architecture should consider not only balancing time, but also electrical stress, ripple, computational complexity, and fitness.

Keywords— *active cell balancing, Ćuk converter, Neural Network, imitation learning, electrical stress.*