博士学位論文審査要旨

２０２０年1月２１日

論文題目：Development of Deterioration Diagnostic Methods for Secondary Batteries used in Industrial Applications by Means of Artificial Intelligence
（人工知能を用いた産業用二次電池の劣化診断法開発）

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要　　旨：

蓄電池は携帯機器，電気自動車をはじめ，自然エネルギー有効利用に至るまで広範囲に利用され，その重要性はますます高まっている。これら機器の使用時間や特性は蓄電池の特性に大きく依存することから，電池自体の特性改善に加え，劣化を診断してより効率的に電池を運用することが求められている。

本論文は，人工知能を用いた２次電池の劣化診断法を開発し，エネルギーの有効利用に資する技術を確立した。機器動作時の電池電圧・電流波形と電池劣化特性との関連性を人工知能により学習し，機器稼働時に電池の劣化を診断することができる。なお，この関連性は複雑であるが，非線形分析を得意とする人工知能は電池劣化診断に適している。学習には時間を要するものの，診断は短時間になし得ることから，提案法は機器稼働時の劣化診断に適している。本論文では，この特徴を生かし，充電率（SOC），容量維持率（SOH）を推定する手法を提案するとともに，電池の等価回路（ECM）を導出している。これらのパラメータは劣化診断は言うに及ばす，電池動作特性の解析，並びに電池応用機器の機能性向上にも適用可能で，極めて応用範囲が広い。

本論文では現在産業応用分野で用いられている，リチウムイオン電池，ニッケル水素電池，鉛蓄電池を対象とし，提案法はあらゆる電池使用機器に応用可能である。さらに，人工知能を利用していることにより，今後開発されるであろう新たな電池にも提案法は対応し得る特徴を有する。本論文では，データを自動収集する充放電装置を開発し，自ら作成することに加え，パーソナルコンピュータで開発した提案診断法を，電池状態監視装置（BMU）や，マイコンなどを用いた計算能力の低い組み込みシステムにも応用可能とする実用的な技術へと深化させ，実証実験し有効性を確認している。

本論文は，蓄電池の新たな劣化診断法を確立し，その有効性を確認しており，社会に大なる貢献をするものと考えられる。よって，本論文は，博士（工学）（同志社大学）の学位論文として十分な価値を有するものと認められる。

総合試験結果の要旨

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要　　旨 :

本論文提出者は，2015 年 7 月アルバニアの Polytechnic University of Tirana，Faculty of Electrical Engineering から Master of Science Degree を得，その後企業や大学における職を経て，2017 年 4 月に本学理工学研究科博士課程（後期課程）に特別学生として入学し，2018 年 4 月に正規学生となり現在在籍中である。

2020 年 1 月 11 日 13 時 10 分より学術講演会が開かれ，およそ 1 時間半にわたり研究成果を英語で講演した。その後，およそ 30 分の間，種々の質疑討論が行われ，提出者の説明により，十分な理解が得られた。講演会終了後，審査委員により学位論文に関連した諸問題につき口頭試問を実施した。

本論文の主たる内容は，MDPI Journal of Energies，および IEEJ Transaction Journal IA にすでに掲載され，十分な評価を受けている。口頭試問では，提出者が実践的な技術に加え，高度な専門的知識・十分な学力を有することが確認された。論文提出者は，国際会議をはじめとして英語による論文発表をし，そのうちいくつかでは論文賞・発表賞等を受賞しており，研究能力に加え，十分な語学能力を有すると認められる。

よって，総合試験の結果は合格であると認める。

博 士 学 位 論 文 要 旨

論 文 題 目：Development of Deterioration Diagnostic Methods for Secondary Batteries used in Industrial Applications by Means of Artificial Intelligence
（人工知能を用いた産業用二次電池の劣化診断法開発）

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要　　旨：

General

In recent years, energy and environmental issues are globally the main concern. Through the improvement and implementation of the power generation systems based on natural energy, it will be possible to solve this problem. The importance of rechargeable batteries nowadays is increasing from the portable electronic devices and solar energy industry up to the development of new Electrical Vehicles (EV) models. In addition, the necessity for larger, efficient and reliable storage systems is heightened. The rechargeable batteries are considered as the most common storage devices. EV and Hybrid Electric Vehicles (HEV) are becoming the most important technologies in transportation due to their environmental affinity and increase of driving autonomy. In the running process of EVs or HEVs, the batteries experience stress from the dynamic operational environment. The charging condition is essential for designing the storage system, while the charging quality of the battery directly affects the battery lifetime and normal operation within the regulated and standardized parameters. The most used battery type is based on Li-Ion chemistry and their derivative types, due to the high energy and power density, high efficiency, higher open circuit voltage (OCV), within its class of battery, wide range of temperature for a normal operation, low maintenance, also long-term usage. However, beside its advantages it introduces as well drawbacks. It is necessary to have a protection system, which helps from over charged and over discharged beyond its normal range of operation. This means that it must be connected with an integrated circuit technology, which is usually resolved by the battery management system (BMS).

Another major problem of Li-Ion batteries is the ageing process. Its ageing process depends, not only on calendar, but also on the charge/discharge cycles. Based on actual technology this type of battery withstand 500-1000 cycles for a normal and safe operation, before their capacity falls. As well the other problems is the difficulty in the accurate estimation of state of charge (SoC) and state of health (SoH), because it is unclear which parameters affect the deterioration process. Although Li-Ion batteries have been used in real applications, still it can be considered an immature technology from most of the researchers of this field. Understanding the advantages and proposing new methods, which can resolve the disadvantages or at least reducing the side effects is the main challenge.

In general, all the batteries introduce high nonlinearity in their behavior, which requires complex models to explain their characteristics. Although the conventional methods confirm and resolve specific problems but their abilities are quite limited and have lack of adaptability for new and unknown problems. In order to resolve and simplify these nonlinearities, unconventional method was used to make an efficient investigation by maximizing the usage of the genuine data obtained through practical experiments. The practical data enabled to create and optimize a solid model based on the Artificial Intelligence (AI) properties, specifically expressed through Artificial Neural Network (ANN) ability. Due to the black box approach of the ANN, it is possible to connect the complex physical phenomenon with a specific physical meaning expressed with a nonlinear logic between inputs and output. Specific input data to relate with the desired output make possible to create a pattern connection with input and output. This ability helps to estimate the desired outputs, behaviors, phenomena in real time, and at the same time

it can be used as a real time diagnosis method. As well, it has the abilities of the optimization and estimation in off-line processing for better results.

Organization of the Thesis

The thesis is based on 8 chapters, where it starts with explanations of the secondary batteries' chemistries, abilities, drawbacks, applicable field followed by the explanation of the AI based on ANN method. Due to the immense ability and possibility for applications of ANN not only as theoretical thinking approach but also as robust and confirmed critical problems resolving with aggressive algorithm, the ANN makes possible and open new opportunities for a real time monitoring, diagnosis and decision-making. Based on these features it was possible to start the investigation of the OCV waveform characteristics of the Li-Ion battery during charging. After parallel works were made to understand the relation process and optimization of the ANN structure for each problem, respectively for the SoC and SoH estimation models.

Also, an investigation on the parameters of the equivalent circuit model (ECM), which variables are more connected with power output, capacity fade, increased of internal temperature, faster deterioration due to the fast charging/discharging, or even the optimized C ratio and the best current waveform for the charging process which helps to decrease the deterioration process. For each of the mentioned problems, a considerable amount of experiments was conducted in order to give some scientific explanations. Selecting the most interesting variables for the ANN database, it was another goal during the process of this research. This helps to increase the quality of the estimation, making the simulation and calculation time shorter, and stable. Also, an interest was shown for the generalization of each problem, from viewpoints of the ANN structure and applicability the proposed model to rechargeable batteries based on different chemistries, type of current waveform, level of load.

Objective of this study

The objective of this study is to propose new and different methods for the real time diagnosis and parameter/fault estimations for the rechargeable batteries. By combining conventional and unconventional methods, it was possible to make an efficient investigation by maximizing the usage of the genuine data obtained through practical experiment. It was possible to create and optimize a solid model based on the AI properties, specifically expressed through ANN ability. Although the conventional methods confirm and resolve specific problems, their abilities are quite limited and have lack of adaptability to new and unknown problems. The contribution is mainly focused on three problems as explained in the further chapters.

In Chapter 4, the investigation was focused on the SoC estimation model, where a basic model was introduced based on OCV estimation of the battery during charging process. This model opens the possibility to improve the model with less necessary inputs of the ANN learning process. In addition, some BMS circuits for battery pack/modules were proposed to be used during operation, which helps to maintain a higher and stable level of voltage.

In Chapter 5, a contribution was made regarding the SoH estimation, i.e., classification of deterioration. As well, a scaled down simulator for the design of power storage system was proposed, which reduces the cost and removes a real size benchmark system. Another important focus of this study was based on the accurate estimation of power and energy consumption in EVs, where the total battery pack was investigated to understand the "behavior and characteristics" of the battery pack during dynamic operation. In the final step of the ANN structure for this problem, only the parameters of an arbitrary single cell from the battery pack was necessary to make an accurate power and energy consumption of EV. As well, through this study it was shown the ability to relate EV's consumption level with the battery deterioration.

In Chapter 6, a parameter estimation of equivalent circuit model (ECM) was proposed based on real time evaluation approach. By dividing into the high and low frequency regions, it was possible to relate specific

parameters of ECM with specific problems and behaviors. Later a deeper investigation was introduced by dividing the frequency regions in more narrow regions and by selecting the best frequency zone for each of the rechargeable batteries, Li-Ion, Ni-MH and Pb. The results of this study shows the ability and further possibilities for progressive improvements of the diagnostic tools as a real time approach, where it was possible to speed up the estimation time, not only with low cost but also with high-accuracy, -adaptivity, -efficiency, and with generalization ability which gives the opportunity for fast adaptation to the related industrial problems. The proposed methods are applicable to real time diagnosis applications and to offline processing. The quality and credibility of the work was continuously confirmed by the comparison with experimental results.

The author has proposed new deterioration diagnostic methods and approaches for secondary batteries, which are totally different from conventional methods. Proposal of new idea, which resolves actual problems of this field, and provision of the opportunity to investigate new problems are the main goal of the author. The proposed methods based on this study open the door to new application fields of the secondary battery from academic perspectives to industrial applications.