Control, design, and implementation of a low-cost ultracapacitor test system

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Abstract: This paper reviews the ultracapacitor (UC) test procedures, establishes simple and economical power electronic conversion system-based UC test equipment, and experimentally evaluates the performance of a UC module. The power converter hardware structure and control algorithms of the designed system are discussed in detail. The high bandwidth and high accuracy current programming capability of the converter for the purpose of charging and discharging the UC, as required during testing, is illustrated via the experimental results. The UC equivalent circuit parameters are extracted. Successful constant current and constant power charging/discharging operating performances are demonstrated. The results of this study help with the design of simple and economical UC test equipment. Furthermore, the power converter and control algorithm developed and demonstrated can be used for energy management applications involving UCs.

Key words: Ultracapacitor, ultracapacitor test procedures, power electronics converters, constant current tests, constant power test, ultracapacitor energy management

1. Introduction

Ultracapacitors (UCs) are capacitors with high capacitance, low equivalent series resistance (ESR), and low-rated voltage values [1–4]. Since UCs are relatively new energy storage devices, they are usually compared with conventional energy storage devices, such as lead acid batteries (LABs) and electrolytic capacitors (ECs). In these comparisons, the energy and power density (E_d, P_d), charge/discharge time, charge/discharge efficiency, and charge/discharge cycle life appear as basic comparison parameters [1,2,5]. In Table 1, UCs are compared with LABs and ECs [5].

According to Table 1, UCs have a smaller, symmetric (equal) charge/discharge time compared to LABs, which must be charged slowly compared to the discharge time. Thus, UCs can be charged and discharged with high current levels. Moreover, considering the charge/discharge efficiency, it is seen that UCs are more efficient than LABs. Table 1 also shows that UCs are between the LABs and ECs in terms of energy and power density. Furthermore, it can be seen that the charge/discharge cycle life values of UCs are higher than those of LABs. Following the general comparison in Table 1, 3 different commercial energy storage devices are compared in Table 2 by considering the energy density [1,2]. Table 2 shows that UCs are between the LABs and ECs involving an order of magnitude in E_d. With the UC cost falling and E_d improving continually, the application fields for UCs have been experiencing rapid growth, and this growth is expected to increase in the coming years.

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The main application field of UCs is energy storage, where the basic operation involves the charging and discharging of UCs. Thus, the whole process could be viewed as the energy management of the UCs. Realizing this process effectively requires an understanding of the electrical performance of the UCs. However, the electrical parameters of UCs cannot be extracted by utilizing standard measurement devices, such as LCR meters, which cannot provide sufficient excitation signal to the UCs due to the very large capacitance [1,2]. Applying a high-valued DC current to the UC terminals in the charging and discharging modes and observing the response of the device is a common method for the performance evaluation of UCs [6,7]. In the market, there are state-of-the-art test devices that are capable of performing UC tests including the application of large DC current signals [8]. However, the cost and complexity of these advanced commercial products is usually high. In this sense, relatively simple and low-cost UC test equipment is favorable to an application/design/R&D engineer involved with UCs. Power electronics converters could be utilized for controlling the charging and discharging processes of UCs. Therefore, specialized test equipment capable of adjusting and controlling the charging and discharging current, as well as the state of the charge level of UCs, could be implemented with power electronics converters. By building up a power electronic converter-based UC test system, designers have both the chance of evaluating the electrical performance of UCs and acquiring the necessary knowledge about the know-how of UC energy management mechanisms [1,2].

In this study, UC tests, based on applying large-valued DC current signals, are reviewed, and in order to carry out the mentioned UC tests, a power electronic converter-based UC test system is designed and implemented. In order to demonstrate the performance of the implemented UC test system experimentally, a laboratory-constructed UC module is utilized. The experimental results demonstrating the electrical performance of the UC module are also included. Additionally, the designed and experimentally verified control system for the energy management (charge-discharge, energy transfer from-to the load, etc.) establishes a good example for the control units and control algorithms of UCs utilizing practical energy systems.

2. Test methods for UCs
The test of the UC aims to evaluate the performance and determine the equivalent circuit parameters of the device. The UC equivalent circuit shown in Figure 1 is a relatively simple and generally sufficient model to
evaluate the performance of UCs for most applications [1,2,6,7,9]. More sophisticated models of UCs can be found in [9–11].

\[
\begin{align*}
R_s & \quad \text{ESR} \\
C_{UC} & \quad \text{Capacitance} \\
R_p & \quad \text{Parallel resistance}
\end{align*}
\]

**Figure 1.** Electrical equivalent circuit model of a UC.

In the model shown in Figure 1, \(C_{UC}\) represents the capacitance, \(R_s\) represents the ESR, and \(R_p\) represents the equivalent parallel resistance of the UC [1,2,6,7,9]. \(C_{UC}\) determines the energy storage capability of a UC, and it is usually given with positive and negative tolerance values in UC datasheets [12]. On the other hand, \(R_s\) stands for the ohmic loss within a UC and determines the maximum power capability of the device, while the leakage current within a UC is modeled by the help of \(R_p\). Moreover, test methods that aim at evaluating UCs with regards to their performance criteria, such as energy and power density, charge/discharge cycle efficiency, and charge/discharge cycle life, are also recommended in many studies [1–6]. This study focuses on the capacitance, ESR, and charge/discharge efficiency of UCs, and in order to evaluate UCs in terms of these parameters, constant current and constant power tests are utilized.

### 2.1. Constant current tests

The charging and discharging characteristics of UCs could be evaluated by means of constant current tests. As a result of this test method, the capacitance and ESR parameters of UCs could be extracted. The constant current test procedure is shown in Figure 2 [1].

During constant current tests, UCs are put into constant current charge/discharge cycles within the voltage range of the device, which is determined by the rated voltage parameter given in the product datasheets as shown in Figure 2. The typical voltage and current profile of a UC during a constant current test is shown in Figure 3. With the help of the test profile shown in Figure 3, the device capacitance \((C_{UC})\) can be calculated by considering the linear part of the UC terminal voltage \((\Delta V_1)\), magnitude of the applied current \((I)\), and time period of the linear voltage variation \((\Delta t)\), as given in Eq. (1). On the other hand, the ESR \((R_s)\) can be calculated by considering the immediate (abrupt) changes of the UC voltage when the test current is applied or terminated \((\Delta V_2)\) and the magnitude of the applied current \((I)\) as given in Eq. (2) [1,2,6,7]. The capacitance and ESR measurements should be repeated for the charging and discharging phases separately [1,2,6,7].

\[
\begin{align*}
C_{uc} &= \frac{I \times \Delta t}{\Delta V_1} \\
R_s &= \frac{\Delta V_2}{I} = \frac{V_{0+} - V_{0-}}{I}
\end{align*}
\]
2.2. Constant power tests

Constant power operation is a frequently encountered operating mode of energy storage units. Constant power tests are used to evaluate the constant power charging and discharging characteristics of UCs. With the help of constant power tests, the cycle efficiency ($\eta$) of UCs can be obtained by integrating and proportioning the
recorded voltage and current profiles of the discharging and charging phases as given in Eq. (3) [1,2,6].

\[
\eta = \frac{\Delta t_{\text{disch arg}}}{\Delta t_{\text{ch arg}}} \int_{0}^{v_{UC}(t)} i_{UC}(t) \times dt
\]

3. Power electronics converter and controller structure for the UC test system

In order to realize the constant current and constant power tests of UCs, a test system capable of performing the charging and discharging of UCs with a controllable current is required. This requirement can be met by means of power electronics converters. While selecting the proper converter topology in this application, designers should consider the low voltage rating of UCs. Usually, the voltage of the source and load are higher than the rated voltage of the UCs in both the charging and discharging modes. Moreover, the selected converter structure should operate in continuous conduction mode in order to provide controllable charging and discharging current. In this study, step-down and step-up DC-DC converters are chosen, respectively, to realize the charging and discharging operations of the UCs with a controllable current. The power electronics converter structure utilized for realizing the UC test system is shown in Figure 4.

![Figure 4. Power electronics converter structure for the UC test system.](image)

With the structure shown in Figure 4, the UC or the UC module is charged by a step-down DC-DC converter supplied by the DC source in the left box. The DC source is formed by the AC utility grid followed by a step-down transformer, a diode bridge, and a large-valued filter capacitor configuration. On the other hand, the energy stored in the UC during testing is discharged to a chopper-controlled resistor by means of a step-up DC-DC converter. The DC chopper at the output of the step-up DC-DC converter is used to maintain the output voltage constant, which simplifies the controller design process of the discharging operation. Instead of using the chopper and resistor-based lossy system, a bidirectional converter and an additional energy storage device can be used. However, using an additional UC increases the cost and complexity, while a battery slows down the discharge process of the UC during testing [1].

For both the charging and discharging operations, current mode control is provided by means of adjusting the switching signals of the controllable switches, \( M_{sd}, M_{su}, \) and \( M_{chp} \). The control mechanisms of the power electronics converters are realized with a microcontroller-based digital design perspective. The first control structure is built for the charging operation and its block diagram is shown in Figure 5.

As shown in Figure 5, the state variables of the charging system are the UC current \( (i_{uc}) \), UC terminal voltage \( (v_{uc}) \), and DC bus voltage \( (v_{dc}) \) measurements. The output generated by the system is the pulse width modulation (PWM) signal, which will be applied to the controlled switch \( (M_{sd}) \) of the step-down DC-DC converter. Inside the controller structure, the digital equivalents of the measurement signals are utilized.
The charging system control process is started with the calculation of the current error \((e_i[n])\) between the current reference \((i_{ref}[n])\) and the measured charging current \((i_{uc}[n])\). In the next step, the error is fed into a linear controller with proportional and integral terms [a proportional-integral (PI) controller]. Next, by means of adding the output of the PI controller \((v_{ref}[n])\) with the measured UC voltage \((v_{uc}[n])\), the output voltage reference of the step-down converter \((v_{ref}[n])\) is obtained. Thus, with the help of this capacitor voltage decoupling term (the added UC voltage acts as a feedforward term), the controller is simplified. The system obtained by the last operation is an RL circuit constituted by the equivalent resistance of the converter inductor and the UC, together with the converter inductance [1]. Consequently, the duty cycle value \((d[n])\) is calculated by proportioning the output voltage reference with the measured DC bus voltage \((v_{dc}[n])\). Inside the microcontrollers, division is a difficult operation. Therefore, scaling \(v_{ref}[n]\) with \(v_{dc}[n]\) (for the purpose of compensating for the PWM unit error due to the \(v_{dc}\) variation) is realized by means of a DC bus scaling algorithm instead of a division operation. The details of the algorithm can be found in [1]. Finally, the duty cycle value is fed into the PWM unit in order to generate the switching signal of the \(M_{sd}\) in PWM format. The microcontroller program flow of the UC charging process can also be found in [1].

For the UC discharging operation, a step-up converter is used and the UC energy is dumped into a small capacitor, \(C_{su}\). The energy dumped into this capacitor is dissipated in a resistor with a DC chopper structure. A step-up DC-DC converter is used for the discharging current regulation. On the other hand, a DC chopper is used to maintain the output voltage of the step-up DC-DC converter constant in order to prevent the effect of the output voltage variation on the performance of the discharging current regulation process. For the current mode control requirement of the step-up converter, both the PI and hysteresis controller structures are used separately. The PI controller-based discharging current control structure is shown in Figure 6, where it can be seen that the PI-based current control process is started with the calculation of the current error \((e_i[n])\) between the current reference \((i_{ref}[n])\) and the measured discharging current \((i_{uc}[n])\). The error is then fed into a PI controller and, as an output, a voltage reference value \((v_{ref}[n])\) is obtained. Since the UC voltage varies significantly during the discharging process, as it is the input of the step-up converter, the PWM unit gain also varies and it is necessary to scale the reference voltage in a similar manner to that of the step-down converter. In this final stage, the duty cycle value \((d[n])\) is obtained by means of proportioning the voltage reference with...
the measured UC voltage \(v_{uc}[n]\) with an input voltage scaling algorithm instead of division operation. The implementation details of the input voltage scaling algorithm can be found in [1]. After the scaling operation, the \(d[n]\) value is fed into a PWM module and, as an output, the PWM signal of \(M_{su}\) is generated.

For the discharging current regulation, a hysteresis-based current control is the second control method that is used, and the block diagram of this method is presented in Figure 7, where it is shown that the hysteresis-based current control structure is simpler than the PI-based current control structure. The only operation is the adjustment of the switching signal of \(M_{su}\) as high (1) or low (0) according to the comparison between the current reference \((i_{ref})\) and the digital equivalent of the measured discharging current \((i_{uc}[n])\). By means of this operation, the discharging current is maintained in a predefined tolerance band.

The last control mechanism used for the UC discharging system is the DC chopper control structure with a hysteresis controller, the block diagram of which is shown in Figure 8. With the control structure shown in Figure 8, the output voltage of the step-up converter is maintained in a tolerance band that reduces the effects of the output voltage variations to the step-up converter current control process. The chopper control unit is independent of the other controllers. The microcontroller program flow for the control structures shown in Figures 6–8 can be found in [1].

4. Hardware realization
In this study, a power electronics converter-based UC test system capable of performing the constant current and constant power tests is implemented. The implemented UC test system is composed of a charge and
discharge energy management system supported by a measurement and data acquisition system. The basic building blocks of the implemented UC test system are shown in Figure 9.

The main component of the implemented UC test system is the charge and discharge energy management system. With this subsystem, test currents are applied to the UCs during testing within the selected voltage limits of the UC terminal voltage. The parameter adjustment part is used to provide the test information to the charge and discharge energy management system. Parameters like the test current magnitude, type of UC test, and UC voltage limits of the test are selected with the help of the parameter adjustment part. In order to monitor the UC terminal behavior for the applied test currents, a measurement system is utilized, and the measurement results are transferred to a PC with the data acquisition system. Finally, the PC is utilized for processing and achieving the test results. The detailed block diagram of the implemented UC test system is shown in Figure 10.

As shown in Figure 10, the charge and discharge energy management system is composed of the power electronic converter and digital controller systems with their subsystems like the gate drive, current protection, and signal conditioning circuits. With the charge and discharge energy management system, the UC current and terminal voltage are sensed, and the measured data are processed by a digital controller structure composed of 2 PIC18F452 microcontrollers in order to realize the control methods shown in Figures 5–8. The printed circuit boards of the power electronics converter and digital controller systems are shown in Figure 11. The power converters use power MOSFETS as the operating voltage is low (less than 100 V, including the switching transients effects).
As shown in Figure 10, the measurement system is composed of a Fluke 43B power quality analyzer and a Tektronix TPS2024 digital storage oscilloscope. The long-term data from the UC tests are recorded with the Fluke 43B, and the recorded data of the UC tests are transferred to a PC via a RS232 interface. Inside the PC, the transferred UC test data can be monitored and processed with the Fluke View Software. The dynamic
performance of the system and instantaneous variation of the UC terminal voltage and current is evaluated with the help of a Tektronix TPS2024 oscilloscope with a high bandwidth Tektronix TCPA 300 AC/DC current probe. The captured waveforms of the UC tests with the oscilloscope can also be transferred to the PC with a USB interface [1]. The implemented UC test system is shown in Figure 12, and its basic components together with its parameters are summarized in Table 3.

**Table 3.** Properties of the implemented UC test system.

<table>
<thead>
<tr>
<th>UC test system ratings</th>
<th>15 A (constant current)</th>
<th>100 W (constant power)</th>
<th>12 V (maximum UC voltage)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transformer</td>
<td>220 V/24 V, 250 VA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C_{dc}, C_{su}, R_{chp}, L_{sd}, L_{su}</td>
<td>27.2 mF, 6.8 mF, 3.13 Ω, 1 mH, 1 mH</td>
<td></td>
<td></td>
</tr>
<tr>
<td>M_{sd}, M_{su}, M_{chp}</td>
<td>MOSFET, IRF2807</td>
<td></td>
<td></td>
</tr>
<tr>
<td>D_{sd}, D_{su}, D_{chp}</td>
<td>Body diodes of IRF2807</td>
<td></td>
<td></td>
</tr>
<tr>
<td>f_{sw}</td>
<td>50 kHz</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sensor</td>
<td>LTS25NP current transducer</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Digital controller</td>
<td>PIC18F452 microcontroller</td>
<td>8 bit word length, 10 bit A/D,</td>
<td>40 MHz clock frequency</td>
</tr>
</tbody>
</table>
When the implemented UC test system is investigated in terms of the hardware design considerations, it is seen that the design approach is simple and cost-effective. First of all, the chosen power electronics converter topology of the implemented test system is very simple and it could be said that it contains the minimum number of controllable switches, which eases the control of the converter system. Moreover, for the control of the power electronics system, a current mode control is used, as seen in Figures 5–8. It could be said that the digital implementation of current mode control does not seem challenging. Therefore, a low-cost microcontroller PIC18F452 is sufficient for the digital implementation for the current mode control of the UC test system. Since the system is composed of low-cost and commonly available off-the-shelf components, the total cost of the tester is extremely low compared to other commercial units. While commercial products are sold at prices of several tens of thousands of euros, the implemented system cost is less than 1000 euros. As a general approach, in the design process of the implemented test system, all components are chosen from off-the-shelf components since the price of the components specific to a unique application is commonly higher. Finally, it could also be concluded that the measurement devices used in the experimental work are standard measurement devices that could be found in any power electronics laboratory.

In order to evaluate the performance of the implemented UC test system, and to see the electrical performance of the UCs, a UC module composed of 5 serially connected UC cells is constructed. Inside the UC module, Maxwell Technologies BCAP1500 UCs, which have a 1500 F-rated capacitance and 2.7 V-rated voltage, are utilized [12]. The constructed UC module and its properties are shown in Figure 13, where it can be seen that the equivalent capacitance rating of the constructed UC module is 300 F and its voltage rating is 13.5 V. The most common failure mechanism of UCs is exceeding the rated voltage of the individual UCs inside the module. Therefore, dividing the module voltage between the UC cells equally is very important. There are many voltage balancing mechanisms that can be used in UC applications, which are summarized in [1]. In this study, a passive resistor-based voltage balancing structure is utilized due to its simplicity. To implement this balancing structure, five 120 Ω resistors are paralleled with the individual UCs inside the module.

![Figure 13. a) UC module and b) electrical equivalent circuit of the UC module.](image)

In order to compare the volumetric energy density of the laboratory-constructed UC module with the electrolytic capacitors, an electrolytic capacitor module is also constructed. The energy storage capabilities of both modules are shown in Figure 14, where it is clearly seen that the volumetric energy density of the UC module is 140 times higher than the energy density of the electrolytic capacitor module. Therefore, it could be concluded that using UCs in energy storage applications instead of electrolytic capacitors will be a rational approach [1].
5. Experimental results

The performance of the UC test system is evaluated by means of computer simulations and experimental results. There is a strong correlation between the simulations and the experimental results. Therefore, only the experimental results of the study are demonstrated in this paper. The simulation results can be found in [1]. Before focusing on the performance of the constructed UC module, the dynamic and steady-state current response of the power electronics converters are investigated via a 15 A step current command response. The performances of the power electronic converters are shown in Figure 15 and are summarized in Table 4.
Table 4. Performance of the power electronics converters.

<table>
<thead>
<tr>
<th>Current controllers</th>
<th>Step-down converter</th>
<th>Step-up converter</th>
<th>Step-up converter</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(PI)</td>
<td>(PI)</td>
<td>(hysteresis)</td>
</tr>
<tr>
<td>( t_{\text{rise}} ) (ms)</td>
<td>2.5</td>
<td>1.36</td>
<td>1.18</td>
</tr>
<tr>
<td>( t_{\text{fall}} ) (ms)</td>
<td>0.96</td>
<td>0.78</td>
<td>0.74</td>
</tr>
<tr>
<td>% overshoot (</td>
<td>_{UC} )</td>
<td>0</td>
<td>33</td>
</tr>
<tr>
<td>( \Delta I_{\text{ripple}} ) (A)</td>
<td>0.5</td>
<td>0.4</td>
<td>1.5</td>
</tr>
</tbody>
</table>

The results in Figure 15 and Table 4 show that both the dynamic and steady-state response of the step-down converter with a PI controller is sufficient for the UC current control application. On the other hand, it is obvious that the overshoot value of the current is at a high level for the step-up converter with the PI controller, although its steady-state current ripple value is at a low level. Finally, when the response of the step-up converter with the hysteresis controller is investigated, it is seen that the current overshoot value is lowered to 0, whereas the steady-state current ripple is almost 4 times higher compared to the PI controller case. Therefore, it could be concluded that there is a tradeoff between the use of PI and hysteresis controllers for the step-up converter in terms of dynamic and steady-state performance. On the other hand, the UC application requires rapid and accurate current control; in particular, the ESR term calculation involves abrupt current interruption for accurate parameter estimation and the capacitor calculation involves an accurate current value. For this reason, a hybrid control mechanism that gathers the advantages of both the PI and the hysteresis controllers is designed in the scope of the study. The flowchart of the hybrid control method is shown in Figure 16, where the hybrid control method is started with the hysteresis controller. The hysteresis controller regulates the process for a starting time period \( T_{\text{START}} \). When the starting time is passed, the current reaches the reference

![Flowchart of the hybrid control structure proposed for the step-up converter.](image-url)

Figure 16. Flowchart of the hybrid control structure proposed for the step-up converter.
without an overshoot, and at this point, a nonzero value is assigned to the integrator of the PI controller. Next, the PI controller is enabled. The nonzero value assigned to the integrator \( \text{Int}_{\text{START}} \) is dependent on the magnitude of the current reference, which is found through computer simulations in this study. After the computer simulation, the hybrid control method is also programmed inside the digital controller. The computer simulation and experimental results of the hybrid controller for a step current reference of 15 A are shown in Figures 17 and 18.

As shown in Figures 17 and 18, the hybrid method is started with the hysteresis controller, and after the starting time has passed, the PI controller is made active. By this approach, the current overshoot value becomes zero and the ripple value is lowered to the level obtained for the PI controller case. It is also seen that there is a smooth current change in the transition period between the 2 methods. This is accomplished by assigning a nonzero value to the integrator of the PI controller related to the 15 A reference before initializing [1]. Thus, an accurate and fast current programming capability is obtained with the given power converter structure.

In order to evaluate the capacitance and ESR of the UC module, and to observe the distribution of the UC module voltage between the individual UC cells, the module is put into a constant current test with a 15 A test current and a 12 V maximum terminal voltage level. The constant current test profile is shown in Figure 19, where it can be seen that the voltage response of the UC module is linear, which shows that the capacitance of the UC module is maintained constant throughout the constant current test.

In order to observe the capacitance variation in the long term, the constant current test is repeated for more than 500 cycles, and a recorded test profile of 20 cycles is shown in Figure 20. With the help of the profile shown in Figure 20 and Eq. (1), the average capacitance values of the UC module for the charging and discharging phases are calculated as 287.37 F and 283.18 F, respectively. The calculated average capacitance values show \(-5.60\%\) and \(-4.21\%\) deviations from the datasheet value. The deviations are very close to the \(\pm 5\%\) capacitance tolerance given in the product datasheet [7]. However, the calculated charging capacitance is higher than the discharging capacitance, which could be explained by considering Figure 21.
As shown in Figure 21, the current on the capacitive branch is lower than the test current in the charging phase, whereas it is higher than the test current in the discharging phase due to the ESR of the UC module. Because of this fact, the charging capacitance is calculated higher and the discharging capacitance is calculated lower than the actual capacitance. Therefore, it could be concluded that the reason for the capacitance measurement deviations is made clear, and since these deviations are within the tolerance mentioned in the product datasheet, the measurement results could be accepted.
After evaluating the capacitance variation, the voltage distribution of the UC module between the individual UC cells is also investigated, and the cell voltage distribution of the UC module is shown in Figure 22. It is seen that a UC module voltage of 11.2 V is distributed between the UC cells as 2.24 V at the end of the charging phase, and a UC module voltage of 7.2 V is distributed between the UC cells as 1.44 V at the end of the discharging phase. Therefore, it could be concluded that the balancing resistor mechanism of the UC module is sufficient for this application.

In the scope of the constant current tests, the ESR value of the UC module is evaluated by measuring the immediate terminal voltage change when the test current is applied or terminated, and by considering Eq. (2). The DC and AC coupled measurements of the immediate voltage change of the UC module are shown in Figure 23. The ESR value of the UC module is calculated as 8 mΩ and 6.67 mΩ by considering the DC and AC coupled measurements, respectively. Therefore, it is seen that the calculated ESR value of the UC module is almost 3 times higher than the datasheet value, which is 2.35 mΩ. It could be concluded that this increase is due to the extra contact resistance within the module, which results from the connections inside the module. The immediate voltage change of the module is investigated for more than 500 cycles to evaluate the ESR variation, and it is observed that the immediate voltage measurements are consistent with Figure 15 during different test cycles.

After the constant current tests, the UC module is put through constant power tests at a 100 W level, and the obtained profile is shown in Figure 24. In this mode of operation, with the power being at a predefined constant and the voltage measured, the current reference is calculated for the constant power and the current controller realizes this current fast and accurately, such that the constant power operating mode is successfully achieved. The design and implementation of this control algorithm was reported in [1]. As shown in Figure 24, the current reference is calculated for the constant power and the current controller realizes this current fast and accurately, such that the constant power operating mode is successfully achieved.
In order to evaluate the efficiency characteristics of the UC module, the constant power test is repeated for more than 100 cycles, and a recorded test profile of 21 cycles is shown in Figure 25. Using the profile shown

![Figure 23. Immediate voltage change measurements.](image1)

![Figure 24. Constant power test profile of the UC module.](image2)
in Figure 25 and Eq. (3), the average efficiency value is calculated as 0.9829, which could be considered as a high value.

![Figure 25. Long-term constant power test profile of the UC module.](image)

6. Conclusion

In this study, a power electronics converter-based UC test system and a UC module were designed and implemented. The implemented low-cost UC test system is very economical and easy to build. Therefore, the given power electronics converter topology, its control methods, and its hardware implementation details could be utilized by researchers and engineers who are conducting research on UCs or designing UC-based applications.

The converter performance was evaluated by considering the dynamic and steady-state response of the system. It is seen that both the dynamic and steady-state performances of the charging system with a PI controller is sufficient. For the discharging system, the dynamic performance of the hysteresis controller and the steady-state performance of the PI controller are sufficient. Therefore, a hybrid control mechanism that gathers the advantages of both controllers was implemented in order to obtain sufficient performance.

The experimental results for the UC module are consistent in theory, although deviations from the datasheet values also exist. The reasons for the deviations are made clear by considering the nonideal components, such as the ESR and extra contact resistance within the UC module. As a general result, it is seen that the parameters of UCs remain constant and stay within the tolerance band given in the product datasheets. Furthermore, it could also be concluded that UCs are efficient and suitable for high-cycle life applications considering the repeatability of the performed tests.

The energy management of the UCs for the test procedure is quite similar to the energy management of UCs in real applications. Thus, the converters and control algorithms implemented in the test systems can be successfully extended to systems utilizing UCs for energy storage.
References


