A Study of Balancer-Less EDLC Stack in A New Power Electric Motor-Driven Capacitor Scooter System

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Abstract—In this study, we focused on an electric motorcycle system with onboard innovative charger using ultracapacitor (EDLC). The electric two-wheel scooter is an excellent performance and environmentally friendly. Moreover, it’s just an effectual solution suitable for energy resource issues and the global environment. This paper discusses with the electric motorcycle using EDLC and an innovative pulse power charger. The beneficial results of prototype performance evaluations and design procedure are performed and discussed in this paper.

Keywords—EDLC based electric scooter (motorcycle); EDLC stacks based pulse power chargers; buck-boost DC/DC converter; voltage balancer-less EDLC assembly stack

I. INTRODUCTION

Recently, electric scooters as effective EV (Electric Vehicle), HEV (Hybrid Electronic Vehicle) and FCEV (Fuel Cell Electric Vehicle) in future have attracted special interest for a powerful and promising approach for energy resource issues and global environmental problems, because of a high degree of efficiency without exhaust gas. Widely used and prosperity of the charger of electric scooters and other vehicles are indispensable to the strategic issues in the latest power electronics of low carbon society. The most crucial problem for the wider diffusion of an existing charging device of the battery toward an effective solution by installing the device in a personal house is extremely long charging time of a battery from a functional viewpoint. Meanwhile, unique pulse power charger would be wider diffusion as to provide a sub power source equipment and energy regeneration type power unit of EV[1]-[4] because of the characteristic of EDLC includes low internal resistance, long-life, highly safe and high-energy density. This paper presents a feasibility results on EDLC based power electric motor-driven scooter with innovative pulse power charging architecture for the expected energy management system for the smart house is studied from a functional point of view. A new EDLC stack based power electric motor-driven scooter with quick pulse charging characteristics are carried out in this paper. This is challenges to overcome before spreading eco-friendly vehicle.

II. CHARACTERISTIC OF EDLC BASED POWER ELECTRIC MOTOR-DRIVEN SCOOTERS

A. Schematic diagram of an EDLC based Power Electric Motor-Driven Scooter

EDLC stack is based on charge-up 60 secs (target charging time) because of EDLC has a transmission capability with a large-current. Fig. 1 depicts the schematic diagram of a proposed electric motorcycle. In this system, EDLC stack is comprised of multi-stage series capacitors connections, because the highest voltage of EDLC is 2.5V/cell. As the voltage of EDLC stacks decreases under the driving state of the proposed scooter, onboard DC/DC converter keeps a constant voltage applied to the inverter (V_o=48V).

Fig.1. Schematic diagram of EDLC-based electric scooter

Fig.2. Prototype of EDLC-based electric scooter and pulse power charger

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EDLC stacks are applied to the voltage specified at highest-voltage \( V_{\text{max}} \) to lowest-voltage \( V_{\text{min}} \) indicated as in Fig. 3. EDLC cell (Nippon Chemi-con Co., Ltd., DDLC2R5LGN)\(^5\) used for this study is demonstrated in Fig. 4.

**B. Design of EDLC Based Power Electric Motorcycle with Super Rapid Pulse Power Charger**

It is assumed the target travel distance is least 5km, since about 90% scooter user does not drive over 5km to the proposal by the document of Nihon Fukushi University traffic survey\(^6\). Meanwhile, target charging time on the proposed electric scooter as is 60secs. Because of about 80% people do not feel a psychological stress within 60secs waiting according to an opinion poll by CITIZEN WATCH CO., LTD.\(^7\).

The electric power consumption \( \eta \) is calculated by the ratio between travel distance \( D_0 \) and 3\( \Phi \) inverter's input energy. Capacitance \( C_E \) of EDLC has 10% permissible levels, and the measured value of the EDLC stack is 8% lower than a specified capacitance \( C_E \) [F]. Therefore, actual EDLC stack capacitance \( C_{E0} \) [F] as the result of eq. (2) in Table 2.

Supply energy \( W_E \) of onboard EDLC a stack is calculated by eq. (3) in Table 2 includes a power loss factor \( \delta \) caused by the capacitor ESR and a resistance between each EDLC cell. Furthermore, \( W_E \) should satisfy the following eq. (4) in Table 2.

The margin for the rated voltage \( V_E \) [V] of EDLC stack is considered. It is only 5%. The EDLC stack is charged-up to \( V_E \) calculated by eq.(5) in Table 2. Then, required maximum input voltage \( V_{\text{max}} \) [V] of DC/DC converter in the proposed electric scooter is calculated by eq. (6). Furthermore, required minimum input voltage \( V_{\text{min}} \) [V] of DC/DC converter in the proposed scooter is calculated by the following eq. (7) from eq. (1) to eq. (6) in Table 2.

\[
\begin{align*}
V_{\text{max}} & \geq V_E = 0.95 \cdot V_{B} \cdot n \\
V_{\text{min}} & \leq V_E = \sqrt{\left( V_E \cdot 0.95 \right)^2 \cdot n^2 - \frac{7.2 \times 10^6 \cdot D_0}{\eta \cdot \left( \frac{C_E \cdot 0.92}{n} \right) \cdot (1 - \phi) \cdot \alpha}}
\end{align*}
\]

Where, \( D_0 \): travel distance [km],
\( \eta \): electric power consumption [km/kWh]
\( V_E \): Voltage of EDLC stack after charging,
\( V_E \): Voltage of EDLC after discharging
\( \alpha \): Energy conversion efficiency of DC/DC converter.

**C. Design Procedure of EDLC assembly with DC/DC Converter**

The input voltage of soft-switching converter is determined by the EDLC assembly numbers range. Equations for the EDLC module design is shown in Table2. It is given in \( V_{\text{min}} \)–\( V_{\text{max}} \) to meet the target travel distance \( D_0 \). The required output energy of DC/DC power supply \( W_O \) [J] as the result of eq. (1) in table2.
Figure 5 is illustrated by eqs. (6) and (7) with \( D_0 = 5 \text{km}, \quad \eta = 120 \text{km/kWh}, \quad C_\text{p} = 1400 \text{F}, \quad V_\text{i} = 2.5 \text{V}, \quad \delta = 2\% \). It presents design criteria of the onboard DC/DC converter in EDLC based electric scooter.

In this diagram, the electric power consumption \( \eta \) is the measurement date. Operating range of DC/DC converter in the electric motorcycle for number \( n \) series connection of EDLC stack units is shown in Fig. 5. Energy conversion efficiency of DC/DC converter is 83\%. The DC/DC converter used for the proposed scooter prototype has a minimum voltage \( V_{\text{min}} = 41 \text{V} \) and maximum voltage \( V_{\text{max}} = 133 \text{V} \) and the number \( n \) of EDLC is designed \( n = 56 \). The required output energy of DC/DC power supply \( W_\text{o} \) is 150kJ, and supply energy \( W_\text{e} \) of EDLC assembly stack is 180kJ.

Figure 6 shows operating characteristics of the quasi-resonant DC/DC converter working under the frequency range of 100kHz to 600kHz, and the rated power is designed for 400W.

### D. Basic Configuration of an EDLC Assembly Module with Parallel-Series Exchanging Switching Circuit

Figure 7 shows a proposed EDLC module with a switching scheme between a parallel/series EDLCs connection. When the travel of the electric scooter is started, a parallel connection mode is selected in the first period in order to keep the output voltage of the EDLC module under the maximum operating input voltage of DC/DC converter. As soon as the output voltage of the EDLC module reaches the minimum operating input voltage of the DC/DC converter, the relay switch is turned ON. Then EDLC module is changed to a series connection mode and operating voltage becomes higher than the minimum operating voltage.

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### III. FEASIBLE EVALUATIONS AND DRIVING PERFORMANCE OF PROTOTYPE ELECTRIC MOTORCYCLE

The actual driving experimental result is showed in Fig. 8 and Table 3. A proposed EDLC module with a switching scheme between a parallel/series EDLCs connection to activate the target travel distance (5.0km). The overall efficiency of the fuel consumption and running distance has decided to 107 km/kWh. This mileage means 400 km/L as crude oil equivalent. On the contrary, the fuel consumption of a gasoline-engine bike is generally about 70 km/L\[8\]. The total efficiency of proposed electric motorcycle using EDLC reaches about 5.7 times which is in comparison with the fuel consumption of a gasoline engine scooter. Supply energy \( W_\text{e} \) of EDLC assembly stack is needed 168kJ (46.6Wh) when the travel distance is 5km (Average speed : 19.1 km/h).

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![Fig.6. Operating characteristic of quasi-resonant DC/DC converter](image)

![Fig.7. The DC/DC converter with onboard EDLC assembly module using Parallel/series switching scheme](image)

![Fig.8. Experimental drive date of a developed electric motorcycle with parallel/series exchanging scheme](image)
Table 3. Experimental test results of a developed electric motorcycle.

<table>
<thead>
<tr>
<th>Connecting mode of EDLC stacks</th>
<th>Parallel</th>
<th>Series</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cruising distance range [km]</td>
<td>3.2</td>
<td>1.8</td>
<td>5.0</td>
</tr>
<tr>
<td>Average speed [km/h]</td>
<td>19.5</td>
<td>18.8</td>
<td>19.1</td>
</tr>
<tr>
<td>EDLC supply energy $W_g$ [Wh]</td>
<td>28.7</td>
<td>17.9</td>
<td>46.6</td>
</tr>
<tr>
<td>Driving power energy $W_p$ [Wh]</td>
<td>26.5</td>
<td>15.0</td>
<td>41.5</td>
</tr>
<tr>
<td>Efficiency of DC/DC converter [%]</td>
<td>92.3</td>
<td>83.8</td>
<td>89.1</td>
</tr>
<tr>
<td>Overall efficiency [km/kWh]</td>
<td>111.5</td>
<td>100.6</td>
<td>107.3</td>
</tr>
</tbody>
</table>

IV. DEVELOPED EDLC BASED PULSE POWER CHARGER

A. Structure of a Pulse Power Rapid Charging Scheme

Stored energy of the energy pool in EDLC based pulse power charging unit is 180kJ. When Onboard energy stack is charged up within target charging time (60 secs), the average output power is estimated at 3kW which is larger than an allowable power of general domestic power in Japan. Hence, pulse power charging unit in Fig.9 is proposed here. A charging-up DC/DC converter in Fig.9 recovers and keeps the energy pool fully charged state by utility power. Utility power for the required recovery time (15 minutes) is only 200W. An EDLC energy pool comprised of EDLC cell assembly can supply enough energy for charging the EDLC assembly module of the developed electric motorcycle and high power mentioned above. A super-rapid charging buck-boost DC/DC converter shown in Fig.9 supplies enough current for charging time 60 secs from the energy pool to the EDLC assembly module in the developed EDLC based electric two-wheel motorcycle. A circuit structure of an entire system shows in Fig.10.

B. Characteristics of EDLC Cell Voltage Balance under the Developed Electric Motorcycle Operation

Figure 11 depicts demonstration test results of EDLC voltage balance in proposed electric scooter. Resultantly, the 1st cycle voltage balance across each EDLC cell in the stack is considerably uneven. However, after repeated charging and discharging cycles, voltage balance converges to small fluctuation naturally. Therefore, proposed EDLC based electric scooter without the complex balance-circuit which has only 5% margin settings for the rated voltage of each EDLC cell can operate because of maximum unbalance value is under 3% from the experimental result.

Fig.9. A schematic configuration of the proposed EDLC-based pulse power charging unit and the EDLC based electric scooter.

Fig.10. Overall circuit structure of electric scooter system
Fig. 11. Characteristics of EDLC Cell Voltage Balance under the EDLC based Electric Scooter.

C. Comparative Characteristics for DC/DC Converter

Estimated are 3 types of DC/DC converters, buck converter, boost converter and buck-boost converter as super-rapid charging DC/DC converter in pulse power charging unit. Table 4 describes input/output voltage and current relationships of these converters under a constant reactor current regulatory scheme. Boost converter cannot operate when the EDLC stack is fully discharged because the input voltage of the boost converter is generally limited to the output voltage.

Table 4. Comparison of DC/DC converters under constant reactor current regulation method

<table>
<thead>
<tr>
<th>Converter Type</th>
<th>Required condition of Input Voltage $V_i$ and Output Voltage $V_o$</th>
<th>Input Current $I_i$</th>
<th>Output Current $I_o$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Buck</td>
<td>$V_i \geq V_o$</td>
<td>$I_i = \frac{V_n}{V_i}I_L$</td>
<td>$I_o = I_L$</td>
</tr>
<tr>
<td>Boost</td>
<td>$V_i \leq V_o$</td>
<td>$I_i = I_L$</td>
<td>$I_o = \frac{V_i}{V_o}I_L$</td>
</tr>
<tr>
<td>Buck-Boost</td>
<td>$-$</td>
<td>$I_i = -\frac{V_o}{V_i + V_n}I_L$</td>
<td>$I_o = \frac{V_i}{V_i + V_n}I_L$</td>
</tr>
</tbody>
</table>

Designed values of super-rapid charging converter in the pulse power charging unit are shown in Table 4 and Table 5. Table 6 indicates characteristic design conditions of EDLC energy pool station for 3 types of DC/DC converters. Though the buck-boost DC/DC converter needs larger reactor current than that of the buck DC/DC converter, numbers of EDLC energy pool for the buck-boost DC/DC converters are smaller than that of the buck DC/DC converter. Therefore, the buck-boost DC/DC type topology is profitably highlighted at a super-rapid pulse charging scheme from a viewpoint of EDLC-based electric scooter cost.

Table 5. Controlled voltage value under super-rapid pulse charging DC/DC converter control scheme

<table>
<thead>
<tr>
<th>Converter</th>
<th>Rated voltage $V_i$ [V]</th>
<th>Total capacitance $C_s$ [F]</th>
<th>Number of EDLC cells</th>
<th>Connecting mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>Buck</td>
<td>214</td>
<td>15</td>
<td>90</td>
<td>Series</td>
</tr>
<tr>
<td>Boost</td>
<td>40</td>
<td>309</td>
<td>68</td>
<td>17 Series</td>
</tr>
<tr>
<td>Buck-Boost</td>
<td>154</td>
<td>20</td>
<td>65</td>
<td>Series</td>
</tr>
</tbody>
</table>

Table 6. Characteristic design conditions of EDLC energy pool station for 3 types DC/DC converters

<table>
<thead>
<tr>
<th>Converter</th>
<th>Energy Pool voltage $V_p$ [V]</th>
<th>Charging time $T_c$ [sec.]</th>
<th>Reactor current $I_r$ of magnetic energy storage [A]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Buck</td>
<td>214</td>
<td>135</td>
<td>67</td>
</tr>
<tr>
<td>Boost</td>
<td>40</td>
<td>17</td>
<td>60</td>
</tr>
<tr>
<td>Buck-Boost</td>
<td>154</td>
<td>53</td>
<td>135</td>
</tr>
</tbody>
</table>

Fig. 12. Experimental result of super-rapid pulse charging.

Figure 12 shows the experimental result of super-rapid pulse power charging scheme. It is noted that required energy 180kJ is successfully charged-up within 60secs.

V. EXPERIMENTAL EVALUATION OF OVERALL SYSTEM

Fig. 13. Standard pattern and result of operation test.
As a result of operative evaluation of the system, it almost matches between standard pattern and the result of the operation pattern in Fig.13. Fig.14 indicates the calculation results of the number that both the energy utilization efficiency and mileage are predominantly better fare than a gasoline engine scooter. Energy transmission efficiency of Wall to the motor is around 75%. This represents the number that both the energy utilization efficiency and mileage are predominantly better fare than a gasoline engine scooter.

VI. CONCLUSIONS

With the great advance of recent power electronics technologies, electric scooter is commanding considerable attention to practical effective method to energy resource issues and the global environment in a low carbon society.

In this paper, a unique pulse power charger and electric two-wheel motorcycle using EDLC as accumulation device have been presented and discussed. In addition, electric motorcycle using a parallel/series switching circuit on the EDLC stack has been considered a practical operation.

Newly developed electric motorcycle employing the latest power electronics technology has been tested and built from a practical point of view. In particular, this work under excellent potentials of this developed electric motorcycle with on board rapid pulse power charging equipment and high performance operating characteristics have discussed on the basis of the measurement data.

It has been found out that the prototype of EDLC parallel-series exchanging switching circuit scheme enables to achieve the full target cruising distance ranges. An optimum super-rapid charging DC/DC converter has been discussed for comparative 3 types of DC/DC converter topologies.

Furthermore, the latest developments of balancer-less EDLC stack based electric scooter to realize super-rapid charging have been demonstrated herein on the basis of the infrastructure.

And then, EDLC based electric scooter for pulse charging due to discharge DC/DC converter in additions motor-driven 3φ voltage-source inverter has been successfully implemented and evaluated from a practical viewpoint.

VII. FUTURE WORKS

As the advanced topics as a next step will be considered as follows

a. Adoption of new WBG power devices. (SiC, GaN)

b. Multi-phase circuit topology of super-rapid pulse power charging converter for EDLC-based electric scooter.


d. Multi-cascaded EDLC-based pulse power charging system.

e. Bridgeless PFC rectifier and seamless systems micro controller scheme.

REFERENCES


