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A New EDLC Electric Scooter with Pulse-Power Super-Rapid Charger

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ABSTRACT
AC motor-driven electric scooters are highly eco-efficient, high performance, more convenient, and air-pollution free. They offer a certain powerful solution to global environmentaland energyproblems. This paper presents a newly-developed super-rapid charging electric motor-driven scooter (Electric Scooter) incorporating EDLC stack change-over power source. Described are practical design criteria of the EDLC stack-based electric scooter with a ZCS-DC/DC high frequency link converter and experimental result of running operation performance. Furthermore, a pulse power Ultracapacitor (EDLC) charger for home use is proposed from a practical point of view.
Keywords—*power electronics, converter, electric vehicle, ultra capacitor*

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I. INTRODUCTION

In recent years, Electric Scooters which are highly efficient as well as air pollution free, have attracted special interest for promising solutions of global environmental problem.

One of the key issues to their successful and wide diffusion is the battery charging infrastructure for Electric Scooters. In order to implement a battery charging infrastructure by installing equipment in private homes, it is the most important problem that battery charging time is too long practically.

Recently, Electric Double Layer Capacitors packs in parallel with Li-Ion battery banks (EDLC) are applied forEV and subway railway systems[1],[2].

In this paper, proposed is an ultracapacitor electric scooter[9], bike and small EV with EDLC super rapid charging system for home use. This novel type of electric scooter can be driven after extremely short-time charging. EDLC can be rapidly charged up with short time because of very large charging and discharging current capability in comparison with a variety of chemical batteries.

Furthermore EDLC stacks are environmentally friendly because not only they do not use heavy and precious metals but also they havelong life and high reliability for million times repeated charge. Described is a design result of the EDLC charging system without battery charging system and running performance evaluation of a prototype system in this paper.

II. SYSTEM CONFIGURATION OF EDLC ELECTRIC SCOOTER

A. Desired Specifications

Table 1 indicates the design specifications of an EDLC electric scooter.

The target charging time is 30 seconds, because people over 80% can wait until 30 seconds without spirit stresses in the result of opinion poll by CITIZEN[3].

On the other hand, the target cruising range is over at least 5km because 90% motorcycle users don't drive longer than 5km in the traffic investigation by Nihon Fukushiuniversity[4].

TABLE I Design specifications of Electric Scooter.

Charging time T_o	30seconds
Cruising distance range D_o	5km

B. Construction of an EDLC Electric Scooter

EDLC stacks can be rapidly charged up with charging time 30 seconds mentioned above because of very large current capability. In the case of lead batteries or lithium ion batteries, a charging time is 30-60 times of EDLC stacks. Figure 1(a) shows a construction of a proposed EDLCelectric scooter. EDLC cells are used in a lot of series connections because their rated voltage is very low. As voltage of EDLC stacks decreases by driving state, a DC/DC converter is used for keeping input voltage V_0 to motor inverter as shown in Fig. 1(a)(b). EDLC module is used in voltage from a maximum voltage V_{max} to a minimum voltage V_{min} as shown in Fig. 1(b). Figure 2 shows the EDLC cell for this study (NIPPON CHEMI-CON, DDLC2R5LGN142)[5].

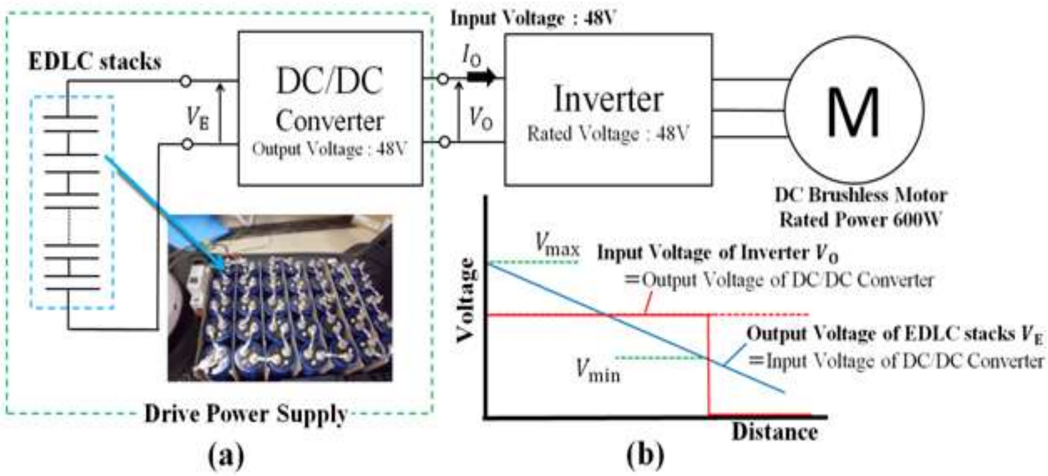


Fig.1. Construction of EDLC electric scooter.

Fig.2. Depicts the EDLC cell
(Rated voltage : 2.5V, Capacitance : 1400F, Size : φ40×150mm,
Weight : 280g) [5]

C. Design of Drive Power Supply

An input voltage ranging from V_{min} - V_{max} of DC/DC converter and number of EDLC in the drive power supply are designed for the target cruising distance range.

Output energy W_0 [J] of drive power supply is represented by the following equation (1).

$$W_0 = 3.6 \times 10^6 \cdot D_0 / \eta \qquad (1)$$

Where, D_0 : cruising distance range [km],
η : mileage energy efficiency [km/kWh]

The mileage energy efficiency is defined as the ratio between the cruising distance range and the input energy to the motor inverter shown in Fig.1.

Capacitance of EDLC specification has ±10% tolerance, and actual value of the EDLC was -8% from typical capacitance C_E [F]. Then, combined capacitance C_{E0} [F] of EDLC stacks is represented by the following equation (2).

$$C_{E0} = (C_E \cdot 0.92)/n \qquad (2)$$

Supply energy W_E delivered from EDLC stacks is represented by the following equation (3) with a power loss factor δ caused by taking into count EDLC module internal resistance and connecting parts.

$$W_E = \frac{1}{2} \cdot C_{E0} \cdot (V_b{}^2 - V_a{}^2) \cdot (1 - \delta) \qquad (3)$$

where, V_b : Voltage of EDLC module before drive ,
V_a : Voltage of EDLC module after drive

Energy W_D delivered from the drive power supply is represented by the following equation (4).

$$W_D = W_E \cdot \alpha \qquad (4)$$

where α : power conversion efficiency of actual DC/DC converter

Considering 5% margin for the rated voltage V_B[V] of EDLC, EDLC module is charged to

$$V_b = 0.95 \cdot V_B \cdot n \qquad (5)$$

Then required maximum input voltage V_{max} [V] of DC/DC converter is represented by the following equation (6).

$$V_{max} \geqq V_b = 0.95 \cdot V_B \cdot n \qquad (6)$$

Energy W_D from the drive power supply is required for the following equation (7) in order to get the cruising distance range D_O.

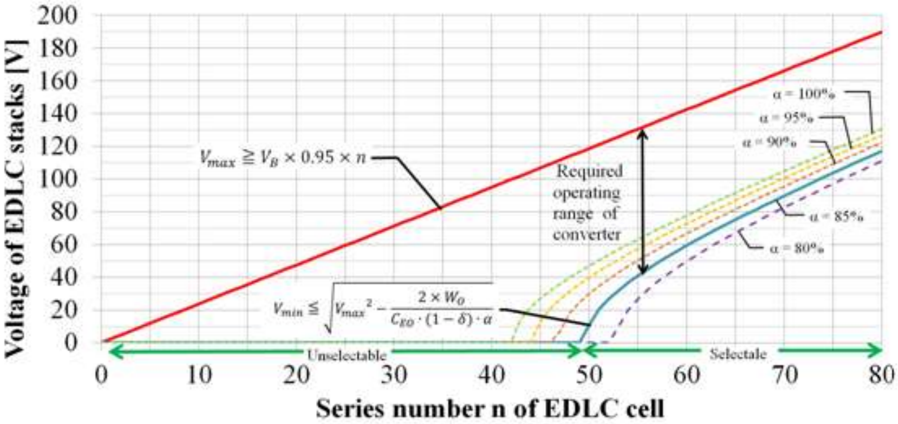
$$W_D = W_0 \qquad (7)$$

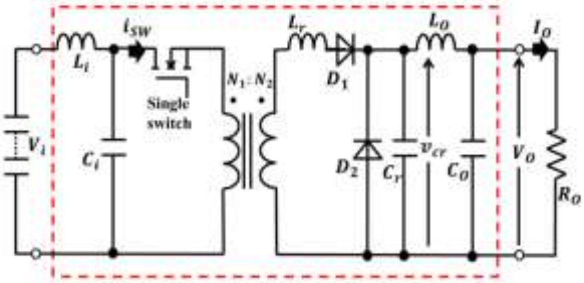
Then required minimum input voltage V_{min} [V] of DC/DC converter is represented by the following equation (8) from equation(1)(2)(3)(4)(5)(7)..

$$V_{min} \geqq V_a = \sqrt{(V_B \cdot 0.95)^2 \cdot n^2 - \frac{7.2\times10^6 D_O}{\eta\cdot\{(C_E\cdot 0.92)/n\}\cdot(1-\delta)\cdot\alpha}} \quad (8)$$

Design criteria of DC/DC converter treated here is specified in Fig. 3 from equations (6) and (8) with D_O= 5km, V_B= 2.5V, C_E=1400F, η = 120km/kWh, δ= 2%. In this case, mileage energy efficiency η is a measured value. Fig. 3 shows required operating range of DC/DC converter for series number n of EDLC cells.
Used is a range decided by characteristic line of α=85% shown Fig. 3, because the DC/DC converter has 85% efficiency. As a minimum operating voltage of the DC/DC converter is 41V, series number n = 56 of EDLC cells and minimum voltage V_{min} =41V.
The DC/DC converter used for this project has minimum voltage V_{min} = 41 V and efficiency α= 85%. Then required maximum voltage V_{max} = 133V and the series number n = 56 of EDLC cells.

Figure 4 illustrates the DC-DC converter circuit and operating waveforms. Figure 5 shows operating characteristics of the DC/DC converter. The current resonant ZCS converter operates under 100kHz-600kHz, and has 400W rated power, 130cc in physical volume, 230g in weight.





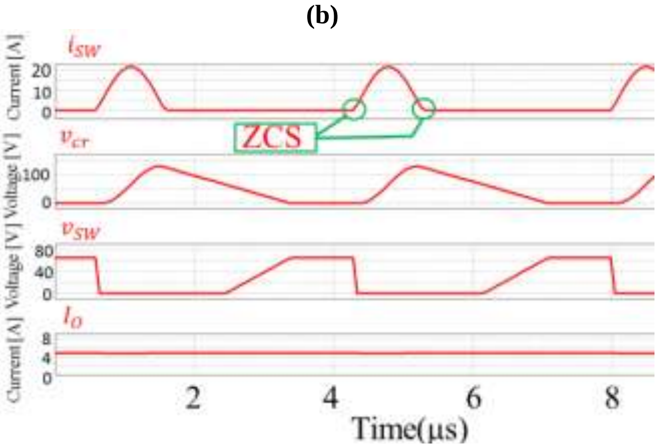
(a)

Fig. 3. Design criteria DC/DC converter treated here.

<circuit constants>

L_i	1mH	C_i	10μF
L_r	1μH	C_r	0.07μF
L_O	1mH	Turns ratio	1 : 1.2

(b)



(c)

Fig.4. Quasi-resonant DC-DC converter circuit and operating waveforms.

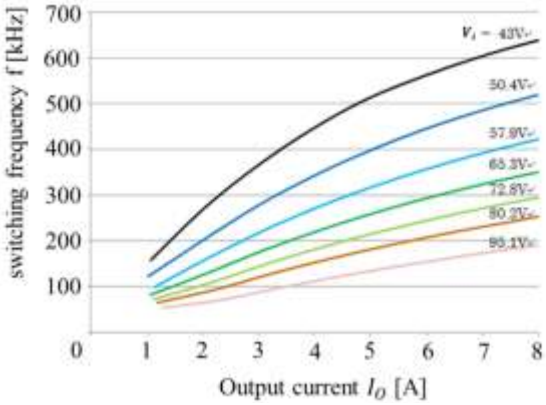


Fig.5. Quasi-resonant DC/DC converter operating characteristics.

The maximum operating voltage of DC/DC converter is 116V which is lower than required maximum voltage 133V above mentioned.
Thereby, developed is a change over system between series and parallel connection of EDLCs.

III. BASIC CONFIGURATION OF AN EDLC MODULE WITH A CHANGE OVER SYSTEM BETWEEN SERIES AND PARALLEL CONNECTION OF EDLCS

Figure 6(a) shows a proposed EDLC module with a change over system between series and parallel connection ofEDLCs.

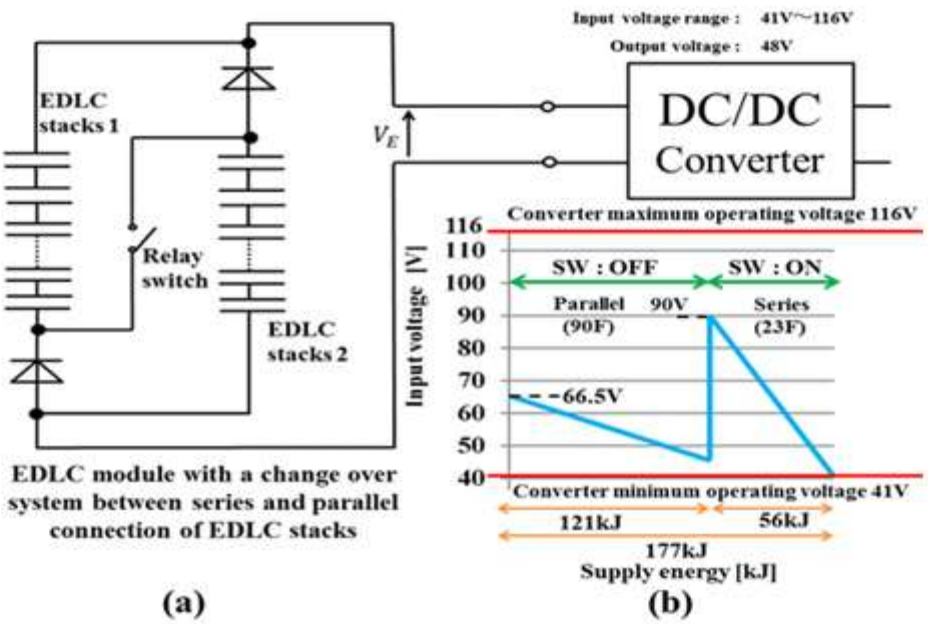


Fig. 6. A proposed EDLC module with a change over system between series and parallel connection of EDLC stacks

A parallel connection mode (relay switch : OFF) is selected in the first period in order to keep the output voltage of the EDLC module under the maximum operating voltage of quasi-resonant DC/DC converter. After the output voltage of the EDLC module reaches the minimum operating voltage of the converter, EDLC module is changed to a series connection mode (relay switch : ON). Then the stored energy of the EDLC module is fully utilized within the allowance of the DC/DC converter input voltage as depicted in Fig. 6(b).
Supply energy W_{EP} in the parallel mode and supply energy W_{ES} in the series mode are represented by the equations (8) and (9), respectively.

$$W_{EP} = 2C_{EO}\,(V_{max}{}^2/4 - V_{min}{}^2)\cdot(1-\delta) \qquad (8)$$
$$W_{ES} = \frac{3}{2}\cdot C_{EO}\cdot V_{mim}{}^2\cdot(1-\delta) \qquad (9)$$

Under the specified conditions of V_{max} = 133V and V_{min} = 41V,
W_{EP} = 120.9kJ = 33.6Wh
W_{ES} = 55.6kJ = 15.4Wh

Then total energy W_E delivered from the EDLC module is represented by the following equation (10).

$$W_E = W_{EP} + W_{ES} = 176.5\text{kJ} = 49\text{Wh} \qquad (10)$$

Cruising distance range D_D expected by a prototype of EDLC electric scooter is larger than the design specification $D_0 = 5$km as shown in the following equation (11).

$$D_D = \eta \times W_D = \eta \cdot \alpha \cdot W_E = 5.0\text{km} \qquad (11)$$

where mileage energy efficiency η : 120 km/kWh,
converter efficiency α : 85%

IV. RUNNING PERFORMANCES OF PROTOTYPE EDLC ELECTRIC SCOOTER ANDEVALUATIONS.

Fig.7. Appearance of a prototype EDLC electric scooter.

Fig.8 Actual running test of a prototype electric scooter.

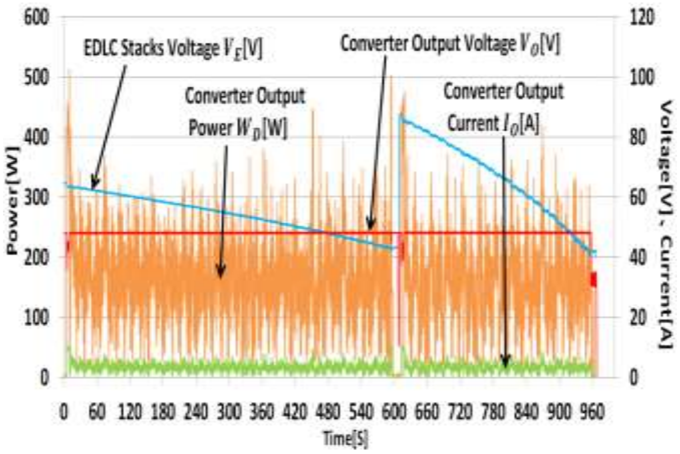


Fig.9 Running test data with a change over system between series and parallel connection of EDLCs. (Average speed : 19.1km/h)

TABLE Ⅱ Experimental running results of a developed EDLC electric scooter.

Connecting mode of EDLC stacks	Parallel	Series	Total
Cruising distance range [km]	3.2	1.8	5.0
Average speed [km/h]	19.5	18.8	19.1
EDLC supply energy W_E[Wh]	28.7	17.9	46.6
Driving power energy W_D[Wh]	26.5	15.0	41.5
Efficiency of DC/DC converter [%]	92.3	83.8	89.1
Total efficiency [km/kWh]	111.5	100.6	107.3

Figure 7 shows an appearance of a prototype EDLC electric scooter. EDLC module is installed into two places for using limited space effectively as shown in Fig. 7.
Actual running test course is a track with 160m per one lap as shown in Fig. 8. Fig. 9 and Table 2 represent the actual experimental running result. The course is flat.

The experimental running result has achieved the target cruising distance range 5.0km. The total efficiency which is the ratio between the cruising distance range and the fuel consumed, has reached to 107km/kWh. Total efficiency of a gasoline engine motorcycle is usually 73km/l[6],[7] i.e. 7.6km/kwh[8]. Then EDLC electric scooter has 14times total efficiency in comparison with gasoline engine motorcycle.
And actual EDLC supply energyW_E needed for cruising distance range D_O= 5km is 46.6Wh(168kJ).

V. FEASIBLE CONSTRUCTION OF CHARGING SYSTEM

Because EDLC module energy $W_E \approx 170$ kJ should be charged in target charging time $T_0 = 30$ s, average output power of a charging unit for the EDLC electric scooter is estimated 5.7kW which is larger than available utility power in an ordinary home in Japan. Then proposed is a pulse power charge system as depicted in Fig. 10.

Anenergy pool composed of EDLC cells in Fig. 10 can supply very high power mentioned above and has enough energy for charging the EDLC module of the developed scooter. A trickle charge converter in Fig. 10 recovers energy pool by utility power and keeps the voltage of energy pool. Utility power for the recovery time estimated as 15 minutes is 200W. A super rapid charging converter in Fig. 10 supply enough current for charging time 30 seconds from the energy pool to the EDLC module in the developed scooter.

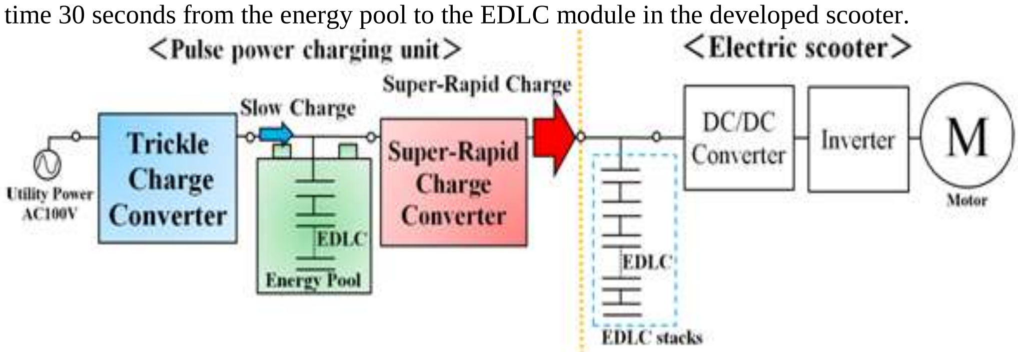


Fig. 10. A configuration of the proposed pulse power charging uni

IV. CONCLUSION

Electric Scooters are expected for promising solutions of environmental problem. In order to realize a battery charging infrastructure for successful diffusion of electric scooters by installing equipment in private homes, developed has been a novel type of electric scooter which can be charged up super rapidly. EDLC has been successfully used for the newly-developed electric scooter which can be completely charged up in very short time just before drive. Presented has been a change over system between series and parallel connections of EDLC stacks in drive power supply to achieve the target cruising distance range. And described has been a quasi-resonant ZCS converter of high power density and its essential circuit performance has been presented.

Furthermore, a pulse power charging unit with EDLC energy pool has been proposed originally. It is noted that the charging unit is suited for domestic utility power in spite of very high power charging. Actual experimental running result of a prototype EDLC electric scooter has been evaluated and discussed from a practical point of view.

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