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An experimental and analytical study of the ultra-capacitor storage unit used in regenerative braking systems

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Abstract

Ultra-capacitor (UC) is a type of rechargeable energy storage unit used in different industrial applications. It has been utilised to transmit high current on acceleration and to accept regenerative braking energy on descending and braking in electric vehicles, and hybrid electric vehicle power applications. In this research, the UC has been tested in the laboratory and studied in the simulation with the aim to investigate a method for harvesting energy. Analysis of electricity generated from the braking process by rotating machinery has been carried out at a designed test rig with the prime objective of monitoring UC charging voltage at different states. The newly proposed modelling and algorithm consider the generator and the UC as two storage units having a capacitance and different voltage levels for dynamic charge transfer and the observation of voltage states for demanding applications. This method defines the generator variable charging behaviour, and the UC response shows an accurate simulation.

Keywords: Ultra-capacitor (UC) storage unit; regenerative braking (RB); generator capacity (C_2); variable charging voltage (VV).

1. Introduction

In an electric vehicle (EV) and hybrid electric vehicle (HEV), one of the most important features of using the DC motor as a propulsion engine is that low maintenance and noise and no carbon emissions [1]. Most importantly, these

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technologies have vigorously relied on upon battery packs as the central storage unit. Consequently, to operate safely and efficiently, the battery in energy storage system (ESS) should be used within safe temperature and voltage ranges. The UC that passes charge and discharge cycles frequently in high current and short duration is used to assist the battery in achieving the energy density of cells, offering almost an extend lifespans, and no environmental issues [2]–[4]. Moreover, UCs have been used to store energy that has additionally made fundamental advances in electric power system [5].

On the other hand, braking of EV and HEV driven by electric motors in regenerative braking (RB) is achieved when the motor is tentatively working as a generator. Pumping charge by the generator at braking to the UC, due to the voltage difference, neither as in a steady current source nor as in a regulated constant voltage source and even it cannot be represented merely like discharging of a capacitor to another one. In the experimental test, the UC shows a variety of behaviour response which gives a spotlight of this research to handle and to measure the effect of the generated voltage and the response of the UC storage unit, with the help of LabVIEW environment.

In recent research studies in a vehicular point of view considering available computer software packages, used to models and to simulate the ESS and the powertrain like SIMPLORER and ADVISOR software [6]–[10]. Also, modelling UC might be considered as an electric circuit [11], [12]. The propulsion engine such as brushless (BLDC) motor can be represented using differential equations for all three-phase voltages[13], [14]. In comparison, this research accomplished with an experimental investigation got the advantage to an accurate representation of system behaviour starting from circuit designing and system representation as a ready-made (black box) models and lumped component for determining the characteristics and dynamics equations to represent overall system performance.

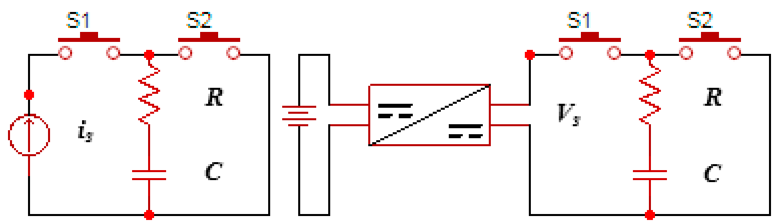
In this research, the UC is charged at a constant current (CC) and then at a constant terminal voltage (CV) with a predefined behaviour. The basic knowledge of fluid mechanics can be taken from the flow rate between two tanks connected at different levels; a modification process of charge transfer had been made to represent the generator and the UC as two storage units with varying charging flow rate and various voltage levels. However, in the proposed method, the variable pumping charge of the generated voltage (VV) when the DC motor works as a generator during descending, and braking process has been investigated and implemented with experimental setups at low power scale in the designed test rig. Based on the results conclusions are given for the variable charging capability of the generator and the UC charging response at different stages in the RB system which is the main contribution added to the designed test rig.

2. Characteristics of the UC energy storage unit

In the experiment, an Eaton 16.2V65F UC storage unit is connected in series with 300 W 8500 Programmable DC Electronic Loads (PEL) powered by a DC power supply. The circuit also contains a DC-DC converter used for voltage regulation. The PEL operates in different operation mode as a CC and CV, with voltage and current values are evaluated and presented in real time. The VV has been implemented by using the BL58EE70W permanent magnet brushless (PMBL) DC motor connected with a designed flywheel in the test rig. In this section, UC ESS experiments are carried out and verified by simulation.

2.1. Charging UC with a constant current (CC), and a *constant voltage (CV) source*

An experimental setup as shown in Fig. 1 is used to test and to evaluate the performance of UC storage units.



(a) Constant current (CC) (b) Constant voltage (CV)

Fig. 1. Charging and discharging UC with different sources

The system operation can be represented as in table 1 below,

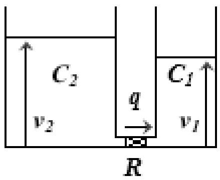
Table 1. Charging and releasing UC at CC and CV sources.

State	S1	S2	Process	Circuit	UC voltage, and current
CC	Closed	Opened	Charging linear ramp	Fig. 1a	$v_{uc(t)} = i_s/C \int_0^t d\tau = i_s\, t\,/C$
	Opened	Closed	Discharging		linear ramp function with (-i_s/C) gradient
CV	Closed	Opened	Charging exponentially	Fig. 1b	$v_{uc(t)} = V_s\left(1 - e^{-t/\tau}\right), i_{uc(t)} = V_s/R\left(e^{-t/\tau}\right)$
	Opened	Closed	Discharging exponentially		$v_{uc(t)} = V_s\,\left(e^{-t/\tau}\right), i_{uc(t)} = -\,V_s/R\left(e^{-t/\tau}\right)$

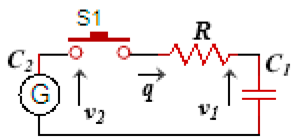
Where, τ=RC is a time constant. Table. 1 demonstrates the voltage and current relationship of the charging and releasing of the UC ESS in CC mode, and in CV mode. The data extracted from this analysis from table 1 is used to initiate boundary conditions on designing and on simulation of the UC for full-charge detection and over-discharge protection when used in energy harvesting and energy management system.

2.2. Charging UC with varying generating voltage (VV) source

The time-varying voltages (VV) resulting from the sudden application of supply sources, usually due to switching. In RB, this happened at the instant of braking when the electric motor works as a generator converting mechanical energy into electrical energy. Considering the variable characteristic of the voltage generated from braking used to charge the UC in ESS, it is proposed that two storages represent the generator (lumped with a connected flywheel) having a capacitance C_2 and the UC connected with them having a capacitance C_1 as shown in Fig. 2a.



(a) Mimic of two storage tanks system



(b) Electrical circuit

Fig. 2. Charging the UC with VV system

Where the charge q flow at a unit time t represents the current, passing from the generator to the UC storage unit in the charging process. Furthermore, C_1, C_2 represent the capacitance of the UC and the unknown capacitance of the generator respectively, while v_1 represents the voltage across the UC and v_2 represents generator terminal voltages. The charge flow rate can be evaluated as;

$$i_{uc(t)} = dq/dt = C_1\, dv1/dt = -\,C_2\, dv2/dt \tag{1}$$

Equation (1) can be simplified to calculate the unknown generator capacitance C_2 as;

$$C_2 = -\,C_1\, dv1/dv2 \tag{2}$$

The worth coming of equation (2) is when it compared with the practical implementation of a different scenario in the designed test rig. It can be concluded that the unknown generator capacitance C_2 which is the most crucial term in the simulation, can be identified experimentally. At any given speed, the voltage conserved by the UC storage unit (initially at zero energy) to the maximum generated voltage by the generator at the instant of switching multiplied by

UC capacitance C_1 represents the generator capacitance. So that, equation (2) can be simplified as $C_2 = -KC_1$. Where K can be evaluated from the experimental measurement which can be described as;

$$K = dv1/dv2 = Max.Stored\ voltage\ in\ UC/Max.Back\ emf\ generated\ voltage$$

Furthermore, from the circuit of the Fig. 2b, the rate of change in v_1, which represents the UC voltage rise when the charge accumulated on it, by applying Kirchhoff's voltage law, can be determined as;

$$dv1/dt = (v2 - v1)/RC_1 \tag{3}$$

While, the rate of change in $v2$, which represents the generator voltage drop when the charge transferred to the UC storage unit, can be determined from equation (2) as;

$$dv2 = -(C_1/C_2)\,dv1,\text{ where, } dv2 = 0 - v2 = -v2, dv1 = v1 - 0 = v1,\ v2 = (C_1/C_2)\,v1 \tag{4}$$

3. Simulation and experimental results

Fig. 3 shows a schematic diagram of the designed and built test rig which is used for energy management and regenerative braking process.

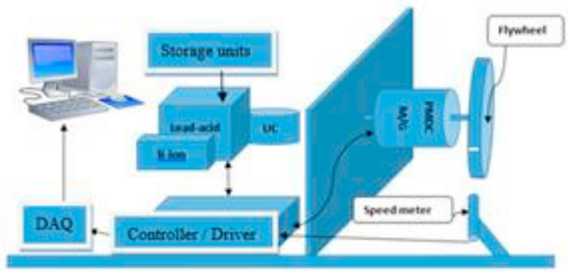


Fig. 3. Schematic of the test rig for regenerative braking study

The overall system simulation can be represented as in the Fig. 4 which describe the motoring operation, and then the generating process at the braking when the motor works as a generator charging the UC storage unit with variable charging voltage.

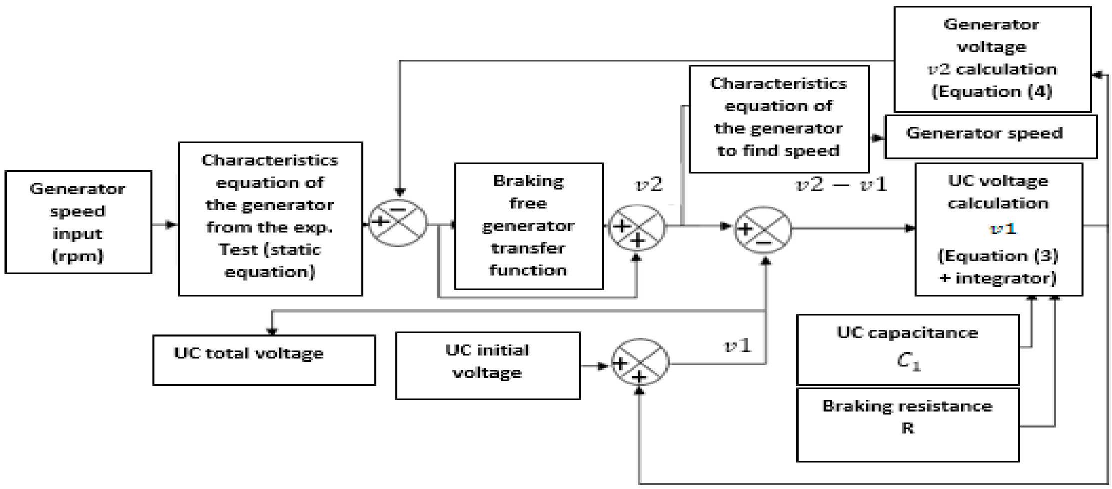
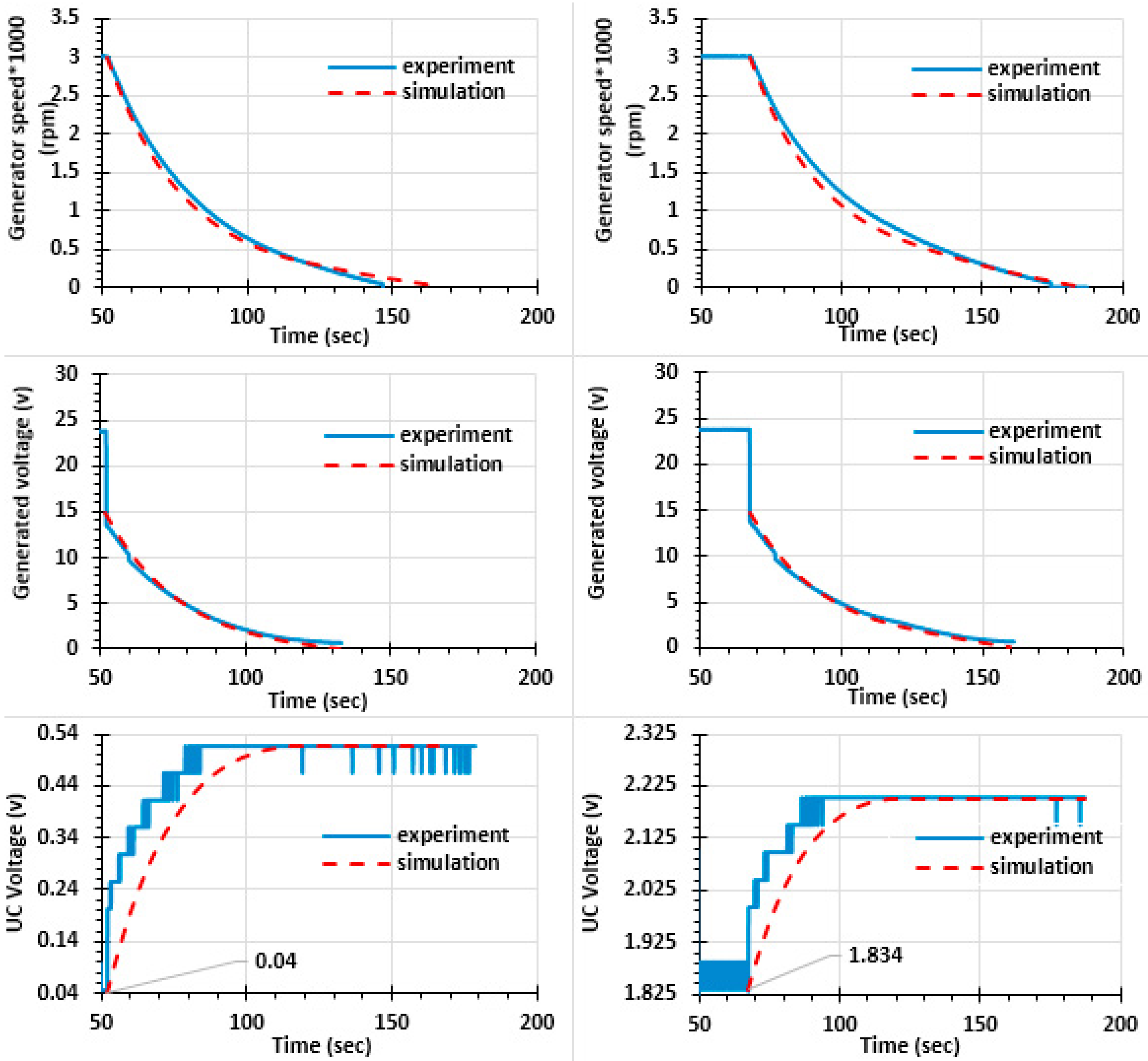


Fig. 4. Simulation flowchart

Fig. 4 demonstrates the steps used to extract the best fit of data retrieved from experiments. The calibration equation is utilised at different stages starting from speed input ending with the inverter output voltage to each phase of the BLDC motor for simulation of the designed test rig. Furthermore, the dynamic equation is carried out by system identification tool available in the LabVIEW program and checked by the tuning process.

RB and energy recovery is accomplished in the analysis of the proposed modelling of the generator and the UC storage unit. Various scenarios have been implemented to investigate the overall system performance, and verification is achieved in the practical test by using a designed test rig to satisfy the requirements as shown in Fig. 5, used to verify conservative energy during the braking process.



(a) Generator speed, generator voltage and UC voltage at 0.04v UC initial value

(b) Generator speed, generator voltage and UC voltage at 1.834v UC initial value

Fig. 5. Case study (experiments and simulation validation) at two different UC states

It is clear from Fig. 5 that, in charging mode, the UC can absorb more energy when it is in a low voltage state, and the stopping time depends on this condition as it compared with its state at a higher voltage level.

4. Conclusion

The newly proposed modelling and algorithm, which takes the essential information of the system from the flow rate associated with two connected tanks to represent charge flow rate in RB, have been considered in this research. The capacity of a container which can be defined by the mass in kg of water required to raise its level by one meter, equivalently, the capacitance of a capacitor is characterised by the amount of charge needed to make a unit potential difference between its plates. The impact of variation in UC voltage state and charging value to the driving characteristics (deceleration and speeding) highly depends on its features and behaviour. Whereas the modelling and the analysis mainly depend on experimental results, different states are examined in this study to investigate the best representation of the designed system components and to study the overall performance. The main finding and novelty are achieved by defining and representing generator capacitance which is the most crucial term in the simulation. Also, by evaluating VV(corresponding to variable charge transfer of the generator) which is used to energise UC storage unit in RB process. Furthermore, defining UC behaviour and its constraint in different excitation, such as in CC and CV mode, to make a decision in energy management and with the system design and performance analysis.

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