Ultracapacitor: Modelling and Characterization for Electric Vehicle Application

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Abstract: Ultracapacitors (UCs) are characterized by its high power storage capacity, Low Equivalent Series Resistance (ESR) which leads to an efficient high charging / discharging currentat a wide range of operating temperatures. UCs are successfully utilized as a supplementary energy sources for electric vehicles (EVs). According to their high power densities they are adopted to operate in quick acceleration, hill-climbing and regenerative braking. So they have been considered for transient power supply and recovery in EVs. An UC-battery combination system can effectively smooth the power fluctuation caused by periodic acceleration and deceleration for different driving cycles. In this paper, the performance characterization of an UC is recorded including measuring the capacitance, equivalent series resistance and the output terminal voltage. The characterization is verified experimentally at different loading conditions in order to model the performance of the UC under different loading and operating conditions. A simplified Fuzzy modelling technique is adopted for capacitance estimation based on the charging/discharging currents and the surrounding temperature. The estimated capacitance from the fuzzy model is very close to the actual value that proofs the high efficiency of the proposed model. The ESR, terminal voltage, and SOC are estimated from the introduced model. The available charge after charging or discharging is estimated based on the estimated terminal voltage and capacitance.

Keywords: **Ultra-capacitor, characterization, modelling, Electric vehicle.**

I. Introduction

The UC is a promising energy storage device with behaviour somewhere between rechargeable battery and traditional capacitor. It can be charged and discharged quickly like a capacitor, but exhibits 20-200 times greater capacitance than conventional capacitors [1]. The advantages of UCs are: High energy storage due to activated carbon electrode to achieve a high surface area, Low Equivalent Series Resistance (ESR) providing high charging and discharging efficiency, Low temperature performance, so it can be used in a wide temperature range, and fast charge/discharge process. Comparing with batteries, UCs can accept a wide range of charging current and can be fully charged within a few minutes. High energy density batteries, like lithium-ion (Li-ion) and nickel metal hydride (NiMH) battery, and fuel cells have been developed for many years ago. They are successfully utilized as energy sources for electric vehicles (EVs). However, their power densities are inadequate under certain operation conditions, namely quick acceleration, hill-climbing and regenerative braking. The UC is a high power density, so it has been considered for transient power supply and recovery in EVs. An UC-battery combination system can effectively smooth the power fluctuation caused by periodic acceleration and deceleration of different driving cycles. The UC supplies and absorbs and the large current pulses during high acceleration and braking conditions, and the battery provides the average power demand. This, in turn, allows for the size of the battery pack to be reduced and its life time to be increased [2-4].

In this paper, the performance characterization of an UC is modelled by measuring the capacitance (C), equivalent series resistance (ESR) and the output terminal voltage (V). The purpose of this model is to estimate the UC state of charge (SOC) which gives an indication of the available energy remained in the UC. The characterization is verified experimentally at different loading conditions in order to study the performance of the UC at different loads and temperatures. Fuzzy modelling technique is adopted for capacitance estimation based on the charging/discharging currents and the surrounding temperature to estimate the SOC of the UC. The estimated capacitance from the fuzzy model is very close to the actual capacitance with an accuracy of 99.97% that ensures the high accuracy of the proposed fuzzy model. Also, the dynamic performance of the UC in electric vehicles (EVs) is carried out by executing the high way (H.W) driving cycle compared with the MATLAB model.=

This paper is summarized as follows: section (II) gives the difference between UCs and other energy storage systems. Section (III) presents the UC modelling including capacitance and equivalent series resistance determination from constant-current charging / discharge tests.

Section (IV) presents the proposed UC fuzzy model for capacitance estimation. Section (V) presents Fuzzy model results. Section (VI) shows the calculation of terminal voltage. Section (VII) shows the SOC estimation. Section (VIII) shows the dynamicperformance of UC in EVs. Section (IX) presents the conclusions.

II. Difference between UCs and other energy storage systems

As shown in Figure (1), the UC lies between conventional batteries and conventional capacitors. They are typically used in applications where batteries have a short fall when it comes to high power and life, and conventional capacitors cannot be used because of a lack of energy. UCs offer a high power density along with adequate energy density for most short term high power applications. The comparison between UCs with other energy storage devices including batteries and conventional capacitor technology is summarized in table (1) [5].

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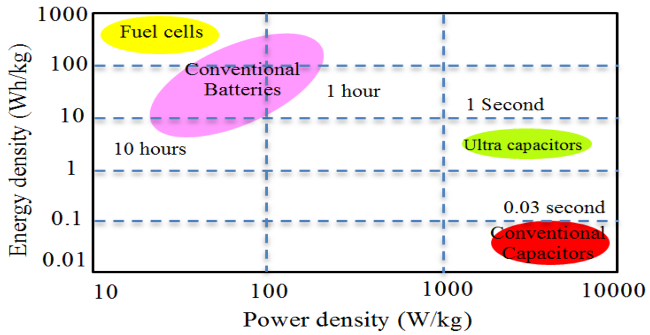

Figure 1: Ragone Plot [5].

Table (1) comparison between UCs, conventional batteries, and conventional capacitors [5]

Available performance	Lead Acid Battery	UC	Conventional Capacitor
Charge time	1 to 5hrs	0.3 to 30s	10^{-3} to 10^{-6} s
discharge time	0.3 to 3hrs	0.3 to 30s	10^{-3} to 10^{-6} s
Energy (Wh/kg)	10 to 100	1 to 10	<0.1
Cycle life	1000	>500000	>500000
Specific power (W/kg)	<1000	<10000	<100000
Charge/discharge efficiency	0.7 to 0.85	0.85 to 0.98	>0.95
Operating temperature	-20 to 100 C	-40 to 65C	-20 to 65C

In order to study the performance of the UC and estimate the key parameters, a constant charge/discharge test is performed. The UC capacitance, equivalent series resistance, and output terminal voltage are estimated from this test.

III. UC Modelling

Difference between the generic MATLAB model and proposed model for UC is that, the MATLAB model is a generic model for ultra-capacitors after feeding the model with the necessary parameters such as rated capacitance, equivalent series resistance (ESR), rated voltage, No. of series capacitor, leakage current, and operating temperature.

The UC block in MATLAB/SIMULINK implements a generic model parameterized to represent most popular types of UCs. This model was built depending on the physical variables, such as interfacial area between electrodes and electrolyte, molar concentration, faraday constant, current density, Helmholtz layer length, and charge transfer coefficient, and other parameters, which are considered an issue for practical modelling in a real system, because not all system designers are familiar with physical quantities which are needed for UC modelling. So this article introduces a simplified practical model based on simple tests for the capacitance estimation at different charging/discharging current rates also at different operating temperatures. Also the other parameters which are needed for modelling and characterization of the UC by the proposed model are estimated by simple tests, such as, equivalent series resistance (ESR), columetric efficiency, etc.

The output variables from each model, such as, terminal voltage, and state of charge (SOC) are compared, and the level of difference is acceptable with respect to model simplicity in a real system.

The RC equivalent circuit of the model is shown in Figure (2). It consists of capacitance, equivalent parallel resistance (EPR) and equivalent series resistance (ESR).The EPR represents the current leakage and influences the long-term energy storage. The ESR gives an indication for the power capability/electrical losses/heating of the UC.The purpose of this model is to calculate UC's SOC and terminal voltage. In order to measure each parameter in the model, a constant current charge/discharge test is performed.

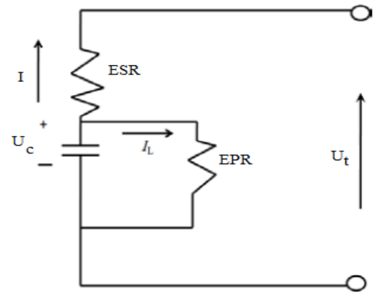

Figure 2: Classical equivalent circuit of an UC.

3.1 Constant-Current Charging / Discharge Tests and experimental system setup

The experimental system setup is shown in figure (3). It consists of an UC (unit under test) contained in a temperature controlled chamber. The UC is connected to a DC electronic load then charged and discharged at different current rates and temperatures.

Figure 3: experimental system setup.

Table (2) shows general technical data provided by manufacturer of the modelled UC.

Table [2]:General technical data of the used UC

Model Maxwell BMOD0083P048	
Rated Capacitance	83Farads
Rated voltage	48V.
Max. current	1000A
Equivalent Series Resistance	0.01 Ω
No. of series cells	18
Leakage Current	3 mA

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The UC is discharged at several current rates and temperatures then the terminal voltage is recorded at each condition. Figure (4) shows the discharging/charging voltage measured experimentally at rate of 5A.

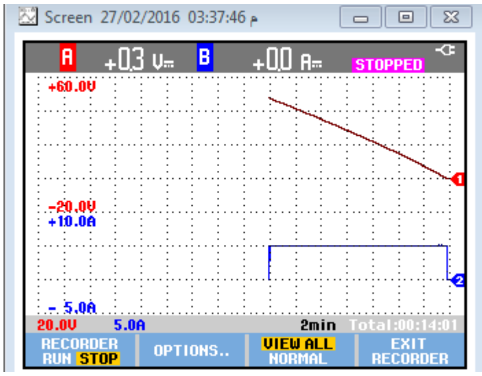

Figure 4-a: Terminal voltage discharging Constant Current (5A)

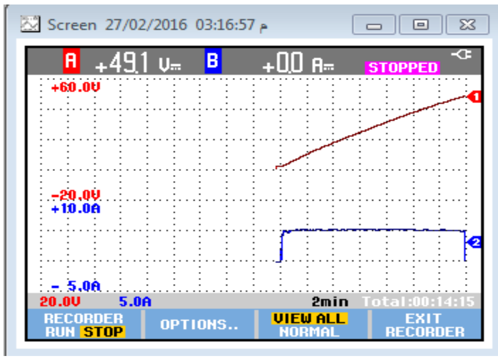

Figure 4-b: Terminal voltage charging Constant Current(5A).

Figure (5) shows UC working voltage versus time at different current rates. It is shown that the discharging time decreases with increasing discharging current.

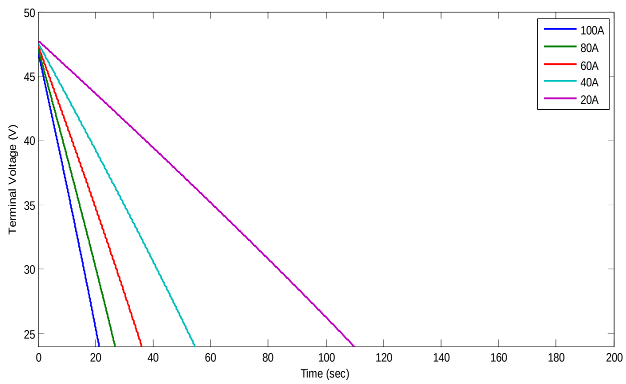

Figure 5: Voltage versus time plot.

3.2 Capacitance Determination from Test Results

There are several methods for capacitance calculation:

First method: The capacitor is discharged at constant current values and the output terminal voltage is recorded then the capacitance is calculated from the following equations:

$$C = \frac{I_{test}\Delta t}{\Delta U} \quad (1)$$

$$\Delta U = 0.9(U_{r} - U_{drop}) - 0.7(U_{r} - U_{drop}) \quad (2)$$

Second method: The load is set to the appropriate constant current, and discharged to 0.1V, or as low as the load can be controlled. Immediately the load is removed once the minimum voltage is reached, allowing the device's voltage to "bounce" back. (The discharge can actually be stopped at any voltage. Depending on equipment, some units can be discharged to 0.1V, and others discharged to ½ of the initial voltage. Values of capacitance will be slightly higher when discharged to ½ initial voltage rather than 0.1V.). The following parameters are measured [5,6].

V_w = initial working voltage V_{min} = minimum voltage under load.

I_d = discharge current V_f = voltage 5 seconds after removal of load.

t_d= time to discharge from initial voltage to minimum voltage

Capacitance calculation:

Capacitance = $(I_d * t_d)/(V_w - V_f) = (I_d * t_d)/V_d$

In this paper the second method is adopted and the UC is discharged to ½initial voltage.

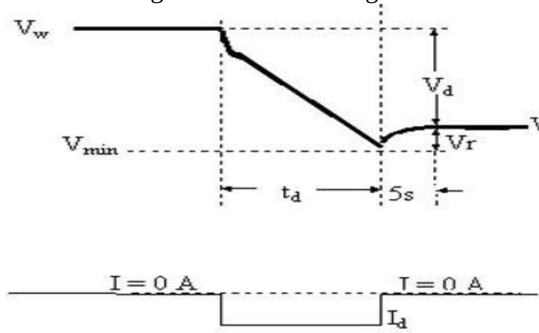

Figure 6: UC capacitance calculation method [6].

A constant current value for charge and discharge process at rate 100mA/F is used to estimate the rated capacitance, which is equivalent to 8.3A for the adopted UC in this work.The charging / discharging cycle is shown in figure (7).

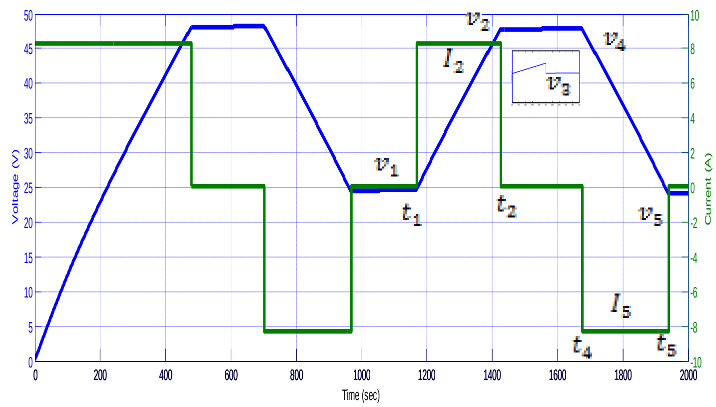

Figure 7: UC charging/discharging cycle at current 8.3A.

3.3 Parameter Calculation:

The results of the second cycle are used to calculate the capacitance and resistance with the followingformulas. The first cycle data are not used because the cell has not been activated and themeasured capacitance and resistance values are different compared to the second cycle and thecycles after [6].

$$C_{ch} = \frac{I_2(t_2 - t_1)}{(v_2 - v_1)} \quad (4)$$

$$R_{ch} = \frac{v_2 - v_3}{I_2} \quad (5)$$

$$C_{dch} = \frac{I_5(t_5 - t_4)}{(v_5 - v_4)} \quad (6)$$

$$R_{dch} = \frac{v_5 - v_6}{I_5} \quad (7)$$

Table (3) summarizes the estimated capacitance at different discharging currents when the UC is discharged to ½ initial voltage at the second column and the UC is discharged to 0.1V at the third column.).Figure (8) shows the UC capacitance as a function of current.

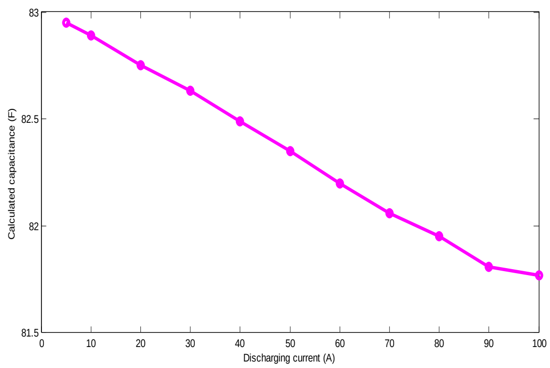

Figure 8: Capacitance versus current plot

Table (3) calculated capacitance at different discharging currents:

Discharging current (A)	Capacitance (F) (Discharging to ½ rated voltage)	Capacitance (F) (Discharging to 0.1V)
5	95.4	82.95
10	95.3	82.89
20	95.16	82.75
30	95	82.63
40	94.9	82.49
50	94.7	82.35
60	94.53	82.2
70	94.37	82.06
80	94.24	81.95
90	94.08	81.81
100	94.06	81.79

3.3 Equivalent series and parallel resistance calculation

ESR value can be calculated from the value of voltage jump/drop when the current direction changes from discharge to charge or vice versa.

$$ESR = \frac{U_{jump/drop}}{\Delta I} \quad (8)$$

For many applications ESR gives an indication for the power capability/electrical losses/heating of the UC.

EPR value can be calculated by charging the UC to its rated voltage, then the UC is kept for 72 hours and the terminal voltage is recorded. The EPR is calculated from the following equation.

$$EPR = \frac{-t}{\ln\left(\frac{v2}{v1}\right) * C} \quad (9)$$

Where: t = time in sec.

V_2= terminal voltage after 72 hours.

V_1 = rated voltage before 72 hours.

IV. UC Fuzzy Model for Capacitance Estimation

Fuzzy systems map measured inputs to desired outputs. They estimate functions by translating the behavior of the system into fuzzy sets and by using rules based on a linguistic representation of export knowledge to process the fuzzy data [7].

In this work a fuzzy modelling for an UC at different discharging rates and different operating temperatures is adopted to estimate the capacitance. The inputs for the fuzzy model are charging or discharging current and the surrounding temperature as shown in figure (9), while the outputs are the UC capacitance at temperature of 25^{o}C and the correction factor which relates the capacitance at any temperature degree to the capacitance at 25^{o}C.

Temperature effects and performance changes over time

The performance of UCs is very stable over a wide operating temperature due to the chemistry and physical makeup of the products. An advantage of the UC's organic based electrolyte is its low freezing point. This enables the UCs to be utilized over a wide range of temperatures, with relatively unaffected performance. In this work the capacitance is estimated at different temperatures (25^{o}C, 40^{o}C, and 65^{o}C) and there is no noticeable change in it.

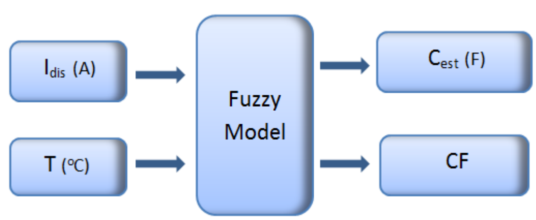

Figure 9: inputs and outputs for the fuzzy model.

The membership function describes the current input variable is shown in figure (10), the membership functions describe the temperature is shown in figure (11). The membership functions describe the capacitance of the UC is shown in figure (12). The membership functions describe the correction factor which relates the capacitance at any

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temperature to the capacitance at 25°C is shown in figure (13).

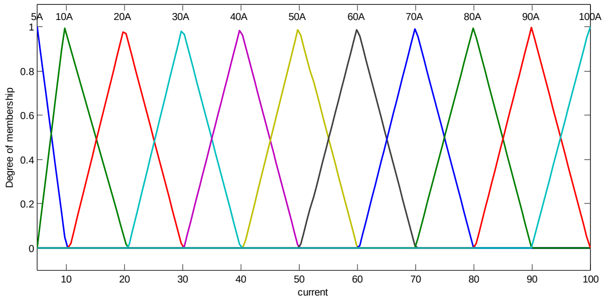

Figure 10: membership function for the current.

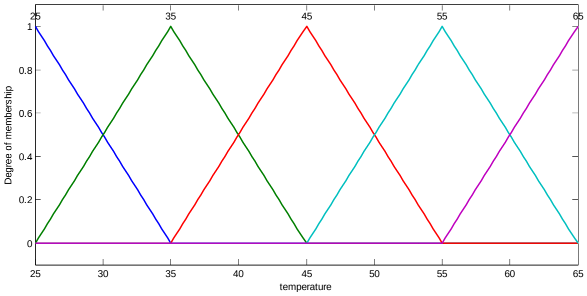

Figure 11: membership function for the temperature.

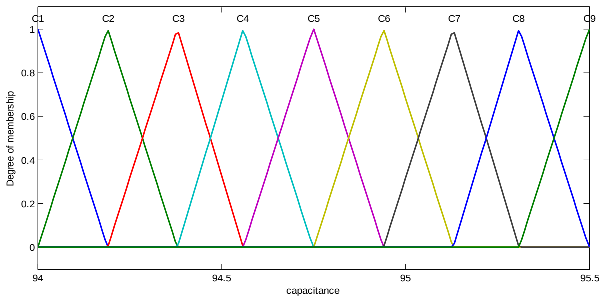

Figure 12: membership function for the capacitance.

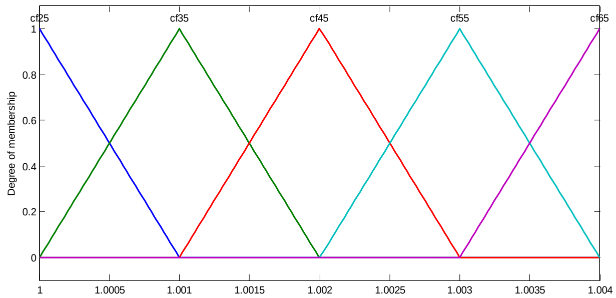

Figure 13: membership function for the correction factor.

V. Fuzzy Model Results

Figure (14) shows the actual capacitance of the UC as compared with the output of the fuzzy model. It is shown the fuzzy model output tracks the actual capacitance. The model accuracy is calculated from the following equation.

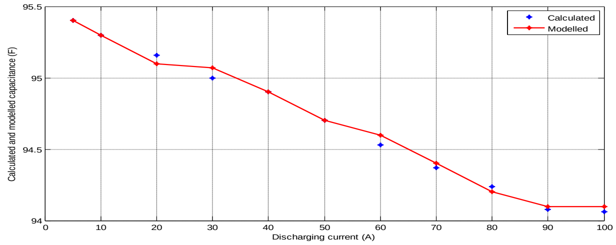

Figure 14: Calculatedand Estimated capacitance from fuzzy model.

$$modelacc. = \frac{1}{n}\sum_{i=1}^{n} 1 - \frac{|C_{calculated} - C_{modelled}|}{C_{calculated}} * 100\% \quad (10)$$

In this work the model accuracy is within 99.97% which proofs the good matching between estimated and actual values.

VI. Calculation of terminal voltage

The UC terminal voltage is calculated from the following equation [1].

$$U_t = U_{co} - \int_0^T \frac{I}{C} dt - IR_s \quad (11)$$

Where: $U_t$is the terminal voltage, U_{co} is the open circuit voltage, I is the demand current, R_s is the equivalent series resistance (ESR). Figure (15) shows the UC estimated terminal voltage at different discharging currents compared with the UC terminal voltage of Matlab/Simulink. The figure shows good matching between the two results.

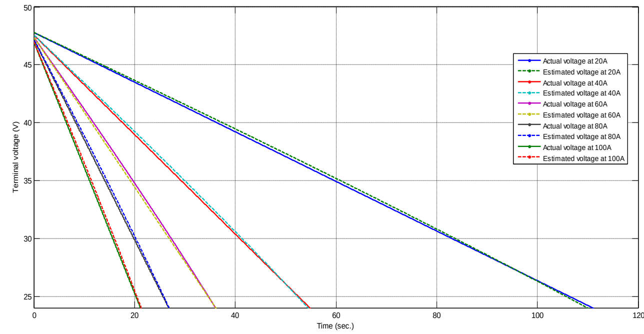

Figure 15: Actual and estimated terminalvoltage at different discharging currents.

VIII. SOC estimation

SOC is estimated by integrating ampere hour, as shownby the following equation [1].

$$SOC = SOC_0 - \int_0^t \frac{\eta I}{Q} dt \quad (12)$$

SOC_0 : initial value of SOC; η : ampere hour efficiency of UC.

Q : Electric charge Q is obtained from formula:

$$Q = C * U \quad (13)$$

C: Capacitance, U: Voltage.

Figure (16) shows the actual and estimated SOC from the proposed fuzzy modelling system at discharging current 8.3A.

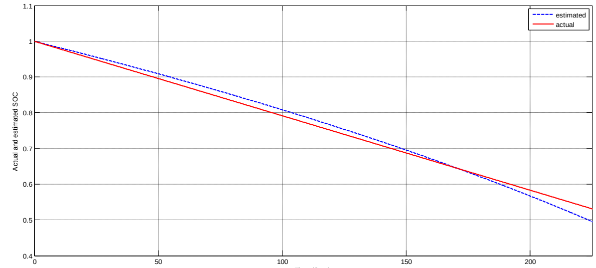

Figure 16: Actual and estimated SOC at 8.3A.

The available energy (E) is calculated by:

$$E = \frac{1}{2} CU^2 \quad (14)$$

VIIDynamic Performance of UC in EVs

In order to validate the UC model in EV applications, comparison tests for a High way (HW) driving cycle between MATLAB model and the proposed model are carried out. The demand current values from the power management controller are fed into both the proposed UC model and the UC MATLAB model. The working voltage calculated by the proposed model is compared to the MATLAB model output.Dynamic test is chosen so as to evaluate the UC's performance in EVs applications [8].Figure (17) shows the charging/discharging current profile emulating the H.W driving cycle.

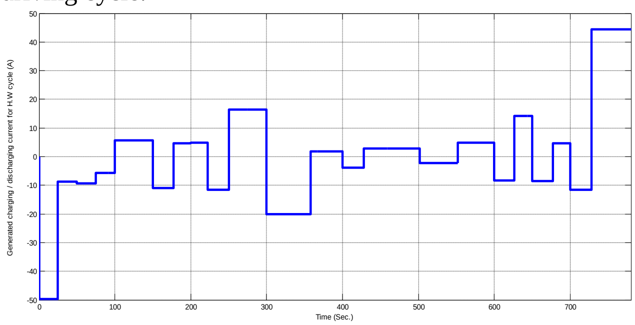

Figure (17): charging/discharging current profile for H.W driving cycle.

Figure (18) shows the comparison between proposed model estimated voltage and the terminal voltage calculated by MATLAB model over time in H.W driving Cycle. The maximum error in working voltage prediction is 1.28%. Figure (19) shows the UC estimated SOC in the HW driving cycle.

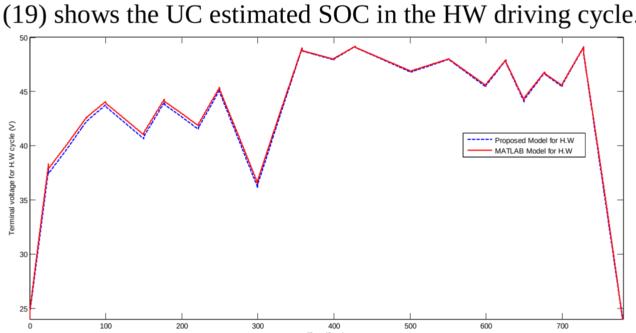

Figure 18: Working voltage duringtime slot of H.Wdrivingcycle for both proposed and MATLABmodels.

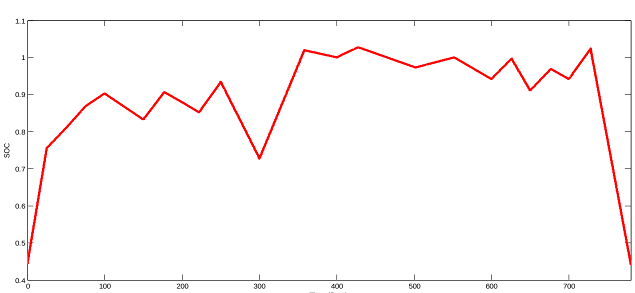

Figure 19: SOC estimation for a time slot ofH.Wdriving Cycle.

VIII Conclusions

A simplified practical model based on simple tests for capacitance estimation at different charging/discharging current rates and different surrounding temperatures for the UC has been carried out. A fuzzy modelling system has been applied for terminal voltage, and SOC estimation at different operating conditions, also the dynamic performance for UC has been verified for the proposed model for H. W driving cycle in EVs applications.The comparison between the proposed model and the MATLAB model shows a good agreement between the two models with an acceptable error.

The proposed model can be embedded on a single chip to enable the power management controllers either in EVs or renewable energy systems to take the corrective action for the optimal power flow.The estimation accuracy is acceptable with respect to the model simplicity and applicability in the real systems.

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