Ultracapacitors as auxiliary energy source in electric vehicles

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Abstract— **Recent and promising anticipated development in energy storage technologies demands adequate energy flow control strategies that will actuate opportunities spawned by this development. In this paper, energy management strategy that relies on fuzzy logic theory is proposed, i.e. controllers that govern functioning of the converters are designed using human reasoning and interrelated fuzzy logic rather than conventional PID controllers. It will be shown how the proposed energy management allows ultracapacitors to be used as an energy source that not only eliminates shortcomings of other sources but can also be used as a tool for optimization of system functioning as a whole.**

Keywords- energy storage; energy management; ultracapacitors

I. INTRODUCTION

It is evident that many factors influence the pace of development of electric vehicles (EV) and hybrid electric vehicles (HEV) industry but the fact that, for the first time, electric cars are the best-selling new cars, in Norway for instance, shows that this industry is on the rise and that appropriate combination of ecological awareness and financial subventions will cause the market to eventually shift towards these forms of transportation rather than transportation powered by fossil fuels. With an increased demand for vehicles that are partially (HEV) or completely (EV) powered by electrical energy, fuel cells, ultracapacitors (UCs) and battery-based electrical sources will find ever increasing utilization. It is important to point out that problems and opportunities of energy storage systems and energy management in EV are very similar to the problems of energy storage found in high power systems such as wind and solar farms. That makes this topic even more important for researchers[1].

In order to use these technologies, control strategies are being developed. All of them take into account the dynamics of chemical processes that occurs in them during energy exchange with, in case of (H)EV, the motor drive. Generally, traction depends on the energy supplied by chemical sources of energy- batteries, UCs, fuel cells and mechanical sources of energy- flywheels, but how that energy is exchanged is of crucial importance for the robustness, longevity and performance of the system. In most EV applications, the battery is used as the primary source of energy, while UCs are used to complement the battery's energy delivery characteristics. In HEV applications, fuel cell is used as the primary source of energy, while batteries and/or UCs are used as secondary energy sources[2][3].

Depending on the technology used in the production of different batteries, UCs and fuel cells, their characteristics differ, but underlying similarities and general attributes can be observed as well. For the sake of clarity of this paper's goals, general properties of the aforementioned energy sources are presented below.

Contrary to other papers that tackle the problems of energy flow in (H)EV, in which each energy source is evaluated as a distinctive source with separate functions[2][3], and little or no direct association with other sources in the system, in this paper UCs are seen exclusively as the *slave* energy source to the other energy sources that are seen as the *master* energy sources. It can be argued that the differences in these two standpoints are subtle, but they do result in a different control strategy.

The control strategy presented is constraited to the case of EV with batteries as the master energy source and ultracapacitors as the slave energy source. The objective is to examine how the system would behave if UCs are used as the source that observes the behavior of the master source and reacts on demand or when necessary. The results obtained from the simulations and presented in this paper and some further experimentation could show us that this approach facilitates the optimization of master energy sources and allows UCs to successfully complement master energy delivery characteristics.

The paper is divided into six chapters. After the introduction, a short overview of electrical energy sources is presented, but only to the extent that it is easier to understand why and how energy management is designed. The details that concern traction are omitted because they are of little importance to this work. Chapter III tackles the choice of converters and explains how batteries and UCs are modeled. In chapter IV, energy management and control structure are analyzed. Chapter V deals with simulation results, while chapter VI contains conclusions and future work considerations.

II. ENERGY SOURCES IN ELECTRIC VEHICLES

This chapter should provide a good starting point for the understanding of the ideas presented in the paper. A reader that is not familiar with these technologies would otherwise find it hard to follow and understand. Fuel cells are presented for educational purposes only, but the system that uses fuel cells instead of batteries could be easily derived from the system used here and thus they are not completely omitted from the paper.

A. Fuel cells

The fuel cell is a galvanic cell in which the chemical energy of fuel, hydrogen or some hydrocarbon like natural gas or methanol, is converted into electrical energy by means of electrochemical processes with air/oxygen. Fuel cell are usually coupled with a tank that stores fuel under high pressure. Essentially, fuel cells act as generators of the constant electromotive force and, as long as a constant flow of fuel and air is supplied, fuels cells should produce energy in consistent manner.

Unlike batteries, the construction of a fuel cell makes it suitable only for electric propulsion, i.e. fuel cells cannot be used to receive electric energy during regenerative braking. Fuel cell powered vehicles have the advantages of a longer driving range without a long battery charging time. In contrast to internal combustion engine powered vehicles, it has the advantage of high energy efficiency and much lower emissions. Currently, a major drawback of fuel cells is that they tend to be very expensive, as they are only starting to be commercially available. Next, the problem with fuel storage is that engineers are still trying to tackle it in economically and practically acceptable way. Also, proper infrastructure for this type of vehicles is nonexistent, which additionally impedes their usage[4][5].

B. Batteries

Batteries are electrochemical devices that convert chemical energy into electrical while discharging, and convert electrical energy into chemical while charging.

There are a number of parameters used to characterize the battery, namely specific energy, specific power, safety, performance, life span, and cost. All of these parameters are properties taken into account when designing the battery energy storage unit for an EV or an HEV. In general, batteries have good energy density, which means that they can be used for energy delivery during relatively long periods of time during which the power demand is slowly changing. On the other hand, batteries mostly have poor power density, which means that they are not fit to be used during short power peaks.

Several types of batteries can be found in the market today, mainly lead-acid, nickel based batteries (NiFe, NiCd, NiMH), and lithium based batteries (lithium polymer Li-P, Li-Ion). For high power applications, two main battery technologies of interest are NiMH and Li-Ion.

An important aspect of handling battery technology is battery lifetime and ageing process. There are a number of different factors that influence its lifetime:

- high temperature. High temperature has a negative influence on the battery's state of health.
- battery's lifetime is closely related to the number of charge/discharge cycles the battery has been subjected to. Also, battery life is shortened by frequent surges of energy.
- Battery should not be completely discharged nor overcharged. The rule of thumb is that battery should always work in the state-of-charge between 20 and 80% of its full capacity, although a single overcharge or over-discharge would not harm the battery too much.

Generally, battery life span is thus extended by slow, controlled flow of energy without fluctuations and within over-discharge/overcharge boundaries[4].

C. Ultracapacitors

Compared to batteries, UCs have a good power density, but poor energy density. This makes them unsuitable to use alone as an energy storage unit. However, their characteristics make them an appropriate auxiliary power source. Particularly, when used as energy storage units along with batteries, UCs can be used to smooth out power to the batteries and to relieve batteries from stress. Additionally, UCs are long lasting, and can go through a very large number of charge/discharge cycles (over one million). UCs are thus more resilient to fluctuations of energy often seen in cars (acceleration and deceleration)[6][7].

III. Battery and UC modeling and choice of converters

A. Battery model

A battery is modeled as a controlled voltage source in series with an internal resistance (Figure 1.). The controlled voltage source is calculated as follows:

$$E = E_0 - K\frac{Q}{Q-it} + Ae^{-B\cdot it} \qquad (1)$$

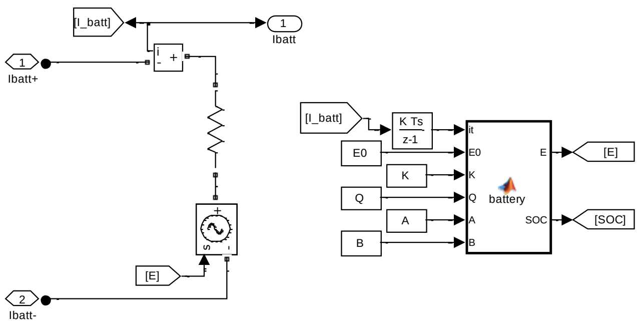


Figure 1. Simulink implementation of battery model.

This equation allows modeling of battery voltage as a function of state of discharge *it.* Quantities used in equation (1) are:

- $it = \int_0^t i_{bat}dt$ battery state of discharge [Ah]
- $A = E_{full} - E_{exp}$ voltage drop during exponential zone [V]
- $K = \frac{\left(E_{full}-E_{nom}+A\left(e^{-B\cdot Q_{nom}}-1\right)\right)\cdot(Q-Q_{nom})}{Q_{nom}}$ polarization voltage [V]
- $B = \frac{3}{Q_{exp}}$ charge at the end of exponential zone $[(Ah)^{-1}]$
- $E_0 = E_{full} + K + Ri - A$ battery constant voltage [V]

Internal resistance R is calculated using :

$$R = V_n\frac{1-\eta}{0.2\cdot Q_n} \qquad (2)$$

where η is battery efficiency, Q is maximum battery capacity and Q_n is rated capacity. To extract battery model parameters, three points on the battery discharge curve are used (Figure 2.):

- fully charged voltage
- end of exponential zone (voltage and charge)
- end of nominal zone (voltage and charge)

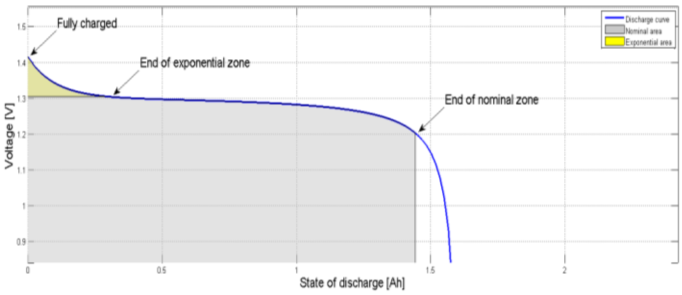


Figure 2. Typical battery discharge curve.

This way of battery modeling gives the same charge and discharge curves. The model used in this paper gives very good results when compared to actual batteries and its ease of implementation makes it suitable for usage. Interested reader can find more detailed explanation of this model in [8]. Figure 3. shows the response obtained by simulation.

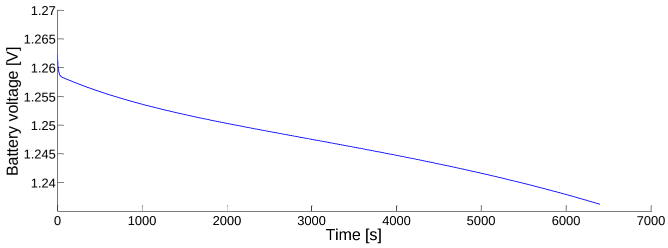


Figure 3. Battery voltage for 0.3 amps discharge current.

B. UC model

Over the last two decades many models of ultracapacitors have been developed. The differences between them are the result of different modeling objectives. Many factors influence the working state of the UC and its lifetime, so different models are trying to capture different characteristics of the UC in order to model its behavior in different circumstances and then draw conclusions about how the UC should be used. This paper uses the model proposed by Zubieta and Bonert[7]. It represents a model that can be easily implemented in some software packages, like Matlab, but still captures basic and most important physical properties of the UC.

Figure 4. shows the implemented Simulink model. This model consists of four parallel branches. The first three branches consist of a capacitor and a resistor, where the first branch has an additional voltage dependent capacitor.

Each branch depicts a different phase of the charging/discharging process – the first has the time constant in order of seconds (thus named immediate branch), the second has the time constant in order of minutes (delayed branch) and the third has the time constant longer than ten minutes (long term branch). The forth branch consists of the big resistor that should model self-discharge process.

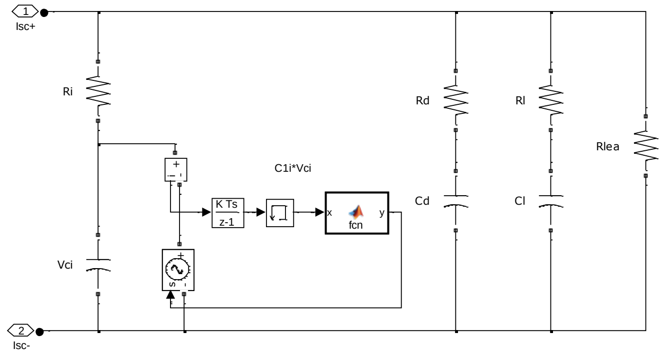


Figure 4. Model of UC.

Figure 5. shows the typical charging curve of the UC obtained by simulation.

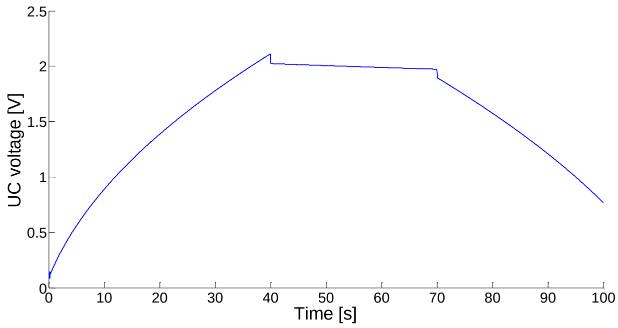


Figure 5. Characteristic UC terminal voltage.

C. Choice of converters

Some papers propose topology that assumes that the battery is connected directly to dc-link, but here both the battery and UC are connected to dc-link via converters, as Figure 6. suggests. The reason for this is better controllability of the battery charging/discharging process. Here the boost converter is used to step up the operating voltage of battery array which is around 200 volts (in Figure 3. only one battery was discharged) to 560 volts, which is standard dc-link voltage for three phase inverters and drives that use 400 volts line voltage. It is thus assumed that the battery is not being used for recuperation.

UCs array is connected to dc-link over the half-bridge converter. This converter is used because it is assumed that both directions of energy flow are permitted, so that UCs can absorb the excess of energy from dc-link and inject energy in case of shortages.

Synchronous drive is used for traction, powered by the three phase inverter that is controlled by standard vector control and space vector modulation. Further details about traction, inverter and control are omitted because they are not, as already explained, of great significance to this topic.

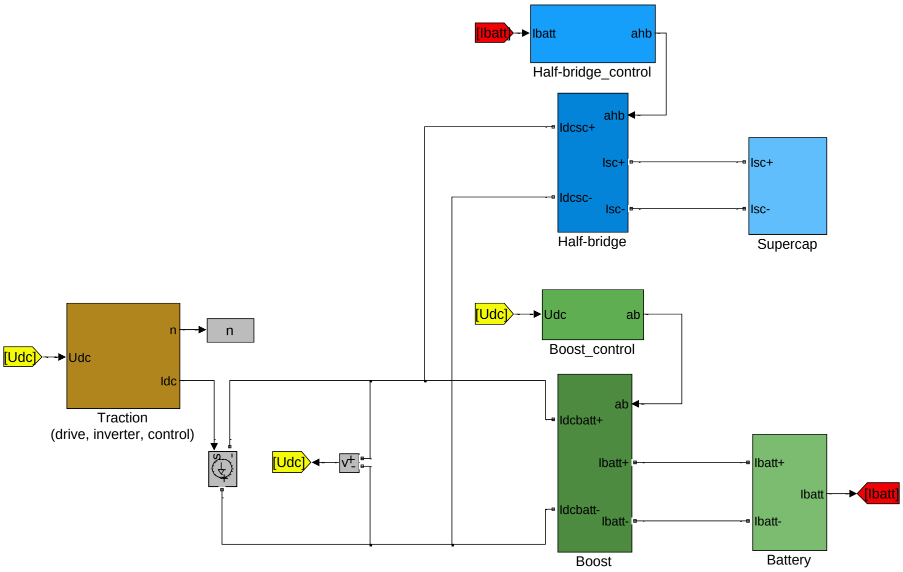


Figure 6. Simulink model of EV.

IV. ENERGY MANAGEMENT

From Figure 6. one can see how Simulink model is organized. Battery and UC banks are on the right, converters and control structures in the middle and traction on the left. It can be observed that there is a current source used in dc-link. This is so because in this simulation a ‘bridge’ between control of power drive, drive itself, inverter on the one side and the rest of simulation on the other is needed since the former is implemented using Simulink toolbox, while the latter (converters and energy sources) is simulated using SimPowerSystem toolbox. Voltmeter measures dc-link voltage and sends this information to the control of the inverter. On the other hand, the current that should be injected/taken from dc-link is calculated using the next expression:

$$I_{dc} = \sum_{x=1}^{q} S_x * i_x \qquad (3)$$

where q is the number of phases, S_x is the switching function for top transistor of x-th leg of inverter (where $S_x \in \{0,1\}$) and i_x is the current flowing through x-th phase.

In this paper, UCs are seen as the slave energy source, in the sense that they are slave to the master energy source, which is batteries. Their purpose is to ensure the best possible working state for the batteries which, as explained above, is the state of perpetual but constant flow of energy with as little fluctuations as possible. Thus UCs should ‘react’ every time the fluctuation in energy flow occurs. These fluctuations occur mostly during acceleration and deceleration. In other words, UC should flatten energy demand curve, and by doing so not only improve the performance of the system, but also the expected lifespan of the batteries.

One way of controlling energy flow in the aforementioned manner is by observing battery current and judging on the *change* in the battery current control half-bridge converter in such a way that injected/absorbed energy from the UC tends to lower this change. It can be seen that one of the outputs from the battery block in Figure 6. is the measured battery current, which is then fed to the half-bridge control block. The content of this block is shown in Figure 7.

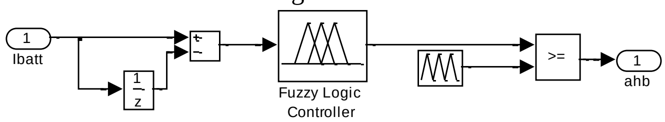
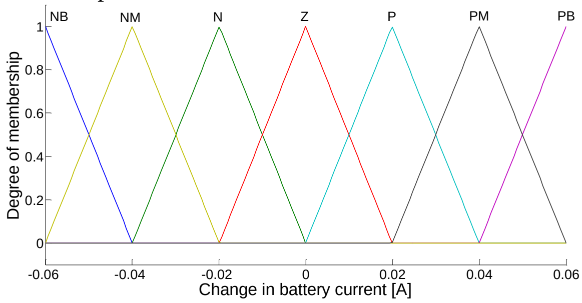


Figure 7. Control for half-bridge converter.

In case of this somewhat unusual control strategy, where the control of one source is dependent on the dynamics in another source, a good approach for designing control strategy is to use human reasoning. For instance, it is clear that when the motor is accelerating it will need a bigger current than when the drive is spinning at a constant speed. Thus, there will be a rise in the current drawn from dc-link, and this sudden rise reflects on the rise in the battery current. To prevent this from happening, UCs should inject energy in dc-link as soon as the change is detected. To do so, duty cycle of half-bridge should change. If the motor is accelerating aggressively, duty cycle should be dramatically lowered or enlarged depending on the regime. It is quite hard to quantify this change and some conventional control strategies would not be as practical as the control based on fuzzy logic.

Fuzzy logic controllers can already be found in numerous applications[9][10][11][12]. Their robustness, simplicity and ability to easily tackle nonlinear and very complex control problems make them very popular among researchers. Here they are used both for the control of the boost converter and control of the half-bridge converter, but only the fuzzy controller for half-bridge is explained in some detail.

The range of the change of the battery current without the usage of UCs was experimentally determined to be between 0.06 amperes and -0.06 amperes and thus this range is used in fuzzification block for the input variable, as it was reasonable to expect that the range of change should stay within these boundaries with UCs used. It should be noted that difference between current and previous value of battery current can be subjected to high influence of measurement noise but this problem wasn't addressed here, partially because it didn't cause any problems during simulation. The range of output variable, duty cycle, was set to be from zero to one. Figure 8. shows the equidistant distribution of membership functions for input and output variables.



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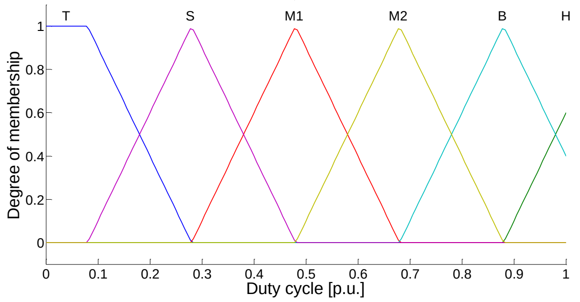


b)

Figure 8. Membership functions: a) change in battery current, b) duty cycle.

The distribution of input variable was fixed at the beginning of the tuning process, while the distribution of membership functions for duty cycle is the result of the tuning process. Number of membership function was chosen intuitively. Rule base that consist of IF-THEN rules was generated by reasoning how duty cycle should change with the change in the battery current. For example, if the change in the battery current is negative big (NB), duty cycle for half-bridge converter should be huge (H), because this duty cycle would stop this change in current sufficiently quickly. The following set of rules was obtained:

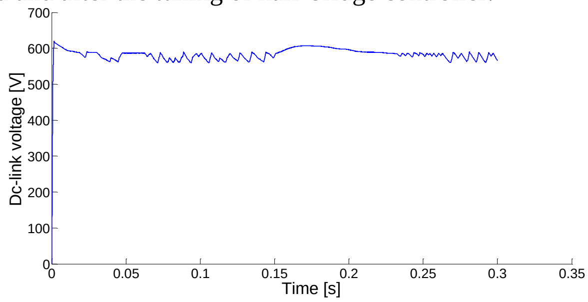
- 1. If (dIbatt is NB) then (a is H) (1)
- 2. If (dIbatt is NM) then (a is B) (1)
- 3. If (dIbatt is N) then (a is M2) (1)
- 4. If (dIbatt is Z) then (a is M1) (1)
- 5. If (dIbatt is P) then (a is S) (1)
- 6. If (dIbatt is PM) then (a is S) (1)
- 7. If (dIbatt is PB) then (a is T) (1)

For deffuzification centroid method is used, while for 'and' method min operation is used and for 'or' method max operation is used. In the next section simulation results will demonstrate how the system behaves with and without UCs.

V. SIMULATION RESULTS

Figure 9. a) shows dc-link voltage without UCs being used. Fluctuations are rather big and are not caused only by the oscillating load but also by the poorly tuned boost controller.

Fuzzy controller for boost converter was purposefully left poorly tuned because in this way time consuming tuning was avoided, but also half-bridge control could have been put to a test to maybe even unrealistic circumstances. This was reasonable because from the battery's standpoint there was no difference in fluctuations caused by the variable load and those caused by the poorly tuned controller. Of course, after the tests were finished, boost converter was properly tuned, but tests with this configuration are omitted. Figure 9. b) shows dc-link voltage with the same control for boost converter as used in picture under a), but now with the UCs used and after the tuning of half-bridge controller.



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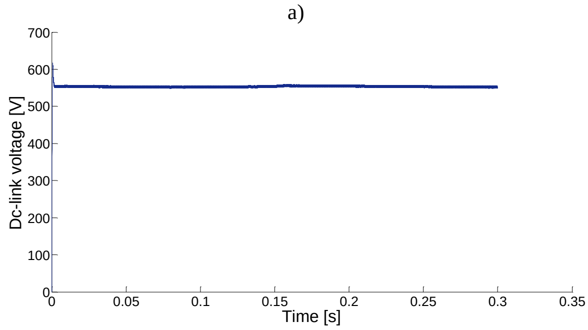
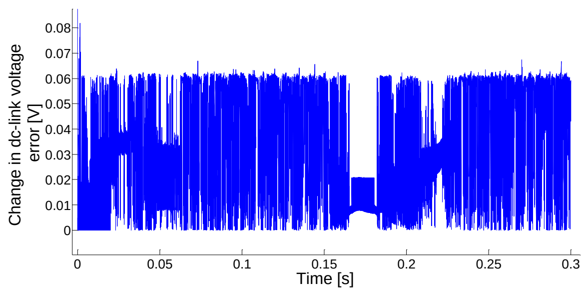


b)

Figure 9. Dc-link voltage without a) and with b) UCs.

It is obvious that voltage is now much steadier and this certainly reflects on battery stress. Figure 10. shows the change in dc-link voltage error. Again, significant improvement is visible. Without the UCs, the change in error oscillates within the range of 0.1 volts, while with UCs within the range of 0.01 volts.



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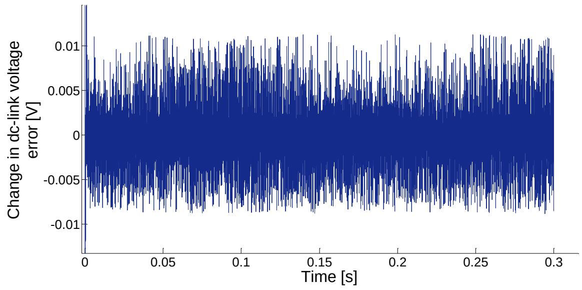
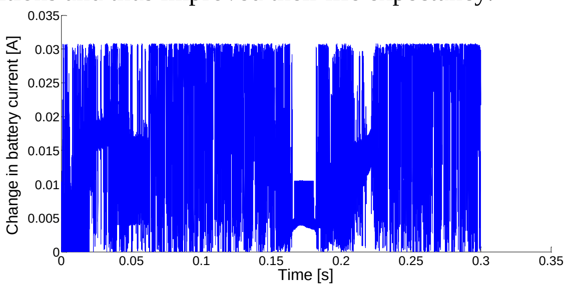


b)

Figure 10. Change in dc-link voltage error without a) and with b) the UCs.

Figure 11. depicts the change in the battery current. In the case without the UCs, it oscillates within the range of 0.03 amperes, while in the case with the UCs used the change oscillates within the range of $6*10^{-4}$ amperes and thus UCs have successfully helped in optimizing battery working conditions and thus improved their life expectancy.



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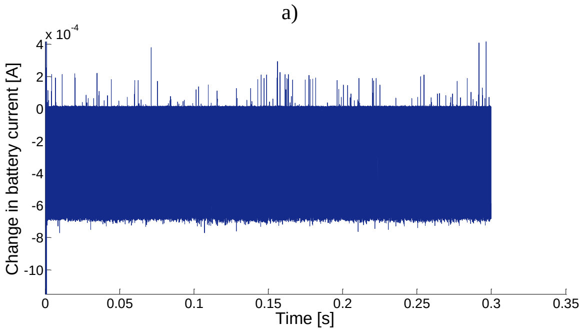
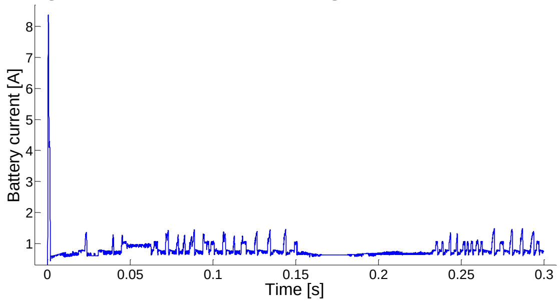


b)

Figure 11. Change is battery current without a) and with b) the UCs.

Figure 12. shows the battery current. It can be seen that the peak current is lowered. In cases of sudden change in the battery current, fuzzy controller of half-bridge is tuned to dramatically change duty cycle and thus inject energy in dc-link and stop the change. In this way surges of energy caused by braking and acceleration are mitigated.



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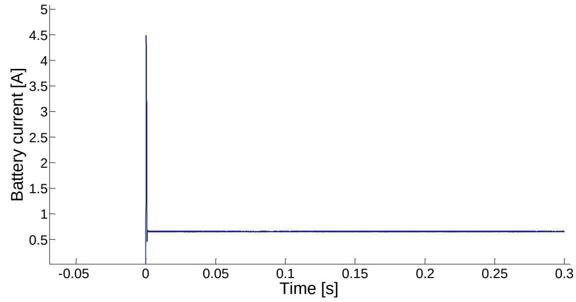

b)

Figure 12. Battery current without a) and with b) the UCs.

Figure 13. show a peak in the UCs' current of over 40 amperes which suggests that the most of the energy needed is supplied from UC bank rather than from battery. Mean value then drops but not to zero which suggests that additional tuning should be done in order to make UCs' current drop to zero so that they save energy for acceleration.

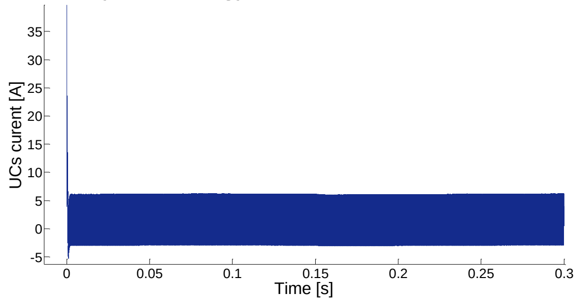

Figure 13. The UCs current.

Figure 14. shows the motor speed curve, which suggests that after acceleration the speed reference is changed (at 0.15 seconds), so that breaking could be simulated.

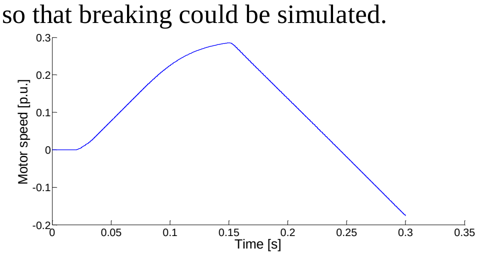

Figure 14. Motor speed.

VI. CONCLUSIONS AND FUTURE WORK CONSIDERATIONS

Based on the simulation results shown in the previous chapter it can be concluded that UCs improve working conditions of the batteries and thus, by judging what causes the batteries to deteriorate, increase their life expectancy and can be used to optimize system performance by using simple and straightforward control strategy. By observing battery voltage, it has been shown that fuzzy control can govern UCs energy flow in the required manner. In some future work, though, these improvements could be quantized in more detail. Next, a bigger motor drive could be used, so that more serious braking and acceleration conditions could be simulated. Also, the research of how easily this control strategy could be used in case of HEV or EV with fuel cells can be pursued.

VII. REFERENCES

[1] Phatiphat Thounthong, Stephane Rael "The benefits of hybridization", IEEE Ind. Electron. Mag., vol. 3,issue 3, pp. 25-37, Sep. 2009.

[2] M. Ortúzar, J. Moreno, J. Dixon, "Ultracapacitor-Based Auxiliary Energy System for an Electric Vehicle: Implementation and Evaluation", IEEE Trans. on Ind. Electron., vol. 54, no. 4, pp. 2147-2156, Aug. 2007.

[3] S. Lukic, S. Wirasingha, F. Rodriguez, J. Cao, A. Emadi "Power Management of an Ultracapacitor/Battery Hybrid Energy Storage System in a HEV", IEEE Vehicle Power and Propulsion Conference, pp. 1-6, VPPC '06, 2006..

[4] Mehrdad Eshani, Yimin Gao, Sebastien E. Gay, Ali Emadi "Modern electric, hybrid electric and fuel cell vehicles", CRC Press LCC, New York, 2005.

[5] Srdjan M. Lukic, Jian Cao, Ramesh C. Bansal, Fernandor Rodriguez, Ali Emadi "Energy storage systems for automotive applications", IEEE Trans. on Ind. Electron., vol 55. Issue 6., pp. 2258-2267, June 2008.

[6] Dimitri Torregrossa, Maryam Bahramipanah, Emil Namor, Rachid Cherkaoui, Mario Paolone, "Improvement of dynamic modeling of supercapacitor by residual charge effect estimation", IEEE Trans. on Ind. Electron., vol. 61, no. 3, pp. 1345-1354, March 2014.

[7] L. Zubieta, R. Bonert, "Characterization of Double-Layer Capacitors (DLCs) for Power Electronics Applications", IEEE Trans. on Ind. App., vol. 36, issue 1., pp. 199-205, Jan.2000.

[8] Olivier Tremblay, Louis-A. Dessaint, Abdel-Illah Dekkiche "A generic battery model for the dynamic simulation of hybrid electric vehicles", IEEE Vehicle Power and Propulsion Conference, VPPC'07, pp. 284-289, 2007.

[9] E. Adzic, Z. Ivanovic, M. Adzic, V. Katic, "Maximum Power Search in Wind Turbine Based on Fuzzy Logic Control", Acta Polytechnica Hungarica, vol. 6, no. 1, pp. 131-149, 2009.

[10] T. Kottas, Y. Boutalis, A. Karlis, "New Maximum Power Point Tracker for PV Arrays Using Fuzzy Controller in Close Cooperation With Fuzzy Cognitive Networks", IEEE Trans. on Energy Conv., vol. 21, no 3, pp. 793-803, Sept. 2006.

[11] Jiangtao Cao, Ping Li, Honghai Liu "An Interval Fuzzy Controller for Vehicle Active Suspension System", IEEE Trans. on Intelligent Transp. Systems, vol.11, no. 4, pp. 885-895, Dec. 2010.

[12] X. Li, "Fuzzy adaptive Kalman filter for wind power output smoothing with battery energy storage system", IET Renew. Power Gener., 2012, Vol. 6, Iss. 5, pp. 340–347.