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# INHERIT

SOLUȚII INOVATIVE PENTRU RANDAMANET RIDICAT IN DOMENIUL TRANSPORTULUI ELECTRIC URBAN

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| ETAPA | 1. Dimensionarea unitatii de stocare cu ultra-condensatori |
| ACTIUNEA | 1.1. Analiza stadiulului actual pentru selectia metodelor de dimensionare a unitatii de stocare a energiei |
| PERIOADA | 31/12/2021 |
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| DATA | 10.11.2020 |

## 1.1. Analiza stadiulului actual pentru selectia metodelor de dimensionare a unitatii de stocare a energiei

### 1_2014_Modeling of the Electrical and Thermal Behaviors of an Ultracapacitor

1. Lee, J., Yi, J., Kim, D., Shin, C. B., Min, K.,Choi,J., Lee, H., "Modeling of the Electrical and Thermal Behaviors of an Ultracapacitor", Energies 2014, 7, 8264-8278.

**Abstract:** This paper reports a modeling methodology to predict the electrical and thermal behaviors of a 2.7 V/650 F ultracapacitor (UC) cell from LS Mtron Ltd. (Anyang, Korea). The UC cell is subject to the charge/discharge cycling with constant-current between 1.35 V and 2.7 V. The charge/discharge current values examined are 50, 100, 150, and 200 A. A three resistor-capacitor (RC) parallel branch model is employed to calculate the electrical behavior of the UC. The modeling results for the variations of the UC cell voltage as a function of time for various charge/discharge currents are in good agreement with the experimental measurements. A three-dimensional thermal model is presented to predict the thermal behavior of the UC. Both of the irreversible and reversible heat generations inside the UC cell are considered. The validation of the three-dimensional thermal model is provided through the comparison of the modeling results with the experimental infrared (IR) image at various charge/discharge currents. A zero-dimensional thermal model is proposed to reduce the significant computational burden required for the three-dimensional thermal model. The zero-dimensional thermal model appears to generate the numerical results accurate enough to resolve the thermal management issues related to the UC for automotive applications without relying on significant computing resources.
**Keywords:** ultracapacitor (UC); model; electrical behavior; thermal behavior

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### 2_2010_ Lithium batteries and ultracapacitors alone and in combination in hybrid vehicles: Fuel economy and battery stress reduction advantages

2. Burke, A., Miller, M., Zhao, H., "Lithium batteries and ultracapacitors alone and in combination in hybrid vehicles: Fuel economy and battery stress reduction advantages", EVS-25 Shenzhen, China, Nov. 5-9, 2010 The 25th World Battery, Hybrid and Fuel Cell Electric Vehicle Symposium & Exhibition.

**Abstract** – Most vehicles presently use batteries for energy storage, but there are vehicle designs in which ultracapacitors alone or in combination with batteries can increase the efficiency of the vehicle and in addition lead to significantly longer battery cycle life. Ultracapacitors can be used alone in charge sustaining hybrid vehicles (HEVs) if the energy storage requirement is less than 150Wh. Simulations show that when ultracapacitors are used alone in HEVs, the roundtrip efficiency of the energy storage is 95-98% and the engine efficiency in on/off operation can be maintained near the peak efficiency value. Vehicle simulations were also run for plug-in hybrid vehicles (PHEVs) using advanced batteries with

high energy density (>300 Wh/kg). The simulations were run with the batteries alone and in combination with ultracapacitors. Simulation results for the electric useage (Wh/mi) and all-electric range and fuel economy (mpg) for the PHEVs using batteries in combination with ultracapacitors and batteries alone are presented. In all cases, the vehicles operate in a more ideal manner using batteries in combination with ultracapacitors than with the batteries alone. In addition, the dynamic stress on the batteries due to high current pulses are greatly reduced using the ultracapacitors.

**Keywords:** ultracapacitors, batteries, combination, plug-in hybrid

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**3_2010_Characterization, Analysis and Modeling of an Ultracapacitor**

3. Fuyuan, Y., Languang, L., Yuping, Y., He, Y., "Characterization, Analysis and Modeling of an Ultracapacitor", Shenzhen, China, Nov. 5-9, 2010 The 25th World Battery, Hybrid and Fuel Cell Electric Vehicle Symposium & Exhibition.

**Abstract—** Ultracapacitors are potentially promising power-augmentation devices in hybrid powertrains. A commercial ultracapacitor module was characterized under standard procedures to assess its performance. Tests were carried out on a platform, with which ambient temperature can be regulated and charge/discharge procedures can be implemented. Key parameters of the ultracapacitor module obtained from tests were used to develop a control-oriented ultracapacitor model proposed in the paper. Simulation results of this model in a stable discharge procedure and in dynamic procedures (i.e. driving cycles) showed excellent agreement with results obtained from experiments, indicating that the ultracapacitor model is accurate enough to be used in further electric powertrain control simulation.

**Keywords—** ultracapacitor, coulometric efficiency, ESR, FreedomCAR, ultracapacitor model

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**4_2014_Ultracapacitors in the Place of Batteries in Hybrid Vehicles**

4. Burke, A., Miller, M., Zhao, H., "Ultracapacitors in the Place of Batteries in Hybrid Vehicles", European Electric Vehicle Congress Brussels, Belgium, 3rd – 5th December 2014

**Abstract:** This paper is concerned with the use of ultracapacitors in hybrid vehicles in place of batteries. In the case of the mild, charge sustaining hybrid, the ultracapacitors would replace a lithium or nickel metal hydride battery: for a stop-start micro-hybrid, the capacitors would be used in combination with a lead-acid battery with the capacitors starting the engine, accepting energy during regenerative braking, and providing accessory loads during relatively short stop periods. Test data are shown for the performance of advanced carbon/carbon and hybrid lithium ultracapacitors indicating higher energy density (more than 2X) than that of commercially available carbon/carbon cells from Maxwell and NessCap. The advanced devices showed no sacrifice in high power capability in order to achieve the higher energy density. Simulations of mid-size passenger cars using the advanced ultracapacitors in micro-hybrid

and charge sustaining hybrid powertrains were performed using the Advisor vehicle simulation program modified with special routines at UC Davis. The influence of the ultracap technology and the size (Wh) of the energy storage unit on the fuel economy improvement was of particular interest. Significant improvements in fuel usage were predicted for all the hybrid powertrains using ultracapacitors for energy storage. The results for the micro-hybrids indicated that a 7-25% improvement in fuel economy can be achieved using a small electric motor (4 kW) and small ultracapacitor units (5-10 kg of cells). The fuel economy improvements for the mild-HEV ranged from over 70% on the FUDS to 20% on the US06 driving cycle. In both micro and mild-HEVs, the differences in the fuel economies projected using the advanced ultracapacitor technologies were very small. It is possible to store more energy using the advanced ultracapacitors, but the fuel savings appear be unaffected. The primary advantage of the advanced ultracapacitors is that the energy storage unit is smaller, lighter, and lower cost and there is more reserve energy storage to accommodate a wider range of vehicle operating conditions. In the mild hybrids, the fuel economy improvement was greater using ultracapacitors than with a lithium battery primarily because of the higher round-trip efficiency of the ultracapacitors.

**Keywords**: ultracapacitor, hybrid electric vehicle, micro-hybrid, mild-hybrid, fuel economy

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**5_2019_Energy Management Strategy of a PEM Fuel Cell Excavator with a Supercapacitor/Battery Hybrid Power Source**

5. Do, T.C. ; Truong, H.V.A. ; Dao, H. V. ; Ho, C.M. ; To, X.D.; Dang, T.D. and Ahn, K.K., Energy Management Strategy of a PEM Fuel Cell Excavator with a Supercapacitor/Battery Hybrid Power Source, *Energies* (ISSN 1996-1073; CODEN: ENERGA), November 2019.

**Abstract:** Construction machines are heavy-duty equipment and a major contributor to the environmental pollution. By using only electric motors instead of an internal combustion engine,
the problems of low engine e_ciency and air pollution can be solved. This paper proposed a novel
energy management strategy for a PEM fuel cell excavator with a supercapacitor/battery hybrid
power source. The fuel cell is the main power supply for most of the excavator workload while the battery/supercapacitor is the energy storage device, which supplies additional required power and recovers energy. The whole system model was built in a co-simulation environment, which is a combination of MATLAB/Simulink and AMESim software, where the fuel cell, battery, supercapacitor model, and the energy management algorithm were developed in a Simulink environment while the excavator model was designed in an AMESim environment. In this work, the energy management strategy was designed to concurrently account for power supply performance from the hybrid power sources as well as from fuel cells, and battery lifespan. The control design was proposed to distribute the power demand optimally from the excavator to the hybrid power sources in di_erent working conditions. The simulation results were presented to demonstrate the good performance of the system. The e_ectiveness of the proposed energy management strategy was validated. Compared with the

conventional strategies where the task requirements cannot be achieved or system stability cannot be accomplished, the proposed algorithms perfectly satisfied the working conditions.
**Keywords**: hybrid excavator; PEM fuel cell; supercapacitor; battery; energy management

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**6_2020_Design and experimental verification of a fuel cell/supercapacitor passive configuration for a light vehicle**

6. Xun, Q. ; Lundberg, S. ; Liu, Y., Design and experimental verification of a fuel cell/supercapacitor passive configuration for a light vehicle, Journal of Energy Storage, 2020, https://www.mathworks.com/help/physmod/sps/powersys/ref/supercapacitor. html.

**Abstract:** The fuel cell/supercapacitor passive configuration without using any DC/DC converters is promising in automotive applications as it can downsize the fuel cell stack, maintain the peak power capability, improve the system efficiency, and remove the need of additional control. This paper presents the design and characterization of a fuel cell/supercapacitor passive hybrid system for a 60 V light vehicle. A detailed design procedure for the passive hybrid test platform is presented with each component modelled and experimentally verified. The voltage error of the fuel cell and the supercapacitor model in the steady state is within 2% and 3%, respectively. Experimental results also validate the function of the passive configuration under conditions of a step load and a drive cycle. The simulation model of the passive hybrid system matches the measurements when a step load current is applied. The supercapacitor provides the transient current due to its smaller resistance while the fuel cell handles the steady state current, which makes it possible to downsize the fuel cell stack. For the drive cycle examined in this paper, the fuel cell stack can be downsized to one third of the load peak power.
**Keywords**: Fuel cell Supercapacitor Passive configuration Power distribution Drive cycle

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**7_2020_Battery super-capacitor hybrid system forelectrical vehicle transportation's systems – an energy integrated approach**

7. Rayguru, M.M., Madichetty, S., Mishra, S.,Battery super-capacitor hybrid system forelectrical vehicle transportation's systems –an energy integrated approach, Journals IET Energy Systems Integration, eISSN 2516-8401, 2020.

**Abstract:** Hybrid energy storage system (HESS) generally comprises of two different energy sources combined with power electronic converters. This article uses a battery super-capacitor based HESS with an adaptive $\lambda$ tracking control strategy. The proposed control strategy is to preserve battery life, while operating at transient conditions of the load. The proposed control strategy comprises of a gain adaptation algorithm, combined with a dead-zone induced feedback. The closed loop system under the influence of this feedback scheme, is proved to be is robust against variation in operating conditions, parameter uncertainties and measurement

noise. Unlike the earlier adaptive controllers for HESS, this strategy does not involve any parameter adaptation routine. Hence, this controller is computationally less intensive and better suited for practical applications involving uncertain environmental conditions. The efficacy of the proposed strategy is verified through numerical simulations and experimental scenarios.

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**8_2020_Mathematical Model of Self-Discharge for Supercapacitors**

8. Fenol, S.D., Caluyo, F. S., Mathematical Model of Self-Discharge for Supercapacitors, Journal of Engineering Science and Technology Review 13 (5) (2020) 77 – 81.

**Abstract:** Self-discharge is one of the most important considerations in manufacturing supercapacitors. This paper discussed two dynamic mathematical models of self-discharge behavior of supercapacitor from the concept of regular capacitor mechanisms and impedance of an R-C circuit, and constant phase elements (CPE), impedance of R-CPE, and fractional order derivatives. The mathematical model was derived from each other to show their equality and relationships.
**Keywords:** Supercapacitor, Self – Discharge, CPE

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9_2017_**Récupérationd'énergiepoursystèmeintégrémoteur roue, application au véhicule électrique**

9. Itani,K., Récupération d'énergie pour système intégré moteur roue, application au véhicule électrique, Energie électrique, Université Paris Saclay (COmUE), 2017. Français.
**Thèse présentée et soutenue à Versailles, le 03 Juillet 2017**

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**10_2016_Electrochemical Double Layer Capacitor Electro-thermal Modelling**
10. Sarwar, W., Marinescu, M., Green, N., Taylor, N., Offer, G.,Electrochemical Double Layer Capacitor Electro-thermal Modelling, Journal of Energy Storage, Volume 5, February 2016, Pages 10-24.

**Abstract:** An electro-thermal model is generated to predict the internal temperature of an Electrochemical Double-Layer Capacitor (EDLC) undergoing high current charging/discharging. The model is capable of predicting the electrical and thermal behaviour of a cell over a wide range of operating conditions. Spiral symmetry is used to reduce the heat generation and transfer model from 3D to a pseudo-3D, which runs faster without losing fidelity.
Unlike existing models, each element in the developed model retains physical meaning and the electrical model is coupled with a high-fidelity thermal model including material geometries, thermal properties and air gaps. Unequal entropy is calculated using first principles, included in the model and compared to experimental data, and shown to be valid.

More entropic heat is generated at the positive electrode than the negative in a typical EDLC, and there is little spatial variation of heat generation rate within the jelly-roll.
The heat-transfer model predicts temperature variations within a cell; this study examines these variations for multiple conditions. Whilst undergoing high current charging (2 seconds, 400A, 650F cell), a temperature gradient in excess of 3.5°C can be generated between the positive terminal and the jelly-roll. The time dependent spatial temperature distribution within a cell is explored.

**Keywords:** Ultracapacitor Modelling, High-Fidelity Thermal Model, Internal Temperature Distribution, Electrode Dependent Entropy, Electro-thermal, Temperature Dependant Electrical Model

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**11_2007_Frequency, thermal and voltage supercapacitor characterization and modeling**

11. Rafika,F., Gualous, H., Gallay, R., Crausaz, Berthon, A., Frequency, thermal and voltage supercapacitor characterization and modeling, Journal of Power Sources 165 (2007) 928–934.

**Abstract:** A simple electrical model has been established to describe supercapacitor behaviour as a function of frequency, voltage and temperature for hybrid vehicle applications. The electrical model consists of 14 RLC elements, which have been determined from experimental data using electrochemical impedance spectroscopy (EIS) applied on a commercial supercapacitor.The frequency analysis has been extended for the first time to the millihertz range to take into account the leakage current and the charge redistribution on the electrode. Simulation and experimental results of supercapacitor charge and discharge have been compared and analysed. A good correlation between the model and the EIS results has been demonstrated from 1 mHz to 1 kHz, from −20 to 60 ◦C and from 0 to 2.5V.

**Keywords:** Supercapacitor modeling; Supercapacitor thermal characterization; Supercapacitor dynamic behavior

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**12_2012_ Sizing of Ultracapacitors and Batteries for a High Performance Electric Vehicle**

12. Martinez, W., Cortes, C., Munoz, L.,"Sizing of Ultracapacitors and Batteries for a High Performance Electric Vehicle", IEEE International Electric Vehicle Conference (IEVC), March 2012, DOI: 10.1109/IEVC.2012.6183242

**Abstract**—One of the main problems in autonomous electric vehicles is the energy storage, because of the use of low capacity batteries with low power delivery. This work shows a way to deal with the energy storage problem on a high performance electric vehicle capable to run a quarter of a mile in 10 seconds. The concept design of the system combines different storage technologies, ensuring the appropriate power delivery to the motors during the short time needed. In order to achieve this goal, it is necessary to determine the optimum size of each storage element to guarantee the vehicle high performance. This work proposes a methodology for evaluating different characteristics of ultracapacitors and batteries, such as mass, volume and cost. After determining the amount of the storage technologies, it is possible

to make an optimal power management in the vehicle, that combined with the control of the motors improves the performance of the electric vehicle.

**Keywords**—High Performance Electric Vehicle, Batteries, Ultracapacitors, Storage System.

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**13_2010_ Common energetic macroscopic representation and unified control structure for different hybrid electric vehicles (THESE)**

13. Chen, K., "Common energetic macroscopic representation and unified control structure for different hybrid electric vehicles", these, Universite Lille 1, 2010.

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**14_2012_ Modelisation, Conception et Experimentation d-un vehicule hybride leger pour usages urbains (THESE)**

14. Mbemba, L. B., "Modelisation, Conception et Experimentation d-un vehicule hybride leger pour usages urbains", These de Doctorat, Universite de FRANCHE-COMTE, 2012.

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**15_2015_ Hardware-In-the-Loop simulation of an electric vehicle using Energetic Macroscopic Representation (THESE)**

15. Jokela, T., "Hardware-In-the-Loop simulation of an electric vehicle using Energetic Macroscopic Representation", Master-s Thesis, AALTO UNIVERSITY, 2015.

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**16_2016_ Gestion d-energie de vehicules multi-sources electriques et hybrides au travers de la representation energetique macroscopique (THESE)**

16. Castaings, A., "Gestion d-energie de vehicules multi-sources electriques et hybrides au travers de la representation energetique macroscopique", These de Doctorat, UNIVERSITE de LILLE, 2016.

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**17_2019_ Methodology applied to couple 1D-3D models on HPC in context of electric vehicle FIAT 500e thermal management design**

17. Tobia, N., Ponchant, M., "Methodology applied to couple 1D-3D models on HPC in context of electric vehicle FIAT 500e thermal management design", 32ndElectric Vehicle Symposium (EVS32)Lyon, France,May19-22, 2019.

**Summary:** In this article, a smart methodology of coupling simulation between Simcenter Amesim and Simcenter Star-CCM+ is defined. It has been implemented to improve, from a thermal point of view, both 1D Model in the Loop simulation and 3D Computational Fluid Dynamics simulation; in fact, CFD receives from 1D MIL more accurate boundary conditions, and in turn gives back results to MiL that uses more accurate data to run. Furthermore, CFD simulation has been performed by using High Performance Computing (HPC). In this way thermal management development is improved with higher level of fidelity for the electric vehicle.

**Keywords:** Model in the Loop, Computational Fluid Dynamics, thermal management

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**18_2018_ Modern Electric, Hybrid Electric and Fuel Cell Vehicles (BOOK)**

18. Eshani, M., Gao, Y., Longo, S., Ebrahimi, K., "Modern Electric, Hybrid Electric and Fuel Cell Vehicles", CRC Press, Third Edition, 2018 by Taylor & Francis Group, LLC.

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**19_2018_ Stratégie intelligente de gestion du système énergétique global d'un véhicule hybride (THESE)**

19. Joud, L., "Stratégie intelligente de gestion du système énergétique global d'un véhicule hybride", These de Doctorat, Université Bourgogne Franche-Comté, 2018. Français.

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**20_2011_ Fuel Cell, Battery and Supercapacitor Hybrid System for Electric Vehicle: Modeling and Control via Energetic Macroscopic Representation**

20. Gauchia, L., Bouscayrol, A., Sanz, J., Trigui, R., Barrade, P.," Fuel Cell, Battery and Supercapacitor Hybrid System for Electric Vehicle: Modeling and Control via Energetic Macroscopic Representation", Vehicle Power and Propulsion Conference, Sep 2011, CHICAGO, United States.

**Abstract-** Nowadays, no electrochemical energy system presents a competitive operation if compared with internal combustion engine, which is the reason for combining electrochemical energy systems to obtain a hybrid energy storage system. This paper presents a fuel cell-battery-ultracapacitor system for vehicle application. The objective of this paper is to present the Energetic Macroscopic Representation (EMR) of the multisource power system.

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**21_2015_Modeling, Evaluation and Simulation of a Supercapacitor Module for Energy Storage Application**

21. Cultura II, A.B., Salameh, Z. M., "Modeling, Evaluation and Simulation of a Supercapacitor Module for Energy Storage Application", International Conference on Computer Information Systems and Industrial Applications (CISIA 2015).

**Abstract**—This paper presents the electrical and mathematical model of the supercapacitor. The equivalent mathematical model derived from electrical model was used to simulate the voltage response of the supercapacitor. The model has been implemented using Matlab software program. Simulation and experimental results of the voltage charging/discharging of the supercapacitor are compared. It was found out that the results obtained using the model is in good agreement with the experimental one. Moreover a mathematical model for the efficiency as a function of discharge time was developed and presented. The effect of charge/discharge rate on the supercapacitor's temperature is also experimentally considered. Experiments show that during charging the temperature rises more than during discharging.

**Keywords-**Supercapacitor;Efficiency;Energy Storage; Temperature

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**22_2017_ Impact of Heating System on the Range of an Electric Vehicle**

22. Horrein, L., Bouscayrol, A., Lhomme, W., Depature, C., "Impact of Heating System on the Range of an Electric Vehicle", IEEE TRANSACTIONS ON VEHICULAR TECHNOLOGY, VOL. 66, NO. 6, JUNE 2017.

**Abstract**—For an accurate evaluation of the driving range of an electric vehicle (EV), many conditions must be considered (road profile, traffic influence, etc.). However, a cabin heating system is not often considered despite its significant impact. In this paper, the impact of the cabin heating system is studied on the driving range of an EV. A real EV is used as a reference. A multidomain model is developed and validated by experimental results on the vehicle. From this validated model, the impact of the heating system on the range is evaluated up to 30% in cold climatic conditions. In a classical approach, an ecodriving mode enables an increase in the range by reducing the vehicle acceleration and velocity. When considering the heating system, the energy balance is more complex: the eco-driving mode can lead to an over-consumption of energy. A better compromise is required as a function of the climatic condition.

**Index Terms**—Electric vehicle (EV), energetic macroscopic, heating system, range, representation, thermal regulation.

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**23_2018_ A review of supercapacitor modeling, estimation, and applications: A control / management perspective**

23. Zhang,L., Huc,X., Wanga,Z., Suna,F., Dorrell,D.G., "A review of supercapacitor modeling, estimation, and applications: A control / management perspective", Renewable and Sustainable Energy Reviews 81 (2018), 1868-1878.

**Abstract:** Supercapacitors (SCs) have high power density and exceptional durability. Progress has been made in their materials and chemistries, while extensive research has been carried out to address challenges of SC management. The potential engineering applications of SCs are being continually explored. This paper presents a review of SC modeling, state estimation, and industrial applications reported in the literature, with the overarching goal to summarize recent research progress and stimulate innovative thoughts for SC control/management. For SC modeling, the state-of-the-art models for electrical, self-discharge, and thermal behaviors are systematically reviewed, where electrochemical, equivalent circuit, intelligent, and fractional-order models for electrical behavior simulation are highlighted. For SC state estimation, methods for State-of-Charge (SOC) estimation and State-of-Health (SOH) monitoring are covered, together with an underlying analysis of aging mechanism and its influencing factors. Finally, a wide range of potential SC applications is summarized. Particularly, co-working with high energy-density devices constitutes hybrid energy storage for renewable energy systems and electric vehicles (EVs), sufficiently reaping synergistic benefits of multiple energy-storage
units.

**Keywords:** Energy storage, Supercapacitor Modeling, State estimation, Industrial applications

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**24_2018_ Multisource Coordination Energy Management Strategy Based on SOC Consensus for a PEMFC–Battery–Supercapacitor Hybrid Tramway**

24. Han, Y., Wang.,T., Li,Q., " Multisource Coordination Energy Management Strategy Based on SOC Consensus for a PEMFC–Battery–Supercapacitor Hybrid Tramway", IEEE Transactions on Vehicular Technology, January 2018 DOI: 10.1109/TVT.2017.2747135.

**Abstract**—For the sake of coordinating multiple energy sources appropriately from power demand and guarantee stage of charge (SOC) consensus of the energy storage systems in different operation conditions, a multisource coordination energy management strategy based on self-convergence droop control is proposed for a large-scale and high-power hybrid tramway. A hybrid powertrain configuration that includes multiple proton exchange membrane fuel cell systems, batteries, and supercapacitors is designed for a 100% low-floor light rail vehicle (LF-LRV) tramway. According to the hybrid system model of LF-LRV tramway developed with commercial equipment, this proposed multisource coordination energy management strategy is assessed with a real driving cycle of tramway. The results obtained from RT-LAB platform testify that the proposed strategy is capable of coordinating multiple energy sources, guaranteeing the SOC consensus and improving the efficiency of overall tramway.

**Index Terms**—Energy management system, hybrid tramway, multi-source coordination, proton exchange membrane fuel cell,self-convergence droop control, stage of charge consensus.

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**25_2020_ Energy Management of a Multi-Source Vehicle by lambda-Control**

25. Castaings,A., Lhomme,W., Trigui, R., Bouscayrol, A., "Energy Management of a Multi-Source Vehicle by lambda-Control", Appl. Sci. 2020, 10, 6541; doi:10.3390/app10186541.

**Abstract:** This paper deals with the real-time energy management of a fuel cell/battery/supercapacitors energy storage system for electric vehicles. The association of the battery and the supercapacitors with the fuel cell aims to reduce the hydrogen consumption while limiting the constraints on the fuel cell and the battery. In this paper, a real-time optimization-based energy management strategy by lambda-control is proposed. Simulation results on a standard driving cycle show that the hydrogen consumption is reduced by 7% in comparison with a fuel-cell-based electric vehicle without any secondary energy storage source. Moreover, the energy management strategy ensures the system safety while preserving the fuel cell and the battery. Experimental results show that the developed energy management strategy is well-suited for the real-time requirements, applicability, and safety.

**Keywords:** energy management; fuel cell; battery; super capacitor; optimization

26. K. Algarny, A. S. Abdelrahman and M. Youssef, "A novel platform for power train model of electric cars with experimental validation using real-time hardware in-the-loop (HIL): A case study of GM Chevrolet Volt 2nd generation," 2018 IEEE Applied Power Electronics Conference and Exposition (APEC), 2018, pp. 3510-3516, doi: 10.1109/APEC.2018.8341610.

Abstract:

This paper presents a novel platform for accurate mathematical modeling of electric cars' propulsion system. It provides, for the first time, a Hardware in-the-Loop (HIL) real-time experimental verification for a case study of GM Chevrolet Volt for both power and control parts in addition to the mechanical part. The novelty of this work can be split into three steps; first, each component of the power-train is accurately modeled taking transient dynamics of all parts of the electric vehicle (EV) into consideration. Secondly, a PSIM simulation platform is consequently developed, to demonstrate the validity of this mathematical modeling. Finally, the Typhoon HIL is used to provide the experimental verification of the proposed model in real-time, which precisely validate the viability of the model. The HIL technology is used to prototype and test the control proposed system while simulating the power circuit on the HIL module platform. The Permanent Magnet Synchronous Motor (PMSM) and the Power Electronics hardware components are simulated in real-time at which the parameters can be changed while the simulation is running. However, the control algorithm is generated as a C code and downloaded to the TI controller that exists on a Digital Signal Processing (DSP) board. The results from the simulation based on PSIM environment and hardware validations using HIL are in agreement, which validates the developed model. The performance has been investigated under different load operating conditions in real-time to verify its robustness. The case study can be extended for any electric car as it provides a generic platform for modeling any propulsion system.

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27. M. Porru, A. Serpi, A. Floris and A. Damiano, "Modelling and real-time simulations of electric propulsion systems," 2016 International Conference on Electrical Systems for Aircraft, Railway, Ship Propulsion and Road Vehicles & International Transportation Electrification Conference (ESARS-ITEC), 2016, pp. 1-6, doi: 10.1109/ESARS-ITEC.2016.7841438.

Abstract:

This paper presents an advanced modelling of an Electric Propulsion System (EPS) for light-duty Electric Vehicles (EVs). It is developed within the Matlab Simulink environment by taking into account suitable models of each EPS components, namely the energy storage system, the electrical drive and the transmission system, as well as the overall vehicle model. Particularly, a Li-ion battery is considered, which supplies a Permanent Magnet Synchronous Machine (PMSM) through a two-level DC/AC converter. The latter is driven by a PI-based control system, which assures adequate PMSM performances at any speed within its operating speed range. Vehicle modelling is introduced as well, i.e. the PMSM is coupled to EV wheels through a single-gear transmission system. The proposed modelling approach is validated through

both conventional and real-time simulations, the latter being carried out by interfacing Matlab Simulink with an OPAL-RT device.

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28. Y. Wang and X. Qu, "A novel real-time simulation platform for testing control algorithm," The 27th Chinese Control and Decision Conference (2015 CCDC), 2015, pp. 4748-4750, doi: 10.1109/CCDC.2015.7162764.

In this paper, a novel real-time simulation platform, used to test the control algorithm, is presented. The platform consists of three parts, which are Matlab/Simulink, PLC and dSPACE. Matlab/Simulink plays the role of controller along with PLC (Programmable Logic Controller), dSPACE simulation system is used to model the real controlled plant, the controller and controlled plant form a closed-loop real-time control system. Both the hardware connection and the communication realization of the platform are described in detail. The platform makes full use of the powerful data processing capabilities, abundant toolboxs of Matlab/Simulink and the profuse modeling methods in dSPACE, it's straightforward and flexible to realize the algorithm and model the controlled plant. Taking the parameter adaptive fuzzy PID as example, the simulation results explicitly show the effectiveness of the platform.

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29. H. Rezgui, F. Rouissi and A. Ghazel, "Design Methodology Proposal of Digital Predistorter Using Matlab and Modelsim Cosimulation," 2018 6th International Conference on Multimedia Computing and Systems (ICMCS), 2018, pp. 1-5, doi: 10.1109/ICMCS.2018.8525972.

This paper details the design of a Digital Predistorter (DPD) based on the Simplified Volterra Series (SVS) model. Our main contributions concern first the design of the predistorter unit using the Look Up Table (LUT) method without additional algorithms to decrease the high number of coefficients required for the PA model. Then, a Matlab and Modelsim cosimulation approach is discussed and performed to evaluate the proposed DPD architecture, in particular synthesis results are presented in terms of required Field Programmable Gate Array (FPGA) resources to implement the proposed predistorter. In addition, the performances of the proposed design are verified using a class AB GaN Power Amplifier (PA) driven by one carrier Long Term Evolution-Advanced (LTE-A) signal with 20 MHz channel bandwidth. It is proven that the LUT predistorter occupies only 55 % of the multipliers (DSP48E1) available in the Zynq-7000 FPGA. Also, the Adjacent Channel Power Ratio (ACPR) attains more than -45 dB.

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30. Y. Kung and Risfendra, "ModelSim/Simulink co-simulation of a sensorless control for PMSM drives based on I-F startup and EKF," 2016 International Conference on Applied System Innovation (ICASI), 2016, pp. 1-4, doi: 10.1109/ICASI.2016.7539749.

A hybrid sensorless control system for the permanent magnet synchronous motor (PMSM) drives using I-f startup method then a smooth transition to EKF-based (Extended Kalman Filter) sensorless field oriented control (FOC) is proposed in this paper. The solution of I-f simple startup method is suitable for the low-speed sensorless control without initial rotor

position estimation and machine parameters estimation. And EKF-based sensorless FOC is appropriate for the medium- and high-speed sensorless control. Therefore, combining the two approaches, the PMSM can be controlled from standstill to the high speed operation smoothly. In this paper, firstly, the mathematical modeling of PMSM is introduced. Also, the I-f startup method and the rotor position estimation algorithms of EKF are conducted. Secondly, a very high-speed IC hardware description language (VHDL) is presented to describe the behavior of the adopted estimation and control algorithm. Finally, to verify the correctness of the designed VHDL code of the adopted estimation and control algorithm, a co-simulation work is constructed by Simulink and ModelSim and some simulation results are demonstrated.

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31. M. E. Şahİn, F. Blaabjerg and A. Sangwongwanİch, "Modelling of supercapacitors based on simplified equivalent circuit," in CPSS Transactions on Power Electronics and Applications, vol. 6, no. 1, pp. 31-39, March 2021, doi: 10.24295/CPSSTPEA.2021.00003.

Abstract

The need for energy storage devices especially in renewable energy applications has increased the use of supercapacitors. Accordingly, several supercapacitor models have been proposed in previous researches. Nevertheless, most of them require an intensive test to obtain the model parameters. These may not be suitable for an initial simulation study, where a simple model based on the datasheet is required to evaluate the system performance before building the hardware prototype. A simplified electrical circuit model for a supercapacitor (SC) based on the voltage-current equation is proposed in this paper to address this issue. This model doesn't need an intensive test for accuracy. The structural simplicity and decent modelling accuracy make the equivalent electrical circuit model very suitable for power electronic applications and real-time energy management simulations. The parameters of the proposed model can be obtained from the datasheets value with a minimum test requirement. The experimental method to provide the parameters of the supercapacitor equivalent circuit is described. Based on the proposed method, the supercapacitor model is built in Matlab/ Simulink, and the characteristics of equivalent series resistance (ESR) measurement and cycle life are compared with datasheets. The simulation results have verified that the proposed model can be applied to simulate the behaviour of the supercapacitor in most energy and power applications for a short time of energy storage. A supercapacitor test circuit is given to test the charge and discharge of supercapacitor modules. The experimental results are suitable for simulation results.

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32. M. Krpan, I. Kuzle, A. Radovanovic and J. V. Milanovic, "Modelling of Supercapacitor Banks for Power System Dynamics Studies," in IEEE Transactions on Power Systems, doi: 10.1109/TPWRS.2021.3059954.

Abstract

The paper presents accurate and simple dynamic model of a supercapacitor bank system for power system dynam- ics studies. The proposed model is derived from a detailed RC circuit representation. Furthermore, a complete control system of the supercapacitor bank is also presented. The proposed model is easy to integrate in any power system simulation software and consists of only up to four standard datasheet parameters. The performance of the proposed model in grid frequency control and low-voltage ride through is illustrated on IEEE 14-bus test system in DIgSILENT PowerFactory. It is shown that in case of transient stability simulations the ideal (simplified) model of the supercapacitor can be used while in case of frequency control the ideal representation may not always be appropriate.

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33. L. Shi and M. L. Crow, "Comparison of ultracapacitor electric circuit models," 2008 IEEE Power and Energy Society General Meeting - Conversion and Delivery of Electrical Energy in the 21st Century, 2008, pp. 1-6, doi: 10.1109/PES.2008.4596576.

Abstract:

Due to ultracapacitorspsila unique features, the electrical performances and reliabilities of electrical systems using ultracapacitors can be improved. It is important to have a good ultracapacitor model for simulation and assisting electrical system design and product development. Several kinds of ultracapacitor models are given these years. Especially, electric circuit models are the interested ones for electrical engineers. This paper concentrates on the electric circuit model. Three basic RC network models are discussed in detail, including modeling ideas, circuit formation, linear/nonlinear factors and evaluations of each model. The general electric circuit model considering the inductance and leakage current effects are given. Model selection depends on the specific applications of ultracapacitor. Based on the analysis in this paper, recommendations of ultracapacitor selection strategies are provided.

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34. X. Chen, A. Pise, A. Hussein and I. Batarseh, "Parameter Extraction of An Ultracapacitor's Equivalent Circuit Model Using a Genetic Algorithm Approach," 2018 IEEE Energy Conversion Congress and Exposition (ECCE), 2018, pp. 2493-2497, doi: 10.1109/ECCE.2018.8558196.

Abstract:

This paper proposes a new method for extracting some equivalent-circuit model parameters of an ultracapacitor using Genetic Algorithm (GA) approach. Ultracapacitors have two main parameters that dictates their performance: internal resistance and the capacitance. These parameters change drastically with temperature variations and age conditions. These parameters also vary from an ultracapacitor to another even if they were from the same manufacturer due to the manufacturing process. Hence, in order to allow accurate prediction

of the ultracapacitor performance, an accurate value of these parameters is vital. The proposed algorithm is presented in this paper followed by experimental verification using a BCAP3000 2.7V, 3000F Maxwell ultracapacitor. The accuracy of the algorithm is evaluated and compared to the traditional Least-square Algorithm (LSA).

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35. H. Miniguano, A. Barrado, C. Fernández, P. Zumel, and A. Lázaro, "A General Parameter Identification Procedure Used for the Comparative Study of Supercapacitors Models," Energies, vol. 12, no. 9, p. 1776, May 2019.

Abstract

Supercapacitors with characteristics such as high power density, long cycling life, fast charge, and discharge response are used in different applications like hybrid and electric vehicles, grid integration of renewable energies, or medical equipment. The parametric identification and the supercapacitor model selection are two complex processes, which have a critical impact on the system design process. This paper shows a comparison of the six commonly used supercapacitor models, as well as a general and straightforward identification parameter procedure based on Simulink or Simscape and the Optimization Toolbox of Matlab®. The proposed procedure allows for estimating the different parameters of every model using a different identification current profile. Once the parameters have been obtained, the performance of each supercapacitor model is evaluated through two current profiles applied to hybrid electric vehicles, the urban driving cycle (ECE-15 or UDC) and the hybrid pulse power characterization (HPPC). The experimental results show that the model accuracy depends on the identification profile, as well as the robustness of each supercapacitor model. Finally, some model and identification current profile recommendations are detailed.

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36. R.A. Dougal, L. Gao, S. Liu, Ultracapacitor model with automatic order selection and capacity scaling for dynamic system simulation, Journal of Power Sources, Volume 126, Issues 1–2, 2004, Pages 250-257, ISSN 0378-7753

Abstract

An ultracapacitor model with automatic order selection of complexity and automatic scaling of capacity is created in Virtual Test Bed platform for complex system simulation and prototyping. The order selection is based upon the variable simulation time step for appropriate level of details of the model, and automatically executed by the model itself, therefore it applies to simulation for both high and low frequencies, or for both fast and slow transients, or even for multi-time scale resolutions. A simple trapezoidal algorithm, rather than the general stiff algorithm, which is complicated in implementation, is used for numerical integration. For a given time step, the truncation error is controlled to be negligible, so that numerical stability and accuracy are ensured for the given order of model complexity. The model is validated by comparing the simulation results to the experimental ones. The

application example of the ultracapacitor model in complex system simulation is also presented.

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37. Lei Zhang, Xiaosong Hu, Zhenpo Wang, Fengchun Sun, David G. Dorrell, A review of supercapacitor modeling, estimation, and applications: A control/management perspective, Renewable and Sustainable Energy Reviews, Volume 81, Part 2, 2018, Pages 1868-1878, ISSN 1364-0321.

Abstract

Supercapacitors (SCs) have high power density and exceptional durability. Progress has been made in their materials and chemistries, while extensive research has been carried out to address challenges of SC management. The potential engineering applications of SCs are being continually explored. This paper presents a review of SC modeling, state estimation, and industrial applications reported in the literature, with the overarching goal to summarize recent research progress and stimulate innovative thoughts for SC control/management. For SC modeling, the state-of-the-art models for electrical, self-discharge, and thermal behaviors are systematically reviewed, where electrochemical, equivalent circuit, intelligent, and fractional-order models for electrical behavior simulation are highlighted. For SC state estimation, methods for State-of-Charge (SOC) estimation and State-of-Health (SOH) monitoring are covered, together with an underlying analysis of aging mechanism and its influencing factors. Finally, a wide range of potential SC applications is summarized. Particularly, co-working with high energy-density devices constitutes hybrid energy storage for renewable energy systems and electric vehicles (EVs), sufficiently reaping synergistic benefits of multiple energy-storage units.

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38. A. Ostadi, M. Kazerani and S. Chen, "Optimal sizing of the Energy Storage System (ESS) in a Battery-Electric Vehicle," 2013 IEEE Transportation Electrification Conference and Expo (ITEC), 2013, pp. 1-6, doi: 10.1109/ITEC.2013.6574521.

Abstract:

Energy Storage System (ESS) is a key component in every Electric Vehicle (EV). The most widely-used ESS in electric powertrains is based on batteries. Optimal sizing of the battery pack in electric vehicles is a crucial requirement as it strongly impacts the manufacturing cost and vehicle weight, thus running cost. This paper addresses optimal sizing of the ESS in a Battery-Electric Vehicle (BEV) based on Particle Swarm Optimization (PSO) method. Simulation results based on the optimally-sized ESS for a vehicle are presented to showcase the resulting system performance and the fact that all constraints are respected.

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39. L.E. Helseth, Modelling supercapacitors using a dynamic equivalent circuit with a distribution of relaxation times, The Journal of Energy Storage, October 2019.

Abstract

Supercapacitors are often modelled using electrical equivalent circuits with a limited number of branches. However, the limited number of branches often cannot explain long-term dynamics, and one therefore has to resort to more computationally challenging basic models governing diffusion and drift of ions. Here, it is shown that consistent modelling of a supercapacitor can be done in a straightforward manner by introducing a dynamic equivalent circuit model that naturally allows a large number or a continuous distribution of time constants, both in time and frequency domains. Such a model can be used to explain the most common features of a supercapacitor in a consistent manner. In the time domain, it is shown that the time-dependent charging rate and the self-discharge of a supercapacitor can both be interpreted in this model with either a few or a continuous distribution of relaxation times. In the frequency domain, the impedance spectrum allows one to extract a distribution of relaxation times. The unified model presented here may help visualizing how the distribution of relaxation times or frequencies govern the behaviour of a supercapacitor under varying circumstances.

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40. H. H. Eldeeb, A. T. Elsayed, C. R. Lashway and O. Mohammed, "Hybrid Energy Storage Sizing and Power Splitting Optimization for Plug-In Electric Vehicles," in IEEE Transactions on Industry Applications, vol. 55, no. 3, pp. 2252-2262, May-June 2019, doi: 10.1109/TIA.2019.2898839.

Abstract

In this paper, we develop formulation of a multi-objective optimization problem (MOOP) to optimally size a battery unit (BU) ultracapacitor (UC) hybrid energy storage system (HESS) for plug-in electric vehicle (EV). In this application, the objectives were to minimize cost, weight, volume of the HESS simultaneously maximizing the remaining cycle life of the BU at the end of the driving cycle. The MOOP is solved by the non-dominated sorting genetic algorithm type 2 algorithm. Detailed mathematical models for the BU and UC are given. The thermal effect on performance and sizing are also included in the formulation. The power demand by the EV powertrain is shared amongst the BU and HESS by two methods: First is by using wavelet transformation, while the second is by using power split ratio. The ratio of the power (i.e., power split) handled by each storage unit was determined by the optimizer. A sensitivity analysis was conducted for the power splitting ratio verification. The problem was solved for using the urban dynamometer driving schedule and the highway fuel economy test driving profiles. This has resulted in sizing of an HESS with lower cost, volume, and weight than those

existing in literature. Finally, the effect of changing the motor type on the MOOP result was investigated.

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