

Behavior Comparison of Hybrid Energy Storage Systems for Pulsed Loads in Electric Vehicles

Adolfo Dannier
DIETI
University of Napoli Federico II
via Claudio 21, 80125, Naples (Italy)
adolfo.dannier@unina.it

Andrea Del Pizzo
DIETI
University of Napoli Federico II
via Claudio 21, 80125, Naples (Italy)
andrea.delpizzo@unina.it

Luigi Pio Di Noia
DIETI
University of Napoli Federico II
via Claudio 21, 80125, Naples (Italy)
luigipio.dinoia@unina.it

Abstract— Pulsed loads are widely diffused on board of the electric vehicles and are related to different devices adopted or to the propulsion/traction performance of the vehicles (e.g. the power required in a vertical take-off by an UAV). This impulsive behavior plays a crucial role for the correct management and sizing of energy storage systems: usually, the combination of different type of storage systems are adopted with the aim to improve the performance of the system, reducing the weight and the occupied volume. The paper proposes the analysis of different configuration of hybrid storage system, based on lithium-ion batteries and supercapacitors, able to supply a power pulsed load: the aim is the investigation of the different behavior of the configurations considering also the dynamic influence of the control in the power supply of the pulsed load. The results are obtained using numerical simulations.

Keywords— Capacitive energy storage, Hybrid Energy Storage Systems, Lithium ion batteries, Pulsed Loads

I. INTRODUCTION

The extensive use of power electronics and electric drives on board of electric and traditional vehicles is constantly growing. The all-electric aircraft/ship concepts [1,2] have determined the possibility of reducing the size of on-board devices, as well as improving their performance and reliability. In many applications it is necessary to feed electrical loads with an impulsive time profile [3,4]. The presence of these loads must be appropriately managed, as they could have an impact on the correct performance of the equipment and on compliance with the power quality indices of the power system [5]. Pulsed power profiles are also present in hybrid/full electric propulsion of aircraft [6,7] and in some charging systems of vehicles with electric propulsion, such as the case of dynamic wireless charging: in fact, the rapid transit of the vehicle on the charging pad reduces the charging time and therefore, the transferred power profile assumes a typical impulsive behavior [8]. Therefore, it is necessary to provide of storage systems and power converters capable of managing these power profiles. Focusing the attention on the storage system, it is well known that lithium electrochemical cells are characterized by high energy density values, while the power density is limited [9]. These characteristics need the use of a hybrid storage, based on at least one component able to manage high peak power such as supercapacitors [10] or flywheels [11]. An important role in the sizing of hybrid storage is strictly related to the type of connection between the different storage devices and the load. In fact, the converter used for the coupling between the energy storage and the grid of power pulsed load, can influence the entire dynamic of power exchange and therefore cannot be neglected during the sizing procedure. Besides, the problem of controlling power electronics interfaces plays an important role because the system dynamic is also dependent by the type of control adopted for the converters. For this reason, paper [13] proposes a robust model predictive control able to manage and reduce the effects of pulsed load on a naval dc microgrid. The converters considered in this case are non-isolated DC-DC converters. Instead in [14] always a model predictive control is proposed, but the adopted converter between the storage system and the pulsed load is a dual active bridge.

Considering the complexity reduction, in the proposed paper the hybrid storage system considered is composed by lithium cells and supercapacitor. Three selected configurations which differ by the voltage value of storage system and the type of power converters are analyzed. For each configuration is integrated also the control of pulsed load supply: in this way it is possible to consider all the effects of the system on the dynamic response. The paper is structured as follows: paragraphs II and III analyze the proposed configuration and the optimization procedure; the numerical applications are in section IV, instead the conclusive consideration is in section V.

II. HYBRID ENERGY STORAGE SYSTEMS FOR PULSED LOADS

The presence of impulsive loads is very widespread on board of aircraft and ships. In fact, the presence of these loads is due to the normal performance of the systems related to the avionics, the control and navigation, entails the necessity to integrate storage systems directly into the on-board grid, or sizing the storage systems for the off-grid power supply of the impulsive load. The recent development of lithium batteries has allowed the introduction into the market of cells with a high discharge rate, therefore capable of guaranteeing a high-power density value ([kW/kg]). Obviously, operating the cells at maximum discharge current involves in a rapid degradation and reduction of the cell lifetime, as well as strong thermal stress due to losses.

Due to the rapid variation of a pulsed load, the study of integration between lithium cells and supercapacitors must consider the transient model of the storage system or using a frequency response model as it is shown in [15]. This analysis can be carried out rapidly considering the first order equivalent circuits of lithium cells and supercapacitor, that are reported in formula (1) and (2):

$$\begin{cases} i_b(t) = \frac{v_c(t)}{R_p} + C_p \frac{dv_c(t)}{dt} \\ v_{oc}(SOC, t) = R_t i_b(t) + v_c(t) + v_{out}(t) \end{cases} \quad (1)$$

$$\begin{cases} i_{sc}(t) = \frac{v_{sc}(t)}{R_{leak}} + C_{sc} \frac{dv_{sc}(t)}{dt} \\ v_{sc}(t) = R_{ES} i_{sc}(t) + v_{out,sc}(t) \end{cases} \quad (2)$$

where:

- SOC is the state of charge of electrochemical cell.
- $v_{oc}(SOC, t)$, $v_c(t)$ and $v_{out}(t)$ are the open circuit, parallel branch and output voltage of the battery.
- $i_b(t)$ is the battery current.
- R_t, R_p and C_p are the parameter of the first order battery model.
- $v_{sc}(t)$ and $v_{out,sc}(t)$ are the open circuit and output voltage of the supercapacitor.
- $i_{sc}(t)$ is the supercapacitor current.
- R_{ES}, R_{leak} and C_{sc} are the series resistance, the leakage resistance, the storage capacitance of the first order supercapacitor model.

The use of first order dynamic equations gives the possibility to describe the behavior of the storage systems components, even if it necessary to highlight also the dependence of the frequency response by the SOC, due to the variation of battery parameters. The integration between supercapacitors and electrochemical cells could requires the use of power electronics converters and advanced controls. Many approaches [12] proposed in literature are based on a direct coupling between supercapacitor and electrochemical cells, using the power converters only to control and fed the impulsive load. This kind of configuration is limited by the impossibility to control in an independent way the two storage sources and this could limit the overall performances of the systems. Other approaches proposed are completely controllable [13,14].

As previously cited, the use of a power converters and the control affects the entire dynamic of the system and, in particular for the case of pulsed load, this must be taken into account during the sizing procedure of the hybrid storage. In order to consider the effect of the control on the storage systems, the proposed paper analyzes different configurations that can be used to supply a pulsed load. The adopted configurations reported in the following sections are inherent the possibility to use high voltage battery pack and supercapacitor, with a semi-direct configuration (battery pack directly linked to the loads and supercapacitor regulated with a dc-dc converter) or a total controlled system with high and low voltage battery and supercapacitor pack.

A. High voltage battery pack supply system without voltage regulation

The first topology consists of a lithium cells battery pack with a high output voltage value, connected directly to the input of pulsed loads. For high value it is means that the output value of battery pack in full charge conditions is higher respect the typical value of voltage of power grid adopted in the applications. Also, the supercapacitors pack is selected with a high values voltage, but due to the rapid variation of its voltage needs to compensate the peak power, a buck converter is connected between the pulsed load input and the supercapacitor pack. The scheme is depicted in Fig.1.

This kind of configuration is useful when the pulsed load is an electrical drive with a variable input voltage range. In this case the buck converter is controlled with the aim to follow the output voltage of the battery pack, regulating the power and the energy provided by the battery based on the opportune choice of the droop control coefficient α (Fig.2).

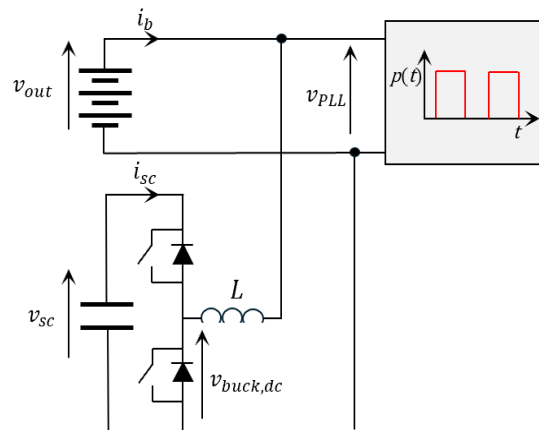


Fig.1 Configuration scheme with a direct coupling between the high voltage battery pack and the pulsed power load drive.

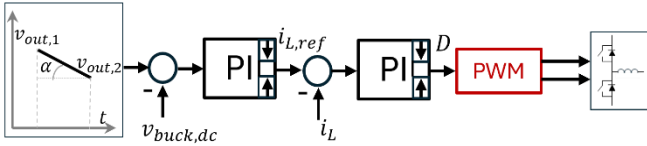


Fig.2 Considered control scheme for the configuration in figure 1.

The coefficient α determines the output voltage variation of the battery and therefore how energy involves from the battery to the pulsed load.

The error between the output voltage battery and the buck converter voltage is processed inside a PI control, calculating the reference value of inductance current $i_{L,ref}$ which is related to the power and energy provided by the supercapacitor.

B. High voltage battery pack supply system with voltage regulation

The previous configuration has a limitation in the control of battery pack and the power control is performed only by the supercapacitor and its converter.

In many applications, the pulsed power load is supplied directly on a grid, where the voltage variations are constrained in a certain limit. In this case, the energy storages are used for the grid main parameters regulation, therefore the control of the output voltage on both the energy storage system is mandatory. The configuration is depicted in Fig.3:

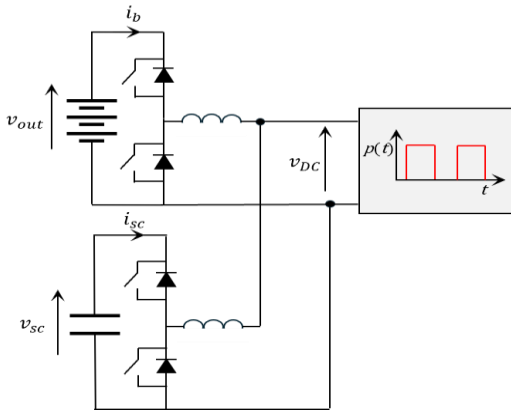


Fig.3 Configuration scheme with high voltage battery and supercapacitor pack coupled with the pulsed power load through a grid with fixed voltage.

instead, the Fig.4 shows the control strategy that is used in this paper.

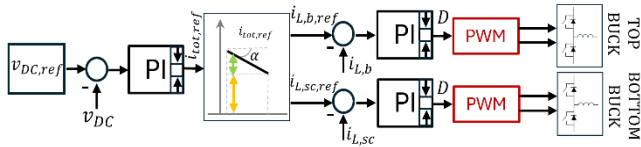


Fig.4 Considered control scheme for the configuration in figure 3.

With the considered control scheme, the voltage variation is compensated by the battery pack and the supercapacitor using a different amount between them, determined always by the α coefficient that is calculated using an optimization procedure.

From the error on the grid voltage v_{DC} it is calculated a total current that depending by the value of α , is divided into two amounts ($i_{L,b,ref}$ and $i_{L,sc,ref}$) which determines respectively the reference current of the two buck converters. In the examined case, the battery pack and the supercapacitor pack are considered with an output voltage greater than the voltage of the grid (this assumption is carried out to reduce the output currents that comes directly from the storage elements).

C. Low voltage battery pack supply system with voltage regulation

The last configuration considered in the paper (Fig.5) is like the configuration reported in II.B, but the battery pack and the supercapacitors are sized with an output voltage below the rated voltage of the grid.

In this case, the two storage systems are connected to the grid with two independent boost converters, and the control depicted in Fig.6 is like the control used for the case II.B.

The configuration is proposed to make a comparison with the one of paragraph II.B.

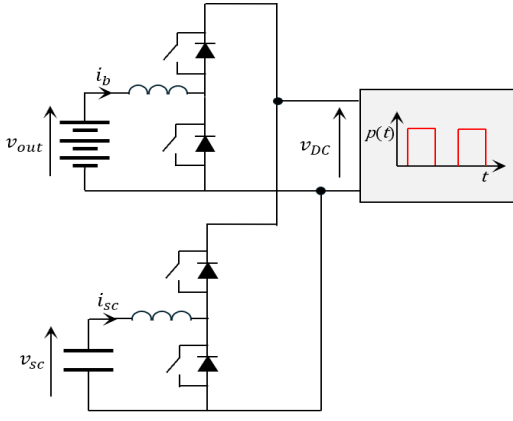


Fig.5 Configuration scheme with low voltage battery and supercapacitor pack coupled with the pulsed power load through a grid with fixed voltage.

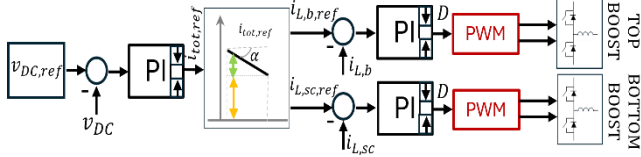


Fig.6 Considered control scheme for the configuration in figure 5

III. OPTIMIZATION PROCEDURES FOR THE CONFIGURATIONS

For each topology presented in paragraph II, an optimization procedure for the sizing of the hybrid storage system is proposed. The adopted optimization procedures are based on the minimization of a single objective function, which is chosen equals to the minimization of the total weight of the battery and supercapacitor, as reported in formula (3):

$$\min f_{obj} = \min(n_p n_s m_b + n_{p,scap} n_{s,scap} m_{scap}) \quad (3)$$

with:

- n_p is the number of parallel branches in the battery pack.
- n_s is the number of series cells in each branch of the battery pack.
- m_b is the weight of a single electrochemical cells.
- $n_{p,scap}$ is the number of parallel branches of the supercapacitor pack.
- $n_{s,scap}$ is the number of series cells in each branch of the supercapacitor pack.
- m_{scap} is the weight of a single supercapacitor.

In formula (3) are presented four unknown variables, that must be determined. These variables can assume only integer values, influencing the choice of the type of method that must be used to solve the optimization problem. The fifth unknown variable is related to the control and its determination requires the solution of the system model with the transient simulations of a fixed pulsed power load. The value of the fifth variable influences directly the objective function, because determines the amount of power and energy of the two different storage unit which involves in the supply of the pulsed power load. Given the complexity of the model, in this work a completely numerical approach is adopted, carrying out simulations with Matlab© and Simulink© as shown in Fig.6.

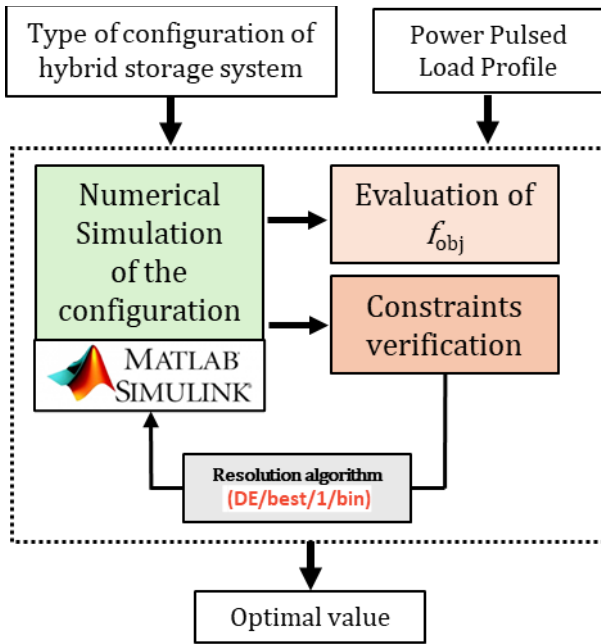


Fig.6 Configuration scheme with low voltage battery and supercapacitor pack coupled with the pulsed power load through a grid with fixed voltage.

As previous mentioned, some of variables are integer number, therefore the differential evolution method (DE/best/1/bin) is adopted for the solution of the optimization problem, that for the three configurations are formulated as follows.

- *Problem statement of configuration of fig.1*

The optimization problem adopted for the configuration reported in paragraph II.A is the following:

$$\begin{cases}
 \min (f_{obj}) \\
 v_{out}(t_{end}) \geq v_{min,PPL} \\
 v_{out}(t_{ini}) \leq v_{max,PPL} \\
 \frac{i_b(t)}{n_p} \leq I_{b,max} \\
 SOC(t_{end}) \geq 0.20 \\
 v_{sc}(t_{end}) \geq v_{min,PPL} \\
 v_{sc}(t_{ini}) \leq v_{max,sc} \\
 \frac{i_{sc}(t)}{n_{p,scap}} \leq I_{sc,max}
 \end{cases} \quad (4)$$

where:

- t_{ini}, t_{end} are the initial and final time of the series of pulsed loads;
- SOC_{end} is the final value of the SOC;
- $v_{min,PPL}$ is the minimum value of voltage allowed by the power pulsed load drive;
- $v_{max,PPL}$ is the maximum value of voltage tolerated by the power pulsed load drive;
- $v_{max,sc}$ is the maximum voltage value of the maximum number of supercapacitor that can be connected in series;
- $I_{b,max}$ is the maximum discharge current of one battery cell;
- $I_{sc,max}$ is the maximum discharge current of one supercapacitor;

- *Problem statement of configuration of fig.3*

The optimization problem for the configuration reported in paragraph II.B is the system (5):

$$\left\{ \begin{array}{l} \min (f_{obj}) \\ v_{out}(t_{end}) \geq v_{DC,min} \\ \frac{i_b(t)}{n_p} \leq I_{b,max} \\ SOC(t_{end}) \geq 0.20 \\ v_{sc}(t_{end}) \geq v_{DC,min} \\ \frac{i_{sc}(t)}{n_{p,scap}} \leq I_{sc,max} \\ v_{DC}(t) \geq v_{DC,min} \\ v_{DC}(t) \leq v_{DC,max} \end{array} \right. \quad (5)$$

with:

- $v_{DC}(t)$ the voltage value of the grid;
- $v_{DC,min}$ minimum voltage value of the grid;
- $v_{DC,max}$ maximum voltage value of the grid;

Respect to the previous problem, the examined case introduces the constraints on the grid voltage that must be guaranteed by the control of both battery and supercapacitor pack.

- *Problem statement of configuration of fig.5*

The configuration of paragraph II.C is sized using the optimization problem in formula (6):

$$\left\{ \begin{array}{l} \min (f_{obj}) \\ v_{out}(t_{end}) \geq v_{Boost,min} \\ v_{out}(t_{ini}) \leq v_{DC,min} \\ \frac{i_b(t)}{n_p} \leq I_{b,max} \\ SOC(t_{end}) \geq 0.20 \\ v_{sc}(t_{end}) \geq v_{Boost,min} \\ v_{sc}(t_{ini}) \leq v_{DC,min} \\ \frac{i_{sc}(t)}{n_{p,scap}} \leq I_{sc,max} \\ v_{DC}(t) \geq v_{DC,min} \\ v_{DC}(t) \leq v_{DC,max} \end{array} \right. \quad (6)$$

where $v_{Boost,min}$ is the minimum input value of the boost converter. Compared with the problem (5), this configuration needs to verify the minimum input voltage in the boost converter with the aim to reduce the duty cycle and keep the good performance of the converter.

IV. NUMERICAL RESULTS

The optimization problems of the three considered configurations are solved using the parameters of battery cells, supercapacitor and grid reported in tables I, II and III. The parameters of the battery are obtained by experimental test on a fully charged 18650 lithium-ion cells, instead the parameters of the supercapacitor are estimated from the datasheet [16]. The battery and capacitor parameters are considered constant during the discharge cycles. The simulation is carried out considering two profile pulses, that are different only by the pulse slope.

TABLE I. PARAMETERS OF LITHIUM ION CELL 18650

Rated voltage (V)	3.6
Maximum Voltage (V)	4.2
Rated Capacity (Ah)	3
Maximum discharge current (A)	20
R_t (mΩ)	30.5
R_p (mΩ)	9.3
C_p (F)	1800
Mass (kg)	0.048

TABLE II. PARAMETERS OF SUPERCAPACITOR

Rated voltage (V)	16
Rated Capacity (F)	58
Maximum peak current (A)	190
R_{ESR} (mΩ)	22

$R_{LEAK} (\Omega)$	640
Mass (kg)	0.63

TABLE III. GRID PARAMETERS

Rated Voltage (V)	270
Maximum Voltage (V)	290
Minimum voltage (V)	260

TABLE IV. LOAD PROFILE OF PULSE TYPE 1

Peak Power (kW)	50
Pulse period (s)	2.5
Pulse width (%)	40
Pulse slope (kW/s)	500
Load duration (s)	20
$v_{max,PPL}$ (V)	800
$v_{min,PPL}$ (V)	270

TABLE V. LOAD PROFILE OF PULSE TYPE 2

Peak Power (kW)	50
Pulse period (s)	2.5
Pulse width (%)	40
Pulse slope (kW/s)	1000
Load duration (s)	20
$v_{max,PPL}$ (V)	800
$v_{min,PPL}$ (V)	270

The results obtained from the optimization procedure are shown in Table VI and in table VII for the pulse of type 1 and 2.

TABLE VI. OPTIMIZATION RESULTS WITH PULSE TYPE 1

	n_s	n_p	$n_{s,scap}$	$n_{p,scap}$	α	f_{obj} (kg)
Configuration of fig. 1	141	5	47	2	0.54	93.06
Configuration of fig. 3	175	2	20	2	0.60	42.00
Configuration of fig. 5	67	4	17	2	0.74	34.3

TABLE VII. OPTIMIZATION RESULTS WITH PULSE TYPE 2

	n_s	n_p	$n_{s,scap}$	$n_{p,scap}$	α	f_{obj} (kg)
Configuration of fig. 1	163	5	41	2	0.20	90.8
Configuration of fig. 3	198	2	18	2	0.27	41.7
Configuration of fig. 5	76	3	11	2	0.66	24.8

In both cases, the results show a similar behavior of the two configurations of fig.3 and fig.5, with a substantial difference of the total mass respect the configuration of fig.1. Considering the two best configurations, the values of the control parameters α gives information between the different behavior: in the high voltage configuration, there is a greater contribution of the battery pack, determining a worse exploitation of the supercapacitors. A similar behavior is highlighted by the simulations for the case of pulse Type 2. In this case, the dynamic of the higher value of pulse slope is balanced by the supercapacitors; the energy required during the slope is reduced and this determines also a reduction of the number of supercapacitors required; while the battery contribution to fed the pulse energy is increased, having a positive effect on the overall weight.

It is necessary to remark that using electrochemical cells and supercapacitor with different parameters and characteristics, some possible changes of the results can be obtained.

V. CONCLUSIONS

The paper proposed the comparison of different configurations for a hybrid electrochemical cells and supercapacitor for the supply of a pulsed power load. Using the dynamic model of the circuit and considering the effect of the control of both the storage devices, different optimization problems are proposed and solved. The aim of the optimization problems is to reduce the weight of the energy storage, defining also the trade-off usage between the lithium cells and supercapacitors considering the effect of the control of power converters. Some simulations are carried out, using the data commercial lithium-ion batteries and supercapacitor and examining two different pulse profile. The results show an appreciable difference respect to the case

without power convert on the battery pack and the case where the battery and the supercapacitor are full controlled by the power converters.

ACKNOWLEDGMENT

We acknowledge financial support under the National Recovery and Resilience Plan (NRRP), Mission 4, Component 2, Investment 1.1, Call for tender No. 104 published on 2.2.2022 by the Italian Ministry of University and Research (MUR), funded by the European Union – NextGenerationEU – Project Title OPTEBUS (2022R93LP3) – CUP E53D23000840006 - Grant Assignment Decree No. 1181 adopted on 27 July 2023 by the Italian Ministry of Ministry of University and Research (MUR).

REFERENCES

- [1] A. Barzkar and M. Ghassemi, "Components of Electrical Power Systems in More and All-Electric Aircraft: A Review," in *IEEE Transactions on Transportation Electrification*, vol. 8, no. 4, pp. 4037-4053, Dec. 2022, doi: 10.1109/TTE.2022.3174362.
- [2] J. S. Thongam, M. Tarbouchi, A. F. Okou, D. Bouchard and R. Beguenane, "All-electric ships—A review of the present state of the art," *2013 Eighth International Conference and Exhibition on Ecological Vehicles and Renewable Energies (EVER)*, Monte Carlo, Monaco, 2013, pp. 1-8, doi: 10.1109/EVER.2013.6521626.
- [3] I. J. Cohen, J. P. Kelley, D. A. Wetz and J. Heinzl, "Evaluation of a Hybrid Energy Storage Module for Pulsed Power Applications," in *IEEE Transactions on Plasma Science*, vol. 42, no. 10, pp. 2948-2955, Oct. 2014, doi: 10.1109/TPS.2014.2298369.
- [4] M. M. Mardani, M. H. Khooban, A. Masoudian and T. Dragičević, "Model Predictive Control of DC–DC Converters to Mitigate the Effects of Pulsed Power Loads in Naval DC Microgrids," in *IEEE Transactions on Industrial Electronics*, vol. 66, no. 7, pp. 5676-5685, July 2019, doi: 10.1109/TIE.2018.2877191.
- [5] P. Gao, Y. Li, M. Huang, W. Yao, X. Zheng and C. Zhang, "An Energy Storage Equipment Sizing Process Based on Static and Dynamic Characteristics for Pulsed Power Load in Airborne Electrical Power System," in *IEEE Transactions on Transportation Electrification*, vol. 10, no. 2, pp. 2899-2911, June 2024, doi: 10.1109/TTE.2023.3303213.
- [6] M. Cameretti, A. Del Pizzo, L. Di Noia, M. Ferrara and C. Pascarella, "Modeling and investigation of a turboprop hybrid electric propulsion system", *Aerospace*, vol. 5, no. 4, pp. 123, 2018.
- [7] E. Fornaro, M. Cardone and A. Danner, "A Comparative Assessment of Hybrid Parallel, Series, and Full-Electric Propulsion Systems for Aircraft Application," in *IEEE Access*, vol. 10, pp. 28808-28820, 2022, doi: 10.1109/ACCESS.2022.3158372.
- [8] M. Reza Gholipour, M. Saradarzadeh, S. Farhangi, "Wireless power transfer pulse charging of lithium-ion battery," *Journal of Energy Storage*, Volume 72, Part B, 2023.
- [9] M. D'Arpino, N. Regmi and P. Ketineni, "Impact of Battery Pack Power Limits on Vehicle Performance," *2023 IEEE Transportation Electrification Conference & Expo (ITEC)*, Detroit, MI, USA, 2023, pp. 1-8, doi: 10.1109/ITEC55900.2023.10187101.
- [10] F. Scuiller, "Study of a supercapacitor Energy Storage System designed to reduce frequency modulation on shipboard electric power system," *IECON 2012 - 38th Annual Conference on IEEE Industrial Electronics Society*, Montreal, QC, Canada, 2012, pp. 4054-4059, doi: 10.1109/IECON.2012.6388938.
- [11] A. T. Elsayed, T. A. Youssef and O. A. Mohammed, "Modeling and Control of a Low-Speed Flywheel Driving System for Pulsed-Load Mitigation in DC Distribution Networks," in *IEEE Transactions on Industry Applications*, vol. 52, no. 4, pp. 3378-3387, July-Aug. 2016, doi: 10.1109/TIA.2016.2535110.
- [12] C. R. Lashway, A. T. Elsayed and O. A. Mohammed, "Hybrid energy storage management in ship power systems with multiple pulsed loads", *Electric Power Syst. Res.*, vol. 141, pp. 50-62, Dec. 2016.
- [13] M. M. Mardani, M. H. Khooban, A. Masoudian and T. Dragičević, "Model Predictive Control of DC–DC Converters to Mitigate the Effects of Pulsed Power Loads in Naval DC Microgrids," in *IEEE Transactions on Industrial Electronics*, vol. 66, no. 7, pp. 5676-5685, July 2019, doi: 10.1109/TIE.2018.2877191.
- [14] L. Chen, S. Shao, Q. Xiao, L. Tarisciotti, P. W. Wheeler and T. Dragičević, "Model Predictive Control for Dual-Active-Bridge Converters Supplying Pulsed Power Loads in Naval DC Micro-Grids," in *IEEE Transactions on Power Electronics*, vol. 35, no. 2, pp. 1957-1966, Feb. 2020, doi: 10.1109/TPEL.2019.2917450.
- [15] A. Kuperman, I. Aharon, A. Kara and S. Malki, "A frequency domain approach to analyzing passive battery–ultracapacitor hybrids supplying periodic pulsed current loads", *Energy Convers. Manag.*, vol. 52, pp. 3433-3438, 2011
- [16] Maxwell Technologies, "Datasheet of 16V 58F MEDIUM CELL MODULE", https://maxwell.com/wp-content/uploads/2021/08/3003212.2_Datasheet_BMOD0058-E016-C02.pdf [accessed: July 31, 2024].