**Analysis of Battery-Supercapacitor Hybrid Energy Storage System with MPC-based PMSM Control for Electric Vehicles**

***Abstract*—The devastating impacts of climate change have become increasingly evident in recent decades, with the key  
responsible sources being the emission of greenhouse gases (GHGs) such as carbon dioxide CO**2 **and sulfur dioxide SO**2**.  
[[1]](#footnote-1)A significant proportion of greenhouse gases (GHGs) originate from the tailpipe emissions of conventional vehicles. Fortunately, electric vehicles (EVs) being a zero carbon transport, have  
emerged as a potential solution to mitigate the repercussions associated with conventional vehicles. However, there are a few major shortcomings of EVs which include a limited driving range, battery degradation and the technical challenges related to developing a robust and efficient Energy Management System (EMS). To address these issues, this paper presents the design of a rule-based EMS for a semi-active Hybrid Energy Storage System (HESS) consisting Battery and Supercapacitors (SCs) by implementing a smart algorithm that harnesses the regenerating braking for battery charging and optimizes power delivery from the HESS. Additionally, a Model Predictive Control (MPC) method is employed to control the speed of the Permanent Magnet Synchronous Motor (PMSM)[[2]](#footnote-2) of EV. The complete model has been designed and analyzed in MATLAB/Simulink environment under specified conditions and the overall response has been thoroughly studied. The simulation outcomes suggest that the proposed system is capable of enhancing energy efficiency, improving power quality as well as stability, and extending the  
battery lifespan. *Index Terms*—Energy Management System (EMS), Hybrid  
Energy Storage System (HESS), Supercapacitor (SC), Semi-active  
Topology, Model Predictive Control (MPC).**

I. INTRODUCTION  
The most ruinous effect of conventional vehicles on the environment is the emission of various noxious gases such as nitrogen oxides (NO*X*), carbon monoxide (CO), carbon dioxide (CO2), sulfur dioxide (SO2) and other greenhouse  
gases (GHGs). A study in 2014 states that, the transportation sector was responsible for 23% of the planet’s total emitted  
CO2 gas [1]. Between 1990 and 2016, New Zealand’s total increase in GHG emissions from transportation was 71.3% wherein 90.7% of these emissions were from road transport.  
The increase in transport emissions during that period was 58.8% and 21.3% in Australia and USA respectively [2]. These statistics reveal the dominance of the percentage share of GHG  
emissions solely from conventional vehicles on the road. For the past few decades, EVs have proved to be a viable option in protecting our environment and combating climate change. As countries worldwide target a low-carbon economy,  
EVs are playing a critical role in transportation decarbonization. Generally, EVs can be categorized broadly into three types such as: Battery Electric Vehicle (BEV), Hybrid Electric Vehicle (HEV) and Plug-in Hybrid Electric Vehicle (PHEV). The primary energy storage element and the driving force for an EV is the battery. Among numerous types of batteries, Lithium-ion (Li-ion) battery is the most widely used battery owing to its fast-charging ability, compact size, and low maintenance requirements [3]–[5]. While the battery in EVs possesses a high energy density  
that enables it to supply energy throughout a driving mission, the battery is adversely affected by other significant operations of EVs, including sudden acceleration and deceleration [4]–[6]. Additionally, the frequent charging and discharging of the battery in EVs to meet their power demands contributes to battery aging [7]. Typically, chargingan EV to full capacity   
takes long hours which can be extremely inconvenient for the daily drivers [8]. With the increased number of charge cycles and temperature fluctuations, the performance of Li-ion batteries degrade leading to reduced driving range and battery lifetime [9]. The cost of replacing an EV battery pack can be  
quite high and battery disposal has a detrimental impact on the environment too [10].  
To address these limitations effectively, a promising solution involves integrating batteries and supercapacitors (SCs) in a coupled system. SCs inherently having high power density are the perfect storage element for serving the dynamic power needs of EVs. They can be charged and discharged thousands of times without affecting performance, allowing for enhanced transient performance and extended battery longevity. Moreover, SCs have the capability of receiving high currents from regenerative braking that contributes to increased driving range. Thus, a combination of battery and SC that forms a Hybrid Energy Storage System (HESS) is attracting researchers since HESS blends the benefits of both battery and SC [6]. However, efficiently connecting the SCs and battery to the DC link poses a significant challenge in

A diagram of a power converter

Description automatically generated

Fig. 1. Schematic diagram of Energy Management System in an Electric Vehicle.

the implementation of a HESS. Semi-active HESS topology refers to a configuration where energy storage components, such as batteries and SCs, are interconnected through a DCDC bidirectional converter. A robust EMS centrally controls  
the power flow among various powertrain components such as batteries, SCs, DC-DC converters, inverters, motors, and more  
[11]. In this paper, a battery and SC-based semi-active HESS has been designed and simulated for EV. The proposed HESS comprises a Li-ion battery and a SC bank consisting of 100 series-connected SCs, each connected to a DC link bus. For managing the power flow optimally, a rule-based EMS has been designed that ensures synergy between the battery and SCs. An intelligent algorithm has been incorporated into the proposed rule-based EMS that can produce power by harnessing regenerative braking. Finally, an MPC-based motor controller has been established for controlling the speed of the 10 kW, 3-phase PMSM of the EV. The complete model has been designed and simulated in MATLAB/Simulink environment and a performance analysis has been conducted in this  
study.

II. METHODOLOGY  
In this section, the proposed Hybrid Energy Storage System (HESS), Energy Management System (EMS) and Model Predictive Control (MPC) based PMSM control techniques will be discussed in detail. The schematic diagram of the system is depicted in Fig. 1. *A. Proposed Semi-active Hybrid Energy Storage System* The proposed HESS has been developed based on semiactive topology, which comprises a 265 V, 100 Ah Li-ion  
battery connected to a bidirectional dc-dc converter, and a 300 V, 10 F SC-bank of 100 SCs directly connected to the DC link bus. The operation of the dc-dc converter is governed to meet the smooth high power demand component.  
This control is achieved by supplying control pulses to the converter, which are generated based on the filtered reference power demand obtained through the application of an adaptive  
filtering algorithm [12]. The inverter converts the DC power from the power-sharing bus to AC power, which drives the Permanent Magnet Synchronous Motor (PMSM). Model Predictive Control (MPC), a sophisticated control technique known for its predictive capabilities, is implemented to regulate the operation of the PMSM with precise control. The parameter values and descriptions of the components in the model are provided in Table I.  
*B. Rule-based Energy Management System Algorithm* The energy management system (EMS) proposed in this study aims to address the power demand by utilizing both Li-ion battery and SC technologies. Specifically, the rule based strategy focuses on utilizing the battery to fulfill the  
high-power and consistent portion of the demand, while the fluctuating part of the demand is handled by the SCs, as shownin Fig 2

.

TABLE1

SPECIFICATION OF PRPPOSED ELECTRICAL VEHICLE MODEL

|  |  |  |
| --- | --- | --- |
| Component | Description | Value |

|  |  |  |
| --- | --- | --- |
| Lithium-icon Battery | Nominal Voltage | 256V |
| Capacity | 100Ah |
| Initial State of charge | 50% |
| Supercapacitor Bank | Nominal Voltage | 300V |
| Capacitance | 10F |
| No. of series connected | 100 |
| Rated Current | 30A |
| PMSM | Rated Power | 10kW |
| Rated Speed | 2300rpm |
| Rated Torque | 41.4N.m |
| DC-Link | Voltage | 300 V |

To achieve this, a low-pass filtering algorithm is adapted to  
extract the smoother part from the reference demand power.  
The transfer function of the low-pass filter can be expressed  
as [12] = 1  
*τs* + 1  
(1) where *τ* is the time constant of the low-pass filter.  
To mitigate abrupt changes and preserve demand power  
integrity, a rate limiter algorithm is applied. It involves computing the difference between the current input sample *x*(*n*)  
and the previous output sample *y*(*n -* 1), expressed as:  
∆*y*(*n*) = *x*(*n*) *- y*(*n -* 1) (2)  
This difference ∆*y*(*n*) is then used to find the output *y*(*n*).  
*y*(*n*) = (*y y*( (*n n - -* 1) + ∆ 1) + sign *y*((∆ *n*)*y*(*n*)) *· L · T s* if otherwise *|*∆*y*(*n*)*| ≤ L · T s* (3)  
where *L* is the rate limit and *T s* is the sampling period. In practical scenarios, there are cases where the SCs need to be charged in parallel with the motor power consumption, particularly when the SCs have a low charge level. Alternatively, the SCs may be tasked with supplying high power  
demand when the battery state of charge is nearing depletion [13]. To effectively manage this issue, four distinct cases of  
different battery State of Charge (SoC) .and SC

charger Level (CL) statuses have been proposed in Table II (14)

TABLE II

Proposed Cases For Battery And SC Charge Status

|  |  |  |
| --- | --- | --- |
| Case | Battery Soc Status(%) | SC-CL Status(%) |
| 1 | 30-100 | 80-100 |
| 2 | 30-100 | 0-80 |
| 3 | 0-30 | 60-100 |
| 4 | 0-30 | 0-60 |

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(1)  
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*y*(*n*) = (*y y*( (*n n - -* 1) + ∆ 1) + sign *y*((∆ *n*)*y*(*n*)) *· L · T s* if otherwise *|*∆*y*(*n*)*| ≤ L · T s* (3)  
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TABLE II  
PROPOSED CASES FOR BATTERY AND SC CHARGE STATUS

|  |  |  |
| --- | --- | --- |
| **Case** 1 | **Battery SoC Status (%)** 30 – 100 | **SC CL Status (%)** 80 – 100 |

2 30–100 0 – 80  
3 0–30 60 – 100  
4 0– 30 0 – 60  
**Case 1:** In this case, both the battery and the SCs will  
supply power to the motor. The battery supplies only the  
smoother portion of the power demand (*Pbat* = *Pd*) while SCs  
are responsible to fully support the fluctuating portion of the  
power demand ( *PSC* = *Pf* ) of the motor. During regenerative  
braking, only the power flow direction is reversed.  
**Case 2:** For this case, the battery charges the SC and also  
supplies power to the motor. The amount of power supplied by  
the battery, *Pbat* is given by Equation 4. The amount of power  
supplied by the supercapacitors, *PSC* is calculated by Equation  
5. The constant factor (212 *CL* ) in both equations is selected based on the equivalence of the Li-ion battery’s storage capacity to about 212 times that of the SCs. This approach is employed to  
transfer the power from the battery to the SCs based on their  
respective charging levels.

|  |  |
| --- | --- |
| *Pbat* = *Pd* + 2 *· SoCbat ·* 212 *CLSC* | (4) |

*PSC* = *Pf -* 2 *· SoCbat ·* 212  
*CLSC* (5)

A diagram of a car driving cycle

Description automatically generated

Fig. 2. Flowchart of the proposed rule-based EMS algorithm.

**Case 3:** In this scenario, the battery supplies less power  
than the power demand of the motor and receives more power  
from regenerative braking. The amount of power supplied by  
the battery, *Pbat* and supercapacitors, *PSC* is estimated by  
Equation 6 and 7, respectively. To accommodate the considerable difference in storage capacity between SCs and batteries,  
the charging power from the SC to the battery is reduced by  
approximately five times compared to the scenario where the  
battery charges the SCs.

|  |  |
| --- | --- |
| *Pbat* = *Pd -  SoCbat* | (6) |

47 *·* CL*SC  
PSC* = *Pf* + 47 *·* CL*SC  
SoCbat* (7)  
**Case 4:** For this case, both the battery and SCs contribute power to the motor, with the battery supporting a  
small proportion (20%) and SCs remaining proportion (80%) of the fluctuating power. Power levels of battery, *Pbat* and  
Supercapacitors, *PSC* are computed using Equation 8 and 9,  
respectively. During regenerative braking, the battery receives  
the majority of the energy since it serves as the primary energy   
storage for the vehicle.   
*Pbat* = *Pd* + 0*.*2 *· Pf* (8)  
*PSC* = 0*.*8 *· Pf* (9)  
Once the battery power requirement is generated through the algorithm, the control pulse is generated by utilizing a  
PID controller. This control pulse is then supplied to the bidirectional buck-boost converter in order to regulate the power flow.  
*C. PMSM Speed Regulation by Model Predictive Control*The speed of the PMSM of the EV is regulated by MPC  
technique. The schematic diagram and the control loop  
of the MPC system is displayed in Fig. 3. To control the  
motor speed, the model takes the reference signals for motor  
speed and stator current as inputs and provides the switching  
pulses to the inverter. The control scheme is designed in the  
two-phase d-q frame, which is obtained from the three-phase  
stator currents using the Park transformation. The Park  
transformation converts the three-phase stator current into  
two-phase d-q axis current as follows [14]:  
*iidq* = 23 *-*cos( sin( *θθ*) cos( ) *-* sin( *θθ--*22*π/ π/*3) cos( 3) *-* sin( *θθ*+ 2 + 2*π/ π/*3) 3)  *iiiacb*  (10)  
where *ia, ib,* and *ic* are the three-phase stator currents and  
*id, iq* are the two-phase d-q axis currents. *θ* is the angle  
between the d-axis and the a-axis.  
After obtaining the two-phase currents, a PI controller is  
used to calculate the reference current *iqref* based on the  
error between the reference speed *wref* and the actual speed  
*w* of the motor. The PI controller output is given by:  
*iqref* = *Kp*(*wref - w*) + *Ki* Z0*t*(*wref - w*)*dt* (11)  
where *K  
p* and *Ki* are the proportional and integral gains of  
the PI controller, respectively.  
The MPC function then takes these reference values along  
with the current values of *id*, *iq*, *w*, Time(*t*), and *θ* as inputs. It also requires the stator phase resistance (*R*), armature inductance (*L*), flux linkage (*λ*), Pole pairs (*p*) and DC link  
voltage (*Vdc*) to be provided for the function to be built. In order to create a cost matrix, the function initializes the possible combinations of switching states (S) for the threephase inverter. Each combination of the switching states is  
stored in (*Sa*, *Sb*, *Sc*) variables [15].  
Consequently, the function calculates the three-phase voltage values (*Vinva*, *Vinvb*, *Vinvc*) based on *Vdc* and the phase states using the following equations:

|  |  |
| --- | --- |
| *Vinva* = *Vdc ·* (2 *· Sa - Sb - Sc*) 3 | (12) |

*Vinvb* = *Vdc ·* (2 *· Sb - Sa - Sc*)  
3  
(13)  
*Vinvc* = *Vdc ·* (2 *· Sc - Sb - Sa*)  
3  
(14)  
The voltage values are then used to calculate the quadrature  
and direct components of the stator voltage, *vq* and *vd*, using  
the following equations:  
*v  
q* =  
2 3  
[(*Vinva ·* cos(*w · t* + *θ · p*)) + (*Vinvb ·* cos(*w · t*+*θ · p* + 4*π*3  
)) + (*Vinvc ·* cos(*w · t* + *θ · p* + 2*π*3  
))  
(15)  
*vd* =  
2 3  
[(*Vinva ·* sin(*w · t* + *θ · p*)) + (*Vinvb ·* sin(*w · t*+  
*θ · p* + 4*π*3  
)) + (*Vinvc ·* sin(*w · t* + *θ · p* + 2*π*3  
)) (16)  
Using these voltage values and the current values, the MPC  
function then calculates the predicted values of the quadrature  
and direct components of the stator current, *iqp* and *idp*, using  
the following equations:

|  |  |
| --- | --- |
| *idp* = (1 *- R · Ts* ) *· id* + *Ts · w i q* + *vd · Ts* | (17) |
| *L* | *L ·* | *L* |

|  |  |
| --- | --- |
| Parameter | Value |
| Simulation Run Time | 50s 20us |
| Sampling period | Case1:Battery=50%,SC=81.44% |
| Li-on battery SoC | Case1:Battery=50%,SC=76.8% |
| Of SCs | Case1:Battery=25%,SC=81.44% |
|  | Case1:Battery=25%,SC=76.8% |
| Time Constant | 0.05s |
| Rate limit | 450000 |
| DC-Link Voltage | 300V |
| Pole paris | 4 |
| PMSM stator phase resistance | 0.0918 |
| Armature inductor | 0.975mH |
| Flux linkage | 0.1688 |

*i  
qp* = (1*- R · Ts  
L*)*·iq - Ts · w  
L  
·id-  
λ · w · Ts  
L*+  
*v  
q · Ts  
L*(18)  
where *R* is the motor resistance, *L* is the motor inductance,  
*λ* is the motor mutual inductance, and *Ts* is the sampling time.  
The MPC function calculates a cost function for each of  
the eight possible combinations of phase states (*Sa*, *Sb*, *Sc*)  
and chooses the combination that minimizes the cost function.  
The cost function is calculated using the following equation:  
*cost*(*i*) = *i*2 *dp* + (*iqref - iqp*)2 (19)  
where *i* is the index of the phase state combination, *idref* and  
*iqref* are the reference current values.  
After evaluating the cost function, the selection process  
determines the most suitable switching states, which are then  
fed as pulses to the three-phase inverter. This strategic configuration enables effective control of the PMSM, maximizing  
its high-speed capability and efficiency.

A diagram of a system

Description automatically generated

Fig. 3. Schematic diagram of model predictive control system

TABLEIII

Simulation Parameters

III. RESULTS AND DISCUSSION

The proposed HESS and PMSM control model were designed and analyzed in MATLAB/Simulink software. Due to  
the complexity of the model, the simulation was conducted  
for 50 seconds only. The simulation parameters and the  
corresponding values have been listed in Table III

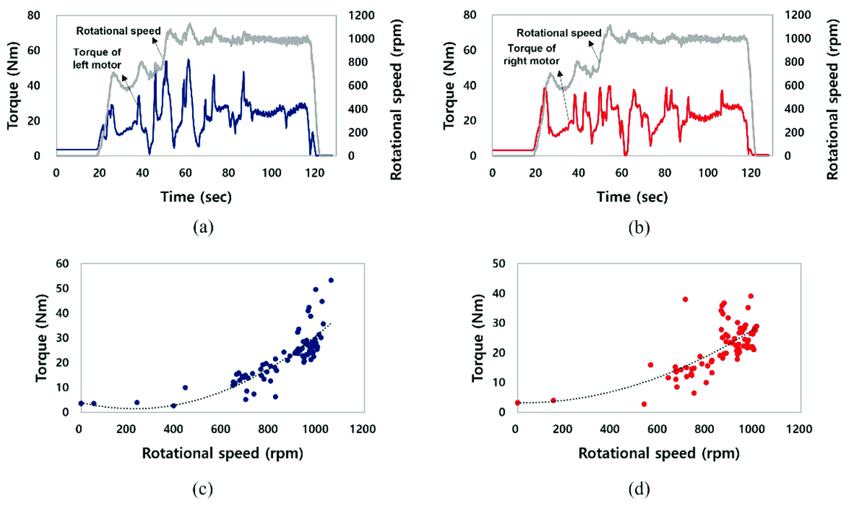


Fig. 4. The required (a) rotational speed and (b) torque for the EV at dynamic   
conditions

The MPC loop receives a variable reference rotational speed  
of the PMSM, ranging from 1990 rpm to 2300 rpm, as depicted  
in Fig. 4a. Additionally, the reference torque supplied to the  
PMSM ranges from -10 N.m to 10 N.m as shown in Fig. 4b.  
While observing Fig. 5, it is evident that the actual rotational  
speed of the PMSM adeptly tracks the reference speed as  
desired

A graph with a line and a red line

Description automatically generated with medium confidence

Fig. 5. Reference and actual speed of the PMSM

Fig. 6a illustrates the power profile of the PMSM, with positive values indicating power consumption and negative values  
representing regenerative power generated by the PMSM. The  
proposed HESS supplies the fluctuating power profile required  
by the PMSM, as shown in Fig. 6b. The battery, serving as the  
primary energy storage, meets the power requirements with a  
smooth and consistent profile, as depicted in Fig. 6c. Conversely, the power profile of the SCs in Fig. 6d demonstrates  
its ability to handle fluctuations in power demand, thereby  
extending the overall battery life.

A screenshot of a graph

Description automatically generated

Fig:6 Power profile: (a) PMSM (b) Total power (C) Battery and (d) SCs

The voltage characteristics are illustrated in Fig. 7a, where  
the battery voltage fluctuates due to the charging and discharging processes. The SC terminal voltage remains stable  
at approximately 300V, contributing to the stabilization of the  
DC link voltage. The current profile of both the battery and  
SC, as shown in Fig. 7b, closely follows the power variations.  
A graph showing a blue and red line

Description automatically generated

Fig. 7. Battery and SC: (a) Voltage profile and (b) Current profile

Fig. 8a presents the SoC profile of the Li-ion battery.  
Initially, from 0 to 8 seconds, the SoC decreases, indicating  
the battery discharging to meet the PMSM power demands.  
Subsequently, in the following 10 seconds, the SoC gradually  
increases, indicating the battery receiving power from the  
synchronous machine regeneratively. A comparison between  
Case 1 and Case 2 in Fig. 8a justifies the battery SoC  
experiencing a faster decline in the latter case. This can be  
attributed to the battery simultaneously charging the SCs also,  
leading to a higher discharge rate. When comparing Case 1  
and Case 3 in Fig. 8b, a similar trend can be observed which  
demonstrates a faster decrease in the charge level for the SCs.

A comparison of a diagram of a schematic diagram

Description automatically generated with medium confidence

Fig. 8. Comparison of four cases: (a) Battery SoC and (b) SC charge level

Fig. 9a exemplifies the stator current, which exhibits changes in amplitude corresponding to torque and speed requirements. The stator current also reveals high ripple caused  
by the electrical torque generated by the PMSM. The realtime efficiency of the model, as portrayed in Fig. 9b, exhibits consistently high values exceeding 98% for both PMSM  
energy consumption and regenerative energy. However, minor fluctuations are observed in the graph, primarily due to rapid switching between the motor and generator modes of the  
PMSM.  
A diagram of a circuit

Description automatically generated

Fig. 9. (a) PMSM stator current and (b) Real-time model efficiency.

IV. CONCLUSION

This paper presents the design and analysis of a rule-based Energy Management System (EMS) for a semi active Hybrid Energy Storage System (HESS) combining batteries and SCs. The proposed EMS is specifically tailored for EVs, ensuring optimal energy management and efficiency. Furthermore, the Model Predictive Control (MPC) strategy has been utilized to control the speed of the PMSM for the proposed model. The battery seamlessly caters the smoother power demands, while the SCs adeptly manages the irregular fluctuations, resulting in extended battery life and elevated system performance. The model efficiency has been measured in real-time surpassing an impressive value of 98%. The comprehensive design and exceptional efficiency underpin the system’s strong suitability for practical EV applications, making it an enticing prospect  
for sustainabl[[3]](#endnote-1)e transportation.

[[4]](#endnote-2)

1. [↑](#footnote-ref-1)
2. [↑](#footnote-ref-2)
3. REFERENCE

   Santos, G. (2017). What are the challenges. *Road transport and CO2 emissions*, 71-74. [↑](#endnote-ref-1)
4. [↑](#endnote-ref-2)