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Control Strategy for numerous Hybrid Energy Storage Systems for Electric Vehicles

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ABSTRACT: Fuel cells are known to be efficient and environmentally friendly, but suffer from slow reaction dynamics. When fuel cells are used as the vehicle's main power source, they cannot quickly adapt to sudden changes in power demand. To overcome this limitation, solutions can be found by integrating batteries and super-capacitors into the system. Additionally, regulating the flow of electricity is critical to extending the life of the energy storage system. This is achieved by keeping the rate of current rise of the fuel cell or battery within a specified value to ensure a stable DC output voltage. To meet these needs, a key control system was created to control the mixed-race control system including fuel cell, battery and super-capacitor in this consideration. The output voltage of the crossovers is controlled using triple DC –DC converters, including double bi-directional converters & aboost-converter. The boost converter controls the fuel cell output current and voltage, while the bidirectional converter controls the battery and the super-capacitor. The relating current for each converter was generated utilizing proven Predictive Control(MPC) and monitored using hysteresis control.

Keywords: Fuel cell, Battery, super capacitor, dc–dc converter, hysteresis, Model Predictive Control (MPC).

I. INTRODUCTION

In addition to the global warming crisis, concerns over the use of fossil fuels are growing around the world. Overconsumption of fossil fuels not only threatens the exploitation of their finite reserves, but also leads to increased air pollution around the world. To address concerns about oil dependence, energy researchers are actively researching alternative energy sources. A promising approach is to prioritize renewable and sustainable energy options. Based on historical data, the number of vehicles is projected to nearly quadruple over the next 50 years, and global oil reserves are projected to be depleted at the current rate of consumption [1]. To address these challenges related to oil dependence and emissions, the development of fuel cells as an alternative energy source has gained considerable momentum, especially in the last decade [2]. Fuel cells use hydrogen from renewable energy sources and produce only water as a by-product, making them environmentally friendly. Due to their lightweight and compact design, fuel cells can be used in a wide variety of applications and are characterized by excellent energy efficiency. These properties make fuel cells an ideal and widely applicable energy source for the future.

Among many types of fuel cells, (PEMFC) are widely used as distributed energy sources and reliable stationary power sources. However, PEMFC faces certain challenges that need to be addressed. Limitations includes low response times due to electric motors, slow electrochemical reactions, and an inability to adapt quickly to sudden load varies when used as a vehicle power supply[2]. Another feebleness is the frequent lack of fuel oroxygen, leading to a pressure drop when energy demand is high[3]–[5]. This phenomenon can lead to degraded performance and can permanently damage the fuel cell electro catalyst, posing a significant risk to overall performance. Furthermore, the economic life of the PEMFC can be limited if the current slope of the PEMFC is not well controlled.

Therefore, it is very important to optimize the economic life of the PEMFC by controlling the current during rapid load changes. When PEMFCs are used as a power source for vehicle propulsion, the yarenotal ways able to provide sufficient power during transients such as starting and accelerating. Additional energy storage (ESS) systems are required to reliably

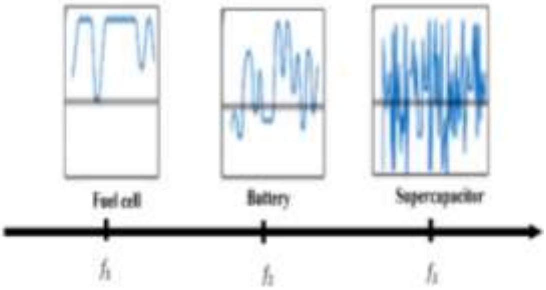

Fig.1:Fuel cells, supercapacitors, and batteries are categorized according to frequency.

meet peak energy demands. Super capacitors and batteries can be used to meet these requirements. Integrating these ESSs can prevent fuel starvation and implement regenerative braking. However, like any other energy source, supercapacitors, and batteries each present their own challenges. Super capacitors have a low energy density, typically providing3 to 5Wh/kg,whilelead-acidbatteriesprovideabout30 to 40Wh/kg. In contrast, super capacitors have significantly higher charging and discharging rates than batteries[5].

In addition to fuel cells, many energy storage systems (ESS) such as super capacitors and batteries are now integrated into hybrid cars. To ensure efficient operation of these hybrid systems, it is necessary to develop energy management strategies aimed at establishing fast and dynamic systems. In this strategy, the fuel cell is assigned the role of the lowest frequency energy source and the super capacitor operates at the highest frequency. As shown in Figure1, the frequency of the battery iskept between the frequency of the fuel cell and the frequency of the super capacitor[3].

Several advanced strategies have been identified as too ambitious. These include the Bidirectional Triple Half Bridge Converter [6], which is a cutting-edge topology for configuring efficient power sources that consider factors like productivity, capacity, energy recovery, and the volume of Energy Storage Systems (ESS) [7], [8]. Additionally, numerous control strategies have been proposed to monitor energy generated by fuel cells, supercapacitors, and batteries. These strategies encompass wavelet switching [9], [10], smooth base control [10], [16], shared stack control [11], supervised control [12], mode control slide [9], [13], and correspondingly controlled [4], [14], ideal control [15], and level control [16]. In all instances, these strategies make adjustments after errors have already been introduced. This is where Model Predictive Control (MPC) proves to be the standard resolution for this issue. Through numerical optimization, MPC provides an ideal management trajectory by predicting future command inputs and the system's response, which are then optimized at regular intervals based on a predefined list. MPC calculations enable the control of large-scale systems with multiple control factors. The effectiveness of MPC has been demonstrated through testing on a hybrid race car, receiving approval for recreational use [17], [18]. In [17], MPC is employed to drive the fuel cell and supercapacitor, while in [18], it is utilized for generating the reference energy of the battery and fuel cell. Furthermore, an MPC-based method has beenmodifying for fuel cells, supercapacitors, and batteries as part of the drive system to generate reference currents for fuel cells and batteries [19]. In this context, a Proportional-Integral (PI) controller is employed to cycle each converter by associating the fuel cell and reference battery currents with the measured fuel cell and battery currents. This predictive control method in the context of trams has been validated through MATLAB/Simulink simulations [19]. However, unlike [19], this paper introduces an MPC-based method for generating reference currents for fuel cells, supercapacitors, and batteries, which are then monitored using hysteresis control. It is also worth noting that [19] focuses on reconstruction results, whereas this paper presents both reconstructive and exploratory reflections. The proposed MPC reconstruction has been implemented using MATLAB and Simulink, and its validity has been confirmed through small-scale experiments. A more comprehensive exploration and analysis of this research can be found in [20]. The article delves into various controller configurations and stack modifications to evaluate the response of the MPC framework.

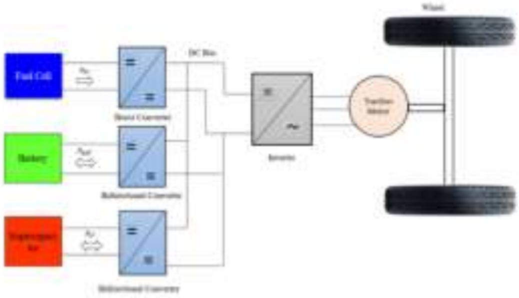

Fig. 2: Topology proposed for the HPS

Several methods have been extensively studied in this area. Two-way, three-half-bridge converters and a novel topology that optimizes power configuration while considering ESS performance, cost, and volume are some prominent examples [6] and [6]. In addition, different control methods have been proposed to manage the energy generated by fuel cells, supercapacitors, and batteries. These include wavelet transform [9], [10], fuzzy logic control [10], [16], load power sharing [11], supervised control [12], sliding mode [13], proportional integral control [4], [14], optimal control [15], and flatness control [16]. However, these methods often correct errors after they occur.

Model Predictive Control (MPC) has emerged as a proposed solution to address this limitation. MPC, derived from mathematical optimization, provides an optimal control structure by predicting future control inputs and plant responses based on the system model and periodically optimizing them based on the system model. on performance indicators. MPC algorithms are capable of controlling large-scale systems with many control variables. The application of MPC in hybrid vehicles has been extensively studied and confirmed by simulation [17], [18]. In [17], MPC is used to drive fuel cells and supercapacitors, while in [18], relay control is used to generate reference power for batteries and fuel cells. For fuel cells, supercapacitors, and batteries in electric vehicle systems, predictive control-based strategies have also been adapted [19].

In this strategy, an MPC-based method is used to generate a reference current for the fuel cell, super capacitor, and battery, which is then monitored using hysteresis control. It should be noted that [19] only focuses on simulation results, while this paper presents both simulation and experimental studies. The proposed MPC was simulated using MATLAB/Simulink and validated by small-scale experiments. Preliminary results of this study have been presented in [20], and a more complete experimental and simulation study is provided in this paper. Various controller parameters and load changes were tested to evaluate the response of the MPC system.

This document is standardized as follows: Part I introduces the topic and highlights HPS (Hybrid Power Source) control and to pology. Part II provides a detailed description of the HPS to pology and control system. System modeling is discussed in Section III. Part IV introduces the proposed Model Predictive Control (MPC) approach, followed by MATLAB/ Simulink simulation of power management control in PartV.

II. HYBRID POWER SUPPLY

The term HPS refers to the integration of fuel cells, batteries and supercapacitors for combined energy applications. HPS is commonly used on vehicles to ensure sufficient power supply. In this section, we present the proposed topology for the HPS system and develop the control method used to effectively manage its operation.

A. HPS topology:

The proposed topology for HPS (Cross breed Control Source) is appeared in Fig. 2. The fuel cell serves as the essential vitality source, whereas the supercapacitor and the battery act as the auxiliary vitality capacity framework (ESS). These sources are associated to the DC transport through a DC-DC converter, shaping a parallel setup.

In addition, a bidirectional converter is integrated into the secondary ESS to assist with charging and discharging. Finally, a boost converter is incorporated into the topology to improve the fuel cell output voltage. This topology provides great flexibility as additional power sources can be easily connected to the DC bus via a parallel connection without requiring reconfiguration of the existing layout. The application of this topology in hybrid automobiles has been analyzed and discussed in previous studies such as [3] and [5].

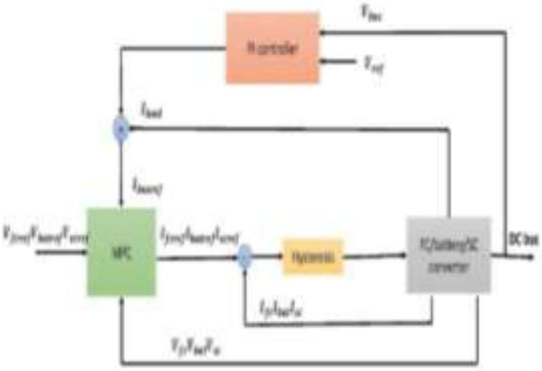

Fig.3:Control scheme for proposed HPS

B. HPS control:

Predictive Control Model (MPC) selection is based on a systematic approach to handling input voltage and system state in a feedback control system. The strategy is to find real-time solutions to constrained optimization problems to determine the best putative inputs. MPC ensures that the DC output voltage remains stable within the reference valueregardless of load changes. In addition, the MPC plays an important role in determining the reference current for each converter. In this study, the reference current generated by the MPC was monitored by hysteresis control, the block diagram of the HPS system with the proposed controller [20], and the detailed diagram is shown in Figure 3 [21].

III. MODEL

To facilitate replication, a dynamic model was developed that captures the properties of the HPS system. The effectiveness of these models was assessed by comparing their response times to the measured response times of his HPS system. A current step input was relatedto the fuel cell, battery & supercapacitor separately &the resulting responses were recorded (see Fig. 4) [22], [25]. The dynamic responses of these models were integrated into the MPC design by discretizing the models and integrating them into the dynamic programming framework related in Section-IV.

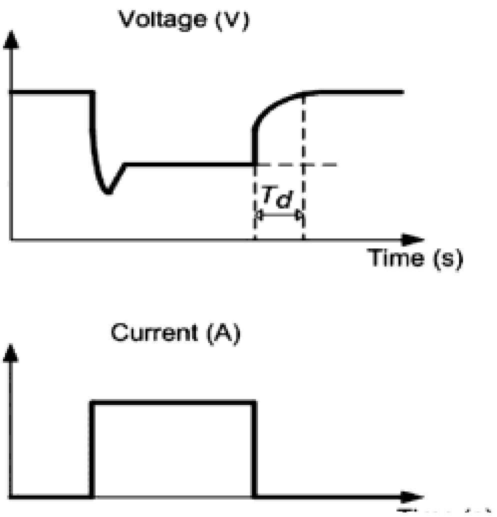

Fig. 4. Current step and time.

A. Fuel Cell:

Fuel cells are the main source of energy production from the chemical reaction between oxygen and hydrogen gas in the presence of an electrolyte. It usually comes in the form of a battery that, when combined, provides more power. Therefore, fuel cells are a good candidate against internal combustion engines in the case of HEVs. But fuel cells have some disadvantages, such as cold starting and poor instantaneous response. These shortcomings can be overcome by using multiple secondary sources to reduce unnecessary load on the power supply and provide a good operating range.

The fuel cell, capable of providing a maximum output power of 50 W. A model was developed based on the fuel cell's I-V curve [23].

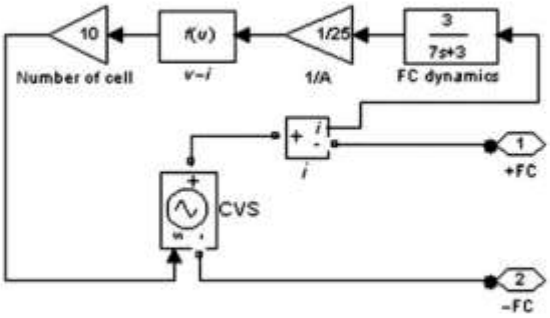

Fig.5: Model for fuel cell

Thefuelcellconsistsofastackof10-cellswithanactive area(A)of25cm2,connectedinseries.Torepresentthefuelcellmodel,aMATLAB/Simulinkdiagramisgenerated asshowninFigure5.

B. Battery:

Fuel cells by oneself cannot provide an appropriate reaction to sudden load changes. It was starting to get cold, and during strong acceleration, the supercapacitor had to discharge. So, in this situation, the battery provides the vital power to meet the needs of the tractor engine. Supercapacitors have a much higher performance than batteries since they have a much lower recharge cycle. The role of the battery in a fuel cell hybrid vehicle can be summarized as acting as a source of power for the vehicle's electrical device, a device that stores the electrical energy produced by the fuel cell when it is charged. Low-load fuel cell support to generate electricity at higher loads is the primary power supply when the fuel cell system is operating at low loads.

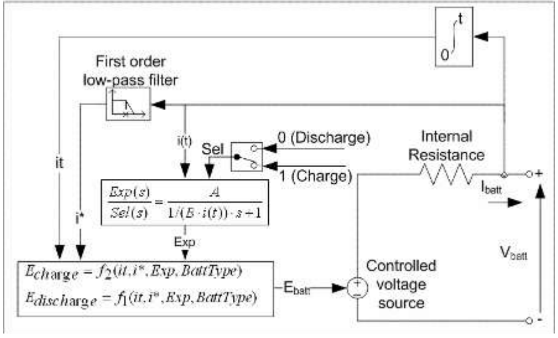

Fig.6: Generic model battery

For this study, a lead-acid battery was selected as an energy storage device. Lead-acid batteries have been widely used for over a century in a variety of applications, including automotive applications, due to their low cost, high capacity and well-established technology. Modeling was carried out using MATLAB/ Simulink and constraints have been incorporated into the model [24]. The battery model used in this work is shown in Figure6[25].

The simulation and test results demonst rate that the battery response time is about 3 seconds.

C. Supercapacitor:

In a supercapacitor, two electrodes are placed parallel to one another with a dielectric material between them. The basic principle of supercapacitors is to capture electrical energy from the charge stored on these electrodes. The correlation between the accumulated electrical energy and the voltage across the electrodes can be observed through the capacitance (C) of the supercapacitor.

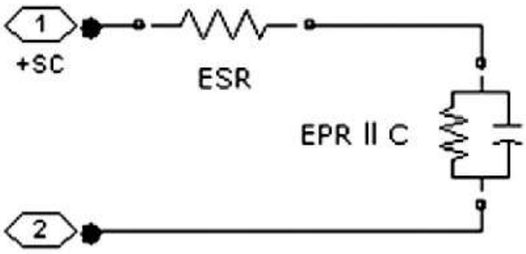

Fig.7: shows the equivalent model the supercapacitor.

The self-discharge loss of a super-capacitoris quantified by the equivalent parallel resistance(EPR), which represents the leakage effect. Overtime, this leakc and e grade the performance of the ESS Energy Storage System. Equivalent Series Resistance(ESR), on the other hand, is the resistance involved in the processes of charging and discharging. In practical applications, only equivalent series resistance is usually considered.

IV. MODEL PREDICTIVE CONTROL

A system, the desired targets for various variables within a process are typically predefined. To achieve these targets, manipulated variables are employed. The fundamental approach involves leveraging the model's understanding of the system's behavior to predict and anticipate future changes that may occur in the process. An easier way to achieve this is to use the Model predictive control (MPC) is a control technique.

A. Linear MPC:

In this study, the application of MPC in power converters involves assuming that the converter dynamics can be presented by a simplified dynamic system containing of a controlled current source and transformer (Figure 8). This state mentis the basis for the construction of the control strategy in this study. Similar generalizations have been applied to control strategies for other hybrid systems[13], [26]. As long as the conversion ratio of the converter does not change and the current reference is smooth enough, this as sumption is correct. The design of the controller ensures the regularity of the current set-point. When the voltage of the DC bus-barand each hybrid power system component is relatively stable, it is reasonable to maintain a fixed turn ratio of the converter.

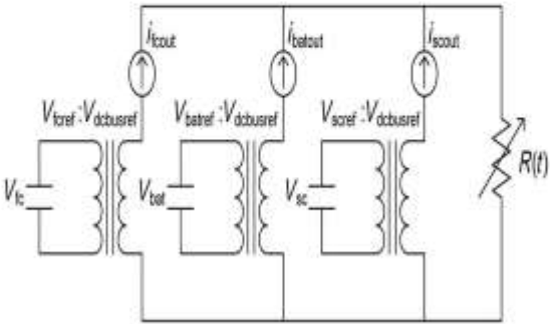

Fig.8: Control design model based on HPS.

The control system consists of two levels of controllers. The first level is the MPC controller, followed by the delay controller. In the simplified circuit model of the HPS with the load change represented by a rheostat (Fig.8) [21], the current references for the hysteresis control are produced bythe model predictivecontrol. The delay controller compares the actual current (I_{fc},I_{bat}, andI_{sc}) with the reference current (I_{fcref}, I_{batref}, I_{scref},) of each power source and generates a PWMsignal for every converter change. To enable model predictive controller implementation, the control model must be discretized. In addition, to ensure a constant reference signal for the converter, it is necessary to monitor the reference signal by including the last entry in the state variable. The following discrete-time state-space model represents a controlled power plant [21]:

In the provided model, the reference voltage of the battery (V_{batref}) and the reference voltage of the super-capacitor (V_{scref}) are interpreted as the state of charge (SOC) of the battery and the super-capacitor, respectively [5].

B. Dynamic Programming:

Energetic programming (DP) could be a capable approach for understanding the optimization issue in MPC. This is especially effective for optimizing dynamic systems. As discussed in this article, in the context of unconstrained MPC, DP does not offer significant advantages over simpler MPC techniques. However, DP is advantageous in the generally constrained MPC case as it enables offline computation of certain expensive tasks [27]. Therefore, the unconstrained MPC DP method presented in this article can be seen as a steppingstone to various general constrained MPC approaches. In the central system control design, MPC penalizes the input and output variables, while DP aims to minimize the quadratic cost of the output. DP also manages the computation of the penalty matrix from time step n to time step n + N. where n represents the current time-step and N represents the period described in MPC.

V. CONCLUSION

This review paper provides a comprehensive overview of research on model predictive control (MPC) for fuel cell, battery, and super-capacitor systems in electric vehicles. This article highlights the potential benefits and challenges associated with MPC-based energy management strategies by examining various studies and advances in this area. It will serve as a valuable resource for researchers, engineers and stakeholders interested in optimizing electric vehicle performance, range and durability through advanced control techniques.

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