Modeling and Experimental Investigation of Energy Management for Hybrid Electric Vehicle based on Variable Structure Control Strategy

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***Abstract*—The current study presents real-time modeling and non-linear controllers-based energy management system (EMS) for multi-energy hybrid Electric Vehicle (EV), where a detailed physics-based dynamic vehicle model has been considered. The main objective of the paper is to regulate the power flow, stabilize DC voltage for an EV driven by a brushless DC motor, and ensure effective power sharing in a hybrid electric system under complex driving circumstances. The approach is based on tracking the reference battery current by backstepping sliding mode control for optimal power distribution. Subsequently, Integral Sliding Mode Control based on barrier function (NBS-ISMC), and Fractional Order Terminal Sliding Mode Control (FOTSMC) are implemented to control the switching operation of converters for Photovoltaic (PV) and Ultra-capacitor (UC), respectively. User-defined and practical standard drive cycles are selected to test the effectiveness of proposed reference current controllers. Real-time experimental validation of the proposed framework using the Speedgoat Performance Real-Time Target Machine will be included in the final paper.**

Keywords— Energy management system, Hybrid Electric vehicle, Nonlinear Control algorithms, Drive cycles, Vehicle dynamics.

I. INTRODUCTION

Hybrid Electric vehicles (HEVs) are environment-friendly with almost zero greenhouse gas emissions, serving as key enablers for climate goals [1]. Withal, multiple energy sources are required to meet desired power and speed requirements for HEVs during real driving conditions. Commercial EVs are evolving to utilize a combination of renewable energy sources, such as fuel cells (FC), batteries, ultra capacitors, and PV cells, to provide simultaneous power to the HEV. Nowadays, HEV with batteries and UC have drawn a lot of attention due to their unique power-sharing capabilities. To meet high-power demands quickly, auxiliary sources like UC or FC are utilized, providing high power density and enabling numerous charging and discharging cycles. A critical unit for effectively managing the energy sources for prolonging lifespan and extending vehicle driving range is the Energy Management System (EMS). Consequently, nonlinear control strategies for EMS and hybrid Energy Storage System (HESS) are investigated in this paper.

Various controllers for the EMS of HEVs have been presented in the literature. In [2], dynamic behaviour of storage elements (battery and supercapacitor) have been observed and EMS has been developed using an artificial neural network (ANN) with a PI controller in parallel to capture the regenerative current. A multi-input–multi-output (MIMO) bidirectional converter with a PI controller is used in [3] for the reference tracking of current and voltage for multiple power sources involved in the HEV. A fractional-order PI controller has been used in [4] to cater the uncertainties present in the EV's HESS. In these linear control strategies, the theoretical stability of control systems is not proven and cannot guarantee global stability for nonlinear DC-DC converters. Mostly, due to the irregular switching behavior of the converters, the mathematical models for HEV are nonlinear in nature and in most of these works, the models are linearized around a specific equilibrium point, hence limiting the flexibility of operation [5].

HEV energy management strategy has been presented in [6] using UC and FC based hybrid energy storage system. The major issue in the design is the use of fixed constant values for resistors, inductors, and capacitors, which however are prone to variations as a function of time due to wear and tear, production faults, and noise [7]. A real-time energy management for FC range extender vehicles based on Lyapunov-based nonlinear control and fuzzy logic-based control has been implemented in [8]. Although for HEV, FC is a good candidate for providing energy, it lacks in providing fast stand-by operation. It provides a long driving range but the high cost and low power density of the FC are the major issues that limit its use as an energy source. Noteworthy, FC exhibits low power density as compared to a battery or UC. It means that during transient load, FC based HEVs cannot provide enough energy. Therefore, HESS has to be combined with renewable energy sources to overcome this problem. Another shortcoming in the literature is lack of consideration for energy losses and vehicle dynamic characteristics including braking and vehicle's mechanical transmission losses [9-11] which could greatly impact the overall operation of vehicular system.

In this paper, EMS is based on nonlinear controller and physics-based electric vehicle model considering braking and vehicle's mechanical transmission losses. The power sources considered for the investigation are PV with DC-DC boost converter and HESS-based battery/UC coupled with bidirectional buck-boost converters. Moreover, back-stepping sliding mode control-based nonlinear controller and fractional order terminal SMC have been proposed to improve the overall dynamic performance of HESS consisting of battery and UC for HEV, while NBS-ISMC has been implemented for Maximum Power Point Tracking (MPPT) of PV to fulfil the load requirement of HEV. User-based vehicular driving cycles are selected to test the effectiveness of the proposed controllers.

The paper is organized as: section II presents the modelling and optimal system design. The proposed EMS methodology has been discussed in Section III. Results and discussion is provided in Section IV, followed by conclusion in Section V.

II. MODELLING AND OPTIMAL DESIGN OF SYSTEM

A parallel-type EV system consisting of an electrical network and a vehicle dynamic system has been considered. The electrical system is composed of a PV panel with a boost converter, HESS (battery, and UC with a bi-directional DC-DC Buck-Boost converter), DC bus, and EMS. The vehicular system consists of the mechanical transmission system, motor and inverter, and other mechanical parts. Figure.1 shows a schematic diagram of the proposed system and EMS based on nonlinear controller. This section consists of modelling electrical network and vehicle dynamic which is essential for the development of EMS.

A. Modelling Electrical Network

The circuit diagram for the electrical system is shown in Figure.2. Three sources are connected to the DC bus through their prospective converters. PV array connected to the DC bus is controlled by unidirectional DC-DC boost converter to maintain the load and generation balance. The DC-DC converter of PV system consists of IGBT switch (S_1), D_1, Inductor (L), input capacitor (C_{PV}) and DC bus capacitor (C_{bus}). The PV generation system is working in continuous conduction mode with two modes of operation for the DC-DC converter. During mode 1, switch S_1 is closed while in mode 2, Diode (D_1) is open. In mode 1, load is disconnected, and inductor is being charged. In mode 2, D_1 is closed which discharges the inductor by connecting it to the load. The mathematical model for capacitor current and inductor voltage, applying volt second and capacitor balance for steady state analysis can be expressed as:

$$\dot{x_1} = \frac{V_{pv} - x_1 R_{pv} - (1 - u_1)x_2}{L_{pv}} \qquad (1)$$

$$\dot{x_2} = \frac{(1 - u_1)x_1}{C_{bus}} - \frac{x_2}{C_{bus}\, R_{pv}}$$

Where x_1 and x_2 are the average values of PV inductor current and DC bus voltage respectively. The u_1 denotes the control input for unidirectional DC-DC boost conductor.

To provide stable output despite the load variation, HESS comprising of battery and UC has been integrated with the PV system. Battery and UC are connected to DC bus through a DC-DC Buck-Boost converter to supply power to the inverter embedded in the vehicle dynamics system which convert DC power into AC, drives the motor to push the EV transmission system. Battery act as auxiliary source with the PV as main source which discharge itself under varying load and driving conditions whereas UC provides instant power during load peaks load owing to its high-power density. Figure 2 shows the topology of HESS which operates in charging and discharging mode depending on state of charge (SoC) and load demand. The expression for charging and discharging behaviour of the battery as a function of load demand can be represented as:

$$M = \int \begin{matrix} 1, I_{batt\,ref} > 0 \\ 0, I_{batt\,ref} < 0 \end{matrix} \qquad (2)$$

Where M is a notation for the charging and discharging behaviour of the battery and $I_{batt\,ref}$ is the reference current of battery. During driving mode when switch S_2 is ON and switch S_3 is OFF, the battery discharge to maintain the power balance. The battery tends to work in boost mode ($I_{batt\,ref}$ > 0). When there is no load attached or PV provides the required power to the DC bus, the battery converter operates in buck mode which enforces the battery to charge $I_{batt\,ref}$ <0. Since, two PWM control signals are required for the operation of the battery converter. Therefore, a virtual controller is introduced to generalize and simplify the battery converter model which is given by:

$$\propto = [M\,(1 - S_2) + (1 - M)S_3] \qquad (3)$$

Where $\propto$ is virtual control consists of battery PWM control signals denoted by S_2 and S_3 for each connected IGBT at battery buck-boost converter. Virtual control is employed to reduce the complexity of mathematical equations for the buck-boost battery model. The mathematical expression for battery can be expressed as:

$$\dot{x_3} = \frac{V_{battery}}{L_{battery}} - \frac{x_3\, R_L}{L_{battery}} - \frac{x_4\ \propto_1}{L_{battery}} \qquad (4)$$

$$\dot{x_4} = \frac{\propto_1\ x_3}{C_{bus}} - \frac{x_4}{C_{bus}\, R}$$

Where x_3 is $I_{battery}$ and x_4 is DC bus voltage. UC is also provided with a DC-DC Buck-Boost converter to allow bi-directional power sharing, charging, discharging, and power regulation. It consists of two IGBTs switches S_4 and S_5, and UC inductor (L_{UC}) with their internal resistance (R_{UC}). UC has characteristics of fast charging and discharging. It provides power during startup situations and handle peak load by providing instant power. The mathematical expression for UC buck-boost converter is given below:

$$\dot{x_5} = \frac{V_{UC}}{L_{UC}} - \frac{x_4\, R_{UC}}{L_{UC}} - \frac{x_6\ \propto_2}{L_{battery}} \qquad (5)$$

$$\dot{x_6} = \frac{\propto_2\ x_5}{C_{bus}} - \frac{x_6}{C_{bus}\, R}$$

x_5 represents the UC current, and x_6 refers to the DC bus voltage due to capacitor current. Using battery, UC, and virtual control model, the average state model of HESS is represented as:

$$\dot{x_3} = \frac{V_{battery}}{L_{battery}} - \frac{x_3\, R_{battery}}{L_{battery}} - \frac{D\, x_7}{L_{battery}} \qquad (6)$$

$$\dot{x_5} = \frac{V_{UC}}{L_{UC}} - \frac{x_5\, R_{UC}}{L_{UC}} - \frac{D\, x_7}{L_{battery}}$$

$$\dot{x_7} = \propto_1 \frac{x_3}{C_{bus}} + \propto_2 \frac{x_5\, R_{UC}}{L_{UC}} - \frac{I_o}{C_{bus}}$$

Where $\propto_1$ and $\propto_2$ are the virtual control for battery and UC respectively. x_7 represents the dynamic value of DC bus voltage under the consideration of averaged HESS mathematical model.

B. Modelling Vehicle Dynamics

The vehicle dynamics system comprises a mechanical transmission system that can reduce motor speed to increase torque and split torque for driving the vehicle which has been modelled in Simulink by Motapon and Dessaint [12]. The vehicle dynamics subsystem includes the modelling of all mechanical parts (viscous friction, reduction gear, differential, brakes, tires, and longitudinal vehicle dynamics). The overall electric all-terrain HEV is shown in the Figure.1

III. PROPOSED EMS METHODOLOGY

In the proposed EMS, a set voltage level is required at the DC bus. A reference battery current has been defined which ensures the required amount of current flow to keep the DC bus voltage levels at a stable threshold so as to maintain the desired performance of HEV electrical motors.

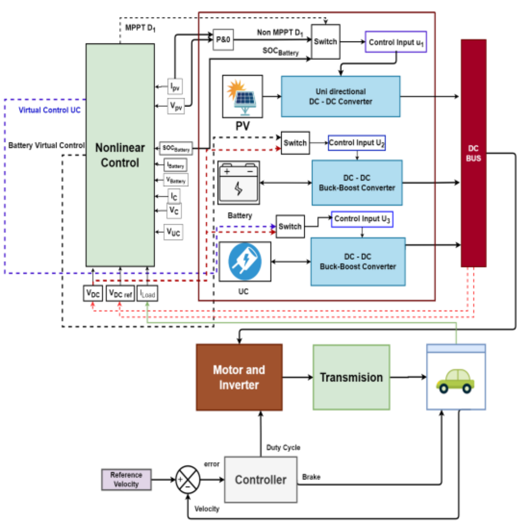


Figure 1: Proposed EMS architecture for HEV

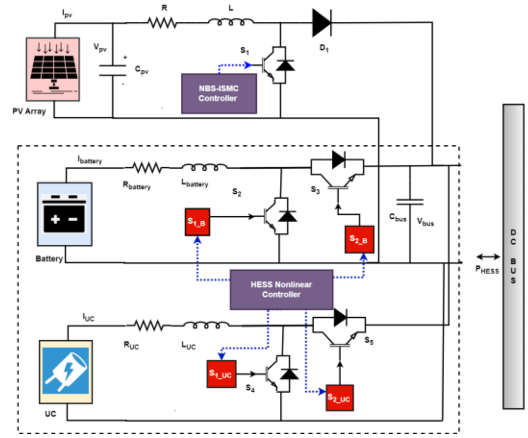


Figure 2: Electrical Network for HEV

Power extraction from the PV array is based on the requirement of connected HESS and load. PV power is thus regulated based on two modes of operation, MPPT and Non-MPPT mode. The control architecture of HESS has been designed in such a way that it utilizes the battery during steady-state operation and UC caters to transients at the DC bus caused by variable electric demand. FOTSMC has been designed for the UC charging and discharging operation. A dynamic battery charging/discharging reference current is generated based on the power demand of the electric load and power output of the PV and UC at any time. The detail design is shown in the following section:

A. PV Controller design:

Power extraction from the PV array is based on the power requirement of the connected HESS and load. PV power is regulated based on the two modes of operation which are PV MPPT and Non-MPPT mode. PV will operate in MPPT mode if battery SoC is less than 98%. In case of non-MPPT, battery SoC is greater than 98% and should not be overcharged due to surplus power available at DC bus. The PV DC-DC boost converter should be adequately controlled in order to ensure the voltage regulation at DC bus during MPPT and Non-MPPT mode of operation. The tracking error (e_1) associated with the DC bus voltage for the efficient operation is introduced. Once the battery is fully charged, sliding manifold, through the control of PV-boost converter duty cycle, only draw that much power form the PV array which is required to keep the DC voltage level at its desired limit by minimizing the error dynamics which can be stated as:

$$e_1 = x_2 - x_{2\,ref} \qquad (7)$$

Where $x_{2\,ref}$ is DC bus voltage reference. Introducing NBS-ISMC sliding manifold for tracking reference voltage, the proposed control design eliminates the need to know the exact bounds on the system model uncertainty. As a result, there is no overestimation of the control gain, which helps to eliminate chattering. Taking time derivative, putting value of x_2 from (1), sliding manifold for NBS-ISMC and solving for control signal duty cycle, we get:

$$u_1 = 1 + \frac{C_{bus}}{x_1}\left(\left(g_{s(1)} * \text{sign}(\frac{g_{s(1)}}{\varphi_s})\right) + \frac{x_2}{R_1 C_{\text{bus}}} - \dot{x}_{2\text{ ref}}\right) + k_1(\lambda)e_1\left[\int_o^t e_1 dt\right]^{\lambda-1} \quad (8)$$

For stability analysis, introducing Lyapunov function analysis in (9) shows that proposed controller meets the stability conditions, which ensures the convergence of error to zero in finite time and the asymptotic stability of the system. It also ensures tracking of the DC volage reference.

$$V_1 = \frac{1}{2}\left|g_{s(1)}\right|^2 = \dot{V}_1 = -g_{s(1)}k_1\left|g_{1(s)}\right|^{\gamma} \text{sign}\left(\frac{g_{s(1)}}{\varphi_1}\right) = -g_{s(1)}k_1\left|g_{s(1)}\right|^{\gamma}\text{sign}\left(\frac{g_{s(1)}}{\varphi_1}\right) \leq 0 \quad (9)$$

B. HESS Controller design:

The control architecture of HESS has been designed in such a way that it utilizes the battery during steady-state operation and UC to cater to the transients at the DC bus caused by the variable electric demand. FOTSMC has been designed for UC charging and discharging operation for catering sudden variations in vehicle speed due to variations in the drive cycle of HEV which led to a large variation in electric load demand. Incorporating error dynamics for UC, time derivative and introducing FOTSMC to resolve the steady state error and solving for virtual control of UC buck boost converter, we get:

$$\propto_2 = 1 + \frac{C_{\text{bus}}}{c_2\gamma|e_1|^{\gamma-1}}\left[\mathcal{D}^{\hat{\alpha}}\dot{S}_1 - c_1\mathcal{D}^{1-\alpha}e_1 + \frac{c_2\gamma|e_1|^{\gamma-1}x_5}{C_{\text{bus}}\,\text{R}} + c_2\gamma|e_1|^{\gamma-1}\dot{x}_{6\text{ ref}}\right] \quad (10)$$

Battery DC-DC buck boost converter helps redirect the power flow from the DC bus under operation of PV and UC. Battery DC-DC converter operates similarly to the UC by performing charging and discharging but it is the battery which keeps a check of all the power coming to the DC bus and consumed by the electric load based on the demand. The dynamic current reference defines the operation of battery-connected converters. The battery operates in two modes of operation:

Charging mode: If the power demand by HEV is less than the power delivered by PV array and UC at any instant of time, battery will operate in charging mode. Consequently, battery will extract all surplus power from the DC bus to abstain the voltage from attaining higher than the allowed level. This surplus power will be stored to use during a power shortfall at the DC bus.

Discharging Mode: In this mode, battery is discharged towards the DC bus to deliver the required electric power demand from the connected load. The discharging current rate is dynamically calculated based on the power shortfall at the DC bus under the action of UC and PV array.

The battery reference current in both modes is obtained based on the DC bus voltage deviation from its desired reference. The duty cycle for generating PWM signals in connected converters is calculated based on the required current flow reference. To ensure the efficient tracking of battery current, error is introduced, taking time derivative and solving for virtual control law:

$$\tau = x_3 = \frac{C_{bus}}{\alpha_1}\left(\frac{x_4}{RC_{bus}} + \dot{x}_{4\text{ref}} - k_3 e_4\right) \quad (10)$$

Where e_4 is the error between battery current and its reference value, C_{bus} is DC bus capacitance. e_5 is the error between required power flow between battery and DC bus. Putting $e_5 = x_3 - x_{3\text{ref}}$ and $x_3 = e_5 + \tau$ in (10) and defining Lyapunov function for errors e_4 and e_5. Time derivative of ($V_3 = \frac{1}{2}e_4^2 + \frac{1}{2}e_5^2$) and putting values of errors and derive the expression:

$$\dot{\tau} = \frac{C_{bus}}{\alpha_1^2}\left[\alpha_1\left(\frac{\dot{x}_4}{RC_{bus}} + \ddot{x}_{4_ref} - k_3\dot{e}_4\right) - \dot{\alpha}_1\left(\frac{x_4}{RC_{bus}} + \dot{x}_{4ref} - k_3 e_4\right)\right] \quad (11)$$

Rearranging the (11), we get:

$$\dot{V}_3 = -k_3 e_4^2 + e_5\left(\frac{\alpha_1 e_4}{C_{bus} + \dot{x}_3 - \dot{\tau}}\right) \quad (12)$$

By taking $\left(\frac{\alpha_1 e_4}{C_{bus} + \dot{x}_3 - \dot{T}}\right) = -k_4 e_5$, the solution of the Lyapunov function will become asymptotic stable with global convergence. Using the aforementioned Lyapunov condition and substituting (12) in (10), we get:

$$\left(\frac{\propto_1 e_4}{C_{bus}} + \frac{V_{battery}}{L_{battery}} - \frac{x_3 R_L}{L_{battery}} - \frac{\propto_1 x_4}{L_{battery}} - \frac{C_{bus}}{\alpha_1^2}\left[\propto_1\left(\frac{\dot{x}_4}{RC_{bus}} + \ddot{x}_{4ref} - k_3\dot{e}_4\right) - \dot{\alpha}_1 C_{bus}\left(\frac{x_4}{RC_{bus}} + \dot{x}_{4ref} - k_3 e_4\right)\right]\right) = -k_4 e_5 \quad (13)$$

Solving (13) to extract actuation PWM switching signals for complementary IGBTs of the buck boost converter to achieve the required power flow between battery and the DC bus.

$$\dot{\alpha}_1 = \frac{\alpha_1^2}{C_{\text{bus}}\left(\frac{x_4}{RC_{\text{bus}}} + \dot{x}_{4\text{ ref}} - k_3 e_4\right)}\left[\frac{C_{\text{bus}}}{\alpha_1}\left(\frac{\dot{x}_4}{RC_{\text{bus}}} + \ddot{x}_{4\text{ ref}} - k_3\dot{e}_4\right) - \left(\frac{V_{\text{balary}}}{L_{\text{batery}}} - \frac{x_3 R_L}{L_{\text{ballery}}} - \frac{\alpha_1 x_4}{L_{\text{batery}}}\right) - \frac{\alpha_1 e_4}{C_{\text{bus}}} - k_4 e_5\right] \quad (14)$$

This power flow will ensure the stability of the electrical network against large variations due to considered inherent nonlinearities of the whole electro-mechanical system.

IV. Results and Discussion

The proposed physics-based HEV architecture has been simulated using the developed nonlinear controllers. The results obtained are discussed in terms of HEV velocity, DC bus voltage, and EMS. Solar irradiation, ambient temperature, and surface temperature for PV have been presented in Figure. 3. Table 1 shows the parameters of the simulated system. The main objective of the EMS is to maintain a stable DC bus voltage under variations in the generated electric power and load demand from the HEV electric drive train. The performance of the proposed EMS-based nonlinear control architecture is shown under variable energy generation and electric load demand.

Power Source Specifications and System parameters	
PV array model	PV Module: Parallel string: 4 & series connected modules per string: 2 Maximum paper & Open circuit Voltage: 120.7 W & 21V Short-Circuit Current & Voltage at MPP: 8 A & 17V. Current at MPP: 7.1 A
Battery	Type: Lithium-ion, Nominal voltage: 24 V, Rated Capacity: 14 A, Initial SoC: 50%
UC	Rated Capacity: 29 F, Equivalent DC Series resistance: 0.003 ohm, Rated Voltage: 32 V, Series and Parallel capacitors: 1
Converters	$C_{bus} = 13000e^{-6}$, $L_{UC} = 0.00355e^{-6}$, $R_{battery} = 0.05$, $L_{battery} = 0.355e^{-6}\ F$, $R_{UC} = 0.05$ ohm, $f_{sw} = 20kz$
Controllers	$k_1, k_2 = 0.001$, $\varphi_{1=}1000$, $c_1, c_2 = 10$, $\alpha_{1,}\alpha_2, = 0.5, 0.5$, $k_3, k_4 = 100, 1000$

Table 1: Parameters of the simulated System

It has been observed in Figure 5 that DC bus voltage is accurately tracking the reference voltage with no steady-state error and with very small undershoots. The control duty cycle for PV using NBS-ISMC has been generated with the combination of MPPT by Perturb and Observe (P&O) and steady-state analysis of PV DC-DC boost converter. The robustness of the controller is analysed by subjecting the vehicle to a variable velocity profile, given in Figure. 4, where it has been accurately tracked with a fast dynamic response.

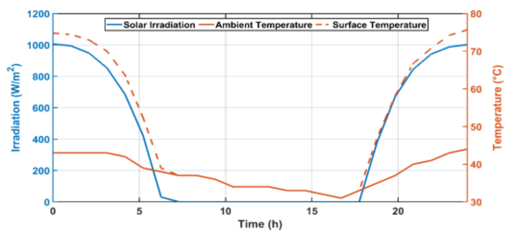
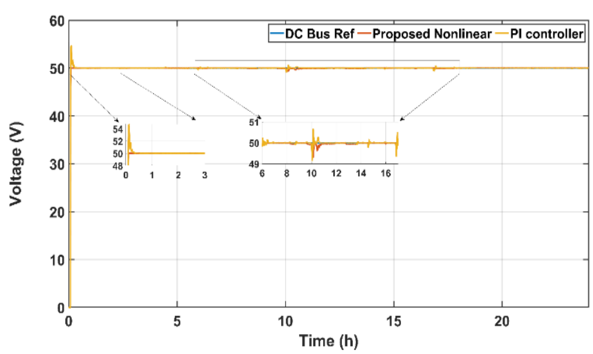


Figure 3: Ambient temperature, Solar Irradiation and surface temperature of the PV array

Sudden variations in vehicle speed due to variations in the



drive cycle of HEV may lead to a large variation in electric load demand. UC power flow management controller activated during large transitions in load demand. UC allows charging and discharging at a high rate which helps redirect sudden shortfall or surplus power at the DC bus. A comparative analysis has been carried out between the proposed nonlinear controller- and PI-based EMS, presented in Figure. 6 where the PI controller exhibits undesired large overshoots and significant oscillations for a notable time duration. Speedgoat performance target machine will be used to validate the performance of proposed controllers in real-time on an HEV digital twin. The experimental setup and target configuration are demonstrated in Figure. 7.

Similarly, speed variation of HEV under Worldwide Harmonised Light Vehicle Test Procedure (WLTP) drive cycle has been shown in Figure. 8. The blue dotted line and red solid line represent actual system and optimal trajectories. It has been shown that proposed system is tracking the desired variable velocity reference with zero steady state error. Figure. 9 and 10 showed the power and current response from all the sources. In this analysis, surface temperature for PV is used.

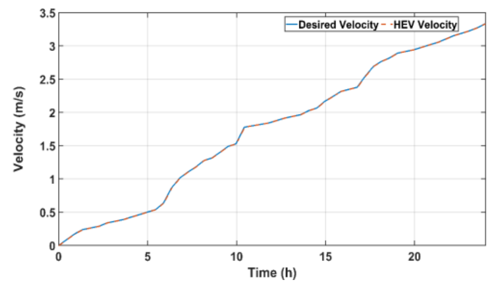


Figure 4: HEV velocity and desired velocity

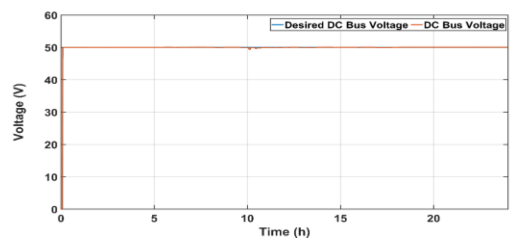


Figure5: DC link Voltage

Figure 6: Comparative analysis of proposed nonlinear controller and PI

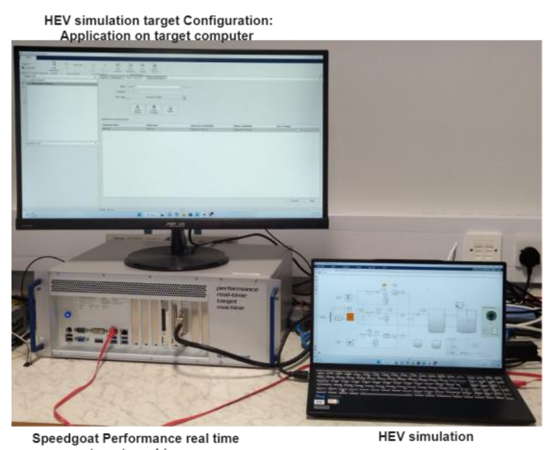


Figure 7: Speedgoat target performance machine for real-time validations of proposed controllers

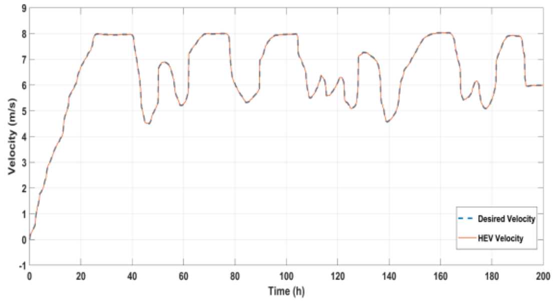


Figure 8: WLTP based vehicle drive cycle.

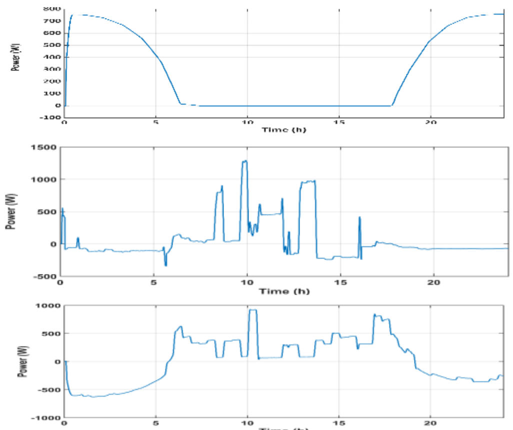


Figure 9: Power flow from sources (PV, UC and Battery

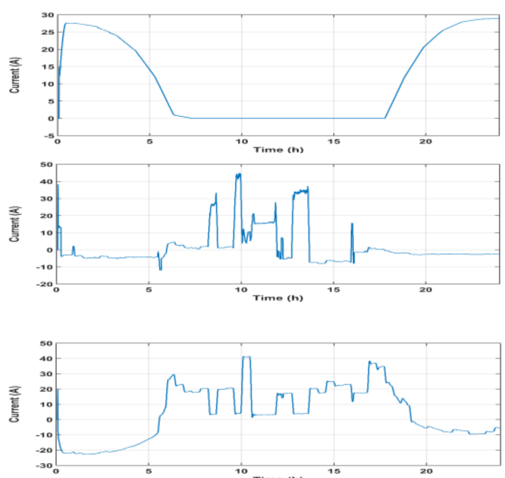


Figure 10: current flow from sources (PV, UC and Battery

CONCLUSION

This paper proposes EMS based on nonlinear controller for a hybrid power system and physics-based HEV under complex driving circumstances. Designed system performance has been modelled in the Simulink environment including electrical and vehicle dynamical system. NBS-ISMC, backstepping sliding mode control and FOTSMC have been implemented for ensuring DC bus voltage, and regulation of power flow between all the power sources and HEV. Nonlinear controllers showed several benefits in terms of good tracking of EMS with variable power sources and load demand. In addition, the global stability of EMS is proven by Lyapunov stability. The performance of the proposed EMS based on nonlinear controllers is analyzed and compared to a PI controller. The results demonstrated that the proposed EMS exhibited greater robustness compared to the PI controller. Different drive cycles including user defined as well as WLTP is used to check the validity of the proposed EMS. The results obtained from MATLAB Simulation clearly shows the effectiveness of proposed system. Comparison of simulation results to the real-time validation from Speedgoat will be provided in the final paper.

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