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Efficiency enhancement strategy implementation in hybrid electric vehicles using sliding mode control

Introduction. *Hybrid electric vehicles are offering the most economically viable choices in today's automotive industry, providing best solutions for a very high fuel economy and low rate of emissions. The rapid progress and development of this industry has prompted progress of human beings from primitive level to a very high industrial society where mobility used to be a fundamental need. However, the use of large number of automobiles is causing serious damage to our environment and human life. At present most of the vehicles are relying on burning of hydrocarbons in order to achieve power of propulsion to drive wheels. Therefore, there is a need to employ clean and efficient vehicles like hybrid electric vehicles. Unfortunately, earlier control strategies of series hybrid electric vehicle fail to include load disturbances during the vehicle operation and some of the variations of the nonlinear parameters (e.g. stator's leakage inductance, resistance of winding etc.). The* ***novelty*** *of the proposed work is based on designing and implementing two robust sliding mode controllers (SMCs) on series hybrid electric vehicle to improve efficiency in terms of both speed and torque respectively. The basic idea is to let the engine operate only when necessary keeping in view the state of charge of battery.* ***Purpose****. In proposed scheme, both performance of engine and generator is being controlled, one sliding mode controllers is controlling engine speed and the other one is controlling generator torque, and results are then compared using 1-SMC and 2-SMC's.* ***Method.*** *The series hybrid electric vehicle powertrain considered in this work consists of a battery bank and an engine-generator set which is referred to as the auxiliary power unit, traction motor, and power electronic circuits to drive the generator and traction motor. The general strategy is based on the operation of the engine in its optimal efficiency region by considering the battery state of charge.* ***Results*** *.Mathematical models of engine and generator were taken into consideration in order to design sliding mode controllers both for engine speed and generator torque control. Vehicle was being tested on standard cycle. Results proved that, instead of using only one controller for engine speed, much better results are achieved by simultaneously using two sliding mode controllers, one controlling engine speed and other controlling generator torque.* References 37, figures 11.

Key words: **hybrid electric vehicles, electric vehicles, sliding mode control, efficiency enhancement.**

Вступ*. Гібридні електромобілі пропонують найбільш економічно доцільний вибір у сучасній автомобільній промисловості, надаючи найкращі рішення для дуже високої економії палива та низького рівня викидів. Швидкий прогрес та розвиток цієї галузі підштовхнули людей до переходу від примітивного рівня до дуже високого індустріального суспільства, де мобільність була фундаментальною потребою. Однак використання великої кількості автомобілів завдає серйозної шкоди довкіллю та життю людини. Нині більшість транспортних засобів покладаються на спалювання вуглеводнів задля досягнення потужності руху на провідних колесах. Отже, необхідно використовувати чисті та ефективні транспортні засоби, такі як гібридні електромобілі. На жаль, раніше стратегії управління серійним гібридним електромобілем не враховували збурення навантаження під час роботи автомобіля і деякі зміни нелінійних параметрів (наприклад, індуктивність розсіювання статора, опір обмотки і т.д.).* ***Новизна*** *запропонованої роботи заснована на розробці та реалізації двох надійних контролерів ковзного режиму (SMC) на серійному гібридному електромобілі для підвищення ефективності з точки зору швидкості та моменту, що крутить, відповідно. Основна ідея полягає в тому, щоб дозволити двигуну працювати тільки тоді, коли це необхідно з урахуванням стану заряду акумулятора.* ***Мета****. У пропонованій схемі контролюються характеристики як двигуна, так і генератора, один контролер ковзного режиму регулює швидкість двигуна, а інший регулює крутний момент генератора, а потім результати порівнюються з використанням режимів 1-SMC і 2-SMC.* ***Метод****. Силова установка серійного гібридного електромобіля, що розглядається в даній роботі, складається з акумуляторної батареї та установки двигун-генератор, яка називається допоміжною силовою установкою, тяговим двигуном та силовими електронними схемами для приводу генератора та тягового двигуна. Загальна стратегія заснована на роботі двигуна в області оптимальної ефективності з урахуванням рівня заряду акумуляторної батареї.* ***Результати****. Математичні моделі двигуна та генератора були прийняті до уваги для розробки регуляторів ковзного режиму як для керування частотою обертання двигуна, так і для керування крутним моментом генератора. Транспортний засіб випробовувався за стандартним циклом. Результати показали, що замість використання лише одного регулятора частоти обертання двигуна набагато кращі результати досягаються при одночасному використанні двох регуляторів ковзного режиму, один з яких керує частотою обертання двигуна, а інший - моментом, що крутить, генератора.* Бібл. 37, рис. 11.

Ключові слова: **гібридні електромобілі, електромобілі, керування ковзним режимом, підвищення ефективності.**

1. Introduction. Advent of high pace development of internal combustion engine (ICE) vehicles and invention of automobile industry is contributing so much by satisfying needs of modern society. This prompted progress of human beings from primitive level to a very high industrial level society where mobility used to be a fundamental need (for instance [1-5]). Automotive industry serves as a backbone towards success and development of a nation. However, the use of large number of automobiles is causing serious damage to our environment and human life. It is causing serious problems, which are affecting our eco system badly. Air pollution and global warming are causing us much trouble. At present most of the vehicles are relying on burning of hydrocarbons in order to achieve power of propulsion to drive wheels. Where heat has been used by the engine and combustion byproducts are released in the atmosphere. By products also comprises of harmful gases like nitrogen oxide (NO) and carbon monoxide (CO) and some of the unburned hydro carbons (HC) which are harmful to environment and human health. Global warming is as result of greenhouse effect, which is happening due to presence of harmful gases like carbon dioxide and methane in the atmosphere. The radiations reflected by the earth are trapped by these gases, resulting in increased temperature. As a result, damaging the whole ecosystem and causing natural disasters.

Over last some decades, the need of clean and fast transportation has increased a lot. Keeping in view the time of need hybrid electric vehicles (HEVs) was developed which offers most fuel efficient and emission free transportation these days. The scholars have been researching more and more to bring out best from them. In order to increase efficiency level, researchers have been applying various optimization techniques on hybrid electric vehicles in order to let them operate at their optimum level. Keeping in view pros and cons of different types of HEV's, researches have been digging out on almost every type of hybrid vehicle. All of them have same components like engine/generator set, power converters, fuel tank, batteries, transmission and traction motors along with some auxiliary electrical loads, the difference lies only the way power is transmitted from engine to wheels. Depending upon architecture of drivetrains, HEVs can be divided into 4 major categories i.e. series hybrid electric vehicle (SHEV), parallel hybrid electric vehicle (PHEV), series-parallel hybrid electric vehicles and complex hybrid electric vehicles. Different scholars have proposed various schemes to improve their efficiency. Due to higher battery cost and small driving range of EVs, HEVs came into existence where hybrid electric vehicles use both ICE and electrical machine to work. It has advantages of both EV and HEV. Furthermore, due to their complex structure scholars have been developing various optimization techniques and control strategies on HEVs to get optimum fuel efficiency and reduced level of emission with enhanced battery life. These control strategies were broadly divided into two main types:

1. Rule based strategies of control mainly depend on the modes of operation of vehicle, and these schemes are easily implemented on real time control techniques. Rule based on control schemes mainly based on heuristic based ideas, human intelligence and without prior knowledge of drive cycle [6]. These controllers were usually based on static points of operation of vehicle components like ICE, generator and motor.
2. In optimization based schemes, the basic aim of the controller is to minimize and optimize the cost function. These cost functions depend upon us; it may be fuel consumption or battery life extension or emissions etc. These strategies were not based on real time energy management directly but if we take instantaneous values of cost function, then it is possible to evaluate on real time. Global optimization requires all prior information regarding state of charge (SOC), driving cycle, response of the driver and type of route. Different optimization techniques have been used by researchers like linear programming, dynamic programming, Pontryagin minimum principle, model predictive control, stochastic control strategies, genetic algorithm etc.

Various research has been done for the electric vehicles modeling [7-10], implantation [11-13] and control [14-20]. Control techniques for electric vehicles are significant to evolve the revolution of automotive industry. In [14] authors developed control algorithms for fuel consumption optimization in parallel hybrid automobiles. For full parallel hybrid mode, a mathematical approach is used whereas for torque assist parallel hybrid an approach is designed from optimal sizing was presented in [15]. Energy management strategy in parallel hybrid electric vehicles (PHEV) by using a variable continuous transmission is discussed in [16]. Later on study developed different control schemes for parallel and series hybrid electric vehicles. These schemes basically focus on decreasing fuel consumption and utilizing battery storage capacity as much as possible [17]. In [18], researchers worked on a power management control based strategy for a parallel configuration hybrid electric truck which further includes minimization of a cost function and reduction of emissions. The study has been carried out by using a model of hybrid vehicle in hybrid engine-vehicle simulation (HE-VESIM) which is developed by a research center named as Automotive Research Centre. In [19] authors presented an algorithm for SHEV's to control electricity generation in order to minimize consumption of fuel based on different parameter like SOC of battery etc. In [20] authors proposed efficiency enhancement strategy in PHEV using model predictive control.

In literature several schemes have been proposed for smooth clutch engagement and low jerks having reduced oscillations, like back stepping motor control, optimal control, model predictive control etc. the primary objective of their research was to introduce such control schemes that reduced the transition oscillations while shifting from a pure electric mode to a pure hybrid mode.

Fuel economy of HEV's are majorly affected by their powertrain configurations, powertrain parameters, and energy management strategies. However, catering all three at a time requires large space and exhaustive optimal control strategy like dynamic programming (DP) which is in fact complex and expensive computationally. A faster and computationally efficient optimization strategy rapid dynamic programming (Rapid-DP) is developed in 2019 authors proposed optimization control of a power split hybrid vehicle where all 3 are optimized simultaneously. A combined optimization strategy was employed on Toyota Prius and Prius++ in order to examine fuel savings and increase in operating mode [21]. In [22] authors presented energy management strategy for series hybrid deep tracked electric vehicle (SHETV) by developing deep Q-learning (DQL) algorithm. Robustness of whole model is improved by utilizing two deep Q-networks with some initial weights and identical structure are built and then trained to estimate action-value function.

In [23] was developed a strategy based on model predictive controller for power split hybrid electric vehicles by developing two management schemes for power-split hybrid electric city bus (HECB), incorporating linear time-varying stochastic model predictive control and Pontriagin minimum principle stochastic model predictive control. Both strategies do have real time fast computational response at cost of complex calculations with increased efficiency.

In [24] analysis based on comparison of energy management strategies for HEV'S was introduced. Different schemes like dynamic programming (DP), Pontryagin minimum principle (PMP) and equivalent consumption minimization strategy (ECMS) were studied. Results revealed that ECMS used to be only implanted in the real time. While, PMP and DP were proved to be more affective energy management strategies in optimal control.

In [25] study presented a point-by-point investigation of the ideal vitality administration issue for plug-in hybrid electric vehicles illuminated utilizing the PMP. In this study, a relation between directions of state and co-state with the battery characteristics has been produced which are not been investigated in a comparative design in earlier writing. A partial area examination is additionally completed demonstrating the partial linearity of the ideal condition of SOC with appreciation to outing length for a mix of certain standard driving cycles. Information picked up from this activity empowers us to build up a versatile vitality administration methodology. Furthermore, a model predictive control (MPC) torque-split system that consolidates diesel motor transient qualities for PHEV was studied to enhance the fuel efficiency of HEV. For most of the HEV applications where the motors continuously experience transient operations, like including start and stop, the impact of the motor transient attributes on the general HEV powertrain mileage turns out to be more declared [26].

In [27] an adjusted SOC estimation calculation is connected here, which incorporates coulomb checking strategy, as well as open circuit voltages, components of weighting and revision variable in order to track the run time SOC productively. Further, nearness of battery and motor together, needs an overall force split plan for their effective usage. In this study, a fuel proficient vitality administration methodology for force split HEV utilizing adjusted SOC estimation technique is produced. Here, the ideal estimations of different overseeing parameters are firstly figured with hereditary calculation and after that nourished to Pontryagin base standard to choose the limit of the power at which motor is turned on. This procedure actually makes the proposed technique a hearty and gives better opportunity to enhance fuel proficiency. The motor effective working area is additionally distinguished which makes the vehicle work in proficient locale and diminish fuel utilization.

In [28] a quantitative investigation of fuel consumption and performance of series hybrid electric vehicle HMMWV (high mobility multi-reason wheeled vehicle) is a vehicle used in military with a routine HMMWV of proportional size is presented. In this paper, a philosophy is displayed by which the efficiency increases because of streamlined motor are separated from the mileage increases due to regenerative braking. In [29] a control based strategy was developed in order to improvise fuel economy and efficiency of engine of series hybrid vehicle using fuzzy logic and sliding mode control. The fuzzy logic controller has two inputs; the vehicle power demand and SOC of the battery and purpose of this controller was to increase engine and battery efficiency levels. Besides, two sliding mode controllers are designed in order to remove uncertainties and disturbances occurred while vehicle is working.

As of late, numerous analysts have been concentrating on the different issues related to control of the SHEV powertrain architectures. In [30] was presented a control scheme for SHEV's based on sliding mode controllers (SMC) with fixed boundary layers. These controllers are aimed to control engine/generator speed and torque, to let them operate in optimal efficiency area. Consequently, affecting fuel economy and also enhanced battery life is expected.

In the previous literature which is related to SHEVs studies are mostly concentrated on control of auxiliary power unit (APU). The work [31] presents a linear adaptive DP, which requires a prior information and knowledge of the plant. In [32] PI controllers were utilized in order to control auxiliary power unit. However highly nonlinear system nature is a great obstacle in getting optimized performance. In order to achieve maximum fuel economy and battery lifetime bi-level energy management strategy for plug-in hybrid electric vehicles with a reference of SOC was achieved by utilizing radial basis function neural networks along with MPC [33]. However, a review papers in [31-35] elaborated vital energy management strategies for various types of HEV's by focusing on both APU control and energy storage system. Pointing various pros and cons of different energy management strategies used to optimize vehicle efficiency. Where all recommendations and suggestions were shared in [33] varying from proportional–integral–derivative controller, operational or state mode, rule-based or fuzzy logic, and equivalent consumption minimization strategies, are explained. Various optimization techniques were discussed including dynamic programming, geometric algorithms (GA's), particular swarm optimization (PSO) etc. Along many other techniques, research on production of hybrid renewable energy has also been done by using fuzzy logic based smart controllers, where improved energy management and optimization was employed by using smart economic strategy based on fuzzy logic. Fuzzy logic was employed efficiently to control hybrid electric energy sources built around solar panels, wind turbine and electric storage system with assistance of electric grid [36]. Efficiencies of HEV's were enhanced by using multiple techniques, and generator torque control is one of the effective ones. Where generator torque was controlled based on second order SMC for three-level inverter-fed permanent magnet synchronous motor [37]. Application of SMC controller helped resolving uncertain noises and ripples, which enhanced torque response.

Nonetheless, these SHEV powertrain control methodologies neglect to adequately address the exceptionally nonlinear parameter varieties and sudden outside aggravations amid the vehicle operation.

Details regarding series hybrid vehicle structure and implementation of sliding mode controllers in order to control engine speed and torque of the generator will be discussed in next section.

The goal of the paper is to study and model series hybrid electric vehicle and implementing two sliding mode controllers; one for controlling engine speed and other one controlling generator torque and as a result they let the series hybrid vehicle to operate only in its optimum efficiency region.

2. Designed scheme. In this research, a series hybrid electric model has been developed on MATLAB/Simulink with additional two SMCs, which helps a lot in catering nonlinearities developed while driving. Both controllers together let the vehicle to optimize performance of vehicle in terms of speed and torque. In this research, the specific control strategy to be proposed aims at to discover the robustness characteristics of SMC against uncertainties of engine/generator set and the power converter. The very basic idea is not let the engine to operate when vehicle is in idle state. When the SOC of battery drops any reference value engine will be turned ON and it will be turned OFF when SOC reaches a maximum reference value. Both two SMCs run at same time to achieve the optimal efficiency of vehicle by controlling speed of engine and. In some recent years, sliding mode control has become hot topic in case of optimization of hybrid vehicles.

Unfortunately, earlier control strategies of SHEV fail to include load disturbances during the vehicle operation and some of the variations of the nonlinear parameters (e.g. stator's leakage inductance, resistance of winding etc.). SMC is very good for applications in automobile industry due to its very basic property of order reduction; also these controllers are less sensitive to all the disturbances during vehicle operation and parameter variation of the plant [4, 5].

The basic aim of this research is to develop two robust and noise free SMCs for speed of engine and generator's torque control. This will eventually increase efficiency of the SHEV. In this research two controllers were applied simultaneously which will actively contribute to increase the efficiency levels of vehicle. These controllers were applied on APU; consisting engine, generator and power converters. Military vehicle HMMWV is also a series hybrid vehicle and this research helps a lot in enhancing its efficiency. The basic idea is to let the engine operate only when necessary keeping in view the SOC of battery. The controllers will help to let the vehicle operate only in their optimum efficiency range.

3. Powertrain components of series HEV. The engine generator set along with AC/DC drivers are connects with the battery pack in series manner with traction motors.

3.1. Vehicle system. The engine used is a diesel engine generating 114 kW at 5000 rpm. A permanent magnet synchronous generator (PMSG) is used with related output of 114 kW with 90 % efficiency. The battery pack of vehicle used is of nickel metal hydride, as they are available commercially also with a voltage of 12V DC. In this project 12 such batteries are connected in series in order to get a voltage of 288 V. Power is being delivered to the wheels using batteries. Two traction motors are used here to deliver power to the load; they are also permanent magnet synchronous motors. One of the motor is directly connected to the rear differential while second one is connected through drive shaft to front one. Figure 1 shows the system including a diesel engine, a PMSG with its respective drive that is AC-DC converter. Motor is connected with their DC/AC converters aims at providing traction power to the wheels. The generator is working both as starter giving starting torque to engine and as an alternator.

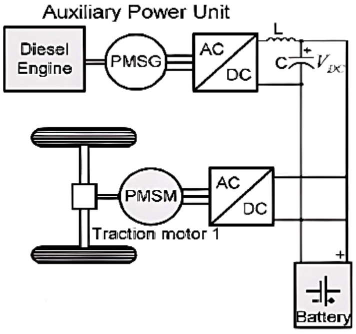

Fig. 1. Schematic diagram of series HEV drivetrain

3.2. Modeling of engine. The modeling of the engine is performed by using torque and speed equations of the engine which are forth order polynomials, found out using least-squares method. Torque T_{es} in terms of speed w_{es} comes out to be:

$$T_{es} = 1.6510 \cdot 10^{-7} \cdot w_e^4 - 0.0002 \cdot w_e^3 + 0.0546 \cdot w_e^2 - \\ - 6.65 \cdot w_e + 361.67 = \sum_{i=0}^{4} \alpha_i w_e^i, \tag{1}$$

where α_i are the polynomial coefficients $i = 0,1,2,3,4$. It is also possible to derive w_{es} as a function of T_{es} such as

$$w_e = 2.32 \cdot 10^{-6} T_{es}^4 - 0.00114 \cdot T_{es}^3 + 0.1937 \cdot T_{es}^2 - \\ - 11.839 \cdot T + 267.963 = \sum_{i=0}^{4} \alpha_i \cdot \beta_i \cdot T_{es}^j, \tag{2}$$

where β_i are the polynomial coefficients $i = 0,1,2,3,4$.

Functional block diagram of APU control system is shown in Fig. 2, where 2 control signals are being generated one for control of engine speed and other for generator torque control using information coming from SOC of battery and generator currents.

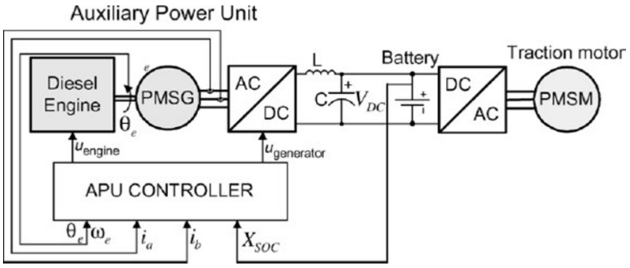

Fig. 2. Functional diagram of APU control system

3.3. Auxiliary power unit (APU). In Fig. 3, Simulink diagram for APU is shown. It comprises of two sliding mode controllers, one PID controller, and two functional blocks are designed in order to calculate reference engine speed and generator torque. In addition, rate limiters and saturation blocks are being employed to let the engine operate in optimum region. A relay is being used to generate ON/OFF signals for auxiliary power unit.

3.4. Modeling of the PMSG. PMSG is used in this research because of its reliability, lower maintenance and more efficiency. The dynamic model of the PMSG is derived reference frame which is synchronous and it is two phase in which with respect to rotation the q-axis is 90° ahead of the d-axis. The dq-axis model of the PMSG is obtained as:

$$\mathrm{d}i_q = -\frac{R}{L_q}\cdot i_q + \frac{w_e \cdot L_d}{L_q}\cdot i_d - \frac{1}{L_q}\cdot v_q + \frac{K_b}{L_q}\cdot w_e ; \qquad (3)$$

$$\mathrm{d}i_d = -\frac{R}{L_d}\cdot i_q + \frac{w_e \cdot L_q}{L_d}\cdot i_q - \frac{1}{L_d}\cdot v_d ; \qquad (4)$$

$$T_g = -K_t \cdot i_q + k_1 \cdot \left(L_d - L_q\right)\cdot i_d \cdot i_q \ , \qquad (5)$$

where i_d, i_q are the d-q axis axis currents of generator respectively; v_d, v_q are the generator's d-q axis voltages; R is the generator resistance; L_d, L_q are the generator's d-q axis inductances; K_t is the torque constant of generator; K_b is the induced voltage constant of generator; T_g is the generator torque; k_1 is the reluctance torque coefficient; w_e is the speed of the engine.

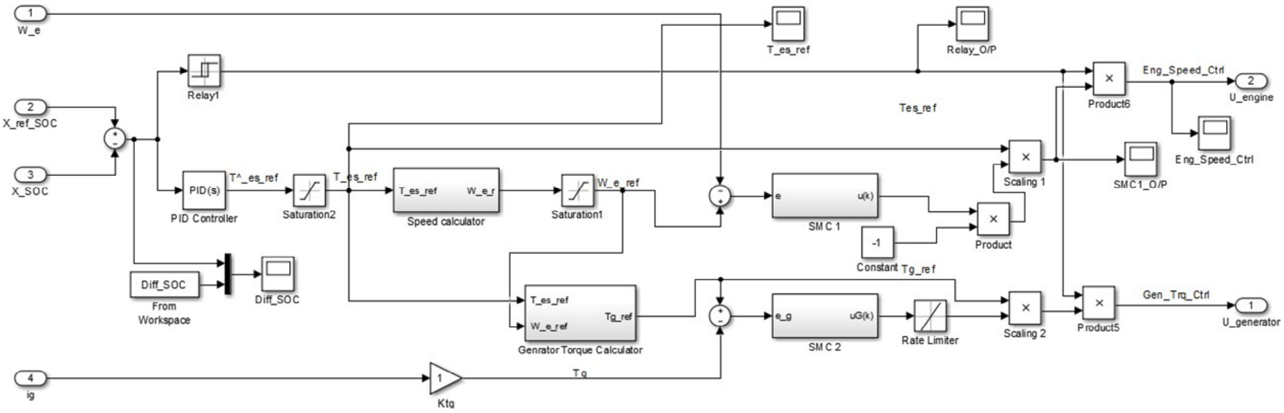

Fig. 3. Schematic diagram of series HEV drivetrain

3.4 Development of control strategy. The control strategy is having the following main aims and objectives. The SOC of the battery is kept between a given minimum and maximum level. When the charge decreases to a certain given lower level ($SOC_{\min}$), the engine will be started or in ON state from idle state EC = 1 and engine is again stopped when SOC reaches a certain maximum level or upper edge ($SOC_{\max}$) then EC = 0:

$$EC = \begin{cases} 1 & SOC_{\min} \geq SOC(t); \\ EC(t-1) & SOC_{\max} > SOC(t) > SOC_{\min}; \\ 0 & SOC_{\max} \leq SOC(t). \end{cases}$$

3.4.1 Parts of APU. (APU) comprises of three parts.

3.4.1.1. Linear PID controller. The basic function of this controller block is to output the reference torque value for the engine, by finding the difference between reference state of charge which is kept 97.7 V here and the actual state of charge of the battery by taking them as its input. After that to assure that the torque value stays in limit, saturation block is placed at the output so that the value stays within a suitable range. Using this optimal region, the speed reference for the optimal efficiency region can be given as:

$$w_e^r = \sum_{j=0}^{4} \beta_j \left(T_{es}^r\right)^j . \qquad (6)$$

The speed calculated is again limited via saturator so that it remains in optimal region. After determining the reference torque and speed values, controllers are designed based on sliding mode with aim to control speed and torque.

3.4.1.2. Sliding mode based engine speed control. Overall efficiency improvement of SHEV requires very good control strategies for highly non-linear dynamics of engine. Hence, a robust SMC, which can be able to acquire a high level robustness against non-linear uncertainties and disturbances of the system, is the main aim of the study. For the control strategy under this research, a simple state space representation, using the model of the engine is:

$$\begin{aligned} &\frac{\mathrm{d}x_{soc}}{\mathrm{d}t} = K \cdot i_b ; \\ &\frac{\mathrm{d}w_e}{\mathrm{d}t} = \frac{1}{J_{tot}} T_{es} - \frac{1}{n \cdot J_{tot}} \cdot T_g , \end{aligned} \qquad (7)$$

where x_{soc} is the state of charge; $i_b = i_q - i_m - i_L$ is the battery current; i_m is the traction motor current; i_L is the parasitic electric load current; i_q is the generator quadrature current; T_g is the generator torque; J_{tot} is the total inertia $J_{tot} = J_g{\cdot}n^2 + J_e$; J_e is the engine inertia; J_g is the generator inertia; n is the generator speed ratio $w_e/w_g = 1.038$; $K = C_b/3600$, C_b is the battery capacity, Ah.

In (1), the torque function is derived for maximum load in terms of demanded speed; in other words, for maximum throttle level (i.e., 1). The throttle level assumes values between 0 and 1 for engine control. Therefore, the torque of the engine should be rewritten as a function of the throttle level, which takes values from 0 to 1 as follows:

$$T_{es} = u \cdot \left(\alpha_0 + \alpha_1 w_e + \alpha_2 \cdot w_e^2 + \alpha_3 \cdot w_e^3 + \alpha_4 \cdot w_e^4\right), \qquad (8)$$

where u is the torque control input (throttle angle 0-100 %).

First, the polynomial approximation in (1) for T_{es}, is substituted in the following equation of motion for the engine:

$$\frac{\mathrm{d}w_e}{\mathrm{d}t} = \frac{1}{J_{tot}} \cdot u \cdot \sum_{i=0}^{4} \alpha_i \cdot w_r^i - \frac{1}{n \cdot J_{tot}} \cdot T_g . \qquad (9)$$

Then, a sliding surface σ, is chosen as

$$\sigma = T{\cdot}e, \qquad (10)$$

where

$$e = w_e^T - w_e . \qquad (11)$$

To ensure system's the stability, Lyapunov conditions are used to derive the sliding mode control law:

$$V = \frac{1}{2}\cdot \sigma^2 > 0 ; \qquad (12)$$

$$\dot{V} = \sigma\dot{\sigma}, \tag{13}$$

which should be equal to $-D\cdot\sigma^2$ to satisfy the condition of negative definiteness of $\dot{V}$. Thus

$$\dot{V} = -D\cdot\sigma^2, \tag{14}$$

where $D>0$.

Consequently

$$\sigma + D\cdot\dot{\sigma} = 0. \tag{15}$$

By taking the derivative of σ and substituting the equation of motion. Inside $\dot{\sigma}$

$$\begin{aligned}\dot{\sigma} &= T^* \cdot \left(\dot{w}_e^t - \dot{w}_e\right) = \\ &= T^* \cdot \dot{w}_e^t - T^* \cdot \frac{1}{J_{tot}} \cdot u \cdot \sum_{i=0}^{4} \alpha_i \cdot w_r^i + \frac{1}{n \cdot J_{tot}} \cdot T_g.\end{aligned} \tag{16}$$

Now u_{eq}, which is equivalent control input, that makes $\dot{\sigma} = 0$ is to be calculated by replacing u with u_{eq}. And it produces

$$u_{eq} = \frac{J_{tot}}{\sum_{i=0}^{4} \alpha_i \cdot w_e^i} \left(\dot{w}_e^t + \frac{1}{n \cdot J_{tot}} T_g \right); \tag{17}$$

$$\dot{\sigma} = T^* \cdot \frac{1}{J_{tot}} \cdot \sum_{i=0}^{4} \alpha_i \cdot w_e^i \cdot \left(u_{eq} - u\right). \tag{18}$$

Substituting in (14) into (18) and discretizing this equation with (18), yields

$$T^* \cdot \frac{1}{J_{tot}} \sum_{i=0}^{4} \alpha_i \cdot w_e^i(k) \cdot \left(u_{eq}(k) - u(k)\right) + D \cdot \sigma(k) = 0 \tag{19}$$

and

$$\begin{aligned}\frac{\alpha(k) - \alpha(k-1)}{T} &= T \cdot \frac{1}{J_{tot}} \sum_{i=0}^{4} \alpha_i \cdot w_e^i(k-1) \times \\ &\times \left(u_{eq}(k-1) - u(k-1)\right).\end{aligned} \tag{20}$$

Assuming that input equivalent control is an average value and nothing else

$$u_{eq} \approx u_{eq}(k-1). \tag{21}$$

Finally generating a chattering free controller named as SMC which is

$$\begin{aligned}u(k) &= u(k-1) + \frac{J_{tot}}{T^* \cdot T \sum_{i-0}^{4} \alpha_i \cdot w_e^i(k)} \times \\ &\times \left((1 + D \cdot T)\sigma(k) - \sigma(k-1)\right),\end{aligned} \tag{22}$$

where T^*, D are positive design parameters.

3.4.1.3. Sliding mode based generator torque control. Now, after engine speed controller at this level torque reference values are already being generated using generator torque calculator used in APU model. By using these values a reference torque value is generated using PID controller, optimized values of engine speed and inertia of the generator as

$$T_g^r = T_{es}^r - J_{tot} \cdot \dot{w}^r. \tag{23}$$

A noise free SMC of torque is designed based on PMSG model, and its state space form is

$$\begin{aligned}\frac{\mathrm{d}}{\mathrm{d}t} \underbrace{\begin{bmatrix} i_d \\ i_q \end{bmatrix}}_{x_g} &= \underbrace{\begin{bmatrix} -\dfrac{R}{L_d} & 0 \\ 0 & -\dfrac{R}{L_d} \end{bmatrix}}_{A_g} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \\ &+ \underbrace{\begin{bmatrix} \dfrac{L_d}{L_q} w_e i_d + \dfrac{K_b}{L_q} w_e \\ \dfrac{L_q}{L_d} w_e i_q \end{bmatrix}}_{\eta} + \underbrace{\begin{bmatrix} -\dfrac{1}{L_d} & 0 \\ 0 & -\dfrac{1}{L_d} \end{bmatrix}}_{B_g} \underbrace{\begin{bmatrix} v_d \\ v_q \end{bmatrix}}_{u_g};\end{aligned} \tag{24}$$

$$T_g = K_t \cdot i_q + K_1 \cdot \left(L_d - L_q\right) \cdot i_d \cdot i_q.$$

As there is large number of rotor teeth so we assume that $L_d \approx L_q$ the torque of the generator becomes

$$T_g \approx K_t \cdot i_q. \tag{25}$$

In state space form

$$\begin{aligned}\dot{x}_g &= A_g \cdot x_g + B_g \cdot u_g + \eta; \\ y &= T_g \cdot x_g = \begin{bmatrix} 0 & K_t \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix}.\end{aligned} \tag{26}$$

By selecting an error surface based on difference of generator currents and by choosing the Lyapunov function, controller is designed in the same way as done previously. Hence, the law for control can be derived as

$$u_g(k) = u_g(k-1) + \frac{B^{-1}}{T}\left((1 + D_g T)\sigma_g(k) - \sigma_g(k-1)\right), \tag{27}$$

where

$$u_g = \begin{bmatrix} v_d^r \\ v_q^r \end{bmatrix}. \tag{28}$$

In generator control mechanism, generator output currents are taken and passed through abc/dq, which is converting them to dq state of reference these are being fed into SMCs, after that output voltages of SMC are again being converted to abc state of references which are then passed through ha PWM generator as a control signal further being fed into IGBT's.

4. Simulations and results. In this section simulations are made on MATLAB/Simulink. Where first a series hybrid vehicle is developed and after that SMCs are implemented in order to control engine speed and generator torque. Simulations of different components of series hybrid vehicle are shown in this section.

4.1. Simulation of vehicle system. In Fig. 4 a reference SOC value of 97 V is fed into APU, w_e (actual speed generated by vehicle) is also used as an input to APU, another input is id which is the current generated by the PMSG. APU is generating optimum values of engine speed and generator torque for engine and generator respectively. Next to APU, is engine which is further connected in series to generator, AC-DC-AC converters and battery. And finally a PMSG is connected to the vehicle shaft. Kph demand block is actually based on reference drive signal, which is being fed and used as a standard cycle on which vehicle is being tested.

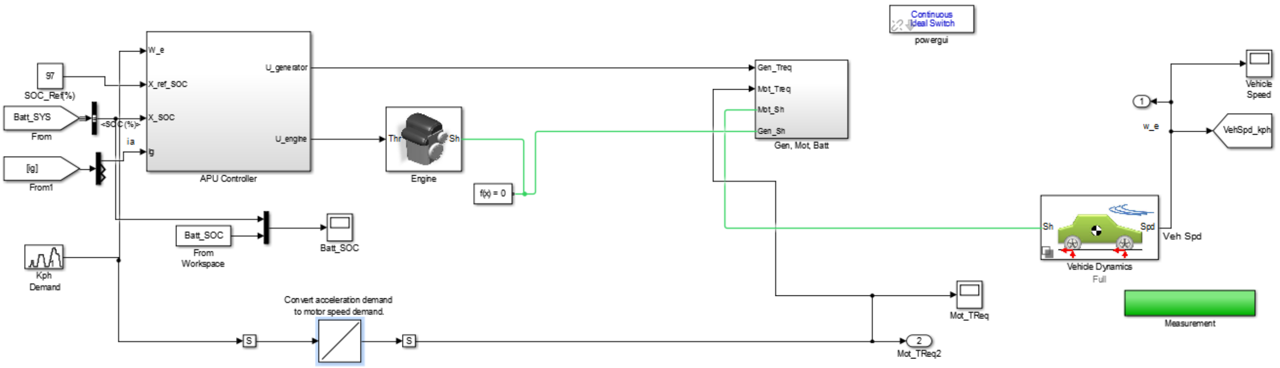

Fig. 4 Overall vehicle system

4.1.1. Simulation of APU. This figure is based on two main parts.

1) A PID controller is used to appropriate reference torque values based on difference between actual SOC and standard SOC value, which is then passed through a saturator to limit the torque value. These torque values are then used as an input by speed calculator block and it output w_{er} speed values by using (2). These speed values are again passed through a saturator in order to limit them. After that w_e coming from actual speed of vehicle and the w_{er} value generated by the speed calculator equation are passed through saturator to get w_{eref}, then passed through a summer to find the error between the two which is then made as an input to SMC 1. Similarly for torque calculation, i_g coming from generator is being multiplied to constant K_{Tg} to get T_g torque and other reference torque value is generated by using previously generated w_{eref} and passing it into torque calculator as an input and output is the respective torque values T_{gref}, now both T_g and T_{gref} are passed into a summer to generate error based on their error SMC 2.

2) Second main part of the APU, are the two sliding mode controllers one is taking error between the speed and generating optimum speed value for engine to be fed into it, and the other one taking error between generator torques and accordingly generating the optimum value for generator torque. The controller designed for engine speed is basically based on (22) and for generator torque is based on (27).

4.1.2 Simulation of engine. The optimum speed u_{engine} is generated by APU is being fed into the engine. A generic spark ignition engine is being used of 114 kW and running at 5000 rpm. Figure 5 is a simulation of engine used in this research. The input speed values are fed into engine as a throttle level between 0 and 1. It is depicting the torque demanded from engine as a fraction of maximum possible torque. If the speed of engine falls below the stall speed, which in this case is 500 rpm, the torque is assumed zero. In this model, F and B are mechanical rotation ports associated with engine shaft. P and FC are output ports via which power of engine and fuel consumption is reported.

4.1.3 Generator, motor and battery. The generator motor and battery of system is connected in series in addition with DC-DC converters (Fig. 6). In this section of simulation, a PMSG of rating 114 kW with related efficiency of 90 % is connected to a DC-DC converter, which is converting AC output of generator to a DC so that is can charge the battery which is next to the converter. The output voltage of DC-DC converter is 500 V. this DC is again converted into AC to be used by synchronous motor. Output is then fed into the vehicle shaft.

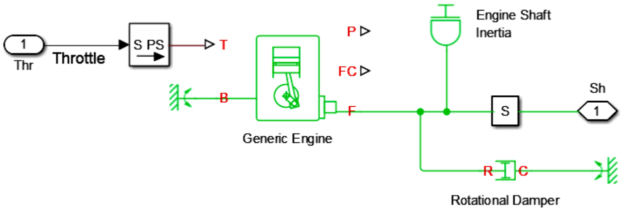

Fig. 5. Speed-torque characteristics of engine

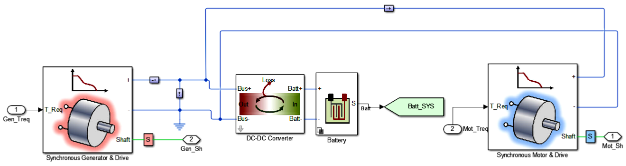

Fig. 6. PMSG, DC-DC converter, battery and motor

In this section of simulation, a PMSG of rating 114 kW with related efficiency of 90 % is connected to a DC-DC converter which is converting AC output of generator to a DC so that is can charge the battery which is next to the converter. The output voltage of DC-DC converter is 500 V. This DC is again converted into AC to be used by synchronous motor. Output is then fed into the vehicle shaft.

4.1.4 Sliding mode based engine speed controller. The simulation model of controller designed for engine speed control based on (29) is basically implemented. Error e is being multiplied with T^* which together makes $\sigma = T^*\cdot e$ the sliding surface. Next this is being multiplied by $(1 + D\cdot T)$ also a delayed signal is introduced making $\sigma=(k–1)$ and both the values are subtracted by passing it into a subtracter, where T^* is randomly taken as 15.032, D equals to 7.6 hence $(1 + D\cdot T)$ equals to 32.526. To find out denominator of equation, T^* is multiplied by T and then passed through polynomial equation block to find $\sum_{i=0}^{4}\alpha_i\cdot w_e^i(k)$, is nothing but (1). Then passed through a divider output $u(k)$ is delayed by 1 and passed through adder to complete the equation:

$$u(k)=u(k-1)+\frac{J_{tot}}{T^*\cdot T\sum_{i=0}^{4}\alpha_i\cdot w_e^i(k)}\times \times\left((1+D\cdot T)\cdot\sigma(k)-\sigma(k-1)\right) \qquad (29)$$

4.1.5 Sliding Mode based Generator Torque Controller. In Fig. 7 equation (27) is implemented in the same way as previous is done.

$$u_g(k) = u_g(k-1) + \\ + \frac{B^{-1}}{T}\left((1 + D_g \cdot T)\cdot \sigma_g(k) - \sigma_g(k-1)\right). \tag{30}$$

Target speed. The standard cycle used as a reference over which vehicle is being tested, where initially from 0 to 1 s vehicle is at off state, then afterwards it starts and accelerates up to 50 rpm uptil 2.5 s. After that it again decelerates and comes to 0 rpm at 3.5 s again increased until 10 rpm at 5 s and again decelerated to zero rpm. And finally at 10 s it comes to rest.

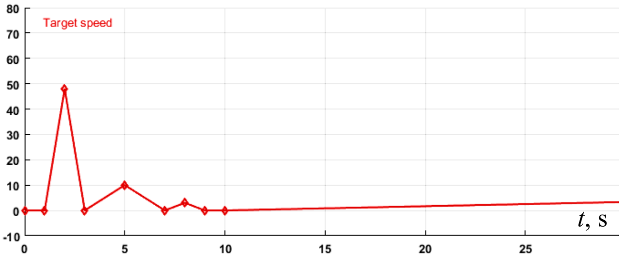

Fig. 7. Standard cycle to test vehicle

4.2 Results. In this section, control methods developed and results are being shown in terms of speed and torque of engine and generator using only one SMC and using both SMC's and their result are compared to see the trend of efficiency.

In the above Fig. 8, SOC is measured versus time. In simulation a reference of 97 V is given below which engine starts shutting down. The graph is showing the trend of battery SOC.

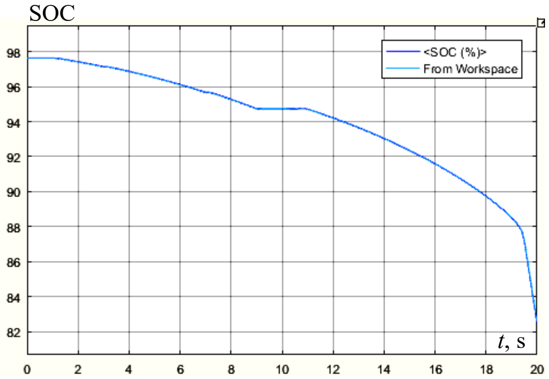

Fig. 8. Battery SOC

In Fig. 9, speed versus time variation of engine is shown. The simulation runs for 20 s over target cycle. First blue graph is using only one controller. For the case when only one controller is applied to the simulation, increase in speed is very less. From zero to 3.5 s speed is negative after that starts increasing and gets maximum upto12 rpm and rests at it until end.

For the case when both controllers are applied, speed graph is more likely following the standard target cycle used. Initially when vehicle is in off state graph is following target cycle and remains at zero rpm until 3.5 s. After that it starts increasing and attains 42 rpm and starts decreasing when vehicle is in deceleration mode. After 10 s speed starts rising and approaching zero.

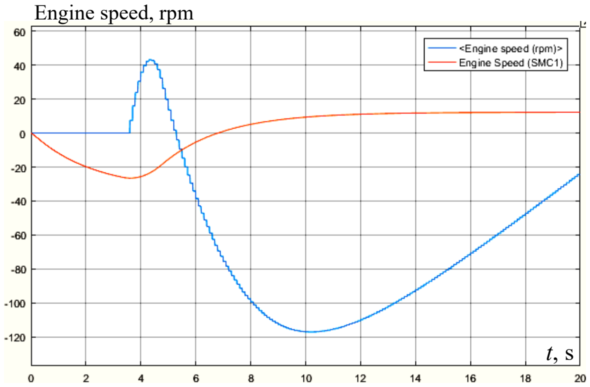

Fig. 9. Engine speed using 1-SMC and 2-SMC's

In Fig. 10, engine torque is shown and there is a great efficiency enhancement in torque also. By using one controller's results seems to be not very satisfactory and maximum gained torque is 0.5 N·m only. While when we implemented both controllers, one controlling engine speed and other controlling generator torque a high torque is added in the system reaching nearly 3 N·m and settling at zero N·m from 10 sec to 20 sec time span.

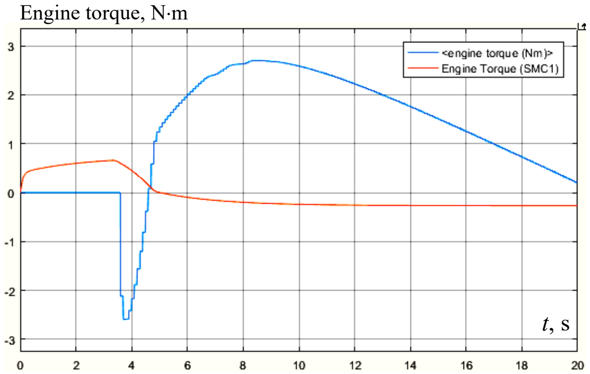

Fig. 10. Engine torque with 1-SMC and 2-SMC's

In Fig. 11, generator torque graphs are shown and compared using 1-SMC and 2-SMC's. while using only one controller, at start it decreases up to 0.6 N·m and then starts increasing at 3.5 s and reach at maximum level of 0.2 N·m. After that approach zero as vehicle comes to rest. As compared to this, a high torque is gained max up to 4.4 N·m in case when both controllers are employed to the system. Hence, results are much better when both controllers are implemented in the system.

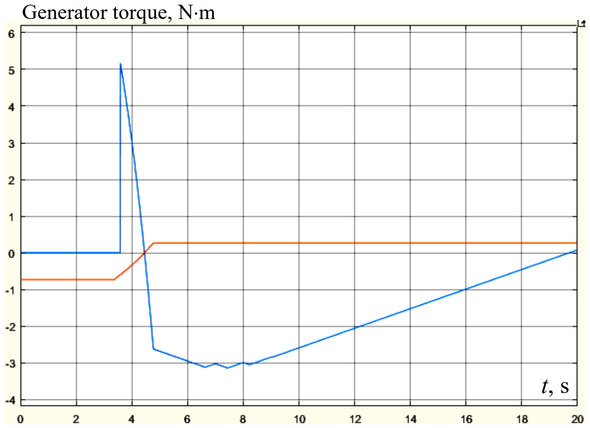

Fig. 11. Generator torque using 1-SMC and 2-SMC's

4.3 Efficiency enhancement. Efficiency enhancement in terms of η is calculated in this section. Using this formula

$$\eta = \frac{\text{obtained speed}}{\text{actual speed}} \cdot 100 .$$

We can easily find out efficiencies in terms of speed by both cased using 1-SMC and 2-SMC's based on their difference we will see how much efficiency is increased by employing second controller to the system.

- **Speed efficiency using 1-SMC.**

Maximum obtained speed is 12 rpm; actual speed needed is 50 rpm:

$$\eta_1 = \frac{12}{50} \cdot 100 = 24\% .$$

- **Speed efficiency using 2-SMC's**.

Maximum obtained speed is 42 rpm; actual speed needed is 50 rpm:

$$\eta_2 = \frac{42}{50} \cdot 100 = 84\% .$$

Hence, increase in efficiency $\eta_2 - \eta_1 = 60$ %.

Therefore, it is very clear that efficiency is increased to a much better extent when both controllers are employed in the system rather than by only using controller for engine generator control enhances the efficiency levels to a much reasonable and acceptable level. SMCs enhanced efficiency level of SHEV to a great extent. These robust controllers helped to reduce noise while vehicle is in operating state. They helped to reduce non-linearities.

5. Conclusion. In this research work, a series hybrid electric model is developed on MATLAB/Simulink and then two robust sliding mode controllers were designed and implemented in order to control engine speed and generator torque so that vehicle would run at maximum possible efficiency level.

As a series hybrid electric vehicle is a highly non-linear system, so a robust controller to be designed is a need of the time. By using two controllers, instead of only one, higher efficiency levels are achieved actually. In past work related to series hybrid electric vehicles, researches mostly focused on control of engine-generator set together called auxiliary power unit. The major development of this research is that two sliding mode controllers have been designed to be used in the system simultaneously, together optimizing speed of the engine and controlling torque of the generator in order to achieve a robust efficiency level in series hybrid electric vehicle.

The results revealed that much higher speed and torque could be achieved by using two controllers simultaneously controlling engine speed and generator torque. By employing both controllers in the system efficiency increases from 24 % to 84 %, hence a net increase of 60 % is observed. Graphs clearly show that by using of two sliding mode controllers a significant amount of speed and torque is added to the system. The basic idea was to not allow the engine to operate outside optimal region. By doing so, fuel consumption is also optimized as vehicle operated only when it is need, while deceleration or idle mode engine shuts off according to control strategy. These sliding mode controllers based control strategies depict the expected robustness via speed and torque. Despite of the load variations and non-linearities, graph tracked the standard cycle to much better level with an efficiency increase of 60 %. The addition of generator torque controller via two sliding mode controllers yields improved performance of series hybrid electric vehicle. The proposed scheme controls all the uncertainties of the system including engine and the generator. When the state of charge of battery drops below a predetermined level engine shuts off, and as engine reaches above the given level engine is stopped.

Conflict of interest. The authors declare that they have no conflicts of interest.

REFERENCES

1. Ding X., Guo H., Xiong R., Chen F., Zhang D., Gerada C. A new strategy of efficiency enhancement for traction systems in electric vehicles. *Applied Energy*, 2017, vol. 205, pp. 880-891. doi: https://doi.org/10.1016/j.apenergy.2017.08.051.

2. Vatsala Ahmad A., Alam M.S., Chaban R.C. Efficiency enhancement of wireless charging for Electric vehicles through reduction of coil misalignment. *2017 IEEE Transportation Electrification Conference and Expo (ITEC)*, 2017, pp. 21-26. doi: https://doi.org/10.1109/ITEC.2017.7993241.

3. Hussain A., Musilek P. Resilience Enhancement Strategies For and Through Electric Vehicles. *Sustainable Cities and Society*, 2022, vol. 80, art. no. 103788. doi: https://doi.org/10.1016/j.scs.2022.103788.

4. Ahmed H., Çelik D. Sliding mode based adaptive linear neuron proportional resonant control of Vienna rectifier for performance improvement of electric vehicle charging system. *Journal of Power Sources*, 2022, vol. 542, art. no. 231788. doi: https://doi.org/10.1016/j.jpowsour.2022.231788.

5. Bouguenna I.F., Azaiz A., Tahour A., Larbaoui A. Robust neuro-fuzzy sliding mode control with extended state observer for an electric drive system. *Energy*, 2019, vol. 169, pp. 1054-1063. doi: https://doi.org/10.1016/j.energy.2018.12.101.

6. Panday A., Bansal H.O. A Review of Optimal Energy Management Strategies for Hybrid Electric Vehicle. *International Journal of Vehicular Technology*, 2014, pp. 1-19. doi: https://doi.org/10.1155/2014/160510.

7. Lekshmi S., Lal Priya P.S. Mathematical modeling of Electric vehicles - A survey. *Control Engineering Practice*, 2019, vol. 92, art. no. 104138. doi: https://doi.org/10.1016/j.conengprac.2019.104138.

8. Patyal V.S., Kumar R., Kushwah S. Modeling barriers to the adoption of electric vehicles: An Indian perspective. *Energy*, 2021, vol. 237, art. no. 121554. doi: https://doi.org/10.1016/j.energy.2021.121554.

9. Kapeller H., Dvorak D., Šimić D. Improvement and Investigation of the Requirements for Electric Vehicles by the use of HVAC Modeling. *HighTech and Innovation Journal*, 2021, vol. 2, no. 1, pp. 67-76. doi: https://doi.org/10.28991/HIJ-2021-02-01-07.

10. Hariri A.-M., Hejazi M. A., Hashemi-Dezaki H. Investigation of impacts of plug-in hybrid electric vehicles' stochastic characteristics modeling on smart grid reliability under different charging scenarios. *Journal of Cleaner Production*, 2021, vol. 287, art. no. 125500. doi: https://doi.org/10.1016/j.jclepro.2020.125500.

11. León R., Montaleza C., Maldonado J.L., Tostado-Véliz M., Jurado F. Hybrid Electric Vehicles: A Review of Existing Configurations and Thermodynamic Cycles. *Thermo*, 2021, vol. 1, no. 2, pp. 134-150. doi: https://doi.org/10.3390/thermo1020010.

12. Llopis-Albert C., Palacios-Marqués D., Simón-Moya V. Fuzzy set qualitative comparative analysis (fsQCA) applied to the adaptation of the automobile industry to meet the emission standards of climate change policies via the deployment of electric vehicles (EVs). *Technological Forecasting and Social Change*, 2021, vol. 169, art. no. 120843. doi: https://doi.org/10.1016/j.techfore.2021.120843.

13. Deb N., Singh R., Bai H. Transformative Role of Silicon Carbide Power Electronics in Providing Low-cost Extremely Fast Charging of Electric Vehicles. *2021 IEEE Fourth International Conference on DC Microgrids (ICDCM)*, 2021, pp. 1-6. doi: https://doi.org/10.1109/ICDCM50975.2021.9504653.
14. Ambuhl D. *Energy Management Strategies for Hybrid Electric Vehicles*. Doctoral dissertation. ETH/ Measurement and Control Laboratory, 2009. 145 p. doi: https://doi.org/10.3929/ethz-a-005902053.
15. Sundstrom O. *Optimal Control and Design of Hybrid Electric Vehicles*. Doctoral dissertation. ETH Zurich Chalmers University of Technology, 2009. 169 p. doi: https://doi.org/10.3929/ethz-a-005902040.
16. Bowles P., Peng H., Zhang X. Energy management in a parallel hybrid electric vehicle with a continuously variable transmission. *Proceedings of the 2000 American Control Conference*, 2000, vol. 1, pp. 55-59 doi: https://doi.org/10.1109/ACC.2000.878771.
17. Stromberg E. *Optimal Control of Hybrid Electric Vehicles*. Vehicular Systems, Dept. of Electrical Engineering, Linkoping University, 2003. 56 p.
18. Chan-Chiao Lin, Huei Peng, Grizzle J.W., Jun-Mo Kang. Power management strategy for a parallel hybrid electric truck. *IEEE Transactions on Control Systems Technology*, 2003, vol. 11, no. 6, pp. 839-849. doi: https://doi.org/10.1109/TCST.2003.815606.
19. Barsali S., Miulli C., Possenti A. A Control Strategy to Minimize Fuel Consumption of Series Hybrid Electric Vehicles. *IEEE Transactions on Energy Conversion*, 2004, vol. 19, no. 1, pp. 187-195. doi: https://doi.org/10.1109/TEC.2003.821862.
20. Beck R., Richert F., Bollig A., Abel D., Saenger S., Neil K., Scholt T., Noreikat K.-E. Model Predictive Control of a Parallel Hybrid Vehicle Drivetrain. *Proceedings of the 44th IEEE Conference on Decision and Control*, 2005, pp. 2670-2675. doi: https://doi.org/10.1109/CDC.2005.1582566.
21. Yang Y., Pei H., Hu X., Liu Y., Hou C., Cao D. Fuel economy optimization of power split hybrid vehicles: A rapid dynamic programming approach. *Energy*, 2019, vol. 166, pp. 929-938. doi: https://doi.org/10.1016/j.energy.2018.10.149.
22. He D., Zou Y., Wu J., Zhang X., Zhang Z., Wang R. Deep Q-Learning Based Energy Management Strategy for a Series Hybrid Electric Tracked Vehicle and Its Adaptability Validation. *2019 IEEE Transportation Electrification Conference and Expo (ITEC)*, 2019, pp. 1-6. doi: https://doi.org/10.1109/ITEC.2019.8790630.
23. Yang R., Yang X., Huang W., Zhang S. Energy Management of the Power-Split Hybrid Electric City Bus Based on the Stochastic Model Predictive Control. *IEEE Access*, 2021, vol. 9, pp. 2055-2071. doi: https://doi.org/10.1109/ACCESS.2020.3047113.
24. Serrao L., Onori S., Rizzoni G. A Comparative Analysis of Energy Management Strategies for Hybrid Electric Vehicles. *Journal of Dynamic Systems, Measurement, and Control*, 2011, vol. 133, no. 3, art. no. 031012. doi: https://doi.org/10.1115/1.4003267.
25. Sharma O.P., Onori S., Guezennec Y. Analysis of Pontryagin's Minimum Principle-Based Energy Management Strategy for PHEV Applications. *ASME 2012 5th Annual Dynamic Systems and Control Conference Joint with the JSME 2012 11th Motion and Vibration Conference, DSCC 2012-MOVIC 2012*, vol. 1, pp. 145-150. doi: https://doi.org/10.1115/DSCC2012-MOVIC2012-8699.
26. Yan F., Wang J., Huang K. Hybrid Electric Vehicle Model Predictive Control Torque-Split Strategy Incorporating Engine Transient Characteristics. *IEEE Transactions on Vehicular Technology*, 2012, vol. 61, no. 6, pp. 2458-2467. doi: https://doi.org/10.1109/TVT.2012.2197767.
27. Panday A., Bansal H.O. Energy Management Strategy Implementation for Hybrid Electric Vehicles Using Genetic Algorithm Tuned Pontryagin's Minimum Principle Controller. *International Journal of Vehicular Technology*, 2016, pp. 1-13. doi: https://doi.org/10.1155/2016/4234261.
28. Nedungadi A., Smith R., Masrur A. Quantitative analysis of a hybrid electric HMMWV for fuel economy improvement. *26th Electric Vehicle Symposium 2012, EVS 2012*, vol. 3, pp. 1999-2007.
29. Chen Z., Zhang X., Mi C.C. Slide Mode and Fuzzy Logic Based Powertrain Controller for the Energy Management and Battery Lifetime Extension of Series Hybrid Electric Vehicles. *Journal of Asian Electric Vehicles*, 2010, vol. 8, no. 2, pp. 1425-1432. doi: https://doi.org/10.4130/jaev.8.1425.
30. Zhang X., Mi C.C., Yin C. Active-charging based powertrain control in series hybrid electric vehicles for efficiency improvement and battery lifetime extension. *Journal of Power Sources*, 2014, vol. 245, pp. 292-300. doi: https://doi.org/10.1016/j.jpowsour.2013.06.117.
31. Saeks R., Cox C.J., Neidhoefer J., Mays P.R., Murray J.J. Adaptive control of a hybrid electric vehicle. *IEEE Transactions on Intelligent Transportation Systems*, 2002, vol. 3, no. 4, pp. 213-234. doi: https://doi.org/10.1109/TITS.2002.804750.
32. Fiengo G., Di Fiore C., Lepore D., Vasca F. Auxiliary power unit control for hybrid electric vehicles. *2003 European Control Conference (ECC)*, 2003, pp. 2304-2309. doi: https://doi.org/10.23919/ECC.2003.7085310.
33. Sulaiman N., Hannan M.A., Mohamed A., Ker P.J., Majlan E.H., Wan Daud W.R. Optimization of energy management system for fuel-cell hybrid electric vehicles: Issues and recommendations. *Applied Energy*, 2018, vol. 228, pp. 2061-2079. doi: https://doi.org/10.1016/j.apenergy.2018.07.087.
34. Zhang X., Guo L., Guo N., Zou Y., Du G. Bi-level Energy Management of Plug-in Hybrid Electric Vehicles for Fuel Economy and Battery Lifetime with Intelligent State-of-charge Reference. *Journal of Power Sources*, 2021, vol. 481, art. no. 228798. doi: https://doi.org/10.1016/j.jpowsour.2020.228798.
35. Xiao B., Ruan J., Yang W., Walker P.D., Zhang N. A review of pivotal energy management strategies for extended range electric vehicles. *Renewable and Sustainable Energy Reviews*, 2021, vol. 149, art. no. 111194. doi: https://doi.org/10.1016/j.rser.2021.111194.
36. Ali Moussa M., Derrouazin A., Latroch M., Aillerie M. A hybrid renewable energy production system using a smart controller based on fuzzy logic. *Electrical Engineering & Electromechanics*, 2022, no. 3, pp. 46-50. doi: https://doi.org/10.20998/2074-272X.2022.3.07.
37. Guezi A., Bendaikha A., Dendouga A. Direct torque control based on second order sliding mode controller for three-level inverter-fed permanent magnet synchronous motor: comparative study. *Electrical Engineering & Electromechanics*, 2022, no. 5, pp. 10-13. doi: https://doi.org/10.20998/2074-272X.2022.5.02.

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