Grenze International Journal of Engineering and Technology, Jan Issue

A Novel Rule based Energy Management Strategy using Fuzzy Logic for Power Management of Plug-in Hybrid Electric Vehicle in Parallel Operation

Mohammad Suhail[1], Abrar Ahmad[2], Sheeraz Kirmani[3] and Munna Khan[4]
[1-4]Department of Electrical Engineering, Jamia Millia Islamia, New Delhi-110025, India
Email: suhailrke.ms@gmail.com, aahmad15@jmi.ac.in, skirmani@jmi.ac.in , mkhan4@jmi.ac.in
[3]Department of Electrical Engineering, Aligarh Muslim University, Aligarh-202001, India
Email: suhailrke.ms@gmail.com

***Abstract*— Electric vehicles and hybrid electric vehicles are revolutionizing the modern transport system and transition to electric vehicle comes with its challenges. The power management of the electric vehicles needs to be an efficient one in order to bring electric vehicles to the mainstream and project them as a viable alternative to the conventional fuel based vehicles. This work presents the power management strategy for plug-in hybrid electric vehicles and electric vehicles using intelligent techniques. The technique uses the fuzzy logic controller for the energy optimization. The fuzzy logic controller calibrates the battery charging process in conformation with the real time power demand, input power of the vehicle speed, real time battery state of charge and motor power. The fuzzy inference system with appropriate set of rules dictates the value of fuzzified linguistic variable. This work is realized using MATLAB-SIMULINK environment and simulations depict the behavior of the battery state of charge and the output power response of the hybrid electric vehicle.**

***Index Terms*— Hybrid electric vehicle, energy management, fuzzy logic, intelligent techniques, parallel drivetrain.**

I. Introduction

Hybrid electric vehicles and electric vehicles are slowly being introduced in the market and have been projected to partially or completely replace the convention fossil fuel based electric vehicles due to the growing interest in environment[1] friendly mode of transportation. The hybrid electric vehicle with less emissions and high fuel efficiency promise an effective alternative to meet the progressive sustainable development[2]. Blended discharge and charge depletion[3] strategies are rule based[4][5] strategies and enabling the state of the art energy management system. The efficient energy management and mode transition[6] enables the utilization of the integral transformation in the parallel powertrain hybrid electric vehicle. The fuzzy logic enables ruled based and adaptive[7] energy management strategy adaptive are gaining popularity due to their simplicity and their easy to implement application in real world scenarios. The adaptive nature of the fuzzy logic rules allows real time[8] automation, mode transition and energy management. This work presents a novel non-linear[9] fuzzy logic system with a rule based fuzzy inference system to optimize the hybrid vehicle for maximum charging during regenerative braking process when the parallel drivetrain hybrid vehicle is under braking operation and

Grenze ID: 01.GIJET.8.1.1

obtain a smooth battery state of charge profile. The IDP-ANFIS control scheme for parallel operation of hybrid electric bus presented in[10] and [11] involve dynamic programming and nuero-fuzzy approach to obtain optimal control trajectories for the energy consumption minimization[12][13]. The fuzzy logic strategy devised in this work is simpler and more feasible in the real world scenario to obtain optimal energy optimization for charging the HEV in real time operation. The section 2 and section 3 of this study deal with the operation of the parallel drivetrain and specification of various drivetrain components. The section 4 describes the mathematical modeling followed by the fuzzy logic controller in section 5. The section 5 and section 6 shows the results and conclusions respectively. The last section mentions the various references that have been cited in this work.

II. Parallel Drivetrain

In case of parallel drivetrain, electric motor and internal combustion engine simultaneously supply power to run the vehicle. The mechanical power is supplied simultaneously by means of a power transfer device. The battery pack used in this case is smaller and relies heavily on the regenerative braking mechanism to charge the battery of the hybrid electric vehicle. In special cases, particularly when the power and torque demand are low, the electric motor can also be used as a generator. The engine, in this case, is connected directly to the mechanical parts of the body and thus the hybrid vehicles run with increased efficiency in long distance driving case. The figure 1 below shows the block diagram and the direction of power flow in a parallel drivetrain. The engine is connected to the shaft by means of a clutch and a power transfer device. The power transfer device governs the power split[14] strategy for the hybrid electric vehicle. The 100kW synchronous motor is connected to the battery by means of an inverter and is directly connected to the shaft to deliver the power to the vehicle. The wheels are connected to the electrical components through a shaft. The power flow is unidirectional in case of internal combustion engine while the power flow is bidirectional on the motor side. This is because the battery can be charged during the braking process through regenerative braking mechanism. This allows efficient battery performance as the engine and motor are able to provide the power simultaneously with high driving reliability and energy saving.

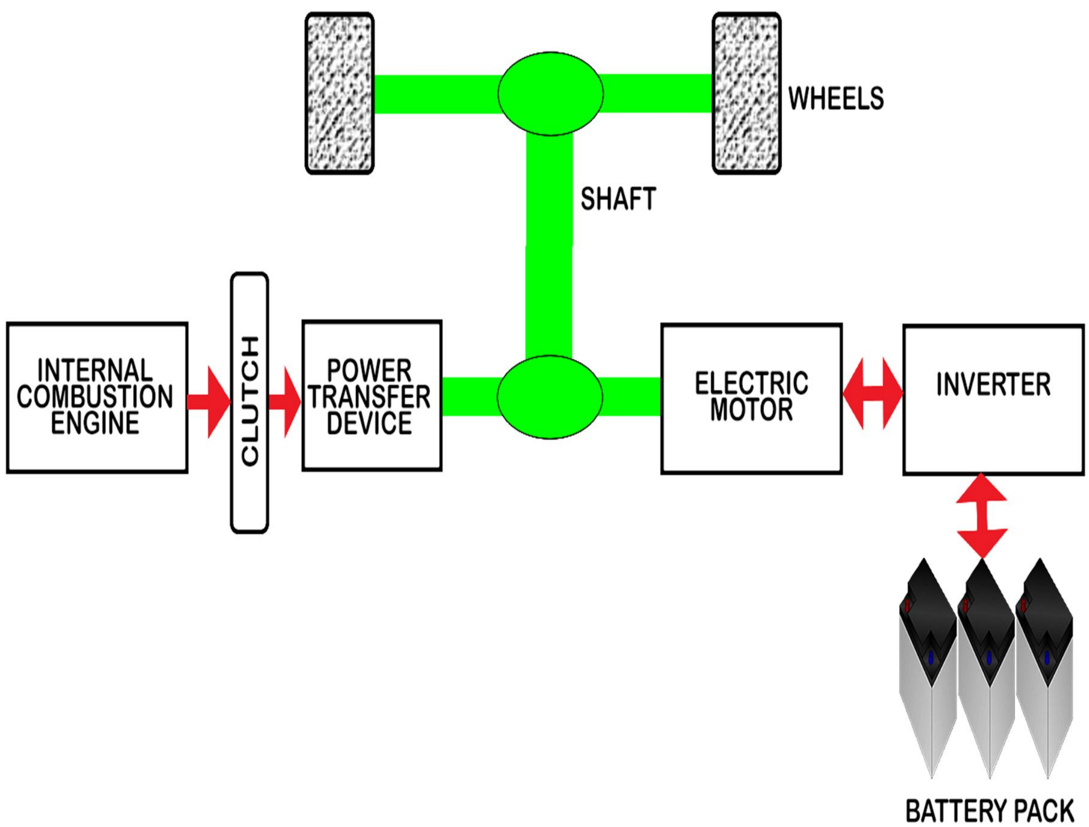

Figure 1.Parallel mode hybrid drivetrain

III. POWERTRAIN SPECIFICATIONS

The tables I, II and III below show the powertrain specifications and rating of different components which for the part of the hybrid powertrain.

TABLE I. COMPONENT RATING

S. No	Component	Rating	Unit
1.	Motor	100	kW
2.	Generator	100	kW
3.	Engine	120	kW
4.	Battery	50	Ah

TABLE II. GENERATOR PARAMETERS

S. No	Parameter	Rating	Unit
1	Stator resistance	0.00475	pu
2	Maximum speed	15000	rpm
3	Maximum torque	400	Nm
4	Time constant	0.04	-
5	Series resistance	0.01	Pu

TABLE III. MOTOR PARAMETERS

S. No	Parameter	Rating	Unit
1	Stator resistance	0.091	pu
2	Maximum speed	10000	rpm
3	Shaft inertia	0.2	Kg-m^2
4	Efficiency	95	%
5	Inductance	0.002	pu

IV. MATHEMATICAL MODELING

The electrical system consists of synchronous motor, synchronous generator, a single phase inverter, a chopper and a battery of 20Ah capacity with a nominal voltage of 500 volts. The speed of the synchronous generator and synchronous motor are given by equation (1)[15].

$$N = \frac{120*f}{P}. \quad (1)$$

Where f is the frequency and P is the number of poles of the generator and N is the synchronous speed. The terminal voltage of the synchronous is calculated by using the relation (2)[15][16].

$$E_f = V - I_a Z_s. \ (2)$$

Where V is the nominal battery voltage, I_a is the armature current, Z_s is the impedance and E_f is the across the motor terminal.

The mechanical power produced by the motor is calculated by equation (3)[15], [17].

$$P_m = E_f * I_a \cos(\delta - \emptyset). \quad (3)$$

Where P_m is the power developed by the motor, δ is the is the load angle and $\emptyset$ is the angle between V and I_a. The final power after separating the losses is denoted by $P_{m'}$ and is given by (4) and (5).

$$P_{m'} = P_m - P_{losses}. \ (4)$$

$$P_{losses} = P_w + P_c + P_{st} + P_{ir} + P_{cs}. \ (5)$$

V. FUZZY LOGIC CONTROLLERA

fuzzy logic controller is designed to optimize the regenerative braking to maximize the transfer of energy to charge the battery. In this controller, four inputs are used and are fed to the fuzzy logic controller by means of a 4 to 1 multiplexer. The output of this fuzzy logic controller is the percentage of energy from regenerative braking used to charge the battery. The fuzzy membership function used in this study is the bell membership function due to the smooth curve and gradual value change and it can be used as a combination of Gaussian and trapezoidal membership functions. Bell membership function is used for all the inputs and the output. The battery state of charge is categorized into low, medium and high categories. Similarly the other 4 inputs are also categorized into low, medium and high categories. The fuzzy system used in this study is mamdani system.

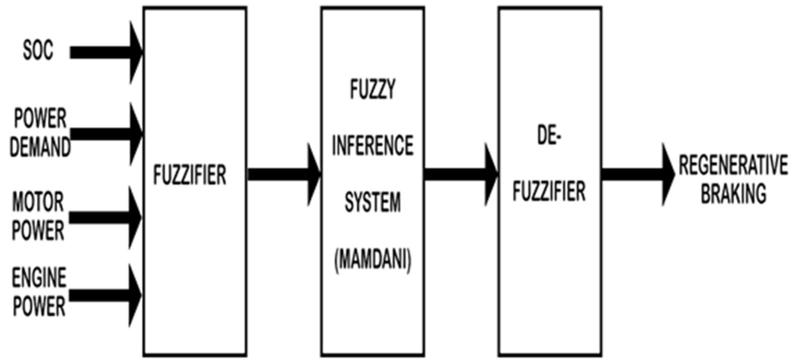

Figure 2.Fuzzy logic controller

The table 4 below shows the fuzzy inference system which is the most important step in the controlling process. The fuzzy inference system interrelate the linguistic variables through a set of rules and converts the entire strategy into a rule based system.

TABLE IV. FUZZY INFERENCE SYSTEM

	Input				**Output**
S. No.	**SOC**	**Power demand**	**Motor power**	**Engine power**	**Charging factor**
1.	Low	High	Not high	Not high	High
2.	low	Medium	Not low	Not low	High
3.	low	High	High	High	Medium
4.	Low	Low	Not low	Not low	High
5.	Medium	High	Not low	Not low	Medium
6.	Medium	Not high	Medium	Medium	High
7.	Medium	Low	Not high	Not high	High
8.	Medium	High	High	High	Medium
9.	High	High	High	High	Low
10.	High	Not high	Not high	Not high	Medium
11.	High	Low	Not high	Not high	High
12.	High	Medium	High	High	Medium
13.	High	High	Medium	High	High
14.	High	High	Low	Medium	Low

V. RESULTS AND DISCUSSION

The MATLAB-SIMULINK environment is used to simulate the above mentioned energy management strategy. The input drive cycle used in this study is the FTP-75 drive cycle which is inbuilt in powertrain blockset.
The FTP-75 represents a drive cycle that can be used to determine the battery response. The reason FTP 75 drive cycle is used is because this drive cycle has minimal idle time and matches the city driving patterns with more gear shift and frequent acceleration and deceleration times. Motor output power is an important parameter to analyze the performance of the hybrid electric vehicle. The electric motor used in this study is a synchronous

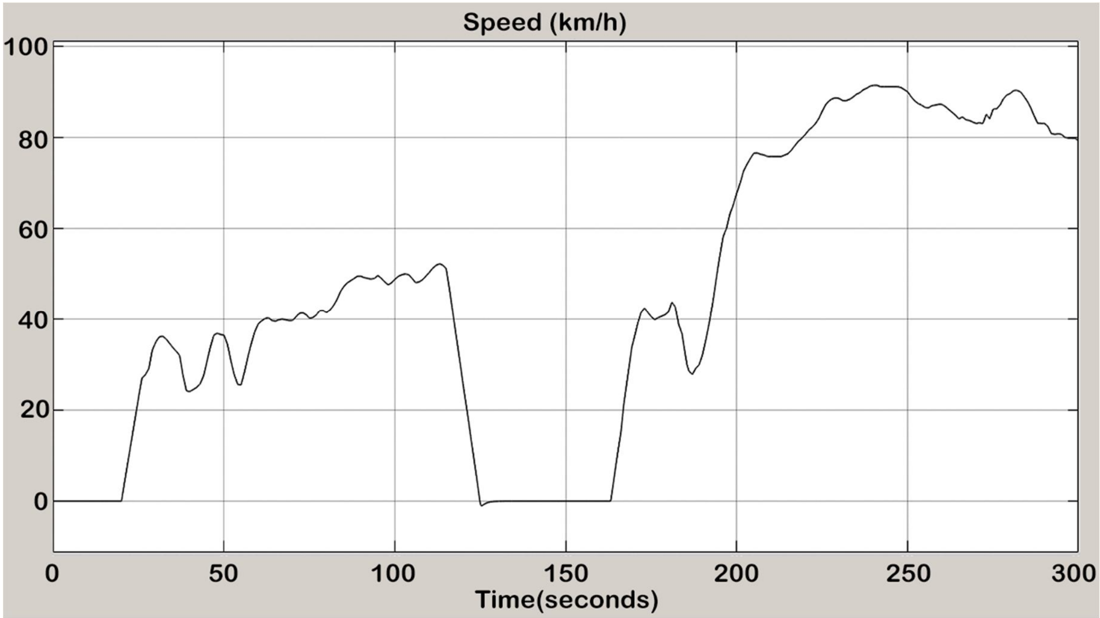

Figure 3.Input drive cycle (FTP-75)

motor with a maximum output rating of 100kW. The motor power plot in figure 4 reveals that due to the parallel operation of the drivetrain, the motor is not overloaded at any instant of time during the drive cycle because the motor and the internal combustion engine supply power simultaneously to run the hybrid vehicle. The peak total power demand during this 300 second drive run is 70kW and mostly the total power supplied by engine ranges from 20-40 kW.

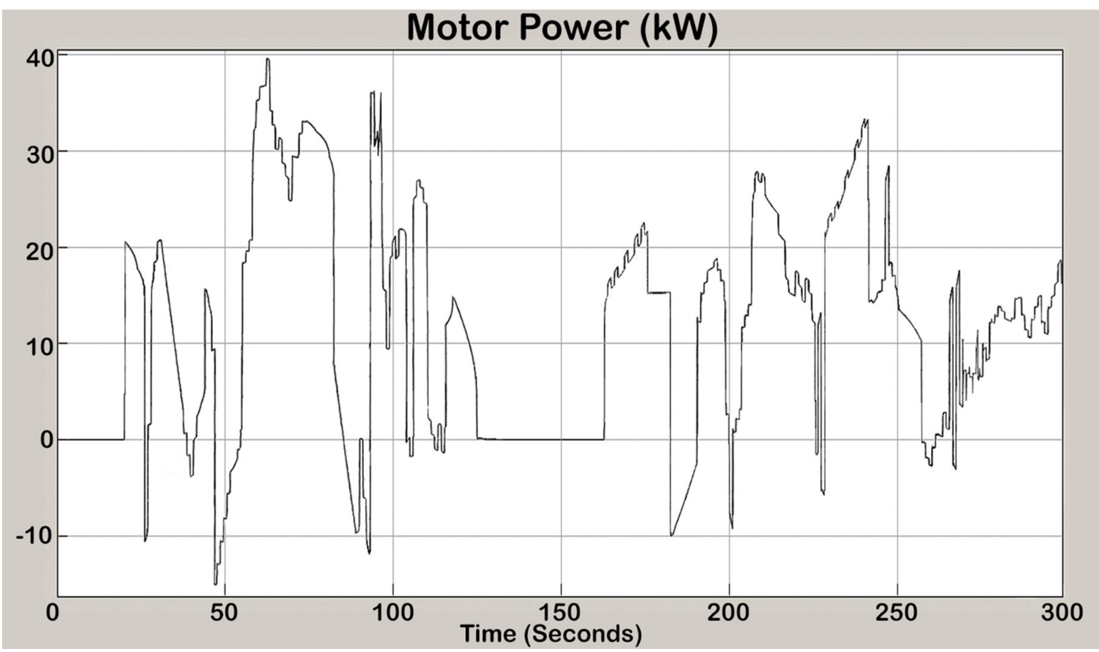

Figure 4.Motor power

The figure 4 shown above shows the power delivered by the motor in a 300 seconds drive cycle. The motor delivers the power above 10kW throughout the drive cycle. The power delivered is 0 kW when the vehicle is in idle state and no power is required from the motor. The peak power delivered by the motor during this operation is 37 kW. The power requirement was occasionally reaching above 20kW.

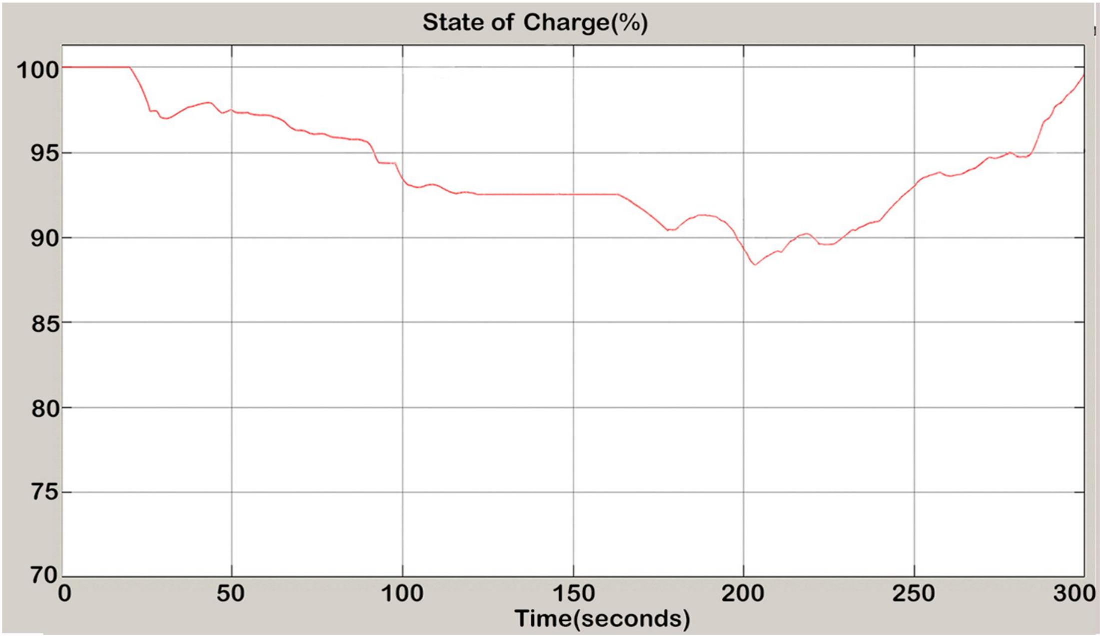

Figure 5.Battery state of charge (SOC) profile

The battery state of charge profile is also plotted for the 300 second operation of the drive cycle and is depicted in figure 5. The initial battery state of charge cut-off is 100%. Since the vehicle is in idle state till 15 seconds, the battery state of charge remains at 100% value as no discharge is happening at this stage. As the vehicle starts to accelerate, the battery starts to discharge and falls to 92%. As the vehicle decelerates, and the braking operation happens, the regenerative operation helps restore the battery charge by charging the battery. This charging-discharging operation is visible in the state of charge plot throughout the drive cycle. Ultimately, at the end of the drive operation at time 300 seconds, the battery state of charge at this stage is 99.5%. The battery starts to charge through regenerative braking process whenever the braking operation is applied and the results are significant. The next section of this study concludes this work.

VI. Conclusions And Future Scope

The fuzzy logic rule based energy management strategy for the parallel drivetrain operation of the plug-in hybrid electric vehicle has been implemented. The response the vehicle and different output parameters have been recorded and shown in the section V. The implemented energy management strategy significantly improves the battery state of charge profile and the curve is smooth. As a result of regular charging from the regenerative braking operation, the Li-ion battery is able to have the state of charge value at 99.5% at the end of the 300 second operation. Thus, this can be effective method to improve the driving range if the hybrid electric vehicle in electric mode which will consequently result in improved economic operation of vehicle, less fuel consumption, lesser carbon emissions and eventually another step toward sustainable development. In future, the scope of this work includes the inclusion of machine learning and deep learning algorithms to optimize the power flow in the hybrid electric and electric vehicles. The fuzzy logic and intelligent adaptive mechanism can be used to further study the energy optimization for repeated travel routes using pattern recognition technique.

References

[1] J. Kim, H. Kim, J. Bae, D. Kim, J. S. Eo, and K. K. K. Kim, “Economic nonlinear predictive control for real-time optimal energy management of parallel hybrid electric vehicles,” *IEEE Access*, vol. 8, pp. 177896–177920, 2020.

[2] H. Kong, Y. Fang, L. Fan, H. Wang, X. Zhang, and J. Hu, “A Novel Torque Distribution Strategy Based on Deep Recurrent Neural Network for Parallel Hybrid Electric Vehicle,” *IEEE Access*, vol. 7, pp. 65174–65185, 2019.

[3] E. Taherzadeh, M. Dabbaghjamanesh, M. Gitizadeh, and A. Rahideh, “A new efficient fuel optimization in blended

charge depletion/charge sustenance control strategy for plug-in hybrid electric vehicles," *IEEE Trans. Intell. Veh.*, vol. 3, no. 3, pp. 374–383, 2018.
[4] A. Rezaei, J. B. Burl, M. Rezaei, and B. Zhou, "Catch energy saving opportunity in charge-depletion mode, a real-time controller for plug-in hybrid electric vehicles," *IEEE Trans. Veh. Technol.*, vol. 67, no. 11, pp. 11234–11237, 2018.
[5] X. Li and S. A. Evangelou, "Torque-Leveling Threshold-Changing Rule-Based Control for Parallel Hybrid Electric Vehicles," *IEEE Trans. Veh. Technol.*, vol. 68, no. 7, pp. 6509–6523, 2019.
[6] C. Yang, Y. Shi, L. Li, and X. Wang, "Efficient Mode Transition Control for Parallel Hybrid Electric Vehicle with Adaptive Dual-Loop Control Framework," *IEEE Trans. Veh. Technol.*, vol. 69, no. 2, pp. 1519–1532, 2020.
[7] S. Wang, X. Huang, J. M. Lopez, X. Xu, and P. Dong, "Fuzzy Adaptive-Equivalent Consumption Minimization Strategy for a Parallel Hybrid Electric Vehicle," *IEEE Access*, vol. 7, pp. 133290–133303, 2019.
[8] A. Rezaei, J. B. Burl, B. Zhou, and M. Rezaei, "A New Real-Time Optimal Energy Management Strategy for Parallel Hybrid Electric Vehicles," *IEEE Trans. Control Syst. Technol.*, vol. 27, no. 2, pp. 830–837, 2019.
[9] B. Liu, T. Wang, H. Wang, and L. Li, "Nonlinear model predictive control for series-parallel hybrid electric buses," *IEEE Access*, vol. 7, pp. 138792–138802, 2019, doi: 10.1109/ACCESS.2019.2941082.
[10] X. Tian, R. He, and Y. Xu, "Design of an Energy Management Strategy for a Parallel Hybrid Electric Bus Based on an IDP-ANFIS Scheme," *IEEE Access*, vol. 6, pp. 23806–23819, 2018.
[11] X. Tian, R. He, X. Sun, Y. Cai, and Y. Xu, "An ANFIS-Based ECMS for Energy Optimization of Parallel Hybrid Electric Bus," *IEEE Trans. Veh. Technol.*, vol. 69, no. 2, pp. 1473–1483, 2020.
[12] B. Zhou, J. B. Burl, and A. Rezaei, "Equivalent consumption minimization strategy with consideration of battery aging for parallel hybrid electric vehicles," *IEEE Access*, vol. 8, 2020.
[13] G. Nobile, G. Scelba, M. Cacciato, and G. Scarcella, "Losses Minimization Control for an Integrated Multidrive Topology Devoted to Hybrid Electric Vehicles," *IEEE Trans. Ind. Electron.*, vol. 66, no. 11, pp. 8345–8360, 2019.
[14] N. Denis, M. R. Dubois, J. P. F. Trovao, and A. Desrochers, "Power Split Strategy Optimization of a Plug-in Parallel Hybrid Electric Vehicle," *IEEE Trans. Veh. Technol.*, vol. 67, no. 1, pp. 315–326, 2018.
[15] D. P. Kothari and I. J. Nagrath, *Electric Machines*, 4th ed. McGraw-Hill Education - Europe, 2010.
[16] D. P. Kothari and I. J. Nagrath, *Power System Engineering*, 3rd ed. McGraw-Hill, 2019.
[17] D. P. Kothari and I. J. Nagrath, *Modern Power System Analysis*, 4th ed. McGraw Hill Education, 2019.