Predictive Control on Power Source Selection in Hybrid Vehicle System

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Abstract. Technology advances day by day. It improves like revolutions. As in TeleCom, the mode of communications advances from electrical lines to optical lines to increase the speed of data transmission and now it is wireless. This pattern holds true for the revolution in automotive industry. It is the part of “Fourth Industrial Revolution” targeting connectivity, electrification and update in customer needs. This revolution is in need of more energy compared to the conventional requirement. Progress in battery technologies are providing us an option towards the electrification of the automobiles. The advancing safety features has demand in power which roots towards electrification. As pulses, the initial effort has taken in improving the utilization of Energy Storage Systems for Electric or Hybrid Vehicles. Drives used in Electric Vehicles (EV) are configured to act as generator during braking, thus charging the Energy Storage System (ESS). This ESS offers efficiency in storing re-generative braking energy, vehicle acceleration and battery safety. Appropriate switching algorithm (ANFIS) is required to control the power supply source during power demand, which based on the past learnings that target to improve the efficiency of control mechanism to maintain the quality of Battery and Super Capacitor in Hybrid Energy Storage System (HESS).

1. Introduction
High performance and quick response of electronic components can be achieved with the current high efficient electronic controllers. Herewith the technology, most of the vehicle manufacturers are moving towards the electrification of complete vehicles, which is the major target to achieve the stringent emission norms without affecting the performance of the vehicle. To achieve this, an update in powertrain architecture required, which is quite difficult and of high cost. So, the topology or the working of vehicles are subject to hybridization, whereas the existing Internal Combustion Engine (ICE) will provide torque and power together with Electric Motor (e-Motor) based on driver demand with the defined control strategy by respective OEM’s. This hybridization has its own sub stages as, Mild Hybrid, Plug-In Hybrid and Full Hybrid, which can be based on series or parallel configuration of ICE and e-Motor configuration. Therefore, these configuration provides efficient way of handling Hybrid system in vehicle and to keep the emission norms according to geo-region’s requirement. Similarly, the design

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and configuration of the power supply system is one of the major domain to be addressed. In electric power supply system, an improvement is expected over the existing 12V system, since the power demand is bigger to drive the vehicle and to meet the instant power demand as like conventional petrol/diesel engines. Batteries are best power storage and discharge components that exist. But on the other hand, life time of the batteries reduces, when there is high power demand to drive heavy load or to meet instant torque request. To resolve the issue with life time of Battery or to increase the life time, an updated or the modified system is expected, which is Hybrid Energy Storage Systems with 48V battery. Topology or the design of this HESS again has many different combinations such as, Battery with Fuel Cells, Battery with Supper Capacitor/Ultra Capacitor, etc… However, this HESS has its own challenges to be addressed. In paper [1], new-regenerative braking system (RBS) was proposed to restore or recharge the HESS with the applied kinetic energy instead releasing it as heat energy which reviles the state-of-art of HESS. Batteries can be used as primary power supply device in Hybrid Vehicles. But, the drawback is, high power demand cannot be handled or delivered by Batteries. Hybridizing this energy storage system will address this downside [2]. Existing research work has deployed results based on rule-based, optimization-based and moving one step ahead with the terrain level information that exist to calculate the power demand based on the location. But all this control strategies has its own drawbacks such as, rule-based depends on instantaneous status of HESS, optimization-based depends on determine the future expectation which may not be similar to the real situation and finally the terrain-based control algorithm showed an improvement but not in the landscapes which is plain area or the geographic [5] – [6]. To address all such areas, by moving ahead with the current control algorithms, the possibility of having the controller ANFIS (Type of Machine Learning), which is trained with specific set of data to react over the request in future to have smooth and faster response either from ICE or HESS [3]-[4].

In this study, Battery and Super Capacitor are considered as HESS to supply the power demand and the source selection control is handled with Adaptive Neuro-Fuzzy Inference System (ANFIS). Based on the State of Charge (SoC) of HESS (Battery and Super Capacitor), conventional ICE is controlled to deliver the power demand without any lag. The simulation result of this paper will provide the control or switching mechanism that can be implemented to improve the efficiency and the performance without affecting battery life and super capacitor.

2. System Design and its Features
The configuration of considered Hybrid Electric Vehicle and the configuration type is available in “figure 1”. Conventional ICE and e-Motor connected in series with Clutch, such that the configuration has possibility to be driven by e-Motor or ICE based on the status of HESS and the power demand.

![Figure 1. Hybrid electric vehicle configuration (series configuration)](image)

Whereas; it is assumed as, the battery is sized properly which is capable to run or deliver the power and
store the energy to a specified range and the super capacitor modeled according to vehicle dynamics and the characteristics are fixed to meet the power supply requirement. 

The overview of power flow can be viewed in figure 2, conventional engine is connected directly to vehicle/load and in parallel it can driver moto as well. Then, motor is also connected to vehicle/load whereas it is has two different inputs, one is electric power supply from BT/SC and from engine. When motor drives the vehicle/load, it is powered with BT/SC and discharges drastically. Once discharged or below the operating region, engine drive the motor as generator to produce power to charge BT/SC in parallel with driving the vehicle/load.

![Figure 2. Overview on power flow](image)

2.1. Function of HESS in Normal Mode (Battery Discharging Mode)

When the vehicle speed is maintained at 20 to 30 kmph or when there is no high torque demand from driver, it is considered as Normal mode. As per the schematic figure 3, during normal mode, batteries will supply the power to e-Motor which in turn drives the vehicle as like conventional ICE and there is no emission [8].

![Figure 3. HESS in normal Mode](image)

2.2. Function of HESS in Acceleration Mode (Super Capacitor / Ultra Capacitor Discharging Mode)

When the torque demand is increased to drive the vehicle at higher rpm/speed, large amount of instant power is expected and which is supplied by Super Capacitor / Ultra Capacitor, since it has the capability to deliver higher power demand without any delay. Figure 3 shows the HESS configuration in acceleration mode.

![Figure 4. HESS in acceleration Mode](image)
2.3. Function of HESS during Re-gen braking with Super Capacitor (Charging Mode)
During braking, the motor is configured to act as generator to store the kinetic energy which lost as heat. If SoC of SC/UC is low or below its operating range, conventional ICE will drive the vehicle and the motor will act as generator to produce power as shown in figure 5.

![Figure 5. Re-generative braking with super-capacitor](image)

2.4. Function of HESS during Re-gen braking with Battery (Charging Mode)
As similar to the functionality in 2.3, charging the battery happens with the power generated by generator during Re-generative braking. Appropriate selection of Bi-Directional DC/DC converter provides an option to improve the performance of the system as shown in figure 6.

![Figure 6. Re-Generative braking with Battery](image)

3. Design and Modelling of ANFIS Controller
Electrochemical models deployed as equivalent electric circuit models, to research on the behaviour of vehicle energy and battery management system. With existing models or the designs, State of Charge of Batteries and the super capacitors can be identified using below set of mathematical models.

To indicate the batteries residual electrical ability of the battery, State of Charge of Battery used and this is usually determined by:

$$\text{SoC}_\text{bat} = \text{SoC}_0 - k_{\text{ch}} k_{\text{dis}} \int \sum I_{\text{bat}} dt / C_{\text{bat}}$$  \hspace{1cm} (1)

where:
- $\text{SoC}_0$ represents initial value of SoC
- $k_{\text{ch}}$ and $k_{\text{dis}}$ represents the coefficients on the current integration from charging to discharging current respectively
- $C_{\text{bat}}$ represents batteries nominal capacity, while $\sum$ is the efficiency in coulomb

The state of charge of the super capacitor, $\text{SoC}_{SC}$, expressed as the ration between the remaining energy and the maximum stored energy of the super capacitor. Using $W = \frac{1}{2} CV^2$, the state of charge defined based on terminal voltage becomes:

$$\text{SoC}_{SC} = W/W_{\text{max}} = V^2/V_{\text{max}}^2 \times 100\%$$  \hspace{1cm} (2)

where:
- $V$ is the terminal voltage of super capacitor
- $V_{\text{max}}$ is equivalent to the rated voltage of the super capacitor
- W is power in super capacitor
- \( W_{\text{max}} \) is maximum power capacity of super capacitor

An adaptive neuro-fuzzy inference system (ANFIS) is a fuzzy system whose membership functions used in neuro-adaptive learning methods as similar to methods used in training neural networks. Fuzzy qualitative approach and NN adaptive capability together forms ANFIS (adaptive neuro-fuzzy inference system).

The algorithm of a fuzzy system is as follows:

- **Fuzzification**
  a) Fuzzy input and output vectors are normalized to achieve universes of discourses
  b) Selection of heuristic number and shape of input and output vector of fuzzy logic
  c) For every crisp input, calculation of membership grades required

- **Fuzzy inference**
  a) Rule base is based on the view of real-time system operations
  b) Active rules to be stored in rule base
  c) Based on fuzzification method, membership grades of rule and final inference grade calculation required.

- **Defuzzification**
  a) Specific defuzzification required to identify fuzzy output vectors
  b) Continuous iteration expected to get desired output parameters
  c) Logic implementation in Hardware

There are two types of fuzzy inference system available, such as Mamdani-Type and Sugeno Type. Michio Sugeno suggested a single spike, a singleton, as the membership function of the consequent rule. A singleton, or more precisely a fuzzy singleton, is a fuzzy set with a membership function that is unity at a single particular point on the universe of discourse and zero everywhere else. However, it differs only in output response of membership functions such as, Sugeno-Type provides either linear or constant values and the other one is vice-versa.

\[
\text{IF } x \text{ is } A \\
\text{AND } y \text{ is } B \\
\text{THEN } z \text{ is } f(x, y)
\]

Where x, y and z are linguistic variables; A and B are fuzzy sets on universe of discourses X and Y respectively; and f(x, y) is a mathematical functions.

In this paper, Sugeno-Type is used for analysis to control the switching between conventional ICE and Hybrid Energy Storage System with the trained ANFIS controller. Real-time applications controlled efficiently by enhancing or modifying the design of existing controllers, such as Fuzzy Controller.

In this experiment, few set of stand drive cycle pattern and few set of driver demand pattern are taken as input to train the ANFIS controller to determine the power demand strategy applicable and those are as shown in figure 7, figure 8, figure 9, figure 10, figure 11 and figure 12.

![Figure 7. Drive cycle 1 (Dataset 1)](speed (kmph))

![Figure 8. Drive cycle 2 (Dataset 1)](Speed (kmph))

![Figure 9. Drive cycle 3 (Dataset 1)](Speed (kmph))
There are three standard driving cycles as shown in ‘figure 7’, ‘figure 8’, ‘figure 9’ and three random driver demand data as shown in ‘figure 10’, ‘figure 11’, ‘figure 12’ is used to train ANFIS controller and the membership functions decided based on vehicle speed and SoC of BT/SC used as below

- **Initial Condition / Normal Condition**
  - if(SC>80) && (DD<30) = SC ON
  - if((SC<80) && (SC>30) )&& (DD<30) = SC ON
  - if((SC<30) && (DD<30)) = ICE ON

- **Drive Condition / Idealizing**
  - if((DD>30)&& (DD<60)) && ((BT>80) && (BT<90)) = BT ON
  - if((DD>30) && (DD<50)) && ((BT>60) && (BT<70)) = BT ON
  - if((DD>30) && (DD<50)) && ((BT<60) && (BT>30)) = BT ON
  - if((DD>30) && (DD<50)) && (BT<30) = GEN ON and ICE ON

- **Fast Acceleration / High power or Torque Demand**
  - if((DD>60)&& (DD<90)) && (BT<30) = GEN ON and ICE ON
  - if((DD>90)&&(DD<120)) = ICE ON and GEN ON
  - if((DD>120)) = ICE ON

Using above set of predefined data and logic conditions, ANFIS controller trained and tested using other set of sample data to test the real time variations. On comparing with PID, these controllers always designed by engineers to control such non-linear plants, but the tuning of parameters for PID controllers was based on the mathematical model of the object, and some control rules, which was difficult to adapt real time variation. Because, it deals with static data but not the real dynamic variations. Moreover, the conventional PID controller has overshoots and settling time issue, which considered for investigation. Finally, the adaptive fuzzy controller trained with different set of data set, which has the provision to predict the future and to react immediately on controlling the power source. This controller designed to have two different inputs, such as State of Charge of Battery and Super-capacitor from HESS and two different outputs that controls the power source in Hybrid Vehicles.

4. Simulation results and discussions

In this section, simulations are performed with trained controller by considering SoC of Battery and Super-capacitor of HESS as inputs and the control of ICE and HESS is determined to achieve quicker response on switching mechanism.
Figure 13 shows the overview of controller design adopted. Assuming, all the electrical components are supplied with the power from Battery in Vehicle.

4.1. Case A (Battery and Super-capacitor is STABLE)

Figure 14 states that as considering battery and the super capacitor is stable and charging and discharging happens at defined period of time during normal driving cycle. Battery discharges till 200s whereas Super-capacitor till 80s, which reviles the real time scenario as the auxiliary components of the vehicle expect power source from battery and no power demand from Acceleration Pedal. The controller determines that, the auxiliary components in vehicle demands battery power and it drains continuously till 200s, though it does not provides supply to drive the motor, because of the auxiliary components demand such as, Air Conditioner, Super Charger, Music System. From figure 14 it is clear that, HESS supplies power till 80s, then engine is switched on to drive the vehicle/load. Because, the expectation is to drive the vehicle with engine to meet the power demand from driver which can be seen in the control status of engine and HESS. Though battery drains, super-capacitor starts charging from 80s to 275s which in-turn SoC of Super-capacitor reaches its peak, triggers HESS to supply the power to drive the vehicle with e-Motor. The same is observed from 350s to 450s.

4.2. Case B (STABLE Battery and UN-STABLE Super-capacitor)

This state of charge of HESS from figure 15 shows the Battery status or the behaviour is quite stable, but not the super capacitor. Due to change in environment or change in temperature, super-capacitor behaviour was not stable to deliver the power demand instantaneously to drive the vehicle. Here, the trained algorithm considers SoC of super-capacitor as major input. Simulation output from ANFIS controller, switches frequently to meet the power demand. At 80s, state of charge of super capacitor drain down to minimum threshold to supply the power and because of this, controller switches off e-Motor and enables ICE to drive the vehicle. During this period, charging of this storage system starts and also with other charging facility available in vehicle. At 260s, ICE was switched off due to maximum capacity at super capacitor. At 400s, the response from controller as quite faster to determine the output based on the training data fed into controller.
4.3. Case C (Alike actions with Battery and Super-capacitor)

The figure 16, the assumptions considered was, the quality, capacity and discharging ability of the battery and super capacitor was considerably excellent. With this excellent quality, it completely drains only after 350s which is quite longer time.

Figure 15. Analysis on Controller Output with STABLE Battery and UN-STABLE Super-capacitor

Figure 16. Analysis on controller output with alike actions with battery and super-capacitor
In this situation, ANFIS controller supposed to switch on the engine at certain point to protect the quality of HESS from over loading the power demand. So, it turns on engine at around 150s where the SoC of HESS goes down beyond 50%. Between 50-30%, control reaction is expected to run vehicle smoothly without reducing the lifetime of HESS components. As discussed earlier, since most of the vehicle components are now updated with electrical components instead mechanical one, we ensure the power from HESS does not goes beyond the limit to maintain the safety precautions.

4.4. Case D (UN-STABLE Battery and STABLE Super-capacitor)

The figure 17, the behaviour of the battery is observed as unstable but not the super capacitor. This situation or the status may cause because of electrical connection problems, environmental issues. In this case, the controller tries to frequently switches from engine to HESS and HESS to engine, which may impact the life of electrical components and loss in fuel efficiency of engine. During this scenario, it is mandatory to react wisely to switch only engine and not the HESS by indicating (Mal-Function Indication Lamp) MIL on the dashboard of the vehicle. This behaviour shows the switching ability of the control logic defined. The controller can be trained with more data to handle this frequent switching.

![Graphs showing the state of charge and control signals](image)

**Figure 17.** Analysis on controller output with UN-STABLE Battery and STABLE super-capacitor

5. Conclusion

In this paper, study on the topologies and the output from ANFIS controller were discussed. Then, ANFIS controller is designed/trained with specific set of data and implemented in MATLAB to identify the response behaviour prediction over future demand request. And the result shows that, the switching from ICE to HESS and HESS to ICE was quicker than the existing controller algorithms which were based on human prediction values or hard coded values. But with ANFIS, the decision based on the learnt value or data from past behaviours. In future, the target is to implement this in the real Hybrid Vehicle as plug-in or add-on software to the existing PCM software.
6. References

[1] Farshid Naseri, Ebrahim Farjah, and Teymoor Ghanbari 2017 An Efficient Regenerative Braking System Based on Battery/Supercapacitor for Electric, Hybrid, and Plug-In Hybrid Electric Vehicles With BLDC Motor IEEE Trans. Vehicular Technology 66 3724 - 3738.

[2] S. M. Lukic, J. Cao, R. C. Bansal, F. Rodriguez, and A. Emadi 2008 Energy storage systems for automotive applications IEEE Transactions on Industrial Electronics 55 2258-2267.

[3] Vijaya Chandrakala K.R.M., Balamurugan. S, Janarthanan. N, and Anand. B 2014 Variable structure fuzzy gain schedule based load frequency control of non-linear multi source multi area hydro thermal system International Journal on Electrical Engineering and Informatics 6 785W22.

[4] Dr. Balamurugan. S 2003 Fuzzy Based Load Frequency Controller For Biomass Power Plant National Conference on Mathematical and Computational Models NCMCM 2003 PSG College of Technology, Coimbatore.

[5] Zhou Lili, Wang Zedi, Yang Libin and Li Dandan 2017 Design of control strategy for hybrid energy storage system based on co-ordination and co-operation IEEE Conference on Smart Grid and Electrical Automation.

[6] J. M. Blanes, R. Gutierrez, A. Garrig´os, J. L. Liz´an, and J. M. Cuadrado 2013 Electric vehicle battery life extension using ultracapacitors and an FPGA controlled interleaved buck–boost converter IEEE Transactions on Power Electronics 28 5940 - 5948.

[7] G. Hongwei, G. Yimin, and M. Ehsani 2001 A neural network based SRM drive control strategy for regenerative braking in EV and HEV Proc. Elect. Mach. Drives Conf.

[8] Faisal H. Khan, Leon M. Tolbert, and William E. Webb 2009 Hybrid Electric Vehicle Power Management Solutions Based on Isolated and Non-isolated Configurations of Multilevel Modular Capacitor-Clamped Converter IEEE Transactions on Industrial Electronics 56 3029-3095.

[9] S. de la Torre, A. J. S´anchez-Racero, J. A. Aguado, M. Reyes, and O. Martinez 2014 Optimal sizing of energy storage for regenerative braking in electric railway systems IEEE Transactions on Power Systems 30 1-9.

[10] J. Cao and A. Emadi 2012 A new battery-ultracapacitor hybrid energy storage system for electric, hybrid, and plug-in hybrid electric vehicles IEEE Transactions on Power Electronics, 27 122-132.