Self Tuning Fuzzy Logic Controlling Chopper Operation of Four Quadrants Drive DC Chopper for Low Cost Electric Vehicle

Saharul Arof¹²
saharul@unikl.edu.my
Muhd Khairulzaman A.K¹
khairulzaman@unikl.edu.my
Jalil, J.A¹
julaida@unikl.edu.my
H. Arof³
a.hamzah@um.edu.my
Mawby, P.A²
P.A.MAwby@warwick.ac.uk

1 - Universiti Kuala Lumpur
2 - University of Warwick
3 - Universiti of Malaya

Abstract—DC drive system for traction are always powered by separately excited and series dc motor controlled by four quadrants dc chopper. However, the operation modes of the conventional H-Bridge four quadrants drive dc chopper for series motor are limited to driving and regenerative braking (only with the presence of residual magnetism), with no capability of reverse operation. Hence, a new Four Quadrants dc drive chopper for series motor in EV’s application, optimized by Artificial Intelligence is developed. This paper further describes the application of Self Tuning Fuzzy Logic for controlling chopper operation of the proposed Four Quadrants dc drive chopper. The appropriate mode of operation will guarantee optimum consumption of the battery power, thus provide longer distance traversed.

Keywords—DC drive, EV and HEV, series motor, four quadrant chopper

I. INTRODUCTION

In future, the electric motor propulsion system (i.e. electric vehicle) will replace the internal combustion system (i.e. mechanical combustion engine) due to its higher efficiency and zero carbon emission [1]. Unfortunately, electric vehicles (EV) are not yet affordable for many people. Hence, the advancement of super capacitor as an alternative to batteries is the catalyst. At present, super capacitor (as big as 12,000F) is available in the market. The super capacitor offers several advantages such as lower weight, cheaper cost and fast charging. However, super capacitor can only operate at low voltage (the most is 2.7V) and it is not suitable for ac drive (which is always operated at high voltage).

Oakley Research National Laboratory; a US based research center has currently producing lower than 5V operating voltage dc motor to suit super capacitor voltage for electric vehicle application. Direct Current (DC) drives which are series and separately excited have once been used as prototypes or products for EVs and HEVs. Examples of such systems are those installed in Peugeot 106, Citroen Saxo, GM EV and Lada [7, 8]. In those days, DC motors had disadvantages in size, weight, performance and reliability. A recent study undertaken at Oak Ridge National Laboratory [4] reported that DC motors are suitable for EV/HEV applications. Such motors shown in figure 1 possess high power output, higher efficiency, smaller size, less weight, long lasting carbon brush and commutator, low operating voltage (less than 50V) and use modular structure i.e. easy to replace parts like carbon brush, etc. [8, 10, 11, 12]. Advanced brush technology used in latest DC motors allows the motor to be operated at low voltages [11, 12] resulting in lower losses. Nowadays, the lifespan of the carbon brush and commutator of a DC motor is longer than the rotor bearing of an AC induction motor [9, 11]. The brush can last until 30,000 km while the commutator can endure 250,000 km before it flushes over [9, 12]. The reliability of the soft-commutated DC motor is now around 90% - 94% [9, 10, 11, 12] while the spark reduction system can further extend the brush life [12]. The total cost of a drive system (AC or DC) for an EV depends on several factors such as the number of gate drive circuits, power electronics devices used, its cooling system, heat sinks, converter, batteries, motor and auxiliary devices. A DC drive system’s lower cost is mainly due to its simple circuit, controller design and control strategies [8, 9, 10]. DC choppers were introduced in the early nineteen sixty using force-commutated thyristor. DC choppers [2] are mainly used to drive dc motors while offering the capability of bidirectional power flow for both motoring and regenerative braking. For EV application using series motor, the common Half-bridge DC chopper offers no capability of regenerative braking, field weakening and resistive braking operations.

In this paper, a novel Four Quadrant DC chopper topology is also introduced. The proposed chopper design is able to reduce power loss and generates fewer ripples. The proposed chopper is aimed to solve common problem on the speed control of series motor in which the speed decreases linearly when loaded.
II. FOUR QUADRANTS DC DRIVE CHOPPER

A. Proposed Chopper Design

The proposed four quadrants chopper design shown in figure 2 consists of three IGBTs used as the main switches, field weakening and bridging IGBTs. $L_M$ is the motor inductance connected in series with the armature windings to smoothen the armature current of the motor and $R_{BV}$ is the brake series resistor.

The chopper has seven modes of operation that are driving, reversing, field weakening, parallel mode, regenerative braking, resistive braking, and generator. When the motor starts to rotate, driving mode is selected. As the motor speed increases above its nominal speed, field weakening mode is selected. In generator mode, the motor behaves as generator and generate power to charge the battery. A regenerative braking mode is selected to slower down the EV while the motor runs above its nominal speed, field weakening mode is selected. In contrary, resistive braking mode is selected to slower down the EV while the motor runs below its nominal speed, as well as charging the battery at the same instant. In contrary, resistive braking mode is selected to slower down the EV while the motor runs below its nominal speed, as well as charging the battery at the same instant. If the motor tends to run with incrementing speed, i.e. EV is driven on steep hill; the parallel mode is selected to prevent drastic speed drops. The chopper is controlled by four sub controllers; i.e. for data distribution, chopper operation, subsequent and delay, and IGBTs firing.

B. Chopper Operation Controller

The chopper operation controller is to choose the most appropriate operation by processing signals obtained from the accelerator pedal, brake pedal, battery voltage, motor speed, and etc. Upon receiving these signals, the controller will generate other signals such as error and rate of speed.

Failing to pick the right most operation could cause chopper failure. If the load is too heavy due to passengers weight or caused by the car is climbing steep hill, the field weakening operation should be avoided.

![Figure 2: Proposed Four Quadrants Drive DC Chopper](image)

![Figure 3: field weakening](image)

Figure 2 shows three conditions with two different loads. S1(normalized) represents motor speed without field weakening running at heavy load. E1 (normalized) represents the battery energy used to run the motor. S2 represents the field weakening action running at low load. The motor speed increase almost 100% and E2 is the battery energy used and the energy power has increased for 100%. At high load as in S3 and E3, when field weakening takes action, the speed of the motor drops to 40% but batteries power used increase for almost 600% . This represents field weakening failure as a result of choosing the wrong chopper operation mode.

The chopper operation process flow is described in figure 4. Several methods can be used to select the most appropriate chopper operation such as the Expert System If then Rules, Fuzzy Logic, Neural Network (NN), Self Tuning Fuzzy Logic (STFL), and ANFIS. The Expert System If then Rules is the common selection method used. However, a drawback of this method is that many rules have to be written depending on each type of chopper operations and input signals. Due to that, additional sensors such as car position sensor and weight sensor are needed in order to ease the control algorithm and to differentiate the chopper operation selection mode. This method requires lots of memory and effort to write the code. Hence, the Artificial
Intelligent (AI) control algorithm such as STLFC is proposed as the selection method for the chopper operation and due to its linearity, the selection or decision making problems would be simplified.

III. CONTROL STRATEGY

Self Tuning Fuzzy has excellently been used as decision maker/operation selection for application such as in the elevator systems [12-14]. Figure 5 shows the process of determining the most suitable chopper operation for EV with STFL controller. STFL controller has seven sets of Fuzzy Logic operators which represents seven modes of chopper operations. When an accelerator pedal or brake command is registered, relevant data on the chopper and EV are needed for computation of input membership function. The signal inputs are then assessed to each of fuzzy operator which represents every single chopper operation mode. Every single fuzzy operator produce output, i.e. Performance Index (PI) which is later compared to each other. The operation with the highest PI is considered the most suitable operation to be picked as the current chopper operation.

IV. SELF TUNING FUZZY LOGIC CONTROLLER

The basic concept of Fuzzy Logic is based on the concept of a crisp input and crisp output. Crisp means the actual data or parameter being used, described either in quantitative or qualitative parameters. Between the crisp inputs and crisp output, all the processes are based on ‘fuzzy’ parameters converted at the beginning of the process. The full architecture is shown in figure 6.

Aimed to simplify the computation, triangular shaped function is used to determine membership function. Five fuzzy variables are defined for each parameter. The use of five fuzzy variables is large enough to provide adequate approximation, save memory storage and reduce complexity in computation.

A. Self Tuning Mechanism

In the self-tuning fuzzy logic controller, the membership functions are modified or adjusted according to the error and rate of speed of the vehicle. Error is the value of speed compared to accelerator pedal and rate of speed is the difference of current speed and the previous speed.

B. Adjustment of Membership Functions

Self tuning of the membership functions is done by reshaping the triangles of the fuzzy variables. Figure 7, 8, and 9 briefly describes how tuning of the membership functions is performed. \( M \) refers to the present \( M \), and \( M_n \) is the new \( M \). Figure 7 is condition at normal load/weight. Figure 8 is condition when the vehicle is heavy loaded such as when the vehicle climbing steep hill. Figure 9 is a condition at light load such as when the vehicle moving downhill. Five triangular-shaped membership functions were shown and five fuzzy variables were defined as Zero (Z), Small (S), Medium (M), Large (L), and Very Large (VL) or Negative Big (NB), Negative small (NS), Zero (Z),
Positive Small (PS), and Positive Big (PB). Tuning is carried out basically by varying the upper, and the lower, bounds of the triangles. Five bounds are identified, labeled, $U_1, U_2, U_3, U_4$, and $U_5$, equally separated from each other by a length $l$ along the universe of discourse. By changing $l$, and the bounds, the membership functions are adjusted accordingly.

Self tuning fuzzy logic controller analyzes the EV conditions to derive specific values used to shape the membership functions according error and rate of speed. The middle bound $U_2$, also labeled $M_e$, is first defined for light, medium, heavy load driving. The respective value is stored in look up table and varied depending on driving condition. Figure 10 shows on how to obtain a new $M$ and $l$ values in order to initiate a correction.

Adjustment of length $l$ is carried out for the five input parameters. Figure 10 shows the algorithm to compute $l$ value. The $l$ value may also be computed by using equation 1. If (maximum – average) is bigger than (average – minimum) then:

\[
 l = \frac{(max - ave)}{2}, \text{ otherwise } l = \frac{(ave - min)}{2} \quad (1)
\]
C. Selection of Fuzzy Rules

The fuzzy rules are prepared in the following form: If A and B and C, then D. Rules are prepared just for its specific driving condition (Driving, Field Weakening, Generator, Regenerative Braking, Resistive Braking, Parallel and Reverse). For example for Driving mode to be selected, the rules are written with respect to conditions that makes driving mode will be possibly selected such as in Table 1. As mentioned before the real traffic situation is a mix of various driving pattern and very much dependence on, accelerator pedal, brake pedal, motor speed, rate of speed, error and total weight of the vehicle. With the self-tuning fuzzy Logic it is not necessary to have specific rules during light, medium, or heavy weight conditions.

<table>
<thead>
<tr>
<th>Operation Mode</th>
<th>Acc pedal</th>
<th>Brake signal</th>
<th>speed</th>
<th>Rate of speed</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Driving</td>
<td>Bigger than zero</td>
<td>Zero</td>
<td>Zero</td>
<td>to medium</td>
<td>NIL</td>
</tr>
<tr>
<td>Field weakening</td>
<td>Medium to high</td>
<td>Zero</td>
<td>Medium</td>
<td>to high</td>
<td>Zero to positive</td>
</tr>
<tr>
<td>Regen brake</td>
<td>NIL</td>
<td>Medium to high</td>
<td>Medium</td>
<td>to high</td>
<td>Zero to negative</td>
</tr>
<tr>
<td>Rheostat brake</td>
<td>NIL</td>
<td>Zero to medium</td>
<td>High</td>
<td>Zer o to positive</td>
<td>negative</td>
</tr>
<tr>
<td>Generator</td>
<td>Low to medium</td>
<td>Zero</td>
<td>Medium</td>
<td>to high</td>
<td>Negative</td>
</tr>
<tr>
<td>Parallel</td>
<td>Medium to high</td>
<td>Zero</td>
<td>Medium</td>
<td>to high</td>
<td>Negative</td>
</tr>
</tbody>
</table>

V. SIMULATION AND ANALYSIS

The performance of the proposed fuzzy-based strategy applying a self tuning fuzzy logic controller can be evaluated on the real hardware system or simulated systems. A real hardware system is difficult to implement, time consuming and expensive. A simulated system is easily developed, time-saving and cost effective. It provides a convenient platform to test the algorithms and to simulate the process of chopper and EV operations. Without causing too many risks in terms of the costs spent and losses brought to the system in case of algorithm failure. Furthermore various parameters can be simply adjusted and optimized, hence speeding up the simulation process towards achieving the desired results.

In this work, a computer simulation is performed as a method to test the fuzzy logic algorithm and to study its performance and effectiveness. For this purpose, MATLAB/Simulink is used to develop the controller and the system. The simulation model used to study the chopper behavior is shown in figure 11. Some parameters values required by the simulation software to simulate the system are provided by the user.

The car is tested according to the accelerator signal (signal 9), brake signal (signal 7) and also according to earth profile shown in figure 13(signal 8). The performance of STFLC as chopper operation controller is also depicted in figure 13. The STFLC controller is able to select the expected operation for the Four Quadrant DC chopper with respect to the test signals given. During start up, STFLC selected the driving mode. As the vehicle speed increases and due to accelerator demand, STFLC selected the field weakening mode. However, when the accelerator signal is let low, the generator mode is selected. In contrary, when the accelerator signal is maximum and the speed still high, the field weakening mode is selected. When brake command is activated but the vehicle speed is still high due to inertia, the regenerative mode should be operated. As the vehicle speed drop further, the resistive braking mode is expected. When brake command is released and replaced with low driving command, and while the vehicle speed is low the STFLC should select driving mode. As the vehicle moves downhill while the driving command is low, the STFLC should select generator mode. However, if the driving command is high the controller should then select the field weakening mode. As the vehicle drives on a steep hill, the speed is expected to drop. Hence, the parallel mode is expected to be selected. Finally, as the vehicle regained its speed the field weakening mode is selected.
Figure 13, 14 and 15 show the result of Self Tuning Fuzzy Logic with respect to Battery SOC, Vehicle Speed and Distance traversed compared to Neural Network and ANFIS chopper operation controllers. From the graph the STFLC performance is less than NN and ANFIS, as it consumes more battery power. The maximum speed of the EV is the lowest as compared to the other two AI operators.

VI. CONCLUSION

DC drive series motor has a high potential to be utilized in EV. This is due to its simple design, low cost and excellent controllability. In summary, the performance of an optimized DC drive system is comparable to that of an AC drive and thus is very suitable for applications in low cost EV. Self Tuning Fuzzy Logic Controller is thus able to be used as the Four Quadrant Chopper Operation Controller since its capability to select the most appropriate chopper operation. With an appropriate tuning of the controller, the EV performance can further be optimized.

REFERENCES


