Fuzzy based controller for a hybrid electric vehicle with MMC and SRM drive

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Abstract. In this article a novel fuzzy control based Hybrid Electric Vehicle (HEV) with Modular Multi Converter (MMC) fed Switched Reluctance Motor (SRM) is investigated. In this proposed approach MMC fed to the SRM motor with integration of Full Bridge (FB) converter. FB switching pattern operates with intelligent fuzzy control algorithm. The MMC inverter fed SRM drive HEV has been successfully simulated with MATLAB software package. The simulation results are proven that the harmonics are mitigated by employing proposed method. Performance characteristics of SRM motor such as, phase voltage, line voltage, speed, torque, rotor current, load torque is obtained, and these are compared with conventional methods i.e. current converter operated HEVs and solar (PV) integrated HEVs. It can be observed from the reported results that the proposed method is providing satisfactory output results.

Keywords. Hybrid Electric Vehicle, MMC converter, full bridge converter, switched reluctance motor.

1. Introduction

Over the recent years, a few iconic names like Hyundai, MG Hector, Tesla, Nissan, Maruti, Tata and Mahindra etc. making the market numerously very high. Industries are boosting their sales and satisfying desired performance to the customers. According to the Indian standards past 2014 more revolutions are coming in EVs and garnering over 3.0 million units are sold. The main aim is to encourage EVs/HEVs to suppress pollution in urban/semi urban smart cities, with replacement of conventional petrol/diesel vehicles [1-2]. India has declared to produce only EVs by 2030. EVs are more popular because its most significant inherent features, that are summarized as follows:

- EVs are mostly ecofriendly – Zero emission of carbon mixed molecules in the air (Remove global warming issues)
By employing EVs and Hybrid EVs fuel savage is more
User friendly characteristics – Easily operated with customer friendly with help of IoT, GPS, MEMS etc. with various smart technologies
EVs have wide range of speed controlling capability
SRMs are more efficient machines because of absence of rotor windings. Mechanical losses are less. It has fixed magnets in its rotor and has high mechanical strength. SRMs are robust in construction and easy to operate. Smooth speed control is possible unlike other AC machines. SRMs have excellent fault re-tolerance capacity because of this nature. It is a most prominent solution to solve power-train issues in EVs/HEVs.

To reach the load demand (torque) SRM drives are fed with Multi pulse (Level) VSCs/Inverters (MLI) or MMC. MMCs are valid promising converters to balance the voltage regulations. MMC converters mitigates the harmonic production in the converter so then leads to improve the comprehensive performance of the system well. MMC provides dynamic voltage compensation unlike MLI converters [3-4].

EVs/HEVs exposure is suffering from the cost that to battery. The major focus of this research article is effective utilization of battery with MMC converters to drive SRM motor in its various operating modes such as: charging, discharging, light load and heavy load. Fuzzy intelligent control algorithm has been adopted to get acceptable performance of the HEV.

The next sections of this article are organized as follows. Section 2 elaborates the structure of HEVs in basic approach and proposed fuzzy operated MMC fed SRM. The design parameters of fuzzy controller are mentioned in section 3. The obtained MATLAB/ Simulink results are described in section 4 and concluded with section 5.

2. System configuration
The implementations of HEVs with various converter networks have been discussed earlier in the literature such as DC-DC current fed converters for EVs [5-6], Multi pulse (four level) inverter fed EVs [7-8], C damped converter fed HEVs [9-10], solar plus battery operated EVs with energy management techniques i.e. droop methods, decentralized, centralized and decoupler approaches, Multi port converter fed HEVs [11-12]. Out of all these traditional techniques, current fed EVs and solar operated EVs are more popular because it prohibited satisfied characteristics. Compared to all these conventional approaches, the proposed MMC fed SRM with a fuzzy controller provides validated simulation results. The EVs are broadly classified into three ways i.e. Battery EVs, Hybrid EVs and Fuel cell EVs.

2.1. Proposed MMC fed SRM Drives
Proposed block diagram of MMC converters fed SRM is shown in Fig. 1. Application of MMC fed drive is to adjust the desired speed of the SRM with variable frequency or voltage. Proposed MMC converter includes six branches and each (Nsub) sub modules is connected in cascade manner together with inductive branch (L), reduces the potential difference between induction machine winding terminals and DC link capacitor. In MMC, each sub module consists of inverter circuit. Each IGBT pair is connected to the capacitor to balance the voltage levels (positive or negative). Proposed MMC fed induction motor drive has two quadrant converters.

Each sub modules is operated by level shifted PWM [14,15] technique; by activating upper IGBT (ON position), sub module output is equal to the capacitor voltage. By operating a lower IGBT (ON position), output voltage is makes as zero. Star connected output voltage (Vs) of number of levels (N1) depends on the number of sub-modules connected in each branch. To obtain desired output voltage a greater number of sub modules are connected in series manner. PWM technique plays a crucial role to match DC voltage (Battery), Vdc and AC voltages (MMC converter output) Vsa, Vsb, Vsc. To control the MMC converter, the voltage of the sub module is to be controlled nearer to the base values.
2.2. Advantages of MMC over VSCs

The MMC converters has emerged as the preferred VSC [16-27] alternative because of; Low losses, Low harmonic distortion, High Scalability, and more Modularity, less THD. It balances the capacitor output voltage so ripple content in output voltage is less.

3. Control strategy

To get desired performance of a system, intelligent control algorithms play a crucial role compared to traditional hysteresis controllers or model droop controllers. In the proposed system, MMC converter is operated with level shift PWM techniques and FB converter is operated with a fuzzy set of rules that are mentioned in Table 2.

| e  | Δe | NB | NS | ZE | PS | PB |
|---|---|---|---|---|---|---|
| NB | NB | NB | NS | NS | NS | ZE |
| NS | NB | NB | NS | NS | ZE | PS |
| ZE | NS | NS | ZE | PS | PS | PB |
| PS | NS | ZE | PS | PS | PB | PB |
| PB | ZE | PS | PS | PS | PB | PB |

The inputs are divided into five groups; NB: Negative Big, NS: Negative Small, ZOE: Zero Area, PS: Positive small and PB: Positive Big and its parameter. The proposed control scheme to operate FB converter is shown in below Fig. 2.
4. Results and discussion

4.1. Current source converter operating EVs

The design parameters of current source converter based EVs are by separating real and imaginary values of impedance. The impedance \( Z \) is mathematically derived as [13],

\[
Z = \frac{-j}{\omega C} + \frac{(j\omega L)(R')^2}{(R')^2 + (\omega L)^2} + \frac{(\omega L)(R')^2}{(R')^2 + (\omega L)^2} - \frac{j}{\omega C}
\]

\[
Z = \frac{(R')(\omega L)^2}{(R')^2 + (\omega L)^2} + j\left(\frac{(\omega L)(R')^2}{(R')^2 + (\omega L)^2} - \frac{1}{\omega C}\right)
\]

\[
Z = \frac{-j}{\omega C} + \frac{(j\omega L)(R')^2}{(R')^2 + (\omega L)^2} + \frac{(\omega L)(R')^2}{(R')^2 + (\omega L)^2} - \frac{j}{\omega C}
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\]

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Z = \frac{(R')(\omega L)^2}{(R')^2 + (\omega L)^2} + j\left(\frac{(\omega L)(R')^2}{(R')^2 + (\omega L)^2} - \frac{1}{\omega C}\right)
\]

The MATLAB Simulink diagram of CSC operated EV is shown in Fig. 3.

![Simulink block diagram of 5kW System](image)

**Figure 3.** Simulink block diagram of 5kW System.

The input current can be calculated as

\[
I = V_\text{in} \left(\frac{(R')^2 + (\omega L)^2}{(\omega L)^2 R'}\right)
\]

(2)

The voltage across capacitor as follows:

\[
V_c = I X_c V_c = I X_c
\]

(3)

\[
V_c = V_\text{in} \left(\frac{(R')^2 + (\omega L)^2}{(\omega L)^2 R'}\right) \left(\frac{1}{\omega C}\right) V_c = V_\text{in} \left(\frac{(R')^2 + (\omega L)^2}{(\omega L)^2 R'}\right) \left(\frac{1}{\omega C}\right)
\]

(4)
The voltage across inductor is expressed as:

$$|V_L| = V_{in}\sqrt{1 + Q^2}|V_L| = V_{in}\sqrt{1 + Q^2}$$  \hspace{1cm} (5)

Where Q indicates the Q factor of the network.

The inductor current is given in Eqn. (6).

$$I_L = \frac{V_L}{L \times \omega} = \frac{V_L}{L \times \omega}$$  \hspace{1cm} (6)

Consider power rating is 5kW, input voltage is 120 Volts, Q factor is 5, TF turns ratio is 2.5 and output voltage is 400V. The MATLAB results of output voltage of inverter, voltage across capacitor, inductor, input current, output of transformer current is shown Fig. 4 to Fig. 8 respectively.

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**Figure 4.** Output voltage of inverter.

**Figure 5.** Voltage across capacitor.

**Figure 6.** Output voltage across inductor.

**Figure 7.** Input current waveform.

**Figure 8.** Output voltage across linear TF secondary winding.
4.2. **PV integrated VSC fed Induction Motor (IM) - EV**

The MATLAB Simulink diagram of PV integrated VSC fed EV is shown in Fig. 9.

![MATLAB model of PV integrated VSC fed IM-EV.](image)

*Figure 9. MATLAB model of PV integrated VSC fed IM-EV.*

The simulation results of output voltage of PV system, armature current, speed and load torque of an induction motor are shown in Figures 10 to 13, respectively.

![Output Voltage of PV system.](image)

*Figure 10. Output Voltage of PV system.*

![Armature current of an Induction Motor.](image)

*Figure 11. Armature current of an Induction Motor.*

![Speed of an Induction Motor.](image)

*Figure 12. Speed of an Induction Motor.*
4.3. Proposed MMC fed SRM-HEVs

In this proposed method, instead of MLI converters MMC converters are preferred for best results. In this MMC, six sub modules are considered. The circuit diagram of MMC with full bridge converter and SRM motor is shown in below Fig. 14. Where A, B and C are represents the phase windings of SRM drive.

\[
U_k = R_k i_k + L_k (\theta, i_k) \frac{di_k}{dt} + \frac{\partial L_k(\theta,i_k)}{\partial \theta} \omega i_k
\]  

where K represents the A, B and C phases

The torque production is defined algebraic sum of three individual of phases torque that is given as

\[
T_e = \Sigma_{k=1}^{3} T_{ek} = \Sigma_{k=1}^{3} \frac{1}{2} i_k^2 \frac{\partial L_k(i_k \theta)}{\partial \theta} T_e
\]  

The load torque (T_l) of SRM drive is expressed as (in terms of its mechanical balance equation)

\[
J \frac{d\omega}{dt} + \mu \omega = T_e - T_l \frac{d\omega}{dt} + \mu \omega = T_e - T_l
\]  

In traditional SRM HEVs the voltage (Vdc) across is always constant but in proposed decentralised BESS with MMC it is varied as per the load torque requirements. The fault tolerance is very less in the proposed method compared to other MLI techniques.

In Figs. 15 to 17, proposed simulation results I_a, I_b and I_c represents the phase currents, V_a, V_b, V_c are phase voltages, for better understanding only V_b phase is highlighted. I_by represents the battery current.
Figure 15. Performance of battery driving at full voltage.

Figure 16. Performance of battery driving with E1 and E2 with E3 and E4 charging.
In Fig. 18, if speed reference is varied to the SRM motor, how load torque varied at constant phase current ($i_b$) is discussed. In these simulation results, load torque is considered as 4 Nm/div with variable input speeds i.e. 300rpm, 800rpm and 1200rpm respectively but in each variation of speed reference acceptable output torque is obtained which means that at any speed, constant load torque is achieved.

Figure 17. Performance of battery driving with E1 with E2 and E5 charging.

Figure 18. Output waveforms of Speed variation and load torque.
Figure 19. Output waveforms of phase current variation and load torque.

In Fig. 19, if the phase current of SRM motor is varied, how load torque is varied constant speed i.e. 350rpm is discussed. Here, phase current is varied from 2A to 3A then proportional load torque is varied.

5. Conclusions
In this paper MMC based SRM motor is discussed for design of HEVs. The dynamic response of the SRM motor is improved by operating SRM motor with fuzzy control algorithm. Obtained simulation results for charging and discharging mode of HEVs in proposed method proved that it works well compared to other traditional approaches. The load torque variation is observed for variation of input step speed variation at constant current and variation load torque at variation of phase current and constant speed. The proposed simulation results are evident that the harmonics at output voltages are mitigated considerably. The MMC converter based SRM motor has been successfully simulated. The MMC converters provide multiple voltage levels through connection of the phases to a series of batteries.

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