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Simulation and modelling of Math Function Based controller implemented with fuzzy and artificial neural network for a smooth transition between battery and ultracapacitor

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ABSTRACT

Electric vehicles (EVs)/Hybrid electric vehicles (HEVs) are implemented with Hybrid Energy Storage System (HESS) to obtain the effective results. HESS has been framed by combining battery with ultracapacitor (UC). Here the battery is used to supply the average power whereas UC can meet the transient power requirement of an electric vehicle. UC always assists the battery during peak power requirements and starting of the motor can also be done. The problem associated with HESS powered vehicle is switching between battery and UC depending upon vehicle road conditions. The main aim of this work is to design a controller for proper switching of energy sources in HESS. With four individual math function, one controller has been designed based on the speed of the electric motor, named as Math Function Based (MFB) controller, further, this has been integrated with ANN as well as Fuzzy logic made two new hybrid controllers. After that two-hybrid controllers have been implemented for the electric motor, thereafter comparative analysis has been made between them and suggested one good controller based on different comparative factors. The two-hybrid controllers have been implemented in four modes and results are discussed in the simulation results and discussion section.

1. INTRODUCTION

The transportation system is one of the major factors for pollution in the atmosphere because IC engine based vehicles are releasing harmful gases to the atmosphere for its successful operation. To avoid that type of obstacle with IC engine based vehicles, those have been replaced with electric vehicles [1-5]. Both EVs and HEVs are having some technical problems associated with their used main energy source that may be battery or fuel cell. Generally, small size batteries are inefficient to meet the transient power requirement of the electric vehicle especially during climbing of hill areas and cold start of the motor because battery having low specific power inherent property. On another hand UCs having high specific power advantage along with the low specific energy that means battery and UC are having opposite characteristics [6-8]. Presently all available energy sources for electric vehicle propulsion having high energy density only, and it doesn't have high power density. The high energy density of a source enhances the driving range and High power density can provide the quick power to the vehicle during transient periods. In order to obtain the efficient energy source for electric vehicle hybridization of both the source are required [9-14].

The hybrid controller has been designed by combining MFB with a different intelligent controller named ANN as well as a Fuzzy logic controller. And these new controllers are worked to perform switching between battery and UC based on the speed of the electric motor [1-2]. Different characteristics multiple sources have been combined with the hybridization concept for electric vehicle application. Here UC and battery are combined and forms HESS with average power can pump by the battery on other hand peak power can be feed by UC. HESS improves the life cycle of battery by reducing the number of charging and discharging periods, this can be achieved with UC only. The efficient combination UC and battery forms better energy storage system than the conventional single battery of fuel cell by fulfilling the all road condition of the electric vehicles [6-10].

Many artificial intelligence techniques have been suggested for HESS by considering unexpected driver behavior as well as load condition. Nowadays more researchers paying more attention to optimize energy usage for better efficient electric vehicle design. Many universal algorithms' have been suggested for optimal usage of fuel like battery [13-15].

For small urban electric vehicles, energy management architecture has been developed. Different characteristics contained energy sources have been integrated like high power density and high energy density. For splitting energy properly between two energy sources rule-based metaheuristic controller has been designed by considering different load conditions on the electric vehicle [1].

A new HESS has been developed with low rating DC-DC converter further it can be compared with conventional HESS, which having large power rating DC-DC converter topology. In designed HESS battery end maintains lower voltage value where UC end maintains higher voltage value. Here UC will supplies the power to the drive until its voltage level is less than the battery voltage level with that comparative constant load has been created for the battery [16]. In addition, the battery is not used to directly harvest energy from the regenerative braking; thus, the battery is isolated from frequent charges, which will increase the life of the battery

A modified soft switching method has been suggested for BDC as well as UDC with coupled inductors. Hysteresis current controller has been used for zero voltage switching up to the maximum load range [17]. An effective energy storage system has been developed for HEV/EV with the neural network controller. The suggested system reduces the energy requirement of the electric vehicle [18].

An effective control strategy has been designed to provide the crest power requirement from UC within 20sec. In remaining all cases average power can be supplied by a battery for electric vehicle [19]. A polynomial control has been used for better power management between UC and battery. Here battery is connected directly to the dc link whereas UC has been connected through BDC to dc link. PIC18F4431 microcontroller has been used for a DC-DC converter for proper power-sharing [20-21].

The main aim of this work is to design a hybrid controller combining Math Function Based (MFB) controller with ANN controller for smooth switching between the battery and UC. This paper is structured as follows. Section II Presents the proposed system model. Section III describes the Math function based controller. Modes of operation of converter model presented in section IV. Section V presents the proposed model control strategy. Section VI describes simulation results and discussions. Finally, the Main conclusions are presented in section VII.

2. PROPOSED SYSTEM MODEL

Figure 1 represents that the proposed model diagram of HESS. This model contains two different sources with different characteristics. In that one source is a battery with high energy density and the second one is UC with high power density. The combination of two sources always gives the good results than a single source. Here UC is used to supply peak and battery is used to supply average power to the electric motor. Switching between the energy sources is the difficult task, in order to overcome that difficulty a hybrid controller has been designed by combining MFB with ANN as well as the Fuzzy logic controller. The hybrid controller always switches the energy sources depending on the speed of the electric motor by controlling the pulse signals of both Unidirectional converter (UDC) and Bidirectional converter (BDC). Here BDC has been connected at UC end and UDC has connected at the battery end. Error signal has been generated by comparing an actual signal as well as a reference signal, after that error given as an input to the ANN as well as the Fuzzy logic controller. Further ANN as well as Fuzzy logic controller generates a controlled signal and has been compared with MFB generated signal, finally required pulse has been generated to the converter depending on the speed of the electric motor.

Figure 2 represents the converter model of hybrid energy storage system. Here Buck and Buck/Boost (BDC) converter model has been preferred with MOSFET switches. One of the converters is connected to the battery end and another converter is connected at UC end. UC end connected converter is a BDC and battery end connected is UDC [8]. During peak power requirements of the motor, BDC acts as a Boost converter remaining cases it acts as Buck converter, which means UC is mending for only to reduce the extra burden on the battery during the transient conditions. The battery is connected here to supply the average power to the motor and it always in the ON condition except some extreme conditions like during cold starting condition. To achieve preferable control of energy storage system overall circuit can be resolved into four sub-circuits.

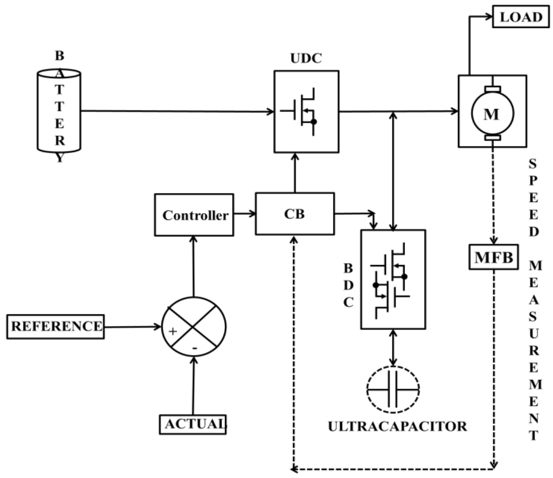

Figure 1. Proposed block diagram model of the hybrid energy Storage system

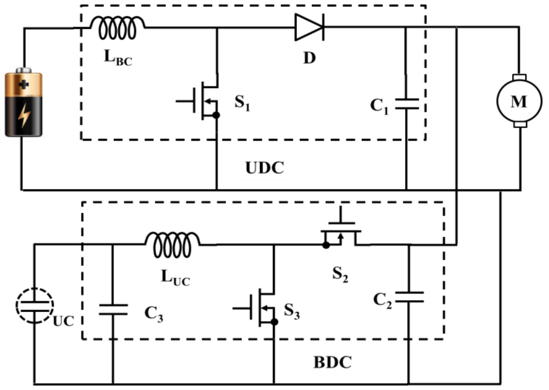

Figure 2. Converter model circuit diagram with HESS

3. MATH FUNCTION BASED CONTROLLER (MFB)

In this work MFB controller acts as a universal controller, this can be designed with four modes which always depending upon the speed of the electric motor. This controller combined with other intelligent controller and made a hybrid controller for the successive smooth transition between the battery and UC. MFB controller always decides the gate signal to the particular switch which can be generated by the other combined controller, which means the designed MFB controller, plays a vital role in the smooth switching of energy sources in HESS. The four math functions generate the pulse signals based on the speed of the motor as follows, further this signal can control the gate signal of particular switches in the converters.

(i) If the speed of the motor is less than or equal to 4800 rpm then MFB generates signal U_1 as 1.

(ii) If the speed is in between 4600 rpm to 4800 rpm then MFB generates signals U_1 and U_2 as 1.

(iii) If the speed of the motor lies between 4801 rpm to 4930 rpm MFB generates signal U_3 as 1.

(iv) If the speed of the motor is greater than or equal to 4931 rpm MFB generates signal U_4 as 1.

All the above signals are used to perform the smooth switching between the battery and UC that means switching between sources can be done by means of MFB controller combined with an ANN as well as the Fuzzy logic controller.

4. MODES OF OPERATION OF CONVERTER MODEL

The switches used in the HESS can operate based on the road conditions of the vehicle. The modeled circuit contains three controlled switches, and that can be operated in four modes. These four modes illustrated with switching action of three switches from below the table.

Table 1. Load condition based switching action

Mode	S_1	S_2	S_3	Load Torque
I	OFF	OFF	ON	Heavy Load
II	ON	OFF	ON	Medium Load
III	ON	OFF	OFF	Rated load
IV	ON	ON	OFF	No Load

4.1 Mode-I operation

In this mode of operation pulse signals have been generated to the only Bidirectional converter (BDC) and there is no pulse generated to the unidirectional converter (UDC).So the switches S_1, S_2 are in OFF position and remain switch S_3 is in ON condition. This mode is related to the heavy load on an electric motor, so total power required by the motor can be supplied by UC only and BDC works as a boost converter.

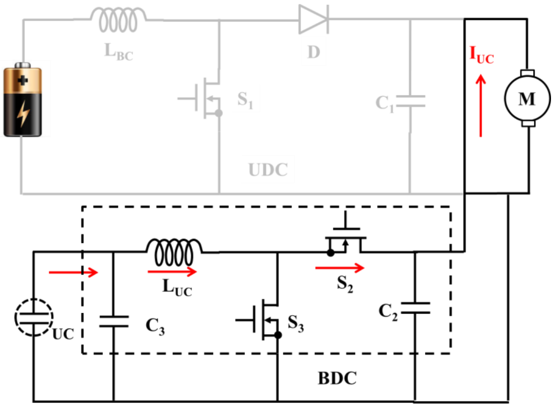

Figure 3. Converter Mode-I circuit diagram with HESS

4.2 Mode-II operation

Whenever slightly more than rated load has been applied to the motor that is related to Mode-II operation. In this mode of operation, the pulse signals have been generated to BDC as well as UDC, which means battery and UC together supply the required power to the motor. The switches S_1, S_3 are in ON condition and remain switch S_2 is in OFF position.

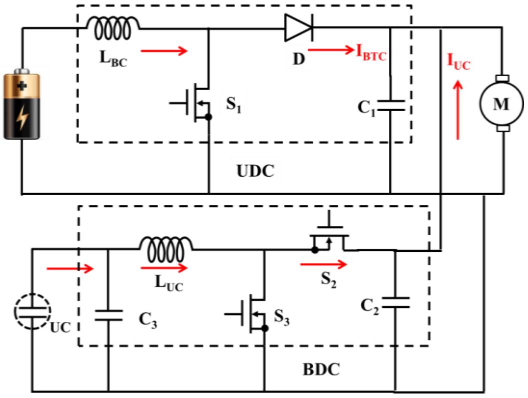

Figure 4. Converter Mode-II circuit diagram with HESS

4.3 Mode-III operation

Mode-III is related to the rated load condition on the motor. During this mode, the pulse signals generated to only UDC as a boost converter that means entire power can be supplied by the battery only required by the electric motor. So switch S_1 only in ON condition and remain two switches are in OFF position. The pulses have been generated to BDC as a boost converter by the hybrid controller.

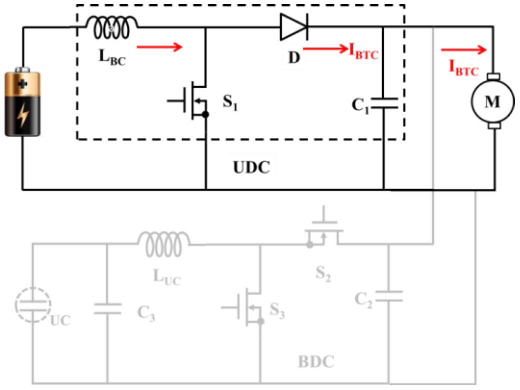

Figure 5. Converter Mode-III circuit diagram with HESS

4.4 Mode-IV operation

In Mode-IV operation pulse signals have been generated to switches S_1 as well as S_2, during this mode of operation BDC and UDC both are in operation but BDC working as a buck converter for charging UC. The battery has supplied the power to the electric motor as well UC for charging.

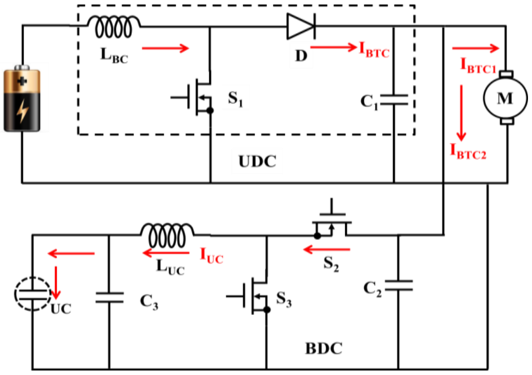

Figure 6. Converter Mode-IV circuit diagram with HESS

5. PROPOSED MODEL CONTROL STRATEGY

The proposed control strategy has been worked in four modes of electric motor operation. Hybrid controllers' has been designed by combining MFB with intelligent controllers. Hybrid controllers always work based on the speed of an electric motor. In mode -I operation pulse signals have been generated to only BDC as a boost converter, during mode-I operation signals have been generated to BDC as well as UDC, in mode-III operation pulse has been generated only UDC as boost converter and mode-IV operation pulse signals have been generated to BDC as buck and UDC as boost.

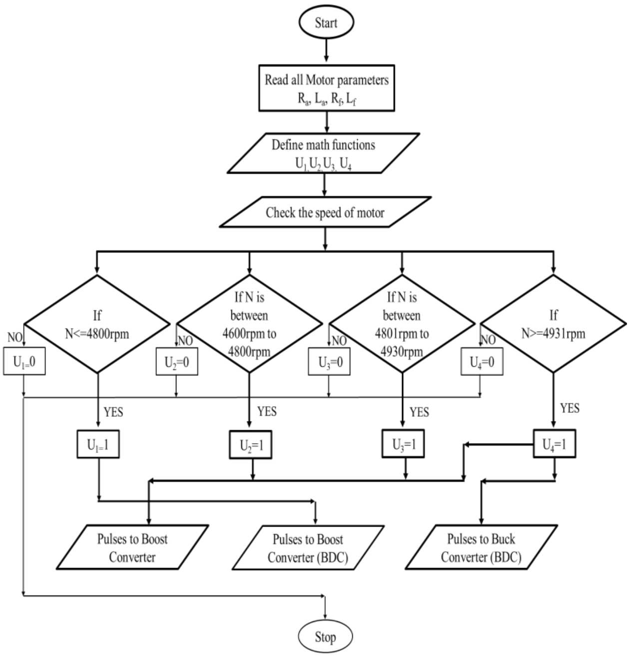

Figure 7. Flowchart of the control strategy

(1) During starting of a motor and heavy loaded condition UC supply the power to the load. In this mode, the math function U_1 gives signal value 1 and remaining all math functions generates signal 0 because during this period the speed of the motor ≤ 4800 rpm. The converter operates based on all math function generated signals. The converters in operation are the boost converter at the UC end.

(2) When the power demanded by the load is beyond the designed range of the battery output power, UC will assist the battery to deliver power to the motor. In this mode of operation, motor speed is from 4600 rpm to 4800 rpm. Hence MFB generates U_1 and U_2 pulse signals as 1 and generates U_3 and U_4 pulse signals as 0. The converters in operation are the boost converter at the battery end and the boost converter at the UC end.

(3) When battery output power matches the desired power of the motor, the battery will only supply the power to the motor. In this mode of operation, the speed of the motor is from 4801 rpm to 4930 rpm. Hence MFB generates a U_3 pulse signal as 1 and generates U_1, U_2 and U_4 pulse signals as 0. At this time, only the boost converter at the battery terminal works.

(4) When battery provides more power than the motor need, the extra power will be used to charge the UC. So the power of the battery will flow into both the UC and the motor. In this mode of operation, motor speed is >4931 rpm. Hence MFB generates a U_4 pulse signal as 1 and generates U_1 ,U_2 and U_3 pulse signals as 0. According to the converters designed, the boost converter at the battery end and the buck converter at the UC end will work in this scenario.

6. SIMULATION RESULTS AND DISCUSSIONS

6.1 Mode-I results

The speed responses of MFB plus ANN and MFB plus Fuzzy during heavy load condition on the electric motor are shown in figure 8. During starting of electric motor both speed responses have been reached steady state with different times, in that MFB plus ANN has taken 0.17 sec and MFB plus Fuzzy has taken 0.22 sec. After that at 1 sec heavy load has been applied to the motor, due to that motor speed response reduced in both controllers case. MFB plus ANN has taken 0.18 sec, MFB plus Fuzzy has taken 0.22 sec to reach steady state after load applied.

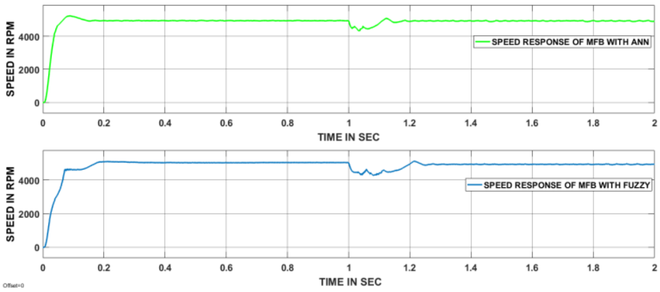

Figure 8. The speed responses of the electric motor during a heavy load condition

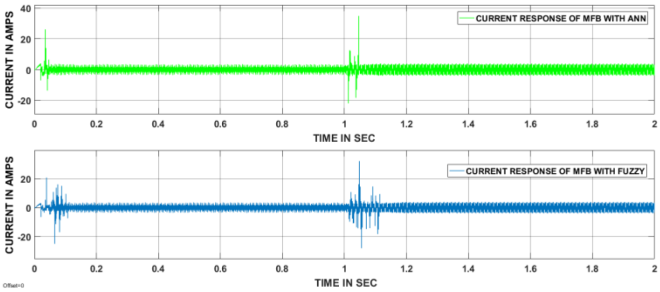

Figure 9. The current responses of the electric motor during a heavy load condition

During heavy load condition, the current response of both controllers as shown in figure 9. After motor reaching steady state, no load has been applied till 1 sec on the motor. At 1 sec heavy load has been applied, corresponding to that huge current variations' has been observed in both controllers current response. Thereafter both current responses have been reached again steady state with a stipulated time depending upon the particular controller action.

The pulse signals have been generated to BDC as well as UDC by MFB plus ANN controller shown in figure 10. During starting of the motor before reaching steady state the pulse signals have been generated to only BDC working as a boost converter. After reaching steady state pulse signal are generated to BDC as a buck and UDC as a boost converter. At 1 sec heavy load applied on the motor during this period the pulse signal generated to only BDC working as a boost converter. After some time again motor reaches steady state and pulse signals have been generated to BDC as a buck, UDC as a boost converter.

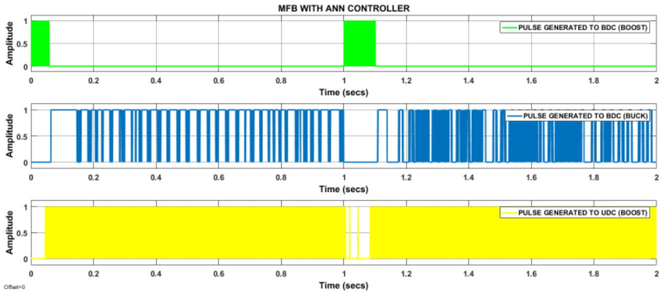

Figure 10. The pulse generated by the MFB with ANN controller during a heavy load condition

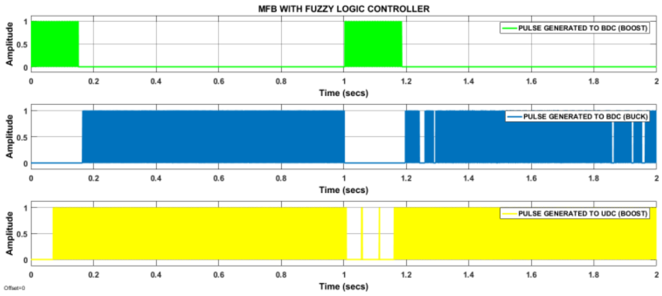

Figure 11. The pulse generated by the MFB with FUZZY controller during a heavy load condition

Figure 11 represents that pulse signals have been generated to BDC as well as UDC by MFB plus Fuzzy controller during heavy load condition.

6.2 Mode-II results

The speed responses of MFB plus ANN and MFB plus Fuzzy during slightly more than rated load condition on the electric motor are shown in figure 12. During starting of electric motor both speed responses have been reached steady state with different times, in that MFB plus ANN has taken 0.17 sec and MFB plus Fuzzy has taken 0.22 sec. After that at 1 sec slightly more than rated load has been applied to the motor, due to that motor speed response reduced in both controllers case. MFB plus ANN has taken 0.05 sec, MFB plus Fuzzy has taken 0.06 sec to reach steady state after load applied.

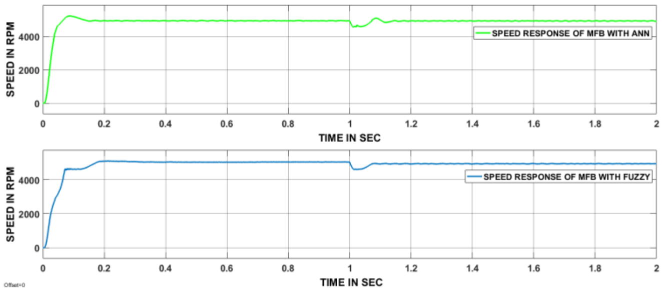

Figure 12. The speed responses of the electric motor during slightly more than rated load condition

During slightly more than rated load condition, the current responses of both controllers have shown in figure 13. After motor reaching steady state, no load has been applied till 1 sec on the motor. At 1 sec slightly more than rated load has been applied, corresponding to that some current variations' has been observed in both controllers current response. Thereafter both current responses have been reached again steady state with a stipulated time depending upon the particular controller action.

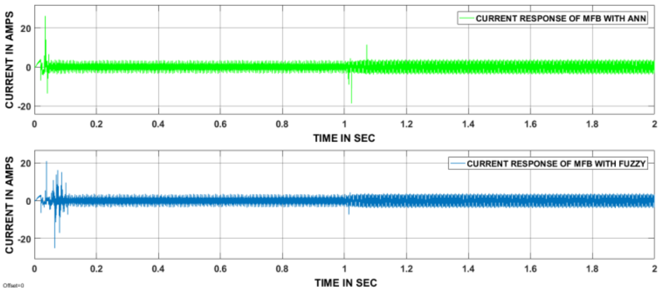

Figure 13. The current responses of the electric motor during slightly more than rated load condition

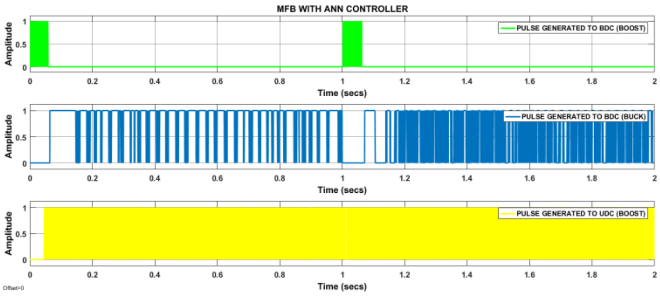

Figure 14. The pulse generated by the MFB with ANN controller during slightly more than rated load condition

The pulse signals have been generated to BDC as well as UDC by MFB plus ANN controller shown in figure 14. During starting of the motor before reaching steady state the pulse signals have been generated to only BDC working as a boost converter. After reaching steady state pulse signal are generated to BDC as a buck and UDC as a boost converter. At 1 sec slightly more than the rated load applied on the motor during this period the pulse signal generated to BDC working as boost and also UDC working as a boost converter. After some time again motor reaches steady state and pulse signals have been generated to BDC as a buck, UDC as a boost converter.

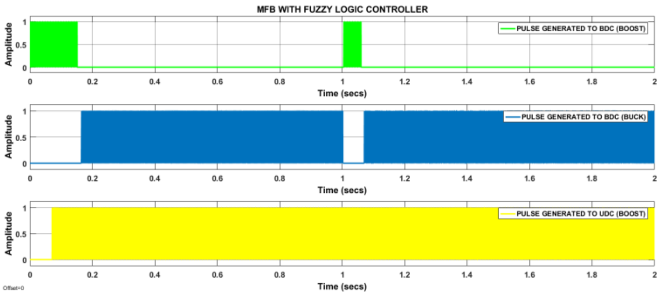

Figure 15. The pulse generated by the MFB with FUZZY controller during slightly more than rated load condition

Figure 15 represents that pulse signals have been generated to BDC as well as UDC by MFB plus Fuzzy controller during slightly more than rated load condition.

6.3 Mode-III results

The speed responses of MFB plus ANN and MFB plus Fuzzy during rated load condition on the electric motor are shown in figure 16. During starting of electric motor both speed responses have been reached steady state with different times, in that MFB plus ANN has taken 0.17 sec and MFB plus Fuzzy has taken 0.22 sec. After that at 1 sec slightly more than rated load has been applied to the motor, due to that motor speed response reduced in both controllers case. MFB plus ANN has taken 0.02 sec, MFB plus Fuzzy has taken 0.04 sec to reach steady state after load applied.

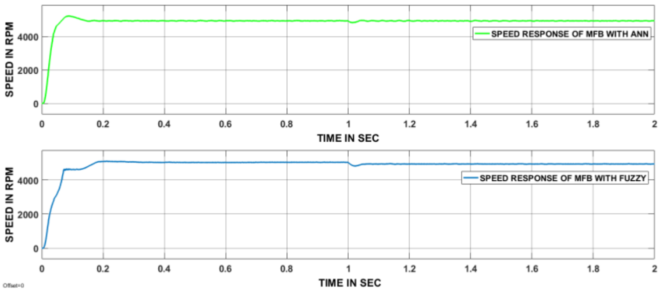

Figure 16. The speed responses of the electric motor during a rated load condition

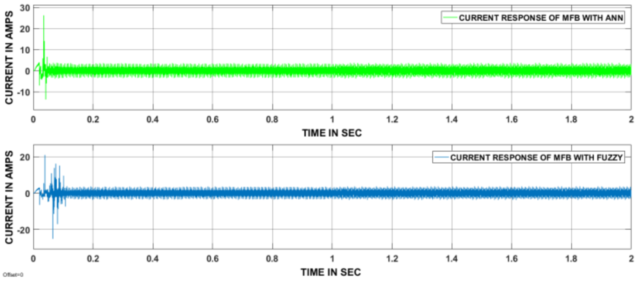

Figure 17. The current responses of the electric motor during a rated load condition

During rated load condition the current responses of both controllers have shown in figure 17. After motor reaching steady state, no load has been applied till 1 sec on the motor. At 1 sec rated load has been applied, corresponding to that current variations' has been observed in both controllers current response. Thereafter both current responses have been reached again steady state with a stipulated time depending upon the particular controller action.

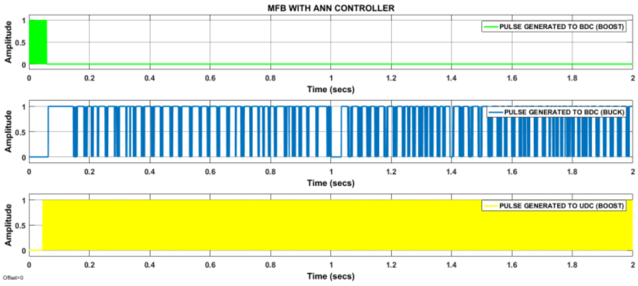

Figure 18. The pulse generated by the MFB with ANN controller during a rated load condition

The pulse signals have been generated to BDC as well as UDC by MFB plus ANN controller shown in figure 18. During starting of the motor before reaching steady state the pulse signals have been generated to only BDC working as a boost converter. After reaching steady state pulse signal are generated to BDC as a buck and UDC as a boost converter. At 1 sec rated load applied on the motor during this period the pulse signal generated to only UDC working as a boost converter. After some time again motor reaches steady state and pulse signals have been generated to BDC as a buck, UDC as a boost converter.

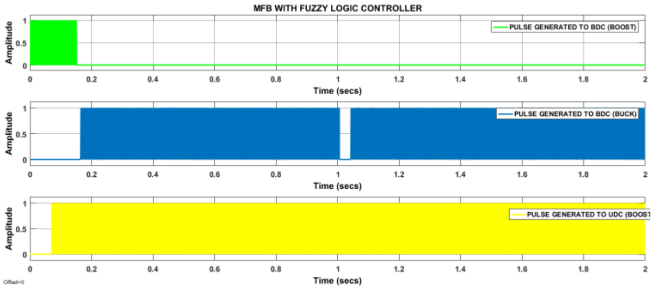

Figure 19. The pulse generated by the MFB with FUZZY controller during a rated load condition

Figure 19 represents that pulse signals have been generated to BDC as well as UDC by MFB plus Fuzzy controller during rated load condition.

6.4 Mode-IV results

The speed responses of MFB plus ANN and MFB plus Fuzzy during rated load condition on the electric motor are shown in figure 20. During starting of electric motor both speed responses have been reached steady state with different times, in that MFB plus ANN has taken 0.17 sec and MFB plus Fuzzy has taken 0.22 sec. After that at 1 sec slightly more than rated load has been applied to the motor, due to that motor speed response reduced in both controllers case. MFB plus ANN has taken 0.02 sec, MFB plus Fuzzy has taken 0.04 sec to reach steady state after load applied.

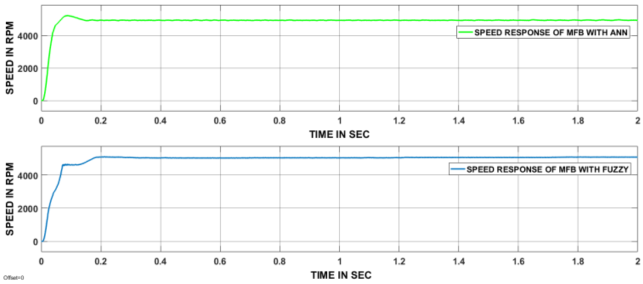

Figure 20. The speed responses of the electric motor during no load condition

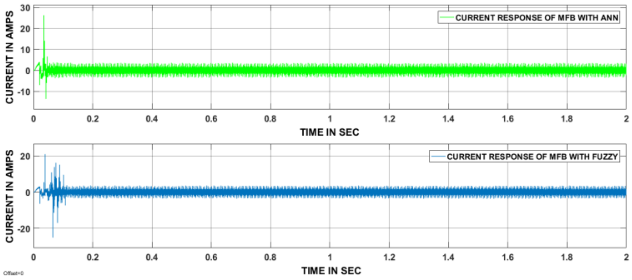

Figure 21. The current responses of the electric motor during no load condition

During no-load condition, the current responses of both controllers have shown in figure 21. After motor reaching steady state, no current variations have been observing due to no load condition.

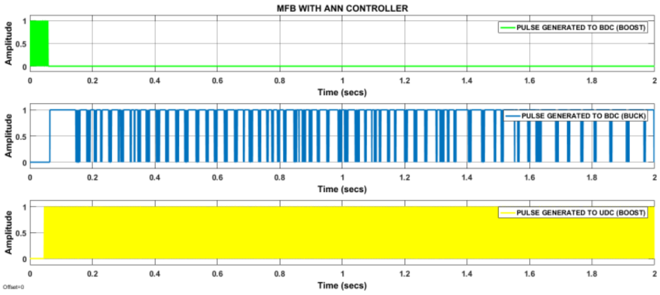

Figure 22. The pulse generated by the MFB with ANN controller during no load condition

The pulse signals have been generated to BDC as well as UDC by MFB plus ANN controller shown in figure 22. During starting of the motor before reaching steady state the pulse signals have been generated to only BDC working as a boost converter. After reaching steady state pulse signal are generated to BDC as a buck and UDC as a boost converter.

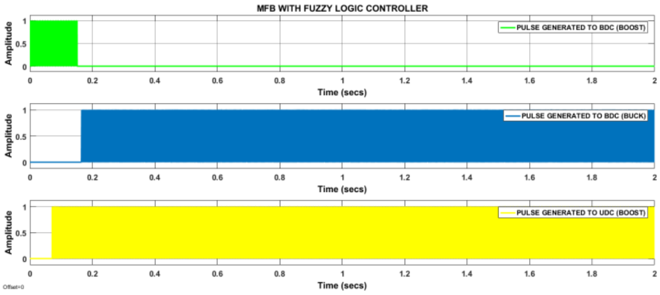

Figure 23. The pulse generated by the MFB with FUZZY controller during no load condition

Figure 23 represents that pulse signals have been generated to BDC as well as UDC by MFB plus Fuzzy controller during no load condition.

Table 2. Operation of the converter based on four modes

Mode Condition	UDC	BDC	Mode of Operation
Mode-1	Off	Boost	Power flow UC to Motor
Mode-2	Boost	Boost	Power flow UC+Battery to Motor
Mode-3	Boost	Off	Power flow Battery to Motor
Mode-4	Boost	Buck	Power Flow to Motor and UC From Battery

Table 3. State of math function based on the speed of the motor

Condition Based on Speed of the Motor	State of Math Function
If Speed is ≤4800 rpm	Math function U_1=1
If Speed is from 4600 rpm To 4800 rpm	Math function U_1=1& U_2=1
If Speed is from 4801 rpm To 4930 rpm	Math function U_3=1
If Speed is >4931 rpm	Math function U_4=1

7. CONCLUSIONS

Table 4. Comparative analysis between Hybrid controllers

Parameter	MFB with FUZZY	MFB with ANN
Delay time	0.05 sec	0.003 sec
Rise time	0.1 sec	0.09 sec
Peak time	0.15 sec	0.1 sec
Settling time	0.22 sec	0.18 sec
Maximum peak overshoot	2%	3%

Table 5. Comparative analysis between Hybrid controllers to reach steady state with and without load

Controller	Time is taken to reach steady state with a load	Time is taken to reach steady state at starting
MFB with FUZZY	0.22 sec	0.22 sec
MFB with ANN	0.18 sec	0.17 sec

The main problem associated with HESS powered electric vehicle can be overcome by designing the MFB controller combined with an intelligent controller termed as a hybrid controller. Here MFB has been combined with ANN as well as Fuzzy formed two different hybrid controllers. The main function of MFB is to control the switching pulses of converters based on the speed of an electric motor on another hand the intelligent controller generates the switching pulse signals by comparing converter reference signal with actual converter signal, finally these two controllers worked together made possible smooth switching between battery and UC based on the speed of an electric motor. Two-hybrid controllers have been adopted in four modes and responded satisfactorily corresponding to the speed the electric motor and generated switching pulses to the particular converter BDC or UDC. The comparative study has been made based on various factors; all comparative study can be tabulated in table 4 and 5 and from that MFB plus ANN has given better performance compared with MFB plus Fuzzy logic controller. All modes MATLAB/ Simulink results are obtained and discussed in section 6.

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