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Design of Hybrid Controller for PV sourced Electric Vehicle with Hybrid Energy Storage System using Regenerative braking.

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***Abstract**: Electric vehicles (EVs) enabled by high efficiency electric motors and controllers and powered by alternative energy sources provide the means for a clean, efficient, and environmentally friendly system. The power demanded by an EV is very variable. Hence HESS (Hybrid energy storage system) as an alternative source have been investigated with the objective of improving the storage of electrical energy. In these systems, two (or more) energy sources work together to create a superior device in comparison with a single source. In batteries and ultra-capacitors have complementary characteristics that make them attractive for a hybrid energy storage system. But the result of this combination is fundamentally related to how the sources are interconnect and controlled. Hybrid Electric Vehicle (HEV) is the most advance technology in automobile industries but long drive range in HEV is still a problem due to limited battery life. For increasing of battery life, two methods are widely used in HEV; one is with fuzzy logic-based battery management strategy and second is through improvement in regenerative braking system. Regenerative braking system used in HEV is to give backup power in deceleration mode which not only make HEV to drive longer but also increase the battery life cycle by charging of ultra-capacitor. The present work is for controlling the source of the motor present in the EV during different driving load conditions and storage of energy by implementing regenerative braking. In the proposed control action, motor speed plays a major role in switch the energy sources in HESS. To attain the objective, another controller has been designed with four math functions corresponding to the speed of the motor termed as Math Function Based (MFB) controller. The MFB controller works based on the motor's speed and this controller creates the closed loop operation of the overall system with smooth operation between the energy sources. Thereafter the designed MFB controller combined with a Fuzzy Logic controller applied to the entire circuit at different load conditions. In the same way, MFB with Artificial Neural Network controller also applied to the circuit. Finally, comparative analysis has been done between two controllers. The motor has been applied with 6 different types of load and simulated. The MATLAB results of MFB with FLC and MFB with ANN has been attained and compared, discussed.*

***Keywords** : Electric Vehicle, HESS (hybrid Energy Storage System), MFB (Math function based), Fuzzy logic Controller, Artificial Neural Network, Regenerative Braking.*

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I. INTRODUCTION

As an Environmental Concern, Current use of heat-combustion engine is a major source of air pollution and may be a cause of global warming and as a Practical Concern, Current conventional cars use a quickly decreasing source of fossil fuel.

Electric vehicles (EV) enabled by high efficiency electric motors and controllers and powered by alternative energy sources provide the means for a clean, efficient, and environmentally friendly urban transportation system. Electric vehicles have no emission, having the potential to curb the pollution problem in an efficient way.

Consequently, EVs are the only zero-emission vehicles possible.

EV's can use regenerative stopping (regain 30% of energy used, theoretically).

As mentioned already, HEV's are more environmentally friendly and the oil supplies for conventional vehicles are being depleted.

Electric vehicle includes locomotives, golf carts, forklifts, buses, nuclear submarines, elevators, cars (Electric Cars) etc. A major challenge for development of electric vehicles having hybrid energy storage system (HESS) is coordination of multiple energy sources and converters.

One of the major challenges in a battery /ultra-capacitor hybrid energy storage system (HESS) is to design a supervisory controller for real-time implementation that can yield good power split performance.

This necessitates the utilization of appropriate controller or energy management strategy.

Many real-time energy management strategies have been proposed that include rule-based control, fuzzy rule-based control, model predictive control (MPC) and neural network method among which the rule-based control, fuzzy rule based and model predictive control are heuristic controllers, which cannot guarantee effective control in different driving scenarios.

An intelligent real-time controller was constructed based on neural network, which was trained by offline optimization results.

Hence the aim was to design a controller which changes the power sources of hybrid energy storage system corresponding to the speed of the electric drive (motor).

II. MODEL OF PV SOURCED ELECTRIC VEHICLE WITH HESS

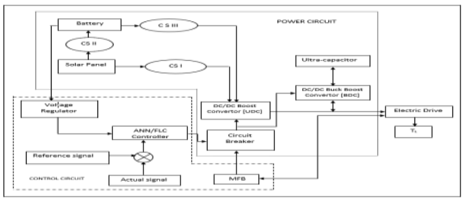

Fig. 1.Block Diagram of HESS. (*PV Sourced Hybrd Energy Storage System EV*)

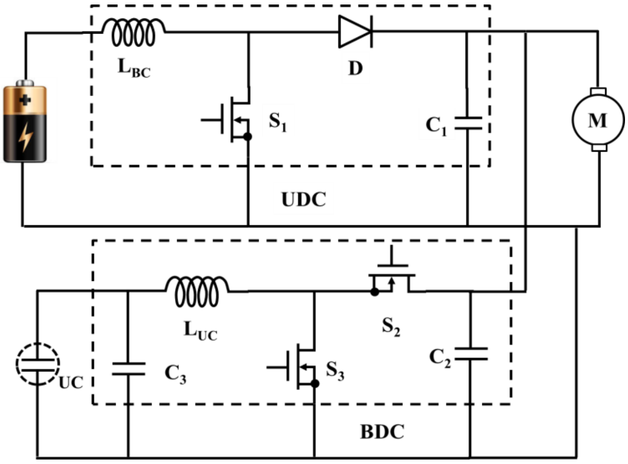

Fig. 2. Circuit Diagram of Converter. (Unidirectional and Bi Directional Converter connected across BLDC motor)

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, to overcome that difficulty a hybrid controller is designed by combining MFB with ANN as well as the Fuzzy logic controller. The hybrid controller can always switch 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 is connected at UC end and UDC is connected at the battery end. Error signal is generated by comparing an actual signal as well as a reference signal, after that error is 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 then compared with MFB generated signal, finally required pulse is 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 (UDC-unidirectional converter) and Buck/Boost (BDC-Bidirectional converter) converter model is 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. During peak power requirements of the motor, BDC acts as a Boost converter remaining cases it acts as Buck converter, which means UC is mend for only to reduce the extra burden on the battery during the transient conditions and also during braking conditions energy is harvested in it. The battery is connected here to supply the average power to the motor, and it is 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 six sub-circuits for six different loading conditions.

The switches used in the HESS are operated based on the road conditions of the vehicle. The modelled circuit contains three controlled switches, and that are operated in six modes. These six modes illustrated with switching action of three switches from below the table I.

Table- I: Load condition-based switching action

Mode	S1	S2	S3	Load Torque
I	ON	ON	OFF	No Load Acceleration
II	ON	OFF	OFF	Rated load
III	ON	OFF	ON	Medium Load
IV	OFF	OFF	ON	Heavy Load
V	ON	ON	ON	Reducing Load from Heavy to No Load
VI	OFF	ON	ON	Regenerative braking

A. Mode-I Operation

The mode I operational circuit is provided in Fig. 3. In this, the switches S1 and S2 are operating and the ultracapacitor gets charged during this time. The motor is operating under no load condition.

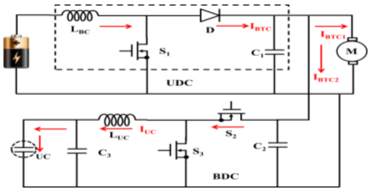

Fig. 3.Converter Mode-I circuit diagram with HESS.

B. Mode-II Operation

The mode II operational circuit is provided in Fig. 4. In this, the switch, S2 and S3 are turned OFF and only S1 operates. The BDC is turned OFF and UDC is supplying power to motor from the PV or battery source. The motor load is operating under rated load condition.

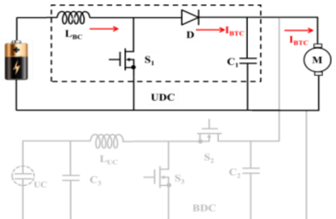

Fig. 4. Converter Mode-II circuit diagram with HESS.

C. Mode-III Operation

The mode III operational circuit is provided in Fig. 5. In this, the switches S1 and S3 are operating and the both the base source and ultracapacitor is providing supply to the motor load (both UDC and BDC are turned ON).

The motor is operating under medium load conditions which are above rated load conditions.

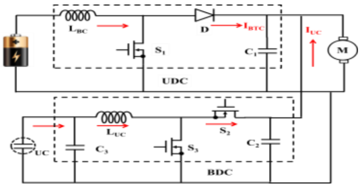

Fig. 5.Converter Mode-III circuit diagram with HESS.

D. Mode-IV Operation

The mode IV operational circuit is provided in Fig. 6. In this, the switch, S3 is operating and the switches S1 and S2 are turned OFF. The ultracapacitor is providing supply to the motor load. The motor is operating under heavy load condition.

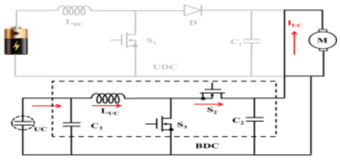

Fig. 6.Converter Mode-IV circuit diagram with HESS.

E. Mode-V Operation

In this mode the load will drastically reduce from heavy load to no load to approach for braking. Hence all the three switches S1, S2 an S3 are in ON position. The different states attained by model are rated load, medium load, and no load.

F. Mode-VI Operation

In Mode-VI operation, BDC is in operation but working as a buck converter for charging UC. The motor acts as a generator during regenerative braking. Kinetic energy generated can be captured by using proper switching technique in motor drive. This energy can be used to charge the Ultracapacitor. Motor speed and input voltage is used as reference parameter to calculate the maximum current produced in motor during braking.

III. DESIGN OF HYBRID CONTROLLER

In this work mainly two controllers are used to achieve the proposed control scheme. The FLC/ANN controller is the one controller and the second one is Math function based controller, a combination of this two controller forms a new controller to switch the energy sources of a hybrid energy storage system according to the electric motor speed. Brief ideas about two controllers have given separately.

A. MFB CONTROLLER

The MFB controller provides the smooth transition between the modes which depends on the speed of the motor. The energy storage devices are switched based on the modes along with the converters. The functionality of the MFB controller depends on the following relations:

- If the rotor speed is less than 4600 rpm, then the signal V1 is high (ON) and other signals V2, V3 and V4 are low (OFF).
- If the speed ranges less than 4800 rpm and greater than 4600 rpm, then the signals V1 and V2 are high and other signals V3 and V4 are low.
- If the speed ranges from 4801 rpm to 4930 rpm, then the signals V1, V2 and V4 are low and the signal V3 is high.
- If the rotor speed is greater than 4931 rpm, the generated signal V4 is high and other three signals are low.

The switching arrangements are shown in the flowchart in Fig 7 an also in Table II. The S1 is operating in all conditions except in heavy load conditions (Mode 4). The switch S2 operates only during no load conditions (Mode 1). The switch S3 operates in both medium and heavy load conditions (Modes 3 and 4).

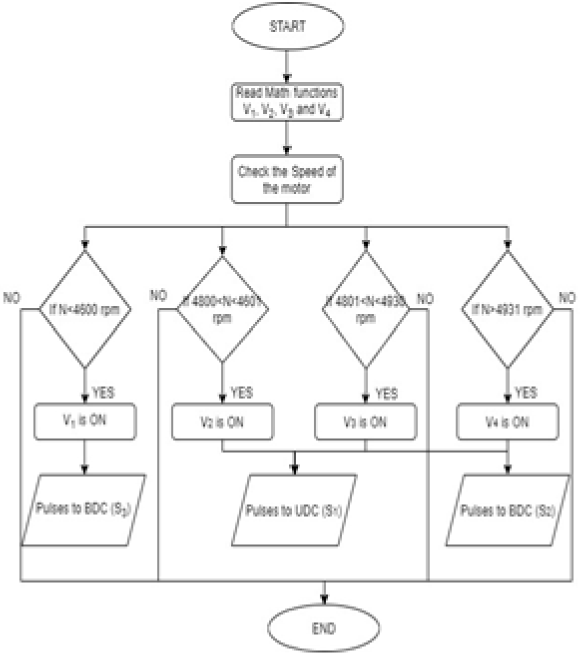

Fig. 7.Flow chart for MFB Controller implementation.

Table- II: State of Math Function based on the speed of the motor.

Condition Based on Speed of the Motor	State of Math Function			
	V1	***V2***	***V3***	***V4***
If Speed is <4800 rpm	1	0	0	0
If Speed is from 4600 rpm to 4800 rpm	1	1	0	0
If Speed is from 4801 rpm to 4930 rpm	0	0	1	0
If Speed is >4931 rpm	0	0	0	1

B. FUZZY LOGIC CONTROLLER

Fuzzy interference system is the key component of fuzzy logic system whose primary function is decision making. The functional diagram of fuzzy logic controller is provided in Fig. **7.**

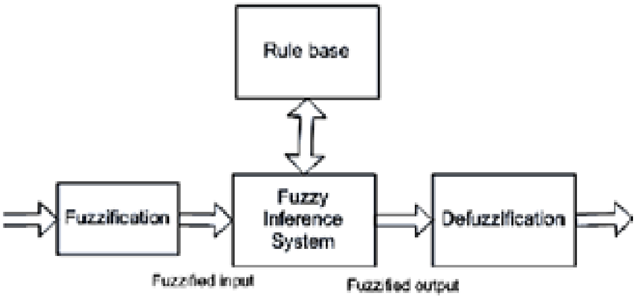

Fig. 8.Functinoal block diagram of Fuzzy Logic Controller.

Fuzzy inference process comprises of following parts:

- Fuzzification of input signals
- Application of the fuzzy operator (AND or OR) in the antecedent
- Implication from the antecedent to the consequent
- Aggregation of the consequents across the rules
- Defuzzification

The rules set for the fuzzy logic controller is provided in Table III as shown below:

Table- III: Rules of FLC Control

Ve/ΔVe	NVL	NL	NM	NS	Zero	PS	PM	PL	PVL
NVL	PVL	PVL	PL	PM	PM	NL	NL	NVL	NVL
NL	PVL	PL	PM	PM	PM	NM	NL	NVL	NVL
NM	PL	PL	PM	PM	PS	NM	NM	NL	NL
NS	PM	PM	PS	PS	Zero	NS	NM	NM	NM
Zero	PS	PS	PS	Zero	Zero	Zero	Zero	NS	NM
PS	Zero	Zero	Zero	NS	Zero	Zero	Zero	PS	PM
PM	NS	NS	NS	NS	NS	PS	PM	PM	PL
PL	NM	NM	NM	NM	NM	PM	PL	PL	PVL
PVL	NL	NL	NL	NL	NL	PL	PL	PVL	PVL

The fuzzy controller will provide the change in duty ratio (ΔD) which will be added with initial duty ratio and provided for pwm pulse generation unit.

The pulse generated is given to the UDC and BDC switches. Both the FLC and ANN control operates under the following conditions:

If $Ve/\Delta Ve > 0$, ΔD is +ve, (1)

If $Ve/\Delta Ve < 0$, ΔD is –ve. (2)

C. ANN CONTROLLER

The ANN senses the change in error voltage and generates the duty ratios as per the equations (1) and (2).

Hence if there is change in irradiation or load conditions, the ANN control is accurate and quicker in response than any other control and provides the appropriate duty ratio to provide load regulation.

The training was done with the help of data taken from the base system.

The Levenberg-Marquardt algorithm is used for training the neural network.

This algorithm requires more memory but minimum time. Training will stop when improvement of generalization stops, as indicated by an increase in the mean square error of the validation samples.

The fitting curve of the training of ANN controller is provided in the following graphs (Fig. 9):

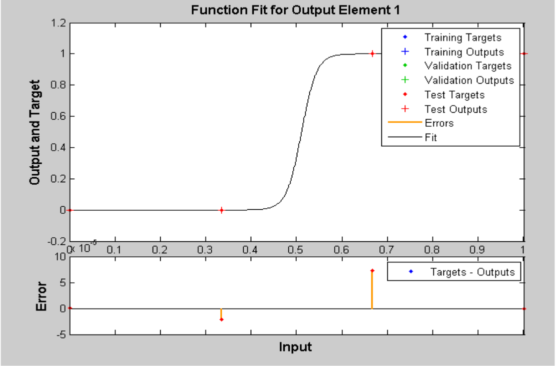

Fig. 9.Fitting curves from neural network training

The regression value obtained from the training of neural network control is 0.99953. The regression curve is provided in the following graphs (Fig 10):

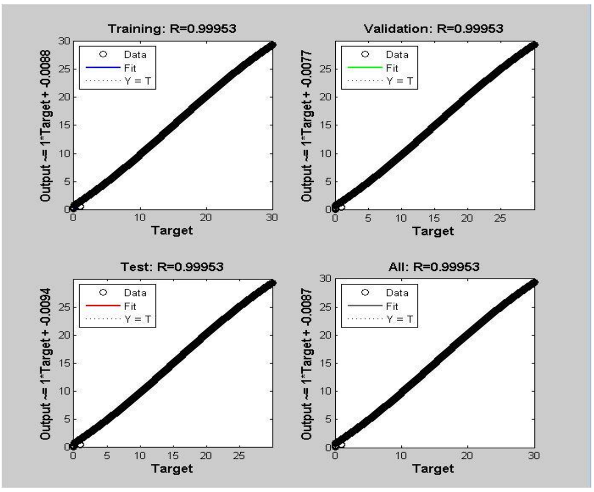

Fig. 10. Regression curves from neural network training

IV. SIMULATION RESULTS

The simulation parameters are provided in Table IV as follows:

Table- IV: Simulation Parameters

Parameters	Values
PV Voltage and Power	48V & 36 KW
Battery specifications	38V, 10.5Ah (Imax = 200A)
Ultracapacitor specifications	29F, 32V (Imax = 190A)
DC motor specifications	120V, 32KW, 4800 rpm
Switching Frequency	5KHZ
Inductors	LUDC = 26μH LBDC = 14μH
Capacitors	CUDC = 27mF CBDC = 32mF

In this, the irradiation is initially 1000W/m2 and at t=1s, the irradiation changed to 0W/m2.

Due to this reduction in irradiation, the PV voltage and power is also getting reduced.

The change in PV voltage and power due to change in solar irradiation is provided in the graph shown in Fig. 11.

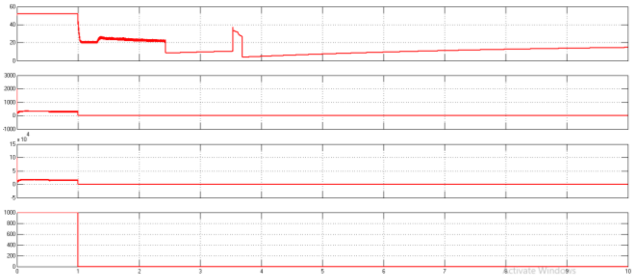

Fig. 11. PV voltage and power for different irradiations

The battery is charging when the PV is generating power and when PV irradiation is reduced, the battery is starting to discharge to provide power to the motor load.

The load torque is varied as in the Table V provided below:

Table- IV: Load Variations in EV System

Time(s)	Torque (Nm)	Mode of operation
0-0.3	0	No load
0.3-1.3	63	Rated load
1.3-2.4	78	Medium load
2.4-2.75	93	Heavy load
After 2.75	< 0	Regenerative Braking

The speed, torque and armature current waveforms are provided below in Fig 12:

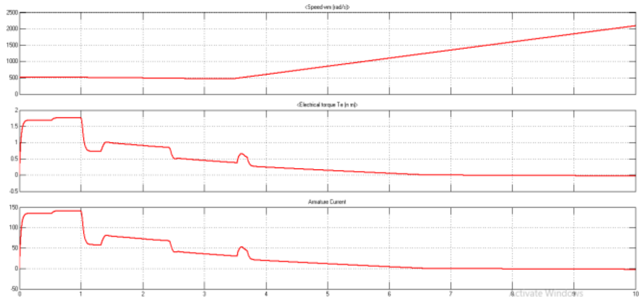

Fig. 12. Rotor speed, Torque and Armature current waveforms of motor load in different loading conditions

The rotor speed is varied when the applied load torques are varied. Initially it is above 4800 rpm as it starts from no load condition and whenever the load is applied, consequently the rotor speed reduces. As the rotor speed reduces, the modes of operation of the proposed system are varied. It is shown in Fig 13 as follows:

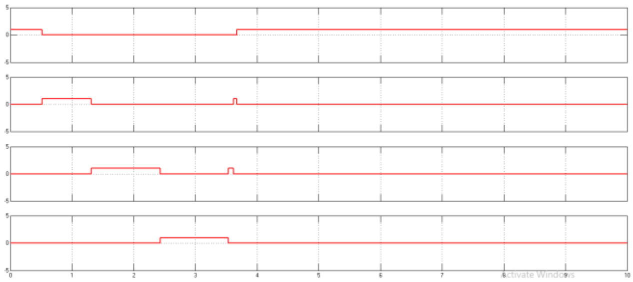

Fig. 13. Modes of Operation Control Waveforms

The %SOC of the battery and ultracapacitor is shown in Fig 14 as follows:

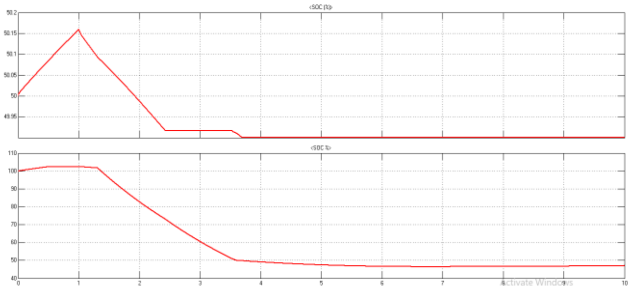

Fig. 14. %SOC of the Battery and UltraCapacitor

Initially both batteries and ultracapacitor is charged from PV source in no load condition. At t=0.3s, the rated load is applied to the motor. After 0.3s, the ultracapacitor is disconnected and battery continued to get charged. At t=1s, the PV source is disconnected due to low irradiation. The battery starts to discharge for rated and medium load conditions. The ultracapacitor connects to the system at t=1.3s for medium load condition and continues to supply the power to motor load in heavy load conditions. In regenerative braking condition, the ultracapacitor gets charged whereas the battery remains disconnected. The voltage and current of UDC is provided in Fig 15 as follow:

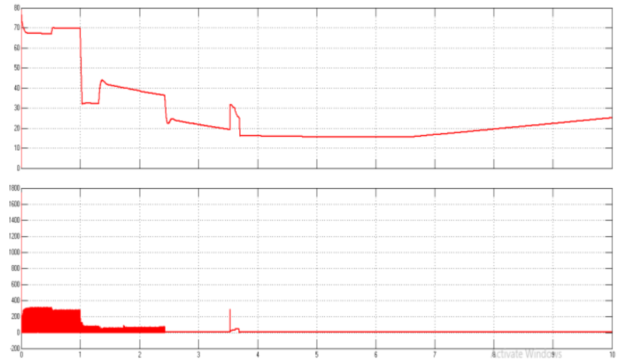

Fig. 15. UDC voltage and current waveforms

The BDC voltage and current waveforms are shown in Fig 16 as follows:

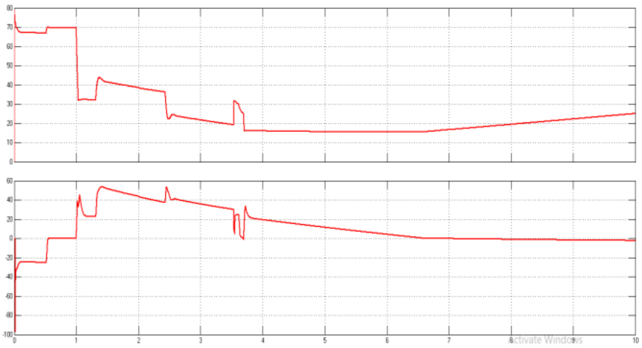

Fig. 16. BDC voltage and current waveforms

The negative direction shows that the current flow is in opposite direction (UC is charging).

Table- V: DC-DC converters state of operation corresponding to modes and power flow path.

Mode Condition	UDC	BDC	Power Flow Path
Mode-1	Boost	Buck	Power Flow to Motor + UC From Battery/PV
Mode-2	Boost	Off (Average current is zero)	Power flow from Battery to Motor
Mode-3	Boost	Boost	Power flow from UC + Battery to Motor
Mode-4	Off	Boost	Power flow from UC to Motor
Mode-5	Boost	Buck /Boost	Power Flow to Motor + UC From Battery/PV gradually
Mode-6	Off	Buck	Power Flow from Motor to UC

Table- VI: State of Charge of Battery and Ultra Capacitor corresponding to modes.

Mode Condition	Battery SOC	UC SOC
Mode-1	Charging	Charging
Mode-2	Discharging	Constant
Mode-3	Discharging	Discharging
Mode-4	Constant	Discharging
Mode-5	Discharging	Charge and then Discharging
Mode-6	Constant	Charging

V. CONCULSION

In this paper, PV sourced EV system with HESS is designed with hybrid control structure. The role of MFB control and FLC/ANN control are analyzed and the control structures are designed and simulated. The motor load was subjected to various loading condition with and without PV source. The modes of operation of the proposed circuit are analyzed and validated with the simulation results. The charging and discharging characteristics of battery and ultra-capacitor are also obtained from the simulation under different loading conditions. The regenerative braking is applied to the motor and the energy from motor windings was retrieved to charge the ultra-capacitor.

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