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Analysis and Implementation of Fuzzy Logic Control and Sliding Mode Control with Split-Pi Converter and Solar Energy Rectified Battery Applications

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Abstract: Due to continuous variation of charging level battery, connected loads are different in electric vehicle (EV) charging stations. The linear controllers such as P, PI and PID does not provide smooth and regulated response in case of EV charging applications as well as power electronics collaboration. Sometimes load changes in sudden situation and EV charging stations comes in instability region. Considering the reasons, this research work discusses on implementation of non-linear controllers for EV battery charging applications. This paper shows and describes the performance of Fuzzy-Logic Controller (FLC) and Sliding Mode Controller (SMC) for EV charging applications. The Fuzzy-Logic controller and sliding mode controller has been developed for Split-Pi converter-based battery charging scheme, and the complete control system has been analyzed and validated by simulation study. Performances have been investigated in detail for checking different characteristics. Split-Pi converter is a recently invented DC-DC converter which has great potential in the power electronics field because it has less components and lower switching losses. The closed-loop operation of this converter topology has been analyzed and discussed with simulation results.

Index Terms: Fuzzy Logic Controller, Sliding Mode Controller, EV Battery, Charging Station, Split-Pi DC-DC Converter, Solar PV Panel.

I. INTRODUCTION

DC-DC converters have so many applications of power conversion operations such as maximum power point tracking, DC bus integration, and industrial electronics. DC-DC converters are able to work on transient switching actions and they are nonlinear in nature. PID controllers or other linear based controllers are commonly used in many designs and simulations. The linear controllers have peak overshoot and oscillations in the output transient response before settling to a final value as they could result in nonlinear change in loads sometimes. There are mainly two categories of control in DC-DC Converters called as voltage mode and current mode control.

The voltage mode control detects the output voltage comparing with reference voltage to produce error output signal, and both output voltage and inductor current are sensed with current mode control [13]. Because of time varying nature of power converters, the designer controls the output voltage by directly controlling the inductor current.

However, the PWM based slide mode control has transient parameters including high voltage ripples in the output. These types of nonlinear controllers are used for a wide range of operating conditions with high dynamic response and to control the converters. Linear controller generates peak overshoot voltages and increase the charging current which will damage the battery in case of battery charging applications [10,11].

Then battery will show nonlinear characteristics and provide instability. We will get output instability by power converters and the system can be unstable [14,15]. Thus, the controllers called fuzzy logic controller and sliding mode controller has been implemented in this paper to improve the charging of battery.

The outcome of FLC and SMC controller based with Split-Pi converter for battery charging has been performed analyzing battery state of charge and charging time. PV model and battery model with charging circuit has been used for simulations in this paper, and the control algorithms have been shown. Finally, the comparison has been made based on the simulation results.

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II. DESIGN OF SPLIT-PI DC-DC CONVERTER

Split-Pi converter is a combination of boost and buck converter, and a capacitor used between boost and buck converter. The circuit diagram of the converter is shown in Fig. 1. The converter can operate in three modes such as buck, boost and buck-boost mode. The switch S1 is turned on and switch S2 is turned off during the whole period of buck mode. Switches S3, S4 are working in a switch mode and operate in antiphase relative to each other as buck converter operates in synchronous mode. The switch S3 is turned on and S4 is turned off during the whole period while operating in the boost mode. Switches S1 and S2 operate in antiphase relative to each other as boost converter operates and works in switch modes.

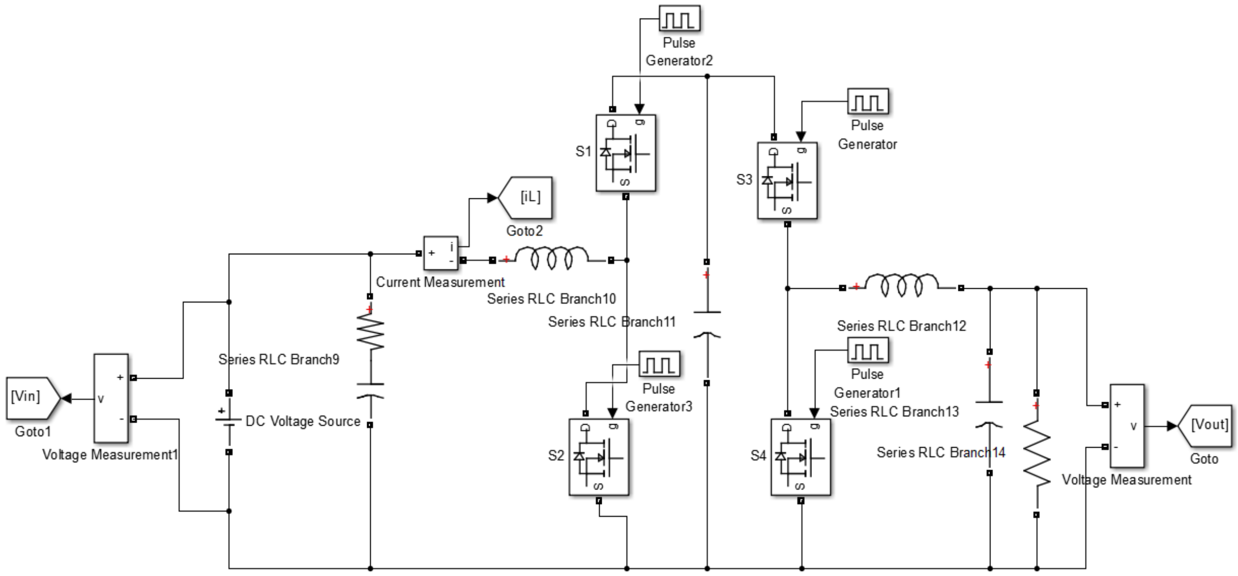

Fig.1. Conventional Split-Pi Converter in MATLAB/Simulink

The buck-boost mode can be used when output voltage is needed to be equal, less or higher compared to input voltage. Switches S1, S4 operates in an antiphase relative to switches S2, S3 in this mode. The advantage of the buck-boost mode is that there will be no possibility of turning on switches in any of the modes which will result in conduction loss in the converter. This converter can be beneficial for high power applications and battery charging applications are also included with all other advantages.

This new topology of a bidirectional converter, named as Split-Pi Converter (US Patent 20040212357 A1) was invented by Timothy Richard Crocker in 2004. This topology has a lot of advantages such as it allows bidirectional flow of power, which can be useful in electric vehicles. This topology can be used in multiphase systems, so it can be connected in parallel also where the dimensions and cost of components can play a significant role. One more advantage is that this converter can provide higher or lower output voltage according to the input voltage [16].

III. ANALYSIS OF FUZZY-LOGIC CONTROL SYSTEM

Fuzzy logic controller (FLC) is one of the commonly used applications of fuzzy set theory. It can be used instead of digital control systems and it requires fuzzy sets. We can also use words instead of numbers for FLC modification. Membership functions are the main elements for the fuzzy operations and fuzzy sets are described by it. The implementation of linguistic fuzzy rules by human operators are measured without the requirements of mathematical model’s parameter estimation for a complex and nonlinear systems.

The FLC is more robust than several control methods because it has faster transient responses [8]. In this paper, firstly a general FLC algorithm developed on MATLAB/Simulink is presented. For developing the fuzzy logic system, five membership functions and a rule table are analyzed. The proposed Split-Pi converter system is simulated by using MATLAB/Simulink operational blocks and control systems. The proposed Split-Pi converter system is basically analyzed for a solar energy-battery system as shown in Fig. 2.

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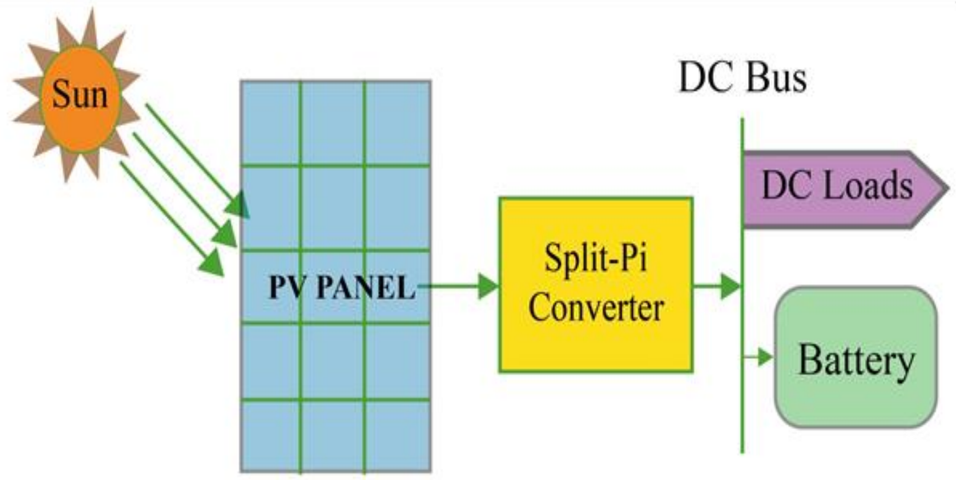

Fig.2. Solar Energy Battery Charging System

The system variables and a rule table which depends on the variables are described for FLC control algorithm. The output voltage of Split-Pi converter is controlled by changing the switching frequency and duty cycle.

The system error is defined as a difference between the reference voltage and measured output voltage. *r(s)* is the reference voltage and *y(s)* are the measured output voltage values for FLC development. Then the error voltage is calculated using Equation (1)

$$e(s) = r(s) - y(s) \qquad (1)$$

The change in the error voltage is also calculated as,

$$de(s) = e(s) - e(s-1) \qquad (2)$$

The membership functions for each of the fuzzy variables are shown in Figure 3(a) and 3(b).

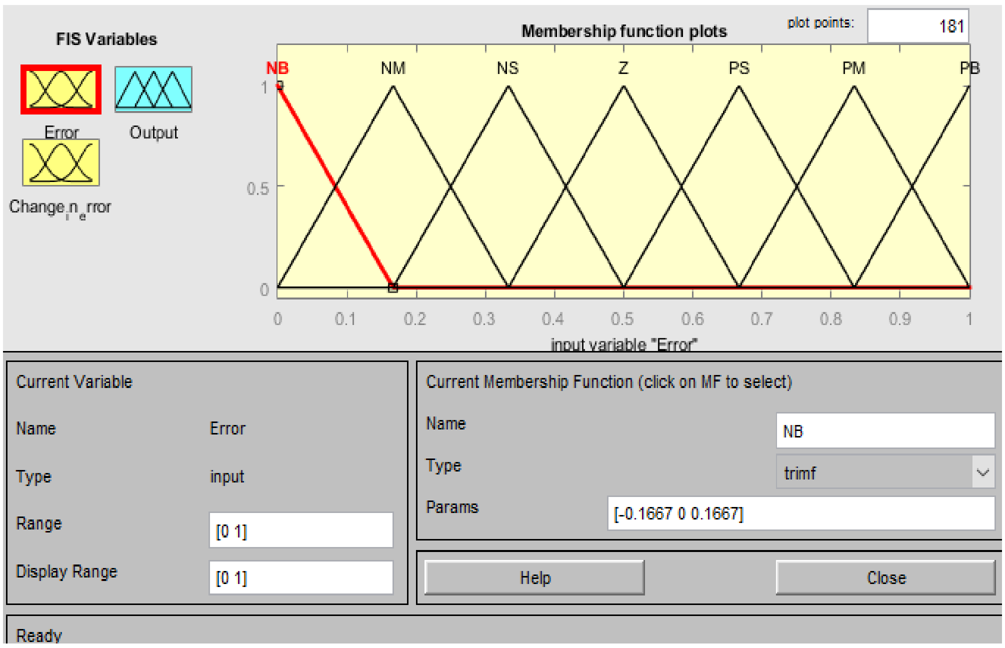

Fig.3(a). Membership Function for Error

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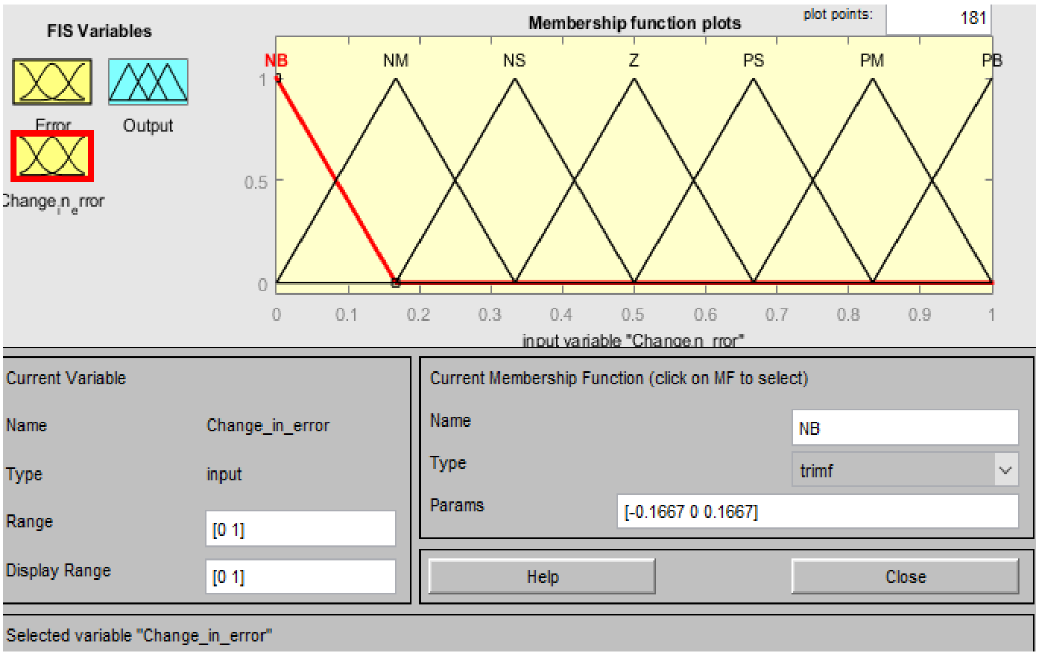

Fig.3(b). Membership Function for Change in Error

To establish the fuzzy logic control system, some of the fuzzy rules can be presented as follows:

1. If e is PB and de is NB, then output is 0.
2. If e is PM and de is NB, then output is -5.
3. If e is PS and de is NB, then output is -50.
4. If e is Z and de is NB, then output is -100.
5. If e is NS and de is NB, then output is -100.
6. If e is NM and de is NB, then output is -100.
7. If e is NB and de is NB, then output is -100.
8. If e is PB and de is NM, then output is 5.
9. If e is PM and de is NM, then output is 0.
10. If e is PS and de is NM, then output is -5.
11. If e is Z and de is NM, then output is -50.
12. If e is NS and de is NM, then output is -100.
13. If e is NM and de is NM, then output is -100.
14. If e is NB and de is NM, then output is -100.
15. If e is PB and de is NS, then output is 50.
16. If e is PM and de is NS, then output is 5.
17. If e is PS and de is NS, then output is 0.
18. If e is Z and de is NS, then output is -5.
19. If e is NS and de is NS, then output is -50.
20. If e is NM and de is NS, then output is -100.
21. If e is NB and de is NS, then output is -100.
22. If e is PB and de is Z, then output is 100.
23. If e is PM and de is Z, then output is 50.
24. If e is PS and de is Z, then output is 5.
25. If e is Z and de is Z, then output is 0.
26. If e is NS and de is Z, then output is -5.
27. If e is NM and de is Z, then output is -50.
28. If e is NB and de is Z, then output is -100.
29. If e is PB and de is PS, then output is 100.
30. If e is PM and de is PS, then output is 100.
31. If e is PS and de is PS, then output is 50.
32. If e is Z and de is PS, then output is 5.

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33. If e is NS and de is PS, then output is 0.
34. If e is NM and de is PS, then output is -5.
35. If e is NB and de is PS, then output is -50.
36. If e is PB and de is PM, then output is 100.
37. If e is PM and de is PM, then output is 100.
38. If e is PS and de is PM, then output is 100.
39. If e is Z and de is PM, then output is 50.
40. If e is NS and de is PM, then output is 5.
41. If e is NM and de is PM, then output is 0.
42. If e is NB and de is PM, then output is -5.
43. If e is PB and de is PB, then output is 100.
44. If e is PM and de is PB, then output is 100.
45. If e is PS and de is PB, then output is 100.
46. If e is Z and de is PB, then output is 100.
47. If e is NS and de is PB, then output is 50.
48. If e is NM and de is PB, then output is 5.
49. If e is NB and de is PB, then output is 0.

These rules can be presented as in Table 1 for three fuzzy regions. The Simulink design will be performed using this rule table and FLC rule based controller.

TABLE I. FUZZY RULE DECISION TABLE

e* \ e	PB	PM	PS	Z	NS	NM	NB
NB	0	-5	-50	-100	-100	-100	-100
NM	5	0	-5	-50	-100	-100	-100
NS	50	5	0	-5	-50	-100	-100
Z	100	50	5	0	-5	-50	-100
PS	100	100	50	5	0	-5	-50
PM	100	100	100	50	5	0	-5
PB	100	100	100	100	50	5	0

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IV. DESIGN OF FUZZY LOGIC CONTROLLER

A fuzzy logic-based controller consists of three sections known as fuzzifier, rule base and defuzzifier as shown in Figure 4.

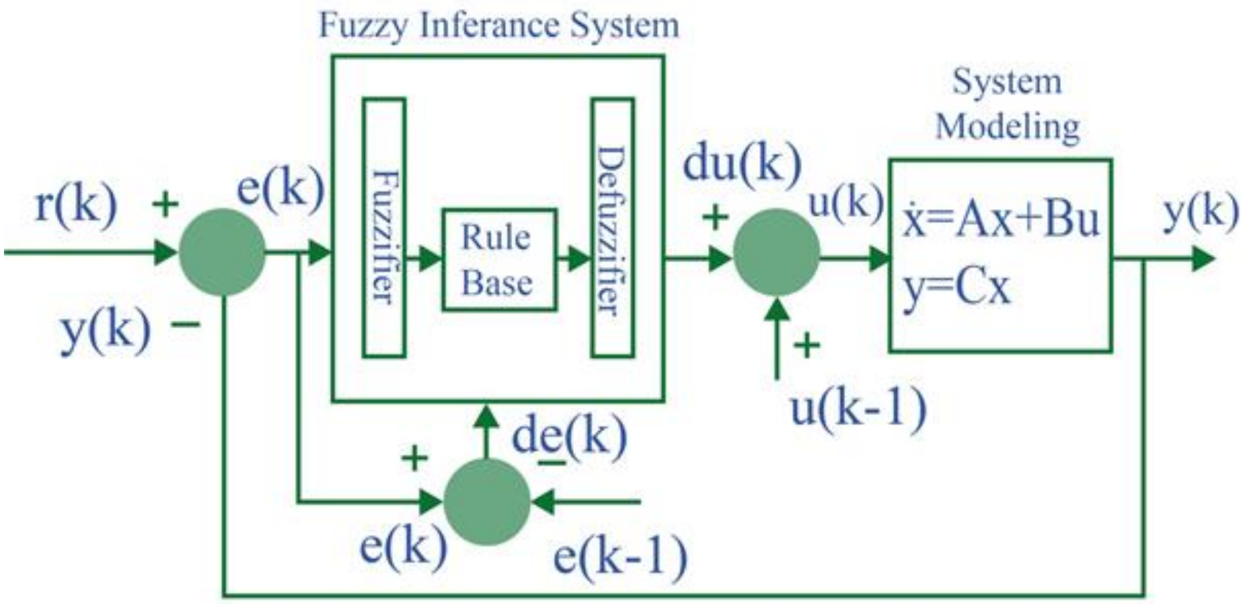

Fig.4. Block Diagram of Fuzzy Logic Controller with Feedback Modeling System

The error and change in error are two input signals with output for each sampling to the FLC and they are converted to generate fuzzy numbers firstly in fuzzifier, and then they are used in a rule table to determine the fuzzy number of the ultimate output signal.

The resultant united fuzzy subsets represent the controller output and finally they are converted into the crisp values. The products in the nominator of defuzzification method is also represented by this process [9].

The crisp values of the fuzzy subsets have maximum membership degree of 1.0 in the corresponding fuzzy subsets which is used in the multiplication process.

V. SIMULATION OF SPLIT-PI CONVERTER AND SOLAR SYSTEM WITH FUZZY LOGIC CONTROLLER

Developing the Fuzzy Logic controller (FLC) with Split-Pi converter and battery are discussed in this part. Simulation of Split-Pi converter with MATLAB/Simulink is shown in Figure 5.

Fuzzy logic controller is added as control system feedback here in simulation. We get the error voltage signal comparing the reference voltage and actual voltage signal, and this error signal is driven by FLC.

A PWM signal is generated with comparison of FLC output signal and a sawtooth signal, and this signal drives the MOSFET switching devices.

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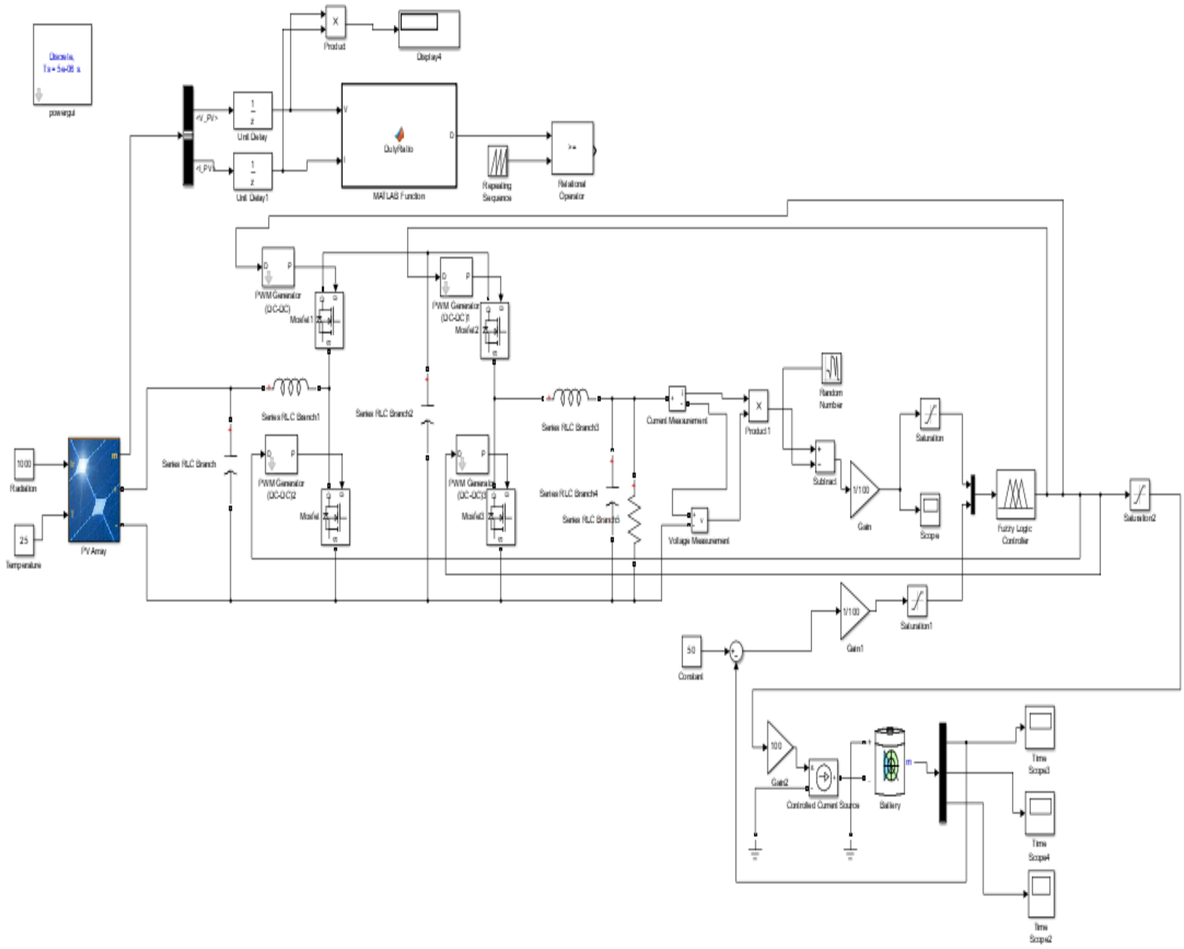

Fig.5. FLC added Split-Pi converter simulation

The Split-Pi converter has been analyzed with 48V (output) and 29V (Input Voltage max. coming from solar PV panel). The battery chosen for this simulation is Lithium-ion battery. The voltage and capacity of the battery is 48V and 150Ah respectively. Simulation Parameters of Split-Pi converter: Inductance = 1000mH, Capacitance = 540µF, Switching Frequency = 10KHz, Output Resistance = 45 Ohms, Input Voltage = 29Volt, Output Voltage = 48Volt etc.

VI. SIMULATION RESULTS

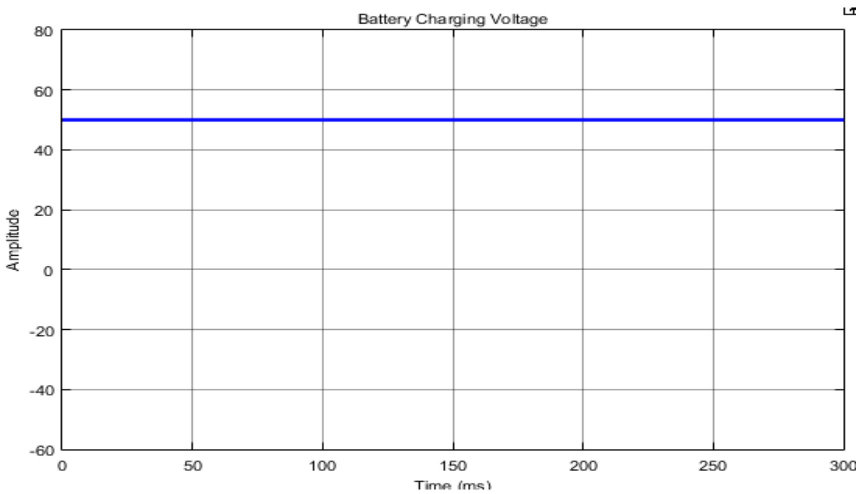

Fig.6. Battery Charging Voltage

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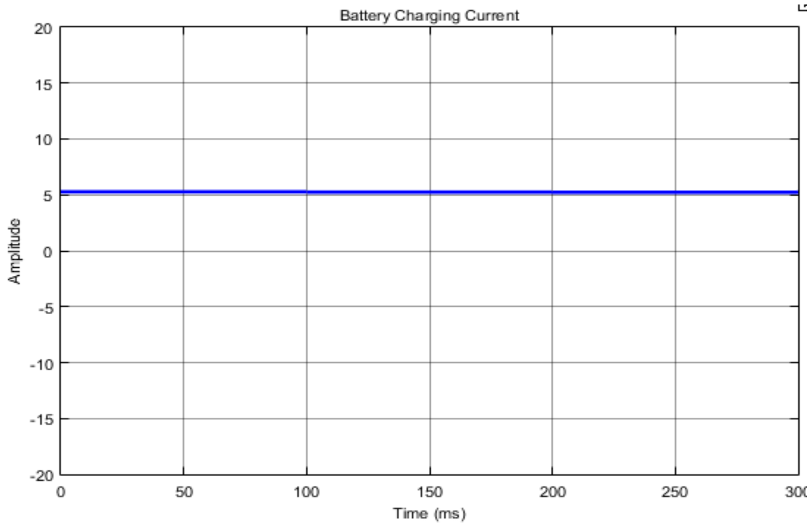

Fig.7. Battery Charging Current

From the output we can see that battery charging voltage is 48 Volt in Fig. 6 and battery charging current is 5.32 Amps in Fig. 7. There is no overshoot in the output voltage and the output system will always be stabilized if closed-loop parameters are anyhow changed. Unlike PI Controller, Fuzzy Logic control has almost zero peak overshoot with low settling time. There is no overshoot found in simulation with fuzzy logic controller here shown in Fig. 6 and Fig. 7.

VII. SLIDING MODE CONTROLLER

Sliding Mode Controller (SMC) is a control system which also works as nonlinear mode. The output of SMC is a discontinuous signal, and this controller overcomes the slow response and transient oscillation caused by dynamic change in load. The SMC output manages the operating region of converter to slide in the cross section and to drive the converter [3,4].

The trails are always designed with multiple control structures sliding towards an adjacent section. For this reason, the entire trail will not occur with single control structure and by this way, the trail slides along the borders of the control system. The locus consisting of the borders is called the sliding surface and this motion of the system is called sliding mode control [5,6]. This methodology is used to force the system by sliding on the surface to reach towards its steady state response or a desired final value. The nonlinear dynamic nature of this controller and its higher characteristics against the disturbance makes it a reliable solution for battery charging applications because it has nonlinear dynamic nature, and also it has robustness against the ripple factor [7,9].

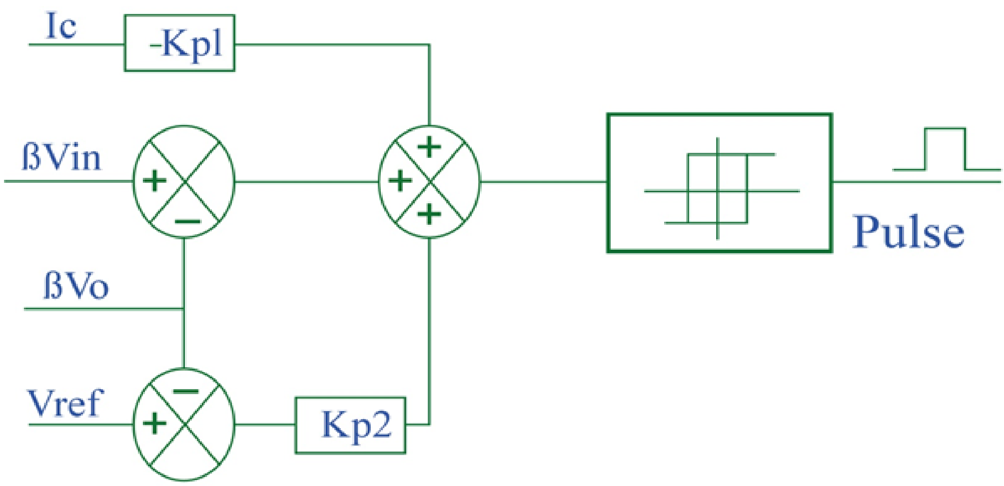

Fig.8. SMC Block Diagram

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The control voltage (Vc) equations in case of Split-Pi DC-DC Converter are essential for the battery charging applications which can be given as:

$$V_c = -K_{p1} i_c + K_{p2} (V_{ref} - \beta V_0) + \beta V_0 \qquad (3)$$

Here, $K_{p1} = \frac{1}{R_L C}$ and $K_{p2} = \frac{V_{ref}}{V_{out}}$

Where, K_{p1} and K_{p2} are the constant gain factors for the feedback signals i_c and $(V_{ref} - \beta V_0)$ respectively.

VIII. SIMULATION OF SPLIT-PI CONVERTER AND SOLAR SYSTEM WITH PROPOSED SLIDING MODE CONTROLLER

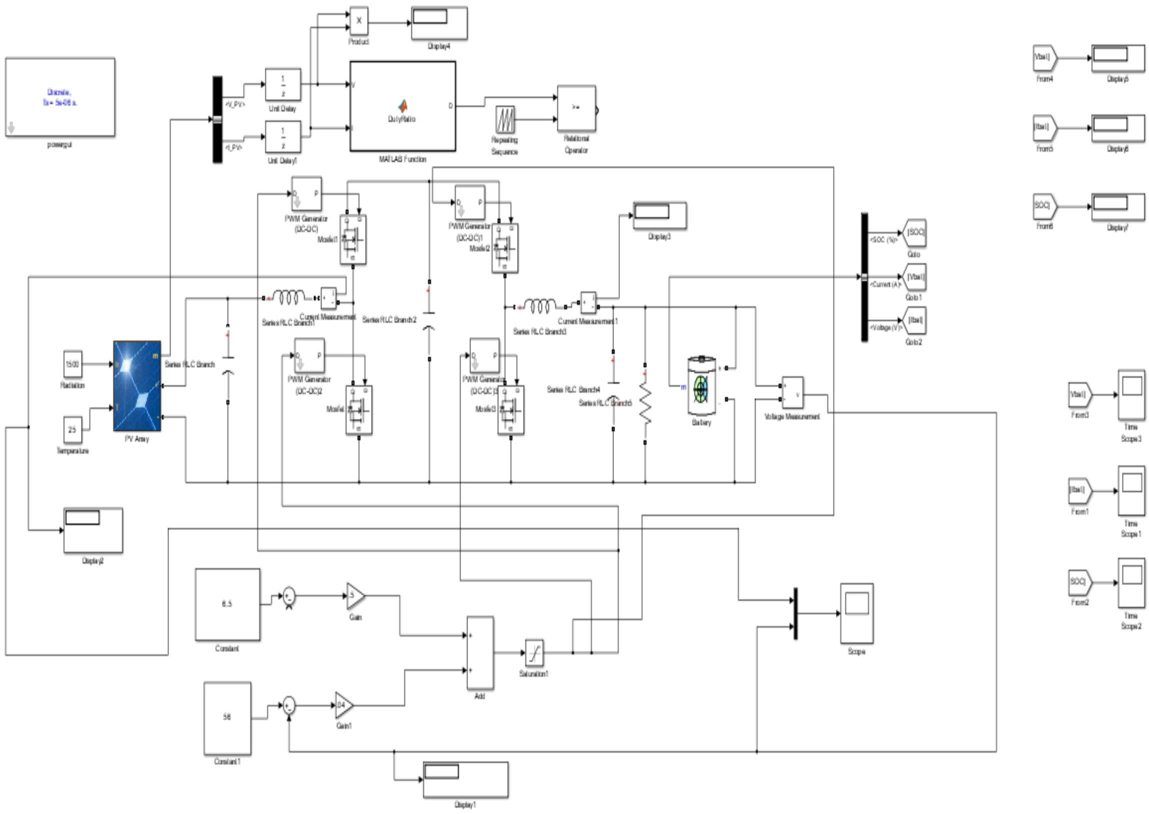

Fig.9. Split-Pi Converter fed SMC Controller

The controller used in this design is Sliding Mode Control (SMC). The simulation model figure of Split-Pi converter with SMC is given in Figure 9.

The Split-Pi converter is designed for 48V(output) with 29V (Input Voltage max. coming from solar PV panel). The battery chosen for this simulation is Lithium-ion battery, and the voltage and capacity of the battery is 48V and 50Ah respectively.

Simulation Parameters of Split-Pi converter: Inductance = 1000mH, Capacitance = 540µF, Switching Frequency = 10KHz, Output Resistance = 45 Ohms, Input Voltage = 29Volt, Output Voltage = 48Volt etc.

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IX. SIMULATION WAVEFORM OF SLIDING MODE CONTROLLER FED SPLIT-PI CONVERTER

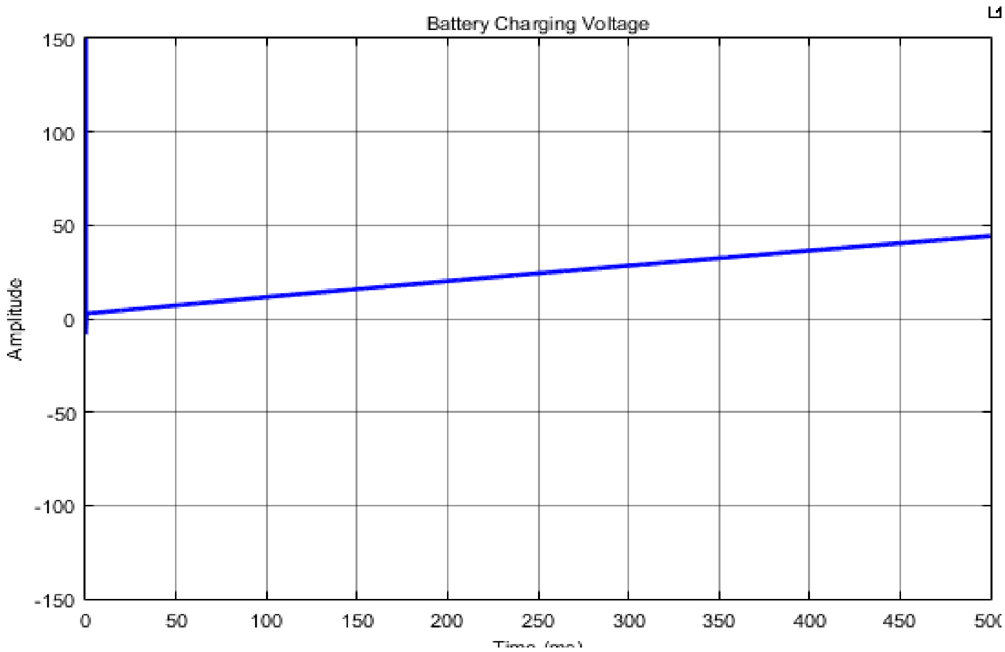

Fig.10. Battery Charging Voltage

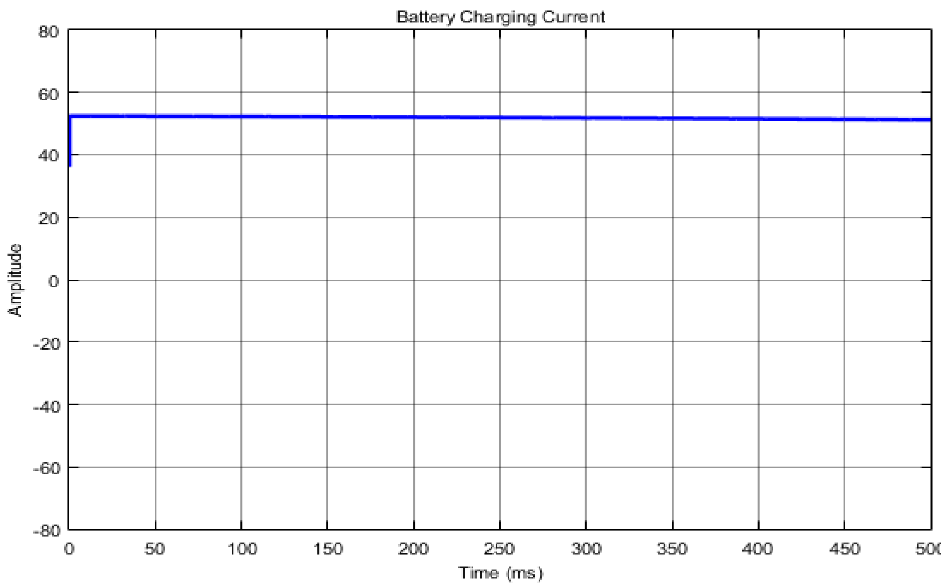

Fig.11. Battery Charging Current

The simulation output of sliding mode controller fed Split-Pi converter is showed in Figure 10 and Figure 11. The peak overshoot and oscillations are completely terminated shown in the above output waveform. Peak overshoot is completely reduced in Sliding Mode Controller as well. We have got the output voltage from SMC slightly less than reference voltage and charging current up to 52 Amps shown in Figure 11. Here voltage and current ripples are approximately zero compared to analyses with other controllers.

PI and PID controller will not be able to provide sufficient control action for sudden change in load. SMC will behave smooth operations in case of nonlinear control actions. Both voltage control mode and current control mode methods are used in this control process to get the constant output [12].

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X. BATTERY CHARGING FROM SOLAR PANEL USING SPLIT-PI CONVERTER WITH MPPT CONTROL

Split-Pi Converter is used with battery connected at the output terminal and this converter is controlled by MPPT algorithm (Incremental conductance MPPT Algorithm) showed in Figure 5 and Figure 9. PV Voltage and current has been processed with MPPT incremental conductance. This MPPT controls the PWM Generator.

The PWM Pulse then control the switch and the converter as well. The battery charging current is controlled and output DC bus voltage is controlled by the MPPT [1,2]. Here perturb and observe based MPPT algorithm has been analyzed. The battery and DC bus voltage is controlled with Fuzzy Logic controller and Sliding Mode controller as the DC bus voltage remains constant developed in both Fig. 5 and Fig. 9.

From the output with both simulations, we find that the MPPT power level is 387.4 for radiation at 1500 and the battery charging current is 0.003274 Amp. If the radiation level is decreased, then the MPPT Power level will decrease and battery charging current will also decrease. If the radiation is 1200, then the MPPT Power level is 311.7. In the meantime, the battery charging current also decreases and that is 0.002844 Amp. The battery current level changes simultaneously with solar radiation level.

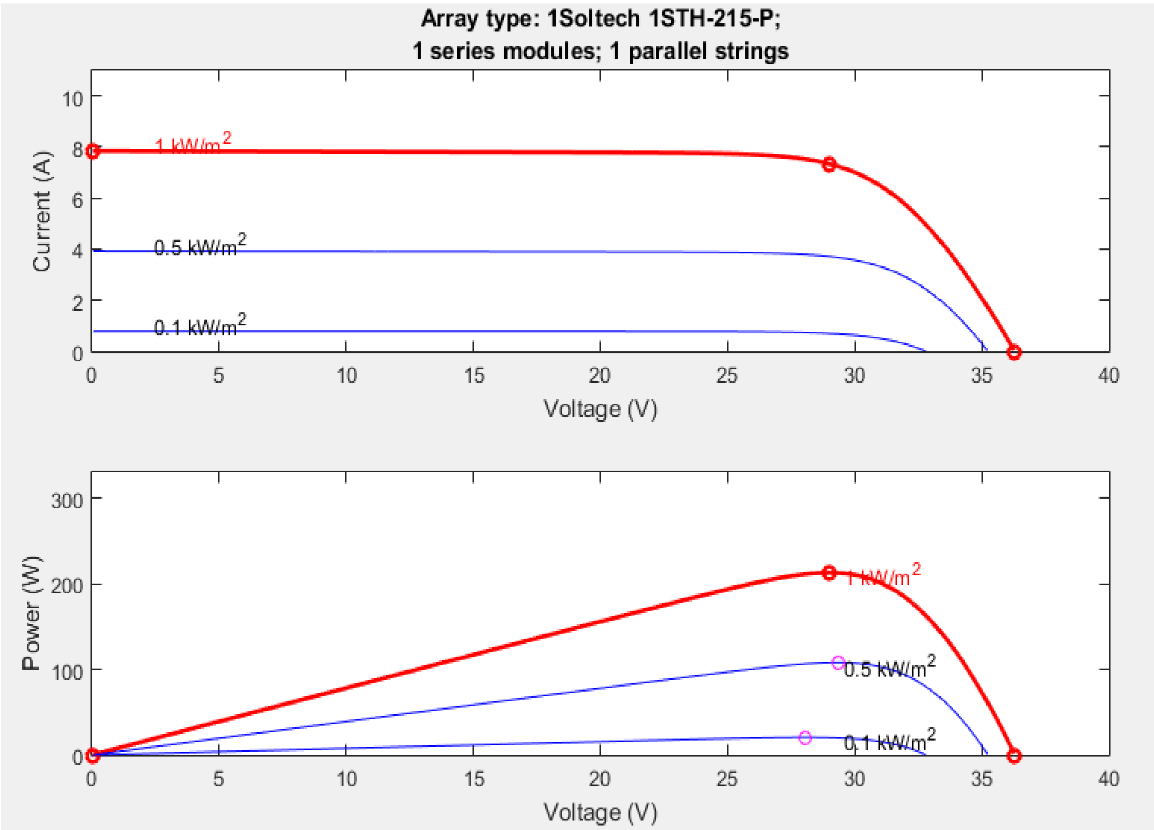

Fig.12. Voltage, Current and Power Curve of Solar Array

<u>MATLAB Function Code:</u>

```
function D = DutyRatio(V, I)

Dmax = 0.70;
Dmin = 0;
Dinit = 0.70;
DeltaD = 0.0001
persistent Vold Pold Dold;
```

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```
dataType = 'double';

if isempty(Vold)
   Vold = 0;
   Pold = 0;
   Dold = Dinit;
end

P = V*I;
dV = V-Vold;
dP = P-Pold;

if dP ~= 0
   if dP<0
      if dV<0
         D = Dold - DeltaD;
      else
         D = Dold + DeltaD;
      end
   else
      if dV<0
         D = Dold + DeltaD;
      else
         D = Dold - DeltaD;
      end
   end
else D = Dold;
end

if D >= Dmax || D <= Dmin
   D = Dold;
end

Dold = D;
Vold = V;
Pold = P;
```

To link the battery with DC bus and transfer energy with flexible control between them in EV charging applications and all their operating modes, a converter with bidirectional power flow capability is necessary for battery stations. The Split-Pi converter has been selected as a new converter which will exchange energy between the batteries and the drive motor. In the forward mode, the converter feeds the DC bus and in the reverse mode, the drive motor works in regenerative mode charging the battery pack through the Split-Pi DC-DC Converter.

This converter passes the power from step up to step down operation and can operate with bidirectional capabilities. They are highly applicable in EV battery management because the batteries are regulated at well understood voltages and the motors will be operated at a wide range of voltages to give a wider range of speed also. The Split-Pi converter includes all these features as it can be added for bidirectional operation, built in filters to reduce EMI issues and lower component count. This converter also has the possibilities of improving efficiency of the machines as it can be proved from its topology.

XI. CONCLUSION

In this paper, a Fuzzy Logic Controlled (FLC) and Slide Mode controlled (SMC) Split-Pi DC-DC converter for solar energy-battery systems has been presented. The Split-Pi converter circuit has been designed with MATLAB/Simulink and simulation results have been verified. FLC and SMC controllers have been modified, and the simulation results are compared. It can be seen from the results that there is no bit of overshoot in output voltage, and the output system is always stable which we cannot see with simulation of PI or PID Controllers. It can be noted that it is possible to use a fuzzy logic controller and sliding mode controller for Split-Pi converter regulated battery charging applications, and also beneficial to simulate the designed circuits in MATLAB/Simulink.

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Both of the controllers maintain the output voltage within threshold limits as well, and eradicates overshoot and generated oscillations completely while transient state comes. The simulation results confirm that analyzing the proposed controllers have no ripple but have fast settling time and zero peak overshoot. All the outputs are well suitable for battery charging applications in EVs and validate the operation of the presented converter topology.

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