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Design and Simulation of Non-Linear Control System fed Bidirectional Converter for Solar Energy Controlled Battery Charging Applications

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Abstract: Due to continuous variations of charging level batteries, connected loads can be different in electric vehicle (EV) charging stations. The linear controllers such as PI, PD, 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 different critical situations and EV charging stations come 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 non-linear Fuzzy-Logic Controller (FLC) and Sliding Mode Controller (SMC) for EV charging applications. The Fuzzy-Logic controller and slide 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 throughout checking different characteristics of both controllers. Split-Pi converter is a recently invented DC-DC converter which has great potential in the power electronics fields. Because it has less components and lower switching losses. The closed-loop operation of this converter topology has been 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 etc. 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. But 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 maintaining the reference voltage to produce error output signal, and both output voltage and inductor current are sensed for 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 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 despite their drawbacks. Because, linear controller generates peak overshoot voltages and increase the charging current transients which will damage the battery in practicing battery charging stabilities [10,11]. Then the battery will show inappropriate characteristics and provide instability. So, we will get unstable outputs by the power converters and the system cannot be stable [14,15]. Thus, the non-linear controllers called fuzzy logic controller and sliding mode controller has been investigated in this paper to improve the charging of the battery. The outcome of FLC and SMC control over Split-Pi bidirectional converter for battery charging applications has been performed, and analyzed over battery state of charge observation of the total charging time in simulation. Charging circuit consisting of battery and PV has been incorporated, and the control methods have been examined throughout the simulations. Finally, the comparison has been made upon the simulation results.

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 two modes such as buck and boost mode. The switch S1 is turned on and switch S2 is turned off during the total period of buck mode. Switches S3, S4 work 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 full period while operating in the boost mode. Switches S1 and S2 operate in antiphase relative to each other same as the boost converter operates and works in switch modes.

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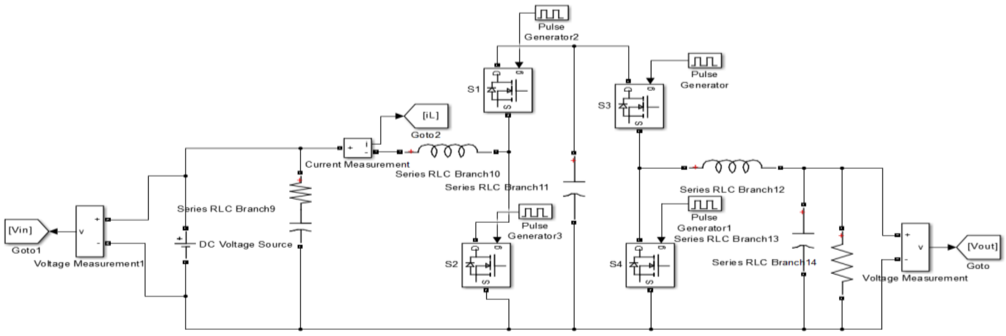

Fig.1. Conventional Split-Pi Converter in MATLAB/Simulink

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 there with all other advantages.

The recent topology of a bidirectional converter, named as Split-Pi converter 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 very useful for electric vehicles also. This topology can also be applicable in multiphase systems, so it can be connected in parallel also where the dimensions and cost of components can play a significant role. Another benefit is that this converter can provide both of higher and lower output voltage with respect of the reference 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 structured. The proposed Split-Pi converter system is simulated by using MATLAB/Simulink operational blocks and control systems. The proposed converter system is basically applied for a solar energy-battery system as shown in Fig. 2.

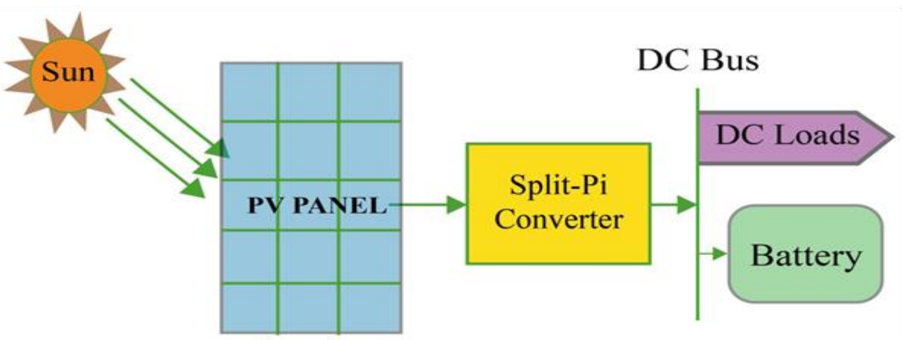

Fig.2. Solar Energy Battery Charging System

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. Here, *r(s)* is the reference voltage and *y(s)* are the measured output voltage values for FLC control development. Then the error voltage is calculated using equation (1)

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

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The change in the error voltage is also calculated as,

$$de(s) = e(s) - e(s\text{-}1) \quad (2)$$

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

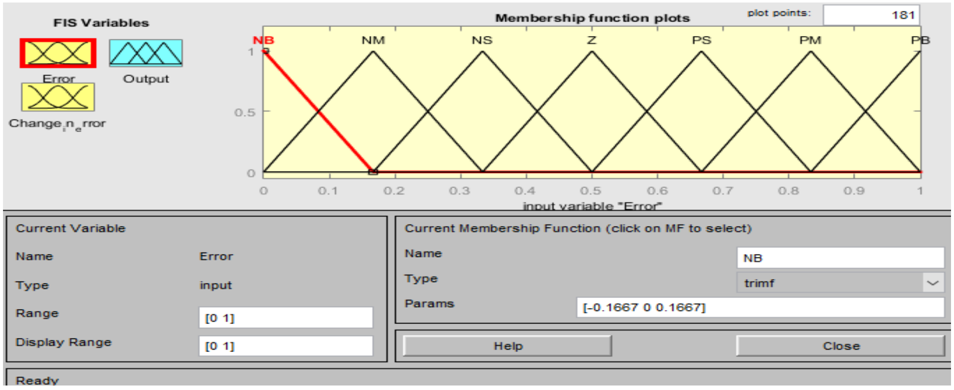

Fig.3(a). Membership Function for Error

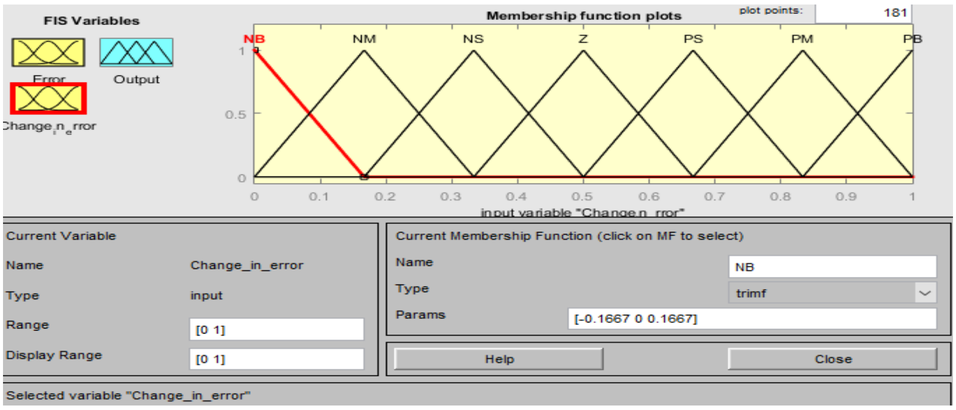

Fig.3(b). Membership Function for Change in Error

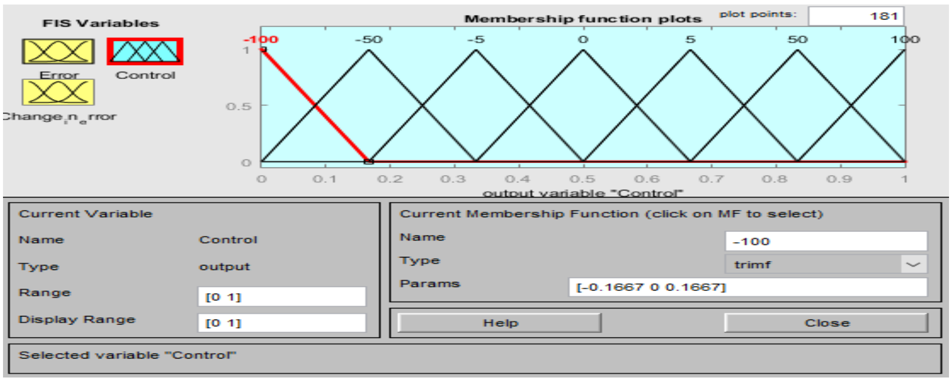

Fig.3(c). Membership Function for Control

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.

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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.
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 the following table for three fuzzy regions. The Simulink design will be performed using this rule table and FLC rule-based controller.

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TABLE. 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

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.

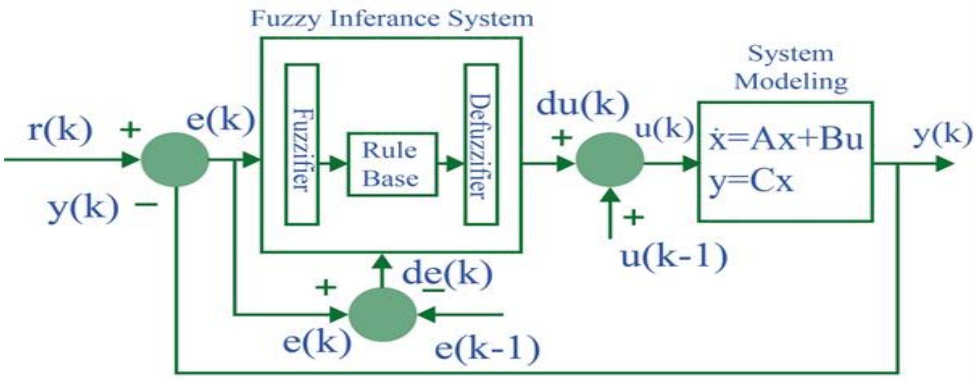

Fig.4. Block Diagram of Fuzzy Logic Controller with Feedback Modeling System

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 the generated signal drives the MOSFET switching devices.

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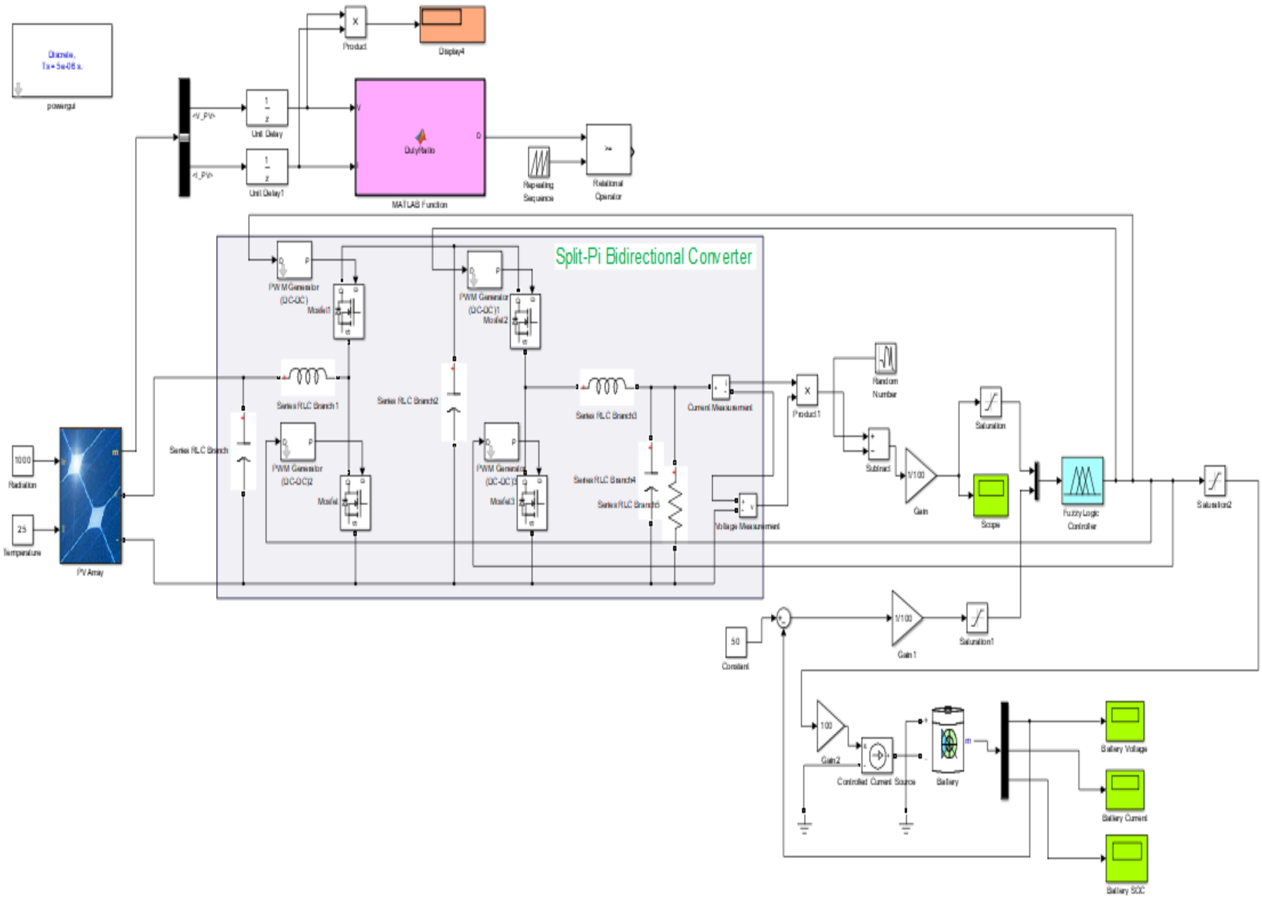

Fig.5. FLC based Split-Pi converter simulation

The Split-Pi converter has been analyzed with 48V (output) and 29V (Input Voltage max. from solar PV panel). The battery chosen for this simulation is lithium-ion battery. The voltage and capacity of the battery is maintained at 48V and 150Ah during the simulation.

Simulation parameters of Split-Pi converter investigated for the proposed analysis: Inductance = 1000mH, Capacitance = 540µF, Switching frequency = 10KHz, Output resistance = 45 Ohms, Input voltage = 29Volt, Output voltage = 48Volt etc.

VI. SIMULATION RESULTS

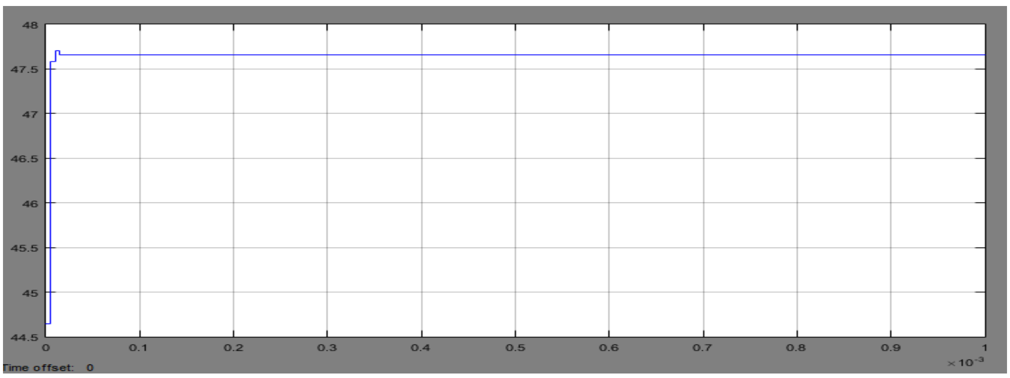

Fig.6. Simulation of Battery Charging Voltage (47.65V Approx.) on FLC

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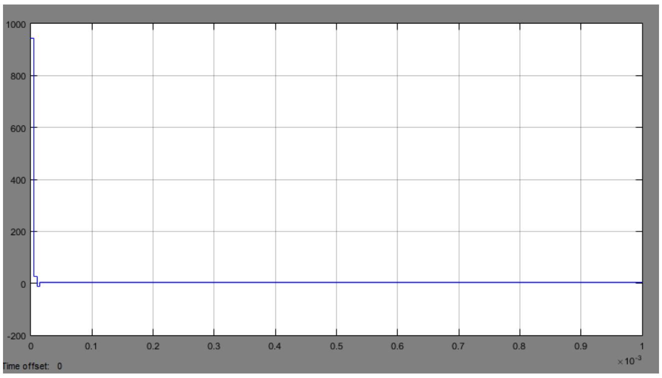

Fig.7. Simulation of Battery Charging Current (5.32A)

From the simulation outputs, we can observe that battery charging voltage is 47.65V (Approx.) in Fig. 6 and battery charging current is 5.32 Amps in Fig. 7. There is a very lower overshoot in the output waveforms, and the output systems will always be stabilized if closed-loop parameters are anyhow changed in terms of simulation. Unlike PID Controller, fuzzy logic control has almost zero peak overshoot with no delay time and low settling time here. The detailed simulation outputs with fuzzy logic controller based bidirectional Split-Pi topology are 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. In addition to these advantages, it has nonlinear dynamic nature and also it has robustness against the ripple factor [7,9].

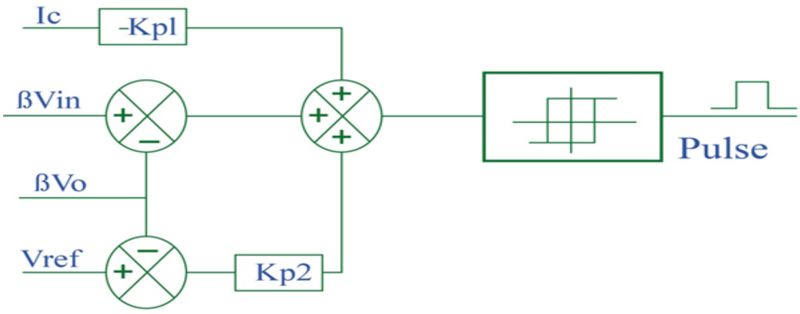

Fig.8. SMC Block Diagram

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:

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

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.

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VIII. Simulation of Split-Pi Converter and Solar System with Proposed Sliding Mode Controller

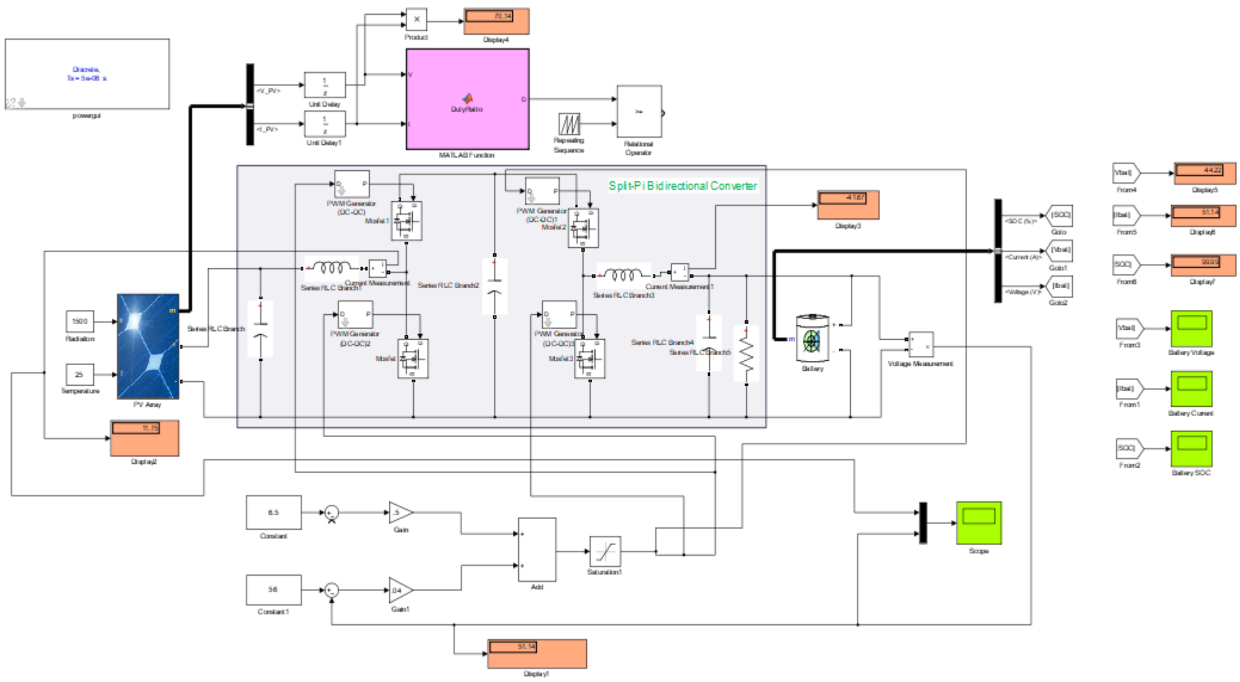

Fig.9. Simulation of Split-Pi Converter fed Slide Mode Controller

The controller used in this design is slide 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. from solar PV panel). The battery chosen for this simulation is lithium-ion battery, and the final output is optimized according to the battery voltage and capacity.

Therefore, the simulation parameters illustrated for the proposed system: Inductance = 1000mH, Capacitance = 540µF, Switching frequency = 10KHz, Output resistance = 45 Ohms, Input voltage = 29Volt, Output voltage = 48Volt etc.

IX. Simulation Waveform of Sliding Mode Controller fed Split-Pi Converter

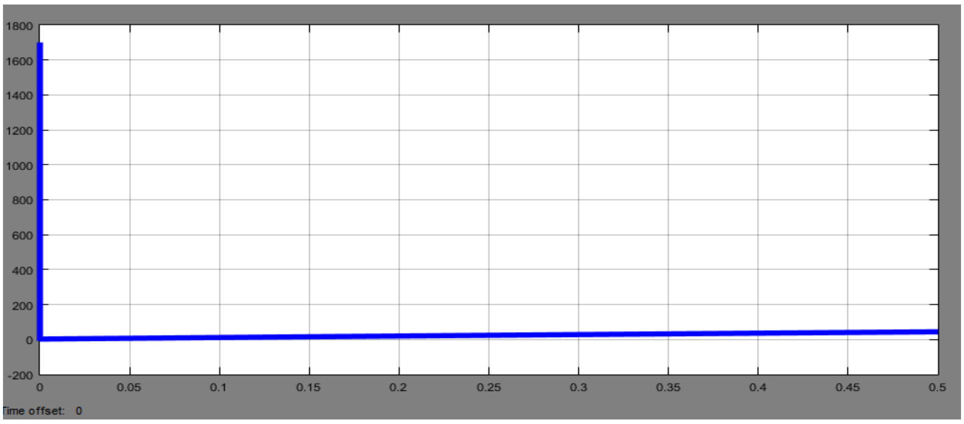

Fig.10. Battery Charging Voltage with SMC fed Converter

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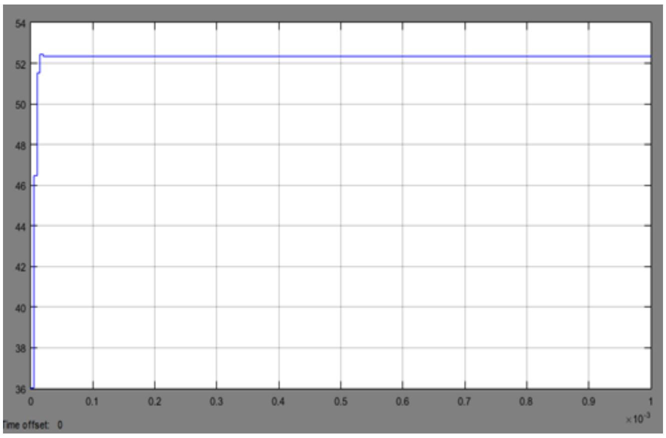

Fig.11. Simulation of Battery Charging Current

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 waveforms. Peak overshoot is almost reduced found in simulation throughout sliding mode controller system same as the non-linear control systems does. We have found the output voltage from SMC slightly less than reference input (shown in the simulation figure 9). It is observed that there are almost zero output ripples comparing to different linear control system analyses and simulations. PI and PID controller will not be able to provide sufficient control action for sudden change in load. But FLC and SMC will provide the smooth operations in terms of nonlinear control actions. Both voltage control mode and current control mode methods are efficient in such control applications to find the accurate output [12].

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 control the switch and the converter as well. The battery charging current and output DC bus voltage is controlled by the MPPT [1,2]. Here perturb and observe based MPPT algorithm has been discussed. The battery and DC bus voltage is controlled with fuzzy logic controller and sliding mode controller as the DC bus voltage is kept constant measured in both of Fig. 5 and Fig. 9.

From observation of the 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. It is clear that the battery current level changes simultaneously with change of solar irradiation level.

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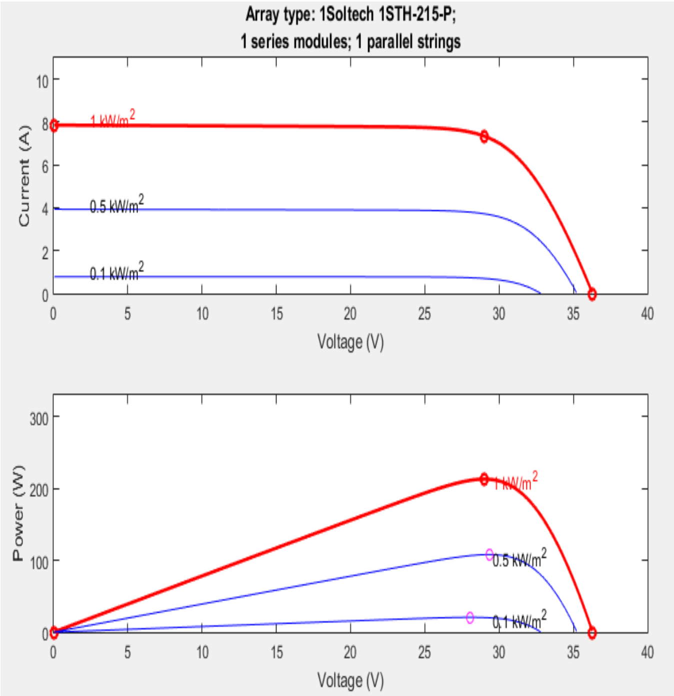

Fig.12. Voltage, Current and Power Curve of Solar Array

<u>M-File Function Code in Simulink:</u>

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

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

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;
```

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```
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 including all operating modes, a converter with bidirectional power flow capability is necessary and useful. The Split-Pi converter has been selected as a new bidirectional 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 bidirectional Split-Pi converter. This converter passes the power from step up to step down modes and can operate implying bidirectional capabilities. This can be highly applicable in EV battery management at present. 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 proposed Split-Pi converter includes all these features as it can be highly applicable for bidirectional EV operations, built in filters to reduce EMI issues and lower component counts. This converter also has the possibilities of improving efficiency for various motor drives as it has been proved from its topology.

XI. CONCLUSION

In this paper, two non-linear controllers named as fuzzy logic controller (FLC) and slide mode controller (SMC) fed Split-Pi bidirectional converter for solar energy-battery systems has been presented and discussed. The Split-Pi converter circuit has been designed with MATLAB/Simulink and simulation results have been verified. FLC and SMC controllers have been performed, and the simulation results are compared. It can be seen from the results that there is no bit of overshoot in the output performances, and the output system is always stable which we cannot see on simulation with linear PI or PID controllers. So, it is beneficial to use a fuzzy logic controller and sliding mode controller for Split-Pi converter-based battery charging applications, and those controllers have better output results comparing to other linear controllers on MATLAB/Simulink platform. Both of the controllers maintain the output voltage within threshold limits as well, and eradicates peak overshoots and higher oscillations completely while transient state comes. The simulation results confirm that analyzing the proposed non-linear controllers and proposed bidirectional converter have no ripples, and have fast settling time covering zero peak overshoot. All the outputs are here well settled throughout every analysis of battery charging applications in EVs and the final outcomes validate the operation of the presented converter methodology.

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