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State space controller of SLCC and design analysis with MPPT approaches

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ABSTRACT

Power systems with standalone properties like remote unit telecommunication network requires high negative DC supply voltage. In such remote places, solar photovoltaic (PV) are used to generate power. Maximum power point tracking techniques (MPPT) gives unregulated voltage from solar panel. This unregulated voltage is converted into regulated voltage by providing proper pulse width modulation (PWM) signal to self-lift cuk converter (SLCC). In comparison with classic cuk converter, SLCC reduces load voltage and load current ripples. This paper focuses on state space controller design and implementation of SLCC used in MPPT based PV system. The switching pulse of SLCC can be generated by perturb and observe (P&O), incremental conductance (IC) and also using fuzzy control. The simulation of SLCC has been performed using MATLAB/Simulink and its specifications in time domain has been compared.

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1. INTRODUCTION

The global demand for energy is consistently on the rise, prompting an increasing interest in alternative and alternative energy sources like biofuel, bio-mass, tidal, wind and solar power. Among these alternative energy sources, solar power systems stand out as a highly flexible option due to their ubiquitous availability on Earth [1]. Photovoltaic (PV) systems, also known as solar power systems converts light energy to electrical energy, providing a clean and sustainable source of power [2], [3]. Converters play an important role in PV systems, ensuring efficient and reliable energy conversion.

The efficacy of basic DC-DC converters (boost, buck-boost) becomes crucial, necessitating high conversion gain and efficiency [4]. This is essential for handling substantial input currents and sustainable stress at load side. These drawbacks can been overcome by self-lift cuk converter (SLCC). In this paper, the SLCC known for its ability to provide high gain with greater power density, improved efficiency and lower ripple current [5]-[10] has been discussed. SLCC show variation in their output due to change in supply as well as load. This can be overcome by implementing controllers such as voltage mode controller, and proportional-integral (PI) controller [11], [12]. To obtain the maximum power from PV system, different algorithms such as perturb and observe (P&O), and incremental conductance (IC) are compared for basic DC-DC converters [13], [14]. State space controller being a robust controller has gained popularity compared to other classical controllers [15]-[17]. In this paper, state space controller has been implemented and time domain specifications of SLCC for different maximum power point tracking techniques (MPPT) techniques has been compared.

The paper structure is outlined as: section 2 explores different MPPT techniques. Section 3 and section 4 elaborate on the operation and simulation results of the SLCC. Finally, section 5 concludes the paper by assessing the performance of the SLCC with various control strategies, including state space controller, P&O, IC, and fuzzy controller.

2. DIFFERENT MPPT TECHNIQUES

Efficiency of solar irradiance which is capable of converting electrical energy by a standard PV is around 30-40%. PV cells efficiency is maximum when the Thevenin impedance equals the impedance of load as per the maximum power transfer theorem using MPPT. ASLCC is employed at source side which is linked to a panel of solar cells to boost the output voltage. Adjusting the pulse width modulation (PWM) signal of the SLCC in a suitable manner enables the matching of source impedance to load impedance.

2.1. Perturbation and observation algorithm

The P&O algorithm is widely utilized for tracking the maximum power from a solar cell. As the name suggests, the reference voltage (Vref) can be either increased or decreased to perturb the system or by manipulating the PWM signal of the SLCC. The effect on the output power can be observed by this algorithm. The direction of the disturbance can be maintained when the P(k) (power value at current state) of the panel is higher P(k-1) (power value at previous state), otherwise, the direction is reversed from the previous cycle. Figure 1 depicts the P&O algorithm flowchart.

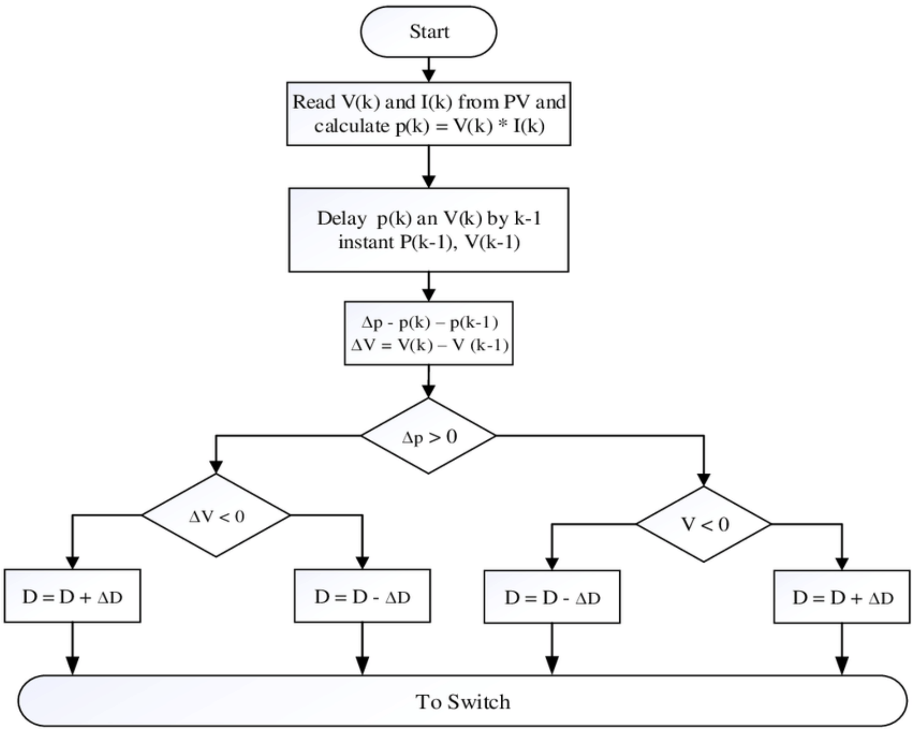


Figure1. Flow diagram of P&O algorithm

2.2. Incremental conductance algorithm

The P&O algorithm have a drawback of oscillation of maximum power tracking in PV which can be overcome by IC method [18]. The IC method determines the change in conductance (di/dv) of the PV systems. In this algorithm load voltage and current of the PV array are monitored by sensors.

$$\frac{dI}{dV} = -\frac{I}{V}\left(\frac{dP}{dV} = 0\right) \quad (1)$$

In (1), the left-hand side (LHS) represents IC of the PV module and the right hand side (RHS) represents the instantaneous values of conductance in PV panel. Using (2) and (3), the maximum power can be calculated and the Figure 2 shows the step-by-step approach for IC.

$$\frac{dI}{dV} > -\frac{I}{V}\left(\frac{dP}{dV} > 0\right) \quad (2)$$

$$\frac{dI}{dV} < -\frac{I}{V}\left(\frac{dP}{dV} < 0\right) \quad (3)$$

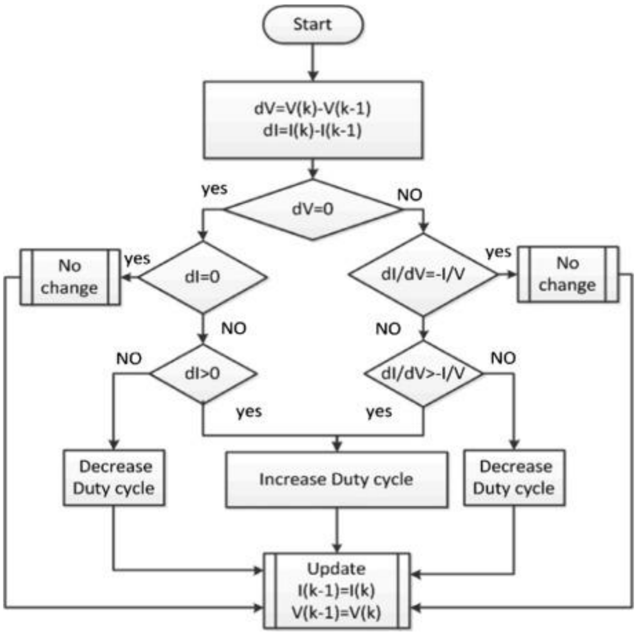


Figure 2. Flow diagram of IC algorithm

2.3. Fuzzy logic MPPT

The fuzzy MPPT shows better operational characteristics like speed, accuracy and adaptability [19] than P&O and IC methods. fuzzy logic-based control (FLC) has become more popular because of its adaptability to imprecise inputs and independence from precise mathematical models and its effectiveness of managing nonlinearity [20], [21]. Based on expert knowledge, rule frame of the fuzzy structure and its outcomes, the fuzzy controller can be designed.

$$Error(e) = V_{ref} - V_o \quad (4)$$

In (4), the FLC takes error value (e) as input variables and produces duty cycle (k) as the output variable which tack the MPP. In this method, by separating the universe of discourse into equal intervals and associating linguistic values with these intervals through membership functions for each input and output fuzzy variable is done. Triangular membership functions for input and output variables are shown in Table 1. The linguistic terms are defined with help of membership functions for each variable, allowing the FLC to make decisions and control the system based on expert rules and fuzzy logic reasoning.

Table 1. Fuzzy membership functions

	Membership functions
NM	Negative medium
NS	Negative small
z	Zero
PS	Positive medium
PM	Positive small

The variables of the input and output have been formed into a set of rules. Output from fuzzy controller is determined using 15 IF-THEN rules. Figures 3 to 5 gives the FLC input voltage, input power and duty cycle (output) membership function respectively. The difference between the reference and output voltage of the FLC is taken as input error and produces a duty ratio for regulating the output voltage of DC-DC converter.

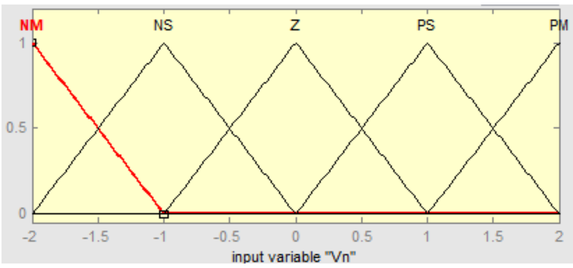


Figure 3. Input voltage membership function

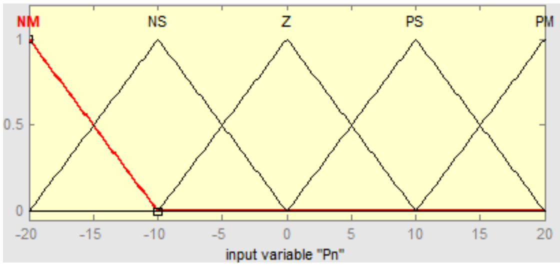


Figure 4. Input power membership function

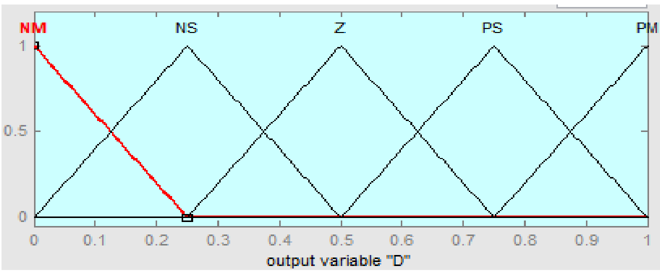


Figure 5. Duty cycle (output)membership function

3. OPERATION AND DESIGN OF SLCC

The circuit of SLCC and its equivalent circuits during switch-on and switch off periods are illustrated in Figures 6 to 8. In this work, continuous conduction mode (CCM) has been analyzed for SLCC. Operating modes of SLCC, the CCM of the converter is described by two distinct modes, 1) switch ON period and 2) switch OFF period.

1) Switch ON period: the equivalent diagram of SLCC switch ON period is shown in Figure 7. When MOSFET is switched ON, Diode D_1 is ON and D_2 is OFF. Capacitor C_1 lifts the output capacitor voltage V_{co} to the capacitor voltage V_C.
2) Switch OFF period: the equivalent circuit of SLCC switch OFF period is shown in Figure 8. When MOSFEET is switched OFF, Diode D_1 is in OFF condition and D_2 becomes ON. Capacitor C_1 lifts the output capacitor voltage V_{co} to the capacitor voltage V_C.

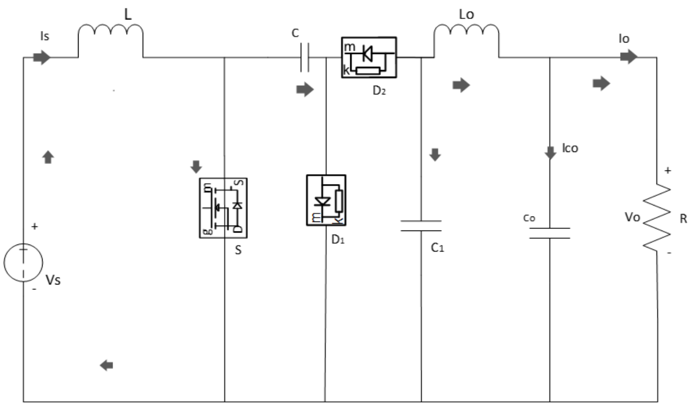


Figure 6. Circuit diagram of SLCC

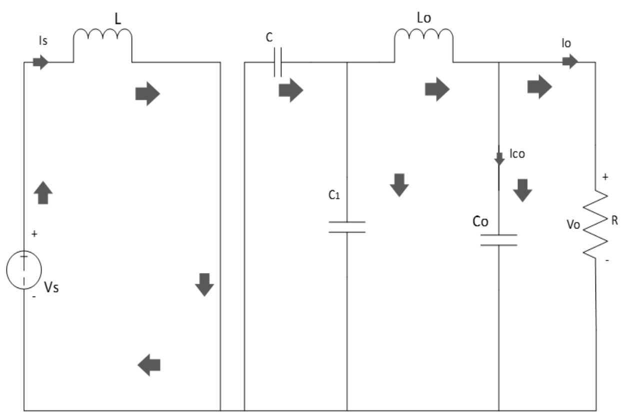


Figure 7. SLCC switching ON period

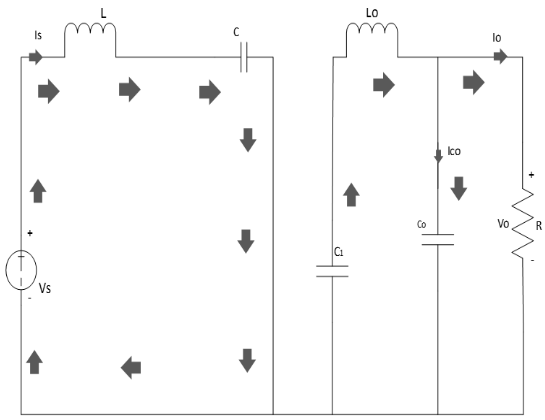


Figure 8. SLCC OFF period

The parameters for negative output SLCC were designed with following considerations and tabulated in Table 2. Input voltage: 96 V, switching frequency: 50 KHz, load resistance: 100 Ohms. For the above design output is obtained as -320 V.

Table 2. Design values

	Values
Input voltage	96V
Output voltage	-320V
D	0.7
Switching frequency(F)	50KHz
L	2.5mH
L_o	250µH
C	13.3µF
$C_0=C_1$	1.2µF
R	100Ω

4. SIMULATION RESULT

4.1. State space controller design

In the state space controller design, the system states are obtained using state space averaging (SSA) technique [22]-[25]. The gain matrix K should be chosen properly and fed back, such that it should be multiplied by states of the system. The input to the system is the state vector x multiplied with the gain vector K i.e., u=−Kx. The value of input, u=−Kx is replaced in (5) to derive the adapted closed loop equations for state space.

$$\dot{x} = Ax + Bu = Ax + B(-Kx) = (A - BK)x \tag{5}$$

Using SSA, obtained state space matrices of SLCC are given below,

$$A=\begin{bmatrix} 0 & 0 & -\frac{(1-D)}{L} & 0 & 0 \\ 0 & 0 & \frac{D}{L_0} & \frac{1-D}{L_0} & \frac{1}{L_0} \\ \frac{1-D}{C} & \frac{D}{C+C_1} & 0 & 0 & 0 \\ 0 & \frac{C(1-D)+C_1}{(C+C_1)C_1} & 0 & 0 & 0 \\ 0 & \frac{1}{C_0} & 0 & 0 & -\frac{1}{RC_0} \end{bmatrix} B=\begin{bmatrix} \frac{V_{in}}{L(1-D)} \\ \frac{V_{in}+(1-D)V_{C0}}{L_0(1-D)^2} \\ \frac{I_{L0}}{C+C_1}\frac{D}{1-D)} \\ 0 \\ 0 \end{bmatrix} C=\begin{bmatrix} 0 & 0 & 0 & 0 & 1 \end{bmatrix} D=(0)$$

where A - state matrix, B - input matrix of duty cycle and C and D - output matrix. The eigenvalues of matrix (A - BK) govern the stability and time domain behavior of the closed-loop system. The eigen values of the system can be determined using MATLAB. Simulink model and output voltage of SLCC with state space controller shown in Figures 9 and 10.

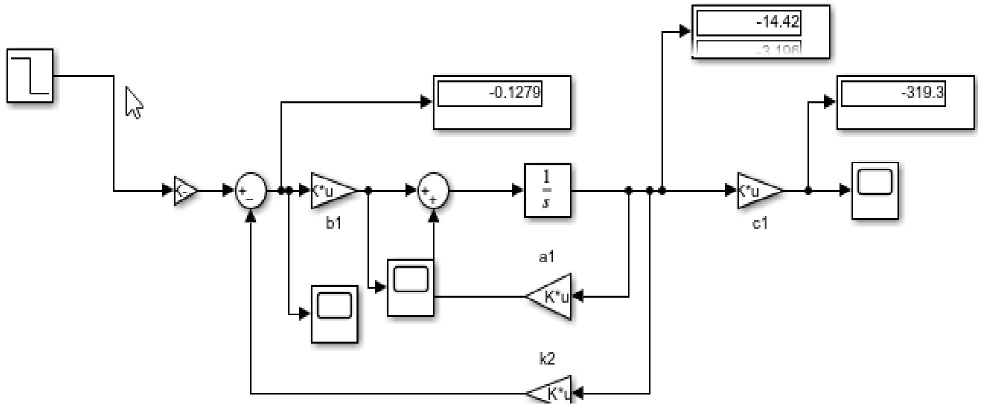


Figure 9. Simulink model of state space controller

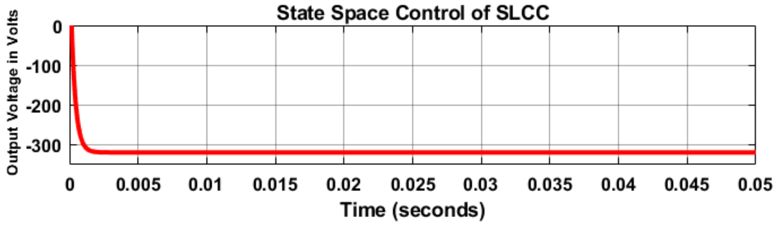


Figure 10. SLCC output voltage with state space controller

4.2. P&O algorithm

The electrical characteristics are employed to obtain the voltage and current output of PV by directly adjusting the PWM signal of the SLCC using this algorithm. The DC-DC converter gives constant power output from the solar panel. From Figure 11, the entire PV system integrated with MPPT and the SLCC, can be modelled using MATLAB/Simulink. The PWM signal of the SLCC can be dynamically tuned through the realization of the P&O algorithm and corresponding output waveforms are illustrated in Figures 12 and 13.

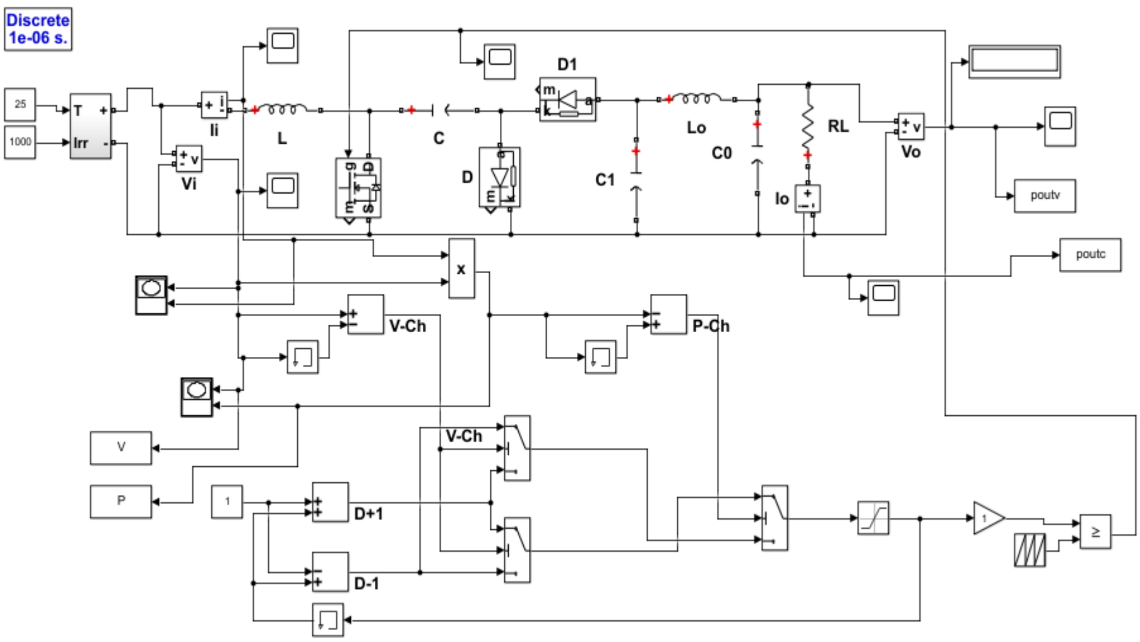
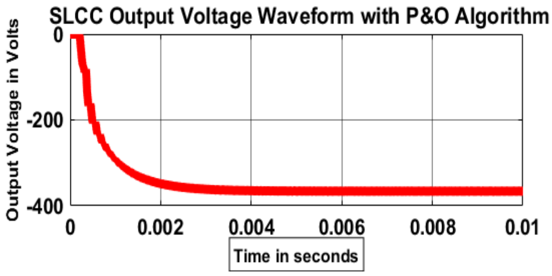


Figure 11. SLCC Simulink model with P&O algorithm



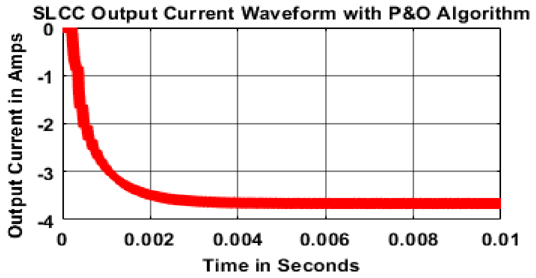


Figure 12. SLCC output voltage with P&O algorithm Figure 13. SLCC output current with P&O algorithm

4.3. IC algorithm

The model incorporating MPPT is simulated using MATLAB/Simulink shown in Figure 14 and PWM signal of the SLCC is dynamically controlled through the IC algorithm and corresponding waveforms are shown in Figures 15 and 16.

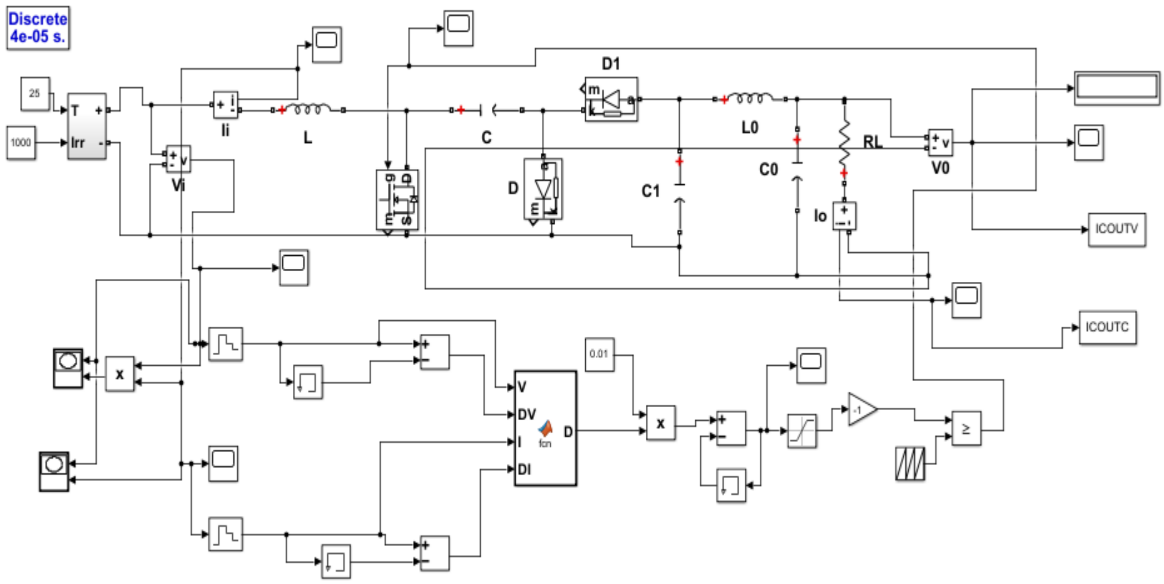
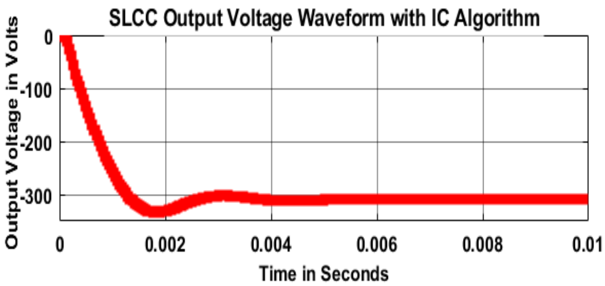


Figure 14. SLCC Simulink model with IC algorithm



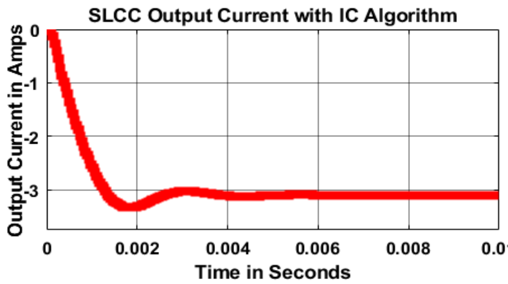


Figure 15. SLCC output voltage with IC algorithm Figure 16. SLCC output current with IC algorithm

4.4. Fuzzy controller

The simulated model incorporating MPPT is shown in Figure 17 and PWM signal of the SLCC can be dynamically varied through a fuzzy controller and corresponding waveforms shown in Figures 18 and 19. Table 3 shows the specification for time domain of SLCC with various MPPT techniques.

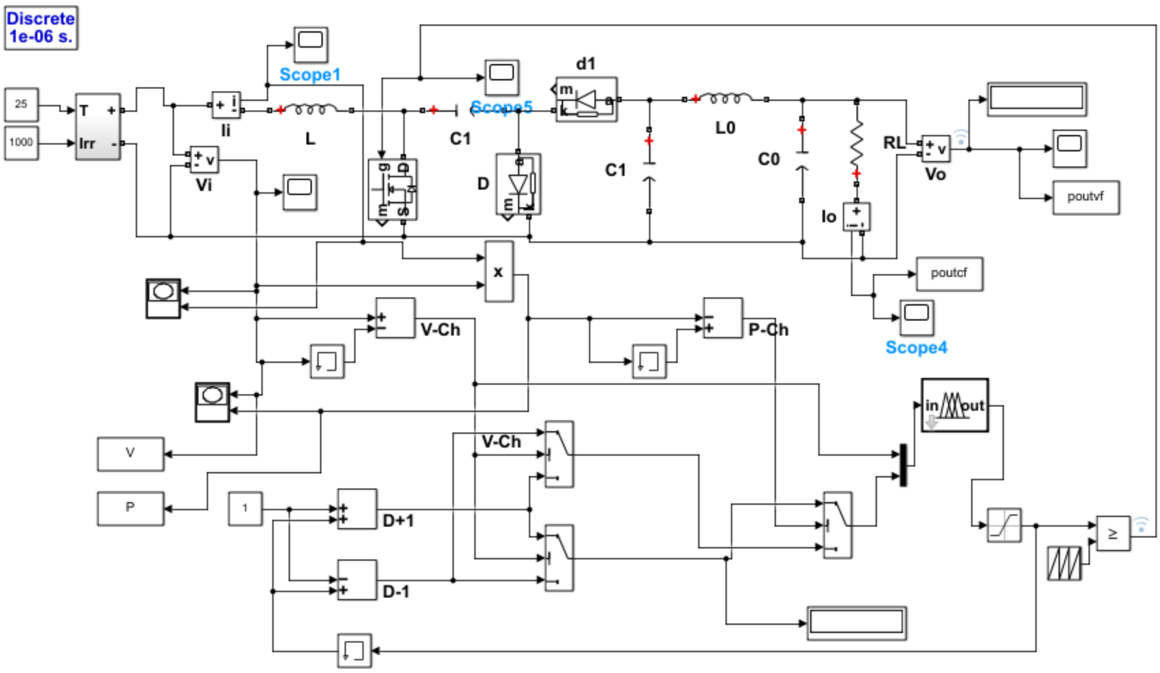
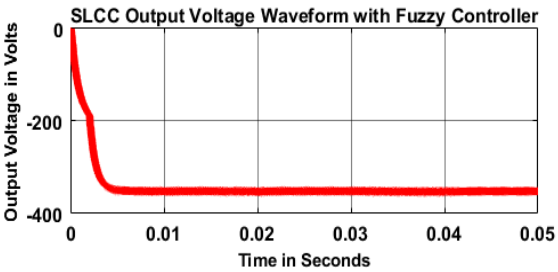


Figure 17. SLCC Simulink model with fuzzy controller



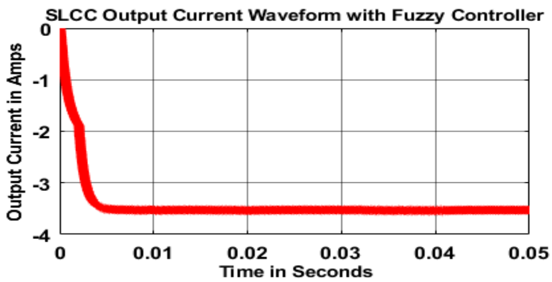


Figure 18. SLCC output voltage with fuzzy controller Figure 19. SLCC output current with fuzzy controller

Table 3. Time domain specification of SLCC

Parameters	State space controller	P&O	IC	FLC
Input voltage (V_{in}) in volts	96	96	96	96
Maximum peak overshoot (M_P) in (%)	0	0	20	0
Settling time (t_s) in sec	0.005	0.005	0.004	0.005
Rise time (t_r) in sec	0.05	0.025	0.001	0.001
Output voltage (V_O) in volts	-319.3	-366	-309.6	-319

5. CONCLUSION

In the proposed work, the implementation of SLCC with various MPPT algorithms and state space controller has been analyzed. The comparison aims to evaluate and discern the effectiveness of different MPPT techniques in optimizing the overall performance of the SLCC. Even though the state space controller is robust in nature but the steady state error cannot be elimated effectively. From the simulation results of SLCC with P&O, IC, and FLC, it has been inferred that the fuzzy controller out performs the other two methods and has less setting time.

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AUTHOR CONTRIBUTIONS STATEMENT

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Jeyaprakash Natarajan	✓	✓	✓	✓	✓	✓	✓	✓	✓			✓	✓	
Nivethitha Devi Manoharan		✓	✓	✓		✓					✓	✓		
Mohanasanthosh Murugan		✓	✓		✓		✓	✓		✓	✓			
Karnati Venkata Lokeshwar Reddy		✓	✓		✓		✓	✓		✓	✓			
Thirumalaivasal Devanathan Sudhakar		✓	✓			✓	✓					✓	✓	✓

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

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