Design and implementation of an improved sliding mode controller for maximum power point tracking in a SEPIC based on PV system

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In this paper, a standalone photovoltaic (PV) system with an improved sliding mode control (SMC) based on the maximum power point tracking algorithm is presented. The system contains a solar panel, a single-ended primary-inductor converter, a control part, and a load. Because of the nonlinear behavior of the switching and solar panels, designing a nonlinear controller for the system is crucial. The principal purpose of this study is to propose a new approach to resist the PV system against uncertain conditions. The stability and robustness of the system are investigated in a normal situation, under uncertainty conditions, as well as under changes in environmental conditions. Both simulation and laboratory experimental results show that the controller has a precise and fast response in comparison with a more conventional controller.

KEYWORDS
dual-output converter, maximum power point tracking, photovoltaic system, single-ended primary-inductor converter, sliding mode controller

1 | INTRODUCTION

Photovoltaic systems (PVs), in both standalone and on-grid types, are inherently expensive and low efficient systems. There are two ways to compensate the costs and increase the efficiency: The structure of the PV generator is changed at the implementation stage; the converter, which is linked to the PV generator, is controlled to attain the maximum power. The latter approach is the so-called maximum power point tracking (MPPT) algorithm. The MPPT methods can be mainly classified as follows: offline, online, and hybrid.

Off-line technique is operated based on an approximation of the open-circuit voltage or the short-circuit coefficient. This is a simple procedure, but it is not sufficiently precise. As a result, online approaches are used to increase accuracy. But in these methods, the speed of tracking the maximum power point is reduced. Hybrid methods are used to a trade-off between online and offline methods, but they are costly methods. In the online methods, perturbation and observation (P&O) and incremental inductance (INC) methods are furthermost commons among other online methods.

In some nonlinear systems, a linear controller such as the proportional-integral (PI), is used. Nevertheless, these MPPT techniques are based on a linearization of the system in proximity of the operation point, while the switching signals of power electronic converters and PV systems are fundamentally nonlinear. In the work proposed by Trejos et al., the input current of the converter is regulated by a linear control of the inductor current, which is based on the linearization of the PV model. This controller cannot guarantee the proper performance of the system at all PV operating points, because the operating point changes with load variations and environmental conditions. In other words, the convergence to the slip surface is an asymptotic one, so in practice, the steady-state current error does not tend to zero. Consequently, nonlinear
controllers will be further approving. Sliding mode control (SMC) is well known as one of the most robust nonlinear controllers. It is also used in solar systems to adjust the voltage of PV.

To overcome the current error problem, Bianconi et al. introduced an SMC independently unaided by the operating point parameters associated with the PV model. In addition, only one wide bandwidth sensor is employed and due to the zero current of direct-current (DC) capacitive, it is easier to use the current sensor for the input capacitor. This approach is a more appropriate method, because it does not depend on the source parameters. However, it uses a linear controller (PI). Therefore, it cannot be accurate in all operating areas of the PV. Montoya et al. applied a conventional SMC to control the photovoltaic system. This nonlinear controller does not have the disadvantages of a linear controller; however, the convergence of the slip surface of a conventional SMC is asymptotic at the distant point of slip surface, ie, its steady-state error (SSE) is not zero at the distant point of slip surface. To fix the problem, a nonlinear controller with a fast terminal slip surface for a boost converter with constant input voltage is proposed in the work by Mamarelis et al., where a boost converter is used to increase the output voltage. However, the converter of a PV system should be able to both decrease and increase the output voltage.

In this paper, a standalone PV system including a PV generator and a buck-boost DC-DC converter has been investigated, and the perturb-and-observe (P&O) MPPT technique is applied to track the maximum power point. The converter is a single-ended primary-inductor converter (SEPIC) with a noninverted voltage at the output. The controller includes the P&O MPPT method and SMC based on an improved fast terminal slip surface. In addition, the proposed controller is implemented in a PV standalone system. Consequently, the proposed control system can track all operating points in normal situations and uncertain conditions. In addition, the controller has a proper dynamic behavior at the distant point of the slip surface.

The rest of the paper is prepared as follows. In Section 2, the configuration of the PV system is presented. The SMC is explained in Section 3. Modeling of the proposed system is presented in Section 4. In Sections 5 and 6, simulation and experimental results of the proposed system are investigated, respectively. Finally, Section 6 concludes the paper.

2 | PHOTOVOLTAIC MODEL

In this study, a polycrystalline panel is used. Figure 1 illustrates the equivalent model of a PV cell. It contains a current source ($I_{sc}$), a diode ($D$), a series resistor ($R_s$), and a parallel resistor ($R_L$). The relationship between voltage and currents of the PV cell model can be obtained as following based on Figure 1:

$$I = I_{sc} - I_D,$$

(1)

$$I_D = I_s \left( \frac{qV_D}{enKT} - 1 \right).$$

(2)

Equation (3) can be achieved by Equations (1) and (2).

$$I = I_{sc} - I_s \left( \frac{qV_D}{enKT} - 1 \right),$$

(3)

where $I$ is the output current of a PV cell, $I_{sc}$ is the short circuit current, $I_s$ is the reverse saturation current, $V_D$ is the voltage of diode, $q$ is the capacity of electron ($q = 1.6 \times 10^{-19}$), $n$ is the quality coefficient of diode, and $T$ is the temperature.

3 | CONTROL STRATEGY

The proposed standalone PV system configuration is displayed in Figure 2. This block diagram consists of solar panels, DC-DC converter, MPPT (P&O), and load. The converter is a SEPIC, which can act both as a buck or boost converter. As
shown in the block diagram, the inputs of MPPT (P&O) block are the voltage and current signals, while the output is $v_{\text{ref}}$. The difference between the PV voltage ($v_{\text{pv}}$) and the reference voltage ($v_{\text{ref}}$), as well as the input capacitor current value ($i_{\text{cin}}$) are inputs of the SMC. As mentioned in the previous section, linear methods of MPPT contain some limitations. They cannot be accurate in all operating areas of the PV. In this paper, a nonlinear MPPT technique based on SMC is suggested to achieve more accurate results. To improve the operation of SMC, a new slip surface is applied. The details of proposed SMC are described in the following section.

4 | SLIDING MODE CONTROL

4.1 | Slip surface selection

The sliding surface is recognized as the essential concept in the SMC. The sliding surface introduces a relationship between dynamics of the system according to the controlling aims. The main conditions of the SMC are reaching to the sliding surface (by switching operation) and stabilizing of system dynamics on the slip surface. Hitting, existence, and stability conditions should be investigated as the required conditions in SMC.

4.2 | Types of slip surfaces

As mentioned, a SEPIC converter with SMC is utilized to track the maximum power point in a standalone PV system. If $X_1$ is the input voltage error of sliding mode and $X_2$ is $X_1$ derivative, then the conventional sliding surfaces (CSMC) can be presented as follows:

$$ S = X_1 + K_1 X_2, $$

(4)

where $K_1$ is the constant term of $X_2$, which is permanently real and positive. Convergence toward the conventional sliding surface is asymptotic. On the other hand, in a limited time scale, the error will not be zero.

4.2.1 | Terminal slip mode controller

Another sliding mode surface can be defined as terminal SMC (TSMC) with the following formula:

$$ S_t = X_1 + K_1 X_2^n, $$

(5)

where $K_1$ is always positive and $n$ is smaller than one and positive ($K_1 > 0$ and $0 < n < 1$). It is worth mentioning that the relation between variables in (5) is nonlinear.

Contrary to CSMC, the convergence to TSMC sliding surface is absolute and the convergence ratio is greater. Also, the convergence rate at nearby points to the equilibrium point increases by the nonlinear phrases like $X_2^n$ in (5). The parameter $n$ is smaller than one; therefore, in the TSMC, the convergence speed decreases at distances far from the equilibrium point.

It is worth mentioning that the exponential phrase $X_2^n$ will become nonreal in (5) if the error signal is negative in the TSMC, which is a disadvantage.

4.2.2 | Fast terminal slip mode controller (FTSMC)

The Fast terminal slip mode controller (FTSMC) is defined to improve the convergence rate of TSMC. The slip surface of FTSMC is illustrated in (6).

$$ S_{ft} = X_2 + K_1 X_1 + K_2 X_1^n $$

(6)

FTSMC sliding surface offers a trade-off between CSMC and TSMC so that it possesses the benefits of both terminal and conventional slip surfaces. However, the problem with negative values is not still resolved, if $X_1$ is negative, the exponential equation will become nonreal.
4.2.3 | Improved fast terminal slip mode controller

The improved fast terminal slip mode controller (IFTSMC) has been introduced to solve the FTSMC problem.\(^{18}\) The sliding surface of IFTSMC is shown in (7).

\[
S_f = X_2 + K_1X_1 + K_2|X_2|^n \text{sign}(X_2),
\]

where \(0 < n < 1\).

5 | A CASE STUDY BASED ON THE NEW SLIDING SURFACE

As mentioned before, a case study is shown in Figure 2, where the SEPIC converter provides impedance matching between the solar panels and the electrical load; and the SMC block (IFTSMC) produces switching signals for the switch gate (it is a power metal-oxide-semiconductor field-effect transistor (MOSFET)).

5.1 | Dynamic analysis of proposed system under study

Here, the dynamic analysis of the SEPIC converter is presented. Figure 3 shows a PV system implemented by the SEPIC converter based on IFTSMC. According to this figure, the IFTSM input variables are written as (8).

\[
\begin{align*}
    x_1 &= -i_{C_m} = i_{m} + \frac{v_{pv}}{R_d} - i_{pv} \\
    x_2 &= v_{pv} - v_{ref}
\end{align*}
\]

In Figure 4, the SEPIC converter’s circuit is illustrated. In (8), \(i_{C_m}\) is the current of input capacitance, \(i_{m}\) is the current of input inductor, \(R_d\) is the differential resistance of the generator, and \(v_{pv}\) and \(i_{pv}\) are the solar panel voltage and current, respectively. The dynamic equations governing the circuit are presented in (9).

\[
\begin{align*}
    x_1 &= -i_{C_m} = i_{m} + \frac{v_{pv}}{R_d} - i_{pv} \\
    x_2 &= v_{pv} - v_{ref} \\
    x_3 &= i_{L_out} \\
    x_4 &= v_{C_s}
\end{align*}
\]
In (9), $i_{L_{out}}$ is the current of output inductor, and $v_{C_s}$ is the voltage of $C_s$ capacitor. To model the system, the differential equations of the SEPIC are obtained in both ON ($u = 1$) and OFF ($u = 0$) states.

### 5.1.1 ON state ($u = 1$)

In this state, the switch $u$ is on, consequently, the diode operates in reverse bias. The differential equations are written in (10) regarding the circuit configuration shown in Figure 5.

\[
\begin{align*}
\dot{x}_1 &= -\frac{1}{R_dC_{in}}x_1 + \frac{x_2}{L_{in}} + \frac{v_{ref}}{L_{in}} - i_{pv} \\
\dot{x}_2 &= -\frac{x_1}{C_{in}} - v_{ref} \\
\dot{x}_3 &= -\frac{x_4}{L_{out}} \\
\dot{x}_4 &= \frac{x_3}{C_s}
\end{align*}
\]  

(10)

### 5.1.2 OFF state ($u = 0$)

In this state, the switch $u$ is turned off, and the diode is forward biased. The differential equations can be derived according to the circuit structure presented in Figure 6, as shown in (11).

\[
\begin{align*}
\dot{x}_1 &= -\frac{1}{R_dC_{in}}x_1 + \frac{x_2}{L_{in}} - \frac{x_4}{L_{out}} - i_{pv} + \frac{v_{ref}}{L_{in}} - \frac{v_{o}}{L_{in}} \\
\dot{x}_2 &= -\frac{x_1}{C_{in}} - v_{ref} \\
\dot{x}_3 &= \frac{v_{o}}{L_{out}} \\
\dot{x}_4 &= \frac{x_3}{C_s} - \frac{x_2}{C_sR_d} - \frac{v_{ref}}{C_sR_d} + \frac{i_{pv}}{C_s}
\end{align*}
\]  

(11)

According to (9), (10), and (11), the hitting, existence, and stability conditions of the controller will be investigated.

### 5.2 PV system controlled by IFTSMC

The sliding surface is calculated to implement MPPT in the SEPIC converter of the case study in (12) based on (7).

\[
S = (v_{pv} - v_{ref}) + K_2|v_{pv} - v_{ref}|^\alpha \cdot \text{sign}(v_{pv} - v_{ref}) + K_1i_{C_{in}}
\]  

(12)

where $i_{C_{in}}$ is the current of input capacitance, $v_{pv}$ is the output voltage of the panels, and $v_{ref}$ is the output voltage from the P&O algorithm. The aim is setting the voltage error to zero, i.e., $v_{pv} - v_{ref} = 0$. Because of the existence of nonlinear absolute relation term ($|v_{pv} - v_{ref}|^\alpha$) in the sliding surface equation, the convergence to sliding surface is complete. The stability and availability conditions of the system with IFTSMC will be investigated in the following.
5.2.1 Availability condition

Essentially, the availability condition warrants that the controller signal operates within the time derivative of the switching function. Therefore, the availability condition (as shown in (13)) must be fulfilled:

\[
\frac{d}{du} \frac{dS}{dt} \neq 0
\]  

(13)

In (14) the time derivative is determined.

\[
\begin{cases}
S \to 0^+, \ u = 1, \dot{S} < 0 \\
S \to 0^-, \ u = 0, \dot{S} > 0
\end{cases}
\]  

(14)

According to the dynamics of the system and (14), (15) and (16) can be derived as:

\[
\frac{x_1}{C_{in}} \cdot \dot{\nu}_{ref} + \left[ \frac{1}{R_{d}C_{in}} x_1 + \frac{x_2}{L_{in}} + \frac{v_{ref}}{L_{in}} - i_{pv} \right] \left( K_1 + K_2 n(x_1)^{n-1} \right) < 0
\]  

(15)

\[
\frac{x_1}{C_{in}} \cdot \dot{\nu}_{ref} + \left[ \frac{1}{R_{d}C_{in}} x_1 + \frac{x_2}{L_{in}} + \frac{v_{ref}}{L_{in}} - i_{pv} - \frac{x_4}{L_{in}} - \frac{v_o}{L_{in}} \right] \left( K_1 + K_2 n(x_1)^{n-1} \right) > 0
\]  

(16)

Equation (17) is obtained by the combination of (15) and (16).

\[
0 < -\frac{x_1}{C_{in}} + \dot{\nu}_{ref} - \left[ \frac{1}{R_{d}C_{in}} x_1 + \frac{x_2}{L_{in}} + \frac{v_{ref}}{L_{in}} - i_{pv} \right] \left( K_1 + K_2 n(x_1)^{n-1} \right) \left( -\frac{x_4}{L_{in}} - \frac{v_o}{L_{in}} \right) \left( K_1 + K_2 n(x_1)^{n-1} \right)
\]  

(17)

In (14), $C_{in}$ is the input capacitor, $\nu_{ref}$ is the reference voltage which comes from the P&O, $L_{in}$ is the input inductor and $v_o$ is the output voltage of the converter. $K_1$, $K_2$ and $n$ are the IFTSMC coefficients which their optimal values should be calculated. It ought to be noticed that

\[
i_{pv} = i_{sc} - I_R \left( e^{\alpha v_{ref}} - 1 \right)
\]  

(18)

where $I_R$ is the current of reverse saturation and $\alpha$ is the voltage of reverse-biasing. With respect to (17), to satisfy (16), the (11) is obtained. According to (13) and (17), the availability condition can be achieved as follows:

\[
K_1 + K_2 n(x_1)^{n-1} \neq 0
\]  

(19)

In fact, IFTSMC is achievable when (19), (11) and (17) to be satisfied.

5.2.2 Stability condition

$U_{eq}$ will be obtained as the switching signal if both the time derivative and the sliding surface of the sliding surface are zero and the inequality $0 < U_{eq} < 1$ is legitimate. Hence, the condition of equivalent control will be established. By putting the dynamics of system in the Equation (17), $U_{eq}$ can be obtained.

\[
U_{eq} = \frac{x_1}{C_{in}} \cdot \dot{\nu}_{ref} + \left[ \frac{1}{R_{d}C_{in}} x_1 + \frac{x_2}{L_{in}} + \frac{v_{ref}}{L_{in}} - i_{sc} + a I_R e^{\alpha v_{ref}} - \frac{x_4}{L_{in}} - \frac{v_o}{L_{in}} \right] \left( K_1 + K_2 n(x_1)^{n-1} \right)
\]  

(20)

By assuming that the inequality $0 < U_{eq} < 1$ is always true and according to the Equation (20), the inequality (21) can be gained.

\[
\left| \frac{d\nu_{ref}}{dt} \right| > \frac{x_1}{C_{in}} + \left[ \frac{1}{R_{d}C_{in}} x_1 + \frac{x_2}{L_{in}} + \frac{v_{ref}}{L_{in}} - i_{sc} + a I_R e^{\alpha v_{ref}} - \bar{u} \left( \frac{x_4}{L_{in}} + \frac{v_o}{L_{in}} \right) \right] \left( K_1 + K_2 n(x_1)^{n-1} \right)
\]  

(21)

where $\bar{u} = u_{eq} - u_{sw}$, $u_{sw}$ is switching signal, $u_{sw} = K_p \text{Sign} (S_p)$, $S_p$ is improved slip surface, and $K_p$ is a positive value. To investigate (21), the values of $K_1$, $K_2$, and $n$ should be specified.
TABLE 1 IFTSMC constant values

| IFTSMC Constants | Values |
|------------------|--------|
| $K_1$            | 0.2    |
| $K_2$            | 0.9    |
| $n$              | 0.219  |

Specify $K_2$: The purpose of the suggested slip surface is error correction between PV and reference voltages ($v_{PV} - v_{ref}$). Due to the fact that the switching is not ideal, the result is always oscillating in practice, around the slip surface. If the oscillation is assumed to be $H/2$, according to (4):

$$v_{PV} - v_{ref} = 0 \rightarrow -\frac{H}{2} \leq K_2 \Delta i_{C_{in}} \leq +\frac{H}{2}$$

and

$$|K_2| \Delta i_{C_{in}} \leq H.$$ (23)

The value of $H$ depends on the controller. $\Delta C_{in}$ can be chosen according to the practical limitations of the switching frequency, as follows:

$$f_{sw} = \frac{v_{PV} (v_o - v_{PV})}{\Delta i_{C_{in}} L v_o}.$$ (24)

Assuming that $K_1$ is a real and true value, $n$ is positive and smaller than one and $K_2$ is determined. According to (21) and trial and error, $K_1$ and $n$ are obtained as shown in Table 1. It is worth mentioning that the trial and error is used to select a precise coefficient for the controller through considering the stability criteria. In other words, selecting the coefficient of the stability constraint is a necessary condition in this method in which there is no any instability risk.

6 | SIMULATION RESULTS

The system is simulated in MATLAB/Simulink for three case studies: without severe environmental changes (normal mode), disconnecting one of the parallel panels, and shade effect.

Figure 7 shows the normal mode. In this case, a 230 W solar panel is utilized. Environmental temperature and radiation change normally which results in a slight deviation of $v_{ref}$. In Figure 7, the variation starts at 0.1 s and output PV voltage ($v_{PV}$) has been returned to conventional condition after 0.01, which shows that the IFTSMC is fast enough to trace the maximum power point.

To investigate the second case, two 230 W connected panels are used. As shown in Figure 8 in 0.1 s, when one panel is disconnected, the PV system is able to operate with another panel and trace the maximum power point after 0.012 s.

In Figure 9, the shade effect on PV panels is examined, where a 230 W panel is used. The voltage fall is observed when the shade affects one of the panels. As shown, the PV voltage has returned to the regular situation after 0.013 s.

The last two case studies verify that the controller of proposed system is stable against uncertain conditions. In addition, the simulation results demonstrate 99.1% efficiency of IFTSMC.

To compare the efficiency of the proposed IFTSMC controller with other methods presented in previous studies, some important parameters such as efficiency, settling time, SSE, and chattering of $v_{PV}$ must be investigated. If $h_1$ and $h_2$ are...
6.1 Dynamic analysis of system under study based on simulation

Figure 10 illustrates the state space diagram of SMC dynamics based on improved fast terminal slip surface. It demonstrates the trajectory of state variables and dynamic behaviors of the system, \( X_1 = v_{pv} - v_{ref} \) and \( X_2 = i_{C_{inv}} \). It can be observed that when switching is adopted both availability and stability conditions in the system are established.
7 | EXPERIMENTAL RESULTS

An experimental set up of the proposed system is implemented in the laboratory. As shown in Figure 11, it includes a solar panel, a SEPIC converter, voltage, and current sensors, an Arm microcontroller, a gate driver, a battery, and a load. The ARM LPC2138 and TLP250 are used as the microcontroller and gate driver of MOSFETs, respectively.

Figures 12 and 13 illustrate the voltage, current, and power of the input and the output of the SEPIC in the experimental set. The parameters of SEPIC are shown in Table 3.
FIGURE 13  The output power of the implemented system

TABLE 3  Switching states of the proposed inverter

| Parameters                | Values |
|---------------------------|--------|
| Photovoltaic voltage      | 0–33 V |
| Output voltage            | 30 V   |
| Input capacitance ($C_{in}$) | 33 μF |
| $C_s$ and $C_{out}$       | 220 μF |
| $L_1$ and $L_2$           | 220 μH |

FIGURE 14  Switching frequency of gate driver

FIGURE 15  The output voltage of converter in uncertainly condition (load variation)
The PV voltage is assumed as the reference voltage. By PV voltage and input capacitor current, the proposed controller matches the impedance between input and output of the converter; thus, the maximum power point can be tracked. The PV output power is 213 W, in nominal conditions while the load is 5.7 Ω. The input power is 151 W with 5.29 A and 28.9 V. According to the proper operation of the controller, the output power is equal to 144 W with 28.9 V and 5.05 A, which leads to 95% power efficiency (power efficiency is $P_{\text{output}}/P_{\text{input}}$). The power quality can be improved by using a high quality core for inductors. The switching frequency is 40 kHz, which has been presented in Figure 14.

To verify the stability of the proposed controller versus the uncertainty of the parameters, the load value is increased suddenly from 5.8 to 10 Ω. Consequently, the output voltage is increased from 28.9 V to 30 V (after about 25 ms) with the controller, as shown in Figure 15. The transient performance of the system confirms the fast speed and accuracy of performance of the IFTSMC.

8 | CONCLUSION

In PV systems, the environmental conditions such as the shadow effect, impose direct effect on the stability of the system. This represents a challenge in conventional SMC. The PV system cannot follow the reference voltage of the system. Among the nonlinear controllers, the SMC is proven to be one of the most powerful and easiest to implement in photovoltaic systems. In this article, an IFTSMC is employed to track the maximum power point and to improve the stability, precise, speed, and power efficiency in the PV system including a SEPIC converter. The availability and stability conditions of SMC have been investigated. Based on the simulation and experimental results, the controller follows the PV voltage reference value as expected, under the normal voltage variation and the shade effect with high power efficiency. The system is robust to the uncertainty of parameters. The convergence rate is high. Therefore, it can be a commercial choice for industrial systems.

CONFLICT OF INTEREST

The authors decline any conflict of interest that might bias their work.

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**Used symbols in this paper:**

- **MPPT**: Maximum power point tracking
- **SEPIC**: Single-ended primary-inductor converter
- **PV**: Photovoltaic
- **P&O**: Perturbation and observation
- **INC**: Incremental inductance
- **SMC**: Sliding mode control
- **CSMC**: Conventional sliding surface controller
- **TSMC**: Terminal slip mode controller
- **FTSMC**: Fast Terminal slip mode controller
- **IFTSMC**: Improved fast terminal slip mode controller
- **v<sub>ref</sub>**: Reference voltage
- **v<sub>pv</sub>**: PV voltage
- **i<sub>in</sub>**: Input capacitor current
- **X<sub>i</sub>**: Input voltage error of SMC
- **X<sub>2</sub>, X<sub>1</sub>**: Derivative
- **K<sub>1</sub>**: Constant term of X<sub>2</sub>
- **X<sub>2</sub>**: Exponential phrase of terminal slip mode controller
- **i<sub>in</sub>**: Current of input inductor
- **R<sub>d</sub>**: Differential resistance
- **l<sub>pv</sub>**: Panel current
\( i_{\text{out}} \)  Current of output inductor
\( v_{C_s} \)  Voltage of capacitor \( C_s \)
\( u \)  Switching signal
\( I_R \)  Current of reverse saturation
\( \alpha \)  Voltage of reverse-biasing
\( U_{eq} \)  Switching signal in equilibrium point
\( S_{ft} \)  Improved slip surface
\( K_{ft} \)  Constant term of \( S_{ft} \)
\( f_{SW} \)  Switching frequency