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Twisting Sliding Mode Control based Maximum Power Point Tracking

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Abstract— **For a world where energy demand is increasing day by day, available resources are constantly decreasing. At this point, it is very important to be able to benefit from the sun, which is the main energy source, with minimum damage to the environment. It is possible to produce electricity directly from sunlight through PV panels. Due to the limited efficiency of these panels, MPPT algorithms are always required. In this study, Sliding Mode Control (SMC) based Twisting Sliding Mode Control (T-SMC) MPPT, known for its robust structure, was performed and the results were compared with the classical SMC. The proposed MPPT algorithm is simulated with MATLAB/Simulink. The efficiency of T-SMC based MPPT is obtained as nearly 99%.**

Index Terms—**Boost Converter, Maximum Power Point Tracking, Photovoltaic Panel, Twisting Sliding Mode Control.**

I. INTRODUCTION

DURING TIME, humans were invented new things that got easier the human life. In the ancient ages, the wheel and the animal power were essential. After some eras, the first steam engine which need steam power was invented, then the jobs got easier. The steam has been produced by using fossil fuels in many years and at the following years. This steam (heat) energy has been used to turn the electric generators. With this production, the electricity has been started to use. The electric machines are more efficient than the fossil fuels, but it needed fossil fuel too due to this indirect generation. The environment has been damaged by the burning reaction of the fossil fuels and the burning reactions coproducts have been distorted in the Earth atmosphere and the greenhouse effect has been changed the climate. The main alternative energy sources named as renewable energy is emerged. More clean, sustainable, and efficient power is produced by using renewable energy. At this point, many researches have been carried out in order to benefit more from the sun, which is the main energy source of the world. Recently, photovoltaic (PV) panels have started to be produced in order to convert solar energy directly into electrical energy.

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Solar energy and PV panels are an important issue because they are renewable energy sources, the cost of sustainability is low, the variety of construction materials of PV panels, PV Panels can be produced for various power values. Due to the chemical properties of the materials used in PV panel production, very high efficiency cannot be achieved yet. One of the methods developed to obtain maximum efficiency from these panels is the Maximum Power Point Tracking (MPPT) technique. The aim is to examine new Maximum Power Point Tracking (MPPT) Method form using renewable sources that find more reliable, and efficient systems. There are many algorithms are used to obtain maximum power such as Incremental Conductance (IC), Open Circuit Voltage, Short Circuit Current, Perturb and Observe (P&O).

In a study, the recent application during the time period (1970s-1994), PV system configurations and the PV related issues were examined such as power conditions, protection, islanding, intermittent output and installation [1]. Another study analyzed the PV-thermal module of the real application in Spain. The main aim was to use solar energy to obtain electrical energy. Special type of PV panel was used in the application. From the analysis the radiation effect and the temperature effect were examined to the special PV-thermal panels. The collateral advantage of the system was heat regulation of the building [2] In [3], Hybrid PV/Thermal performance and system usagein the real live applications is researched. Different types of PV panels were used and optimized the system. Results show that the panel should be smaller than the collector unit. Bekker and Beukes were examined the optimal MPPT methods for examining the voltage control and voltage current control condition and they used Hill Climbing MPPT method. It is mentioned that the optimal control is current voltage control method on this study [4] Dachuan and Yuvarajan investigated the Hybrid PV and PEM Fuel Cell system and they tried to determine load sharing between the sources [5]. Dezso et.al. presented research that how to modelling a PV panel from using datasheet values. From known formulas and the given information on the datasheet, they used mathematical calculations and obtained the necessary, but not given data. [6]. In a study, series PV panels were connected different type DC/DC Converters such as boost converter and flyback converter to achieve more efficient systems with lower power stress. It is emphasized that the efficiency of flyback converter is better than boost converter [7]. A comparative MPPT study was performed to PV system and the performance of parasitic capacitance algorithm came to fore [8]. Another research was related with renewable energy sources and electrical vehicles. The main aim was to obtain a smart energy delivery from renewable energy sources to the loads [9]. Alan et.al. studied on assembly the renewable energy to obtain electrical energy sustainably introducing learning method [10]. Yamegueu et.al. examined the hybrid system without storage components. The results shown that if the load changes the PV panel validity effects the diesel generator's efficiency in the hybrid renewable and diesel generator systems [11]. Another study about to improve the efficiency of the series connected PV panels and they were shaded experimentally. The results shown that if the PV panels were directly connected to the DC/DC Converters, the system would work more efficiently. [12]. Sahoo et.al. tried to model of the PV systems by using Simscape simulation program and presented different type circuit topologies [13]. Palizban et.al. investigated the efficiency of the hybrid renewable system contains PV, wind, Fuel Cell, electrolyzer and super capacitor [14]. Active clamp interleved flyback converter was used to increase the efficiency of PV system and the converter was operated on DCM and CCM modes [15]. In another study, Z source inverter was used with PV panels. The DC output voltage was converted to AC by using this inverter driven with sinusoidal PWM. With this method, voltage gain was increased and voltage stresses were reduced [16]. A research was examined to find the maximum power point of the PV panel and it is aimed to obtain fast control with record the sun's radiation and temperature values on the lookup table by using the classical MPPT methods [17]. In a study, the power losses that occur as a result of the use of PV panels by connecting them in arrays and the formation of shadows was researched. It was tried to be solved by connecting each panel to the converter circuit one by one. For this purpose, buck-boost converter was also used to provide high efficiency [18]. A hybrid power system for low power electronics circuits and no-load requirement was investigated to obtain low-cost high efficiency structure [19]. It was aimed to supply the electrical energy needed by electric cars from renewable energy sources as solar energy and fuel cell. The performance was evaluated whether it charges the battery and provides the necessary energy [20]. Kale et.al. was explained to design of a highly efficient and reliable system called micro-inverter which fed from a solar system and to prevent load shedding problem, and islanding problem [21]. The researchers generally use single diode model for PV systems. While a research preferred to use multi-diode model and was simulated with MATLAB [22], others preferred to use the data given datasheets of manufacturers and generalized mathematical models [23]. In another study, PV and thermal panels were used together and artificial neural network were used to get the optimum power under changing temperature and irradiation conditions [24]. A new topology was presented by using buck boost and flyback topologies to provide low voltage to high voltage conversion using renewable energy sources such as PV panels. Benefits were emphasized such as reducing the number of circuit elements in this topology, reducing the diode and switch stress, highly efficiency, and recovering the lost energy [25]. A half wave converter was used to improve the efficiency of PV systems under variable temperature and irradiation. It was aimed to reduce the inductor size and obtain high efficiency with simulations [26]. In [27], Belkaid et.al were aimed to develop the P&O algorithm, also proposed a modified equivalent sliding mode MPPT for better dynamic behavior [28]. Alhammad et.al. was designed a system contains PV panels and thermoelectric generator to feed electrical vehicles efficiently [29]. In a study, PV/TEG hybrid system was presented and controlled with sliding mode control to cope with temperature and irradiation changes [30]. Raju and Mikkili was explored different connection types such as serial, parallel, serial-parallel, Honey-Comb under shading conditions [31].

Additionally, the effects of single diode PV model on current, voltage, resistances and ideality factor were investigated [32]. Mnati et.al. compared the efficiency and dynamic behaviors of P&O, IC, Constant voltage,Open Circuit Voltage techniques [33]. For fast response, fuzzy logic control was used for MPPT and obtained 99% efficiency [34]. Beyarslan was aimed to design a micro-grid structure by balancing the energy need with storage systems aswell as renewable energy sources such as wind, solar and hydroelectric systems. In this way, a system was designed to meet 100% of a region's energy needs [35]. From the literature review, sliding mode control (SMC), fuzzy logic control (FLC), artificial neural network (ANN) and some other methods are much popular to obtain better MPPT performances. Because the performance of traditional methods is limited and modified to achieve the maximum.

There are some studies have been performed to get maximum efficiency under variable atmospheric conditions such as System Identification based ARV MPPT [39], a voltage scanning-based MPPT [40], P&O and INC MPPT Methods using FPGA [41] and system identification-based MPPT [42].

In this study, it is aimed to obtain maximum efficiency from a PV system by using a robust control algorithm. SMC is well known method to control the system under parameter changes and distributions. The amount of radiation is not fixed and is variable. A robust control structure can be obtained with SMC under variable irradiation condition with better MPPT performance. In the meantime, second order SMC algorithms such as twisting SMC (T-SMC) appears with better dynamic behavior. A boost converter fed from PV panel is controlled with T-SMC algorithm to obtain more efficiency and robust structure.

II. PV PANEL MODEL

PV panels are special devices that have been made Silicon and the other materials have p-n junction cells. If the sun light hit this p-n junction and the sun lights contained energy is enough to increase electrons power greater than the band gap (the energy between electrons orbital energy to free electron level). The electrons freed by effect of irradiation with the semiconductor structure that generates electron flow [22] This is the working principle of the PV Panel. In this part The PV Panel Design is detailly discussed [6],[22],[36].

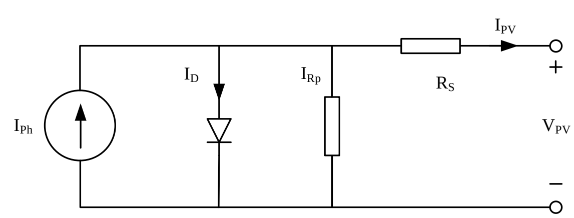

Fig. 1. PV Panel equivalent circuit model (single diode)

The traditional model of PV panel is single diode model and it contains one controlled current source, one diode (controlled current source too), one paralleled, one series resistance.

There are three current loop in this circuit;

- One of them is I_{Ph} current loop
- The second is between I_D and R_p current loop
- The third loop is the I_{PV} current loop

$$I_{PV} = I_{Ph} - I_D - I_{R_p} \tag{1}$$

The current of the diode is given Eq.2 [27,40].

$$I_D = I_{sat} * (e^{k*\frac{V_d}{T_K}} - 1) \tag{2}$$

By using Eq.2 in Eq.1, the final diode current is obtained as Eq.3.

$$I_D = I_{sat} * (e^{\frac{V_d}{n_{cell}*V_{thermal}}} - 1) \tag{3}$$

$$V_t = \frac{quality*k*T_{STC}}{q} \tag{4}$$

$$I_{Ph} = [I_{SCR} + k_i(T - T_{ref})](\frac{S}{S_{ref}}) \tag{5}$$

$$I_{PV} = I_{Ph} - I_{sat} * (e^{\frac{V_{PV}+I_{PV}*R_S}{n_{cell}*V_{thermal}}} - 1) - \frac{V_{PV}+I_{PV}*R_S}{R_p} \tag{6}$$

From above equations, the open circuit, short circuit and at Maximum Power Point expressions can be obtained as follows:

$$I_{short} = I_{Ph} - I_{sat} * (e^{\frac{I_{short}*R_S}{n_{cell}*V_{thermal}}} - 1) - \frac{I_{short}*R_S}{R_p} \tag{7}$$

$$0 = I_{Ph} - I_{sat} * (e^{\frac{V_{PV}}{n_{cell}*V_{thermal}}} - 1) - \frac{V_{PV}}{R_p} \tag{8}$$

$$I_{PV_{MPPT}} = I_{Ph} - I_{sat} * (e^{\frac{V_{PV_{MPPT}}+I_{PV_{MPPT}}*R_S}{n_{cell}*V_{thermal}}} - 1) - \frac{V_{PV_{MPPT}}+I_{PV_{MPPT}}*R_S}{R_p} \tag{9}$$

III. BOOST CONVERTER MODEL

The most commonly used dc-dc converter type in MPPT process is the boost converter. A classic boost converter circuit is shown in the Fig.2.

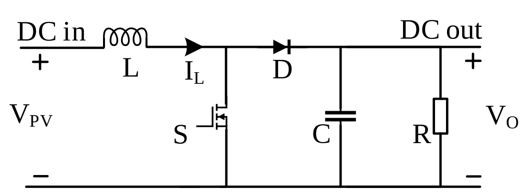

Fig. 2. Boost Converter

The circuit is examined in two cases, depending on whether the power switch S is on and off. Accordingly, the equivalent of the circuit is as in Fig.3. when the switch S is on [27].

- (Switch S on State):
  $0 \leq t \leq d * t_{switch}$
- (Switch S off State)
  $d * t_{switch} \leq t \leq t_{switch}$

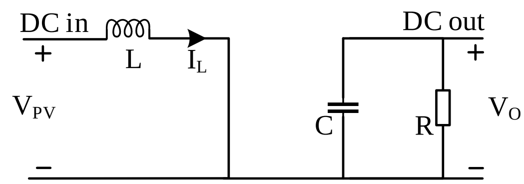

Fig. 3. Boost Converter (Switch S on State)

$$i_L = i_{L_{initial}} + \frac{1}{L}\int_0^t V_L(t)dt \tag{10}$$

Where,

$$V_L(t) = V_{PV} \tag{11}$$

$$i_{L_{initial}} = i_{L_{min}} \tag{12}$$

$$i_L = i_{L_{min}} + \frac{1}{L} * V_L * d * t_{switch} \tag{13}$$

$$\Delta i_L = \frac{V_L(t)*d*t_{switch}}{L} \tag{14}$$

In case the switch is off, the equivalent of the circuit is as given in Fig.4.

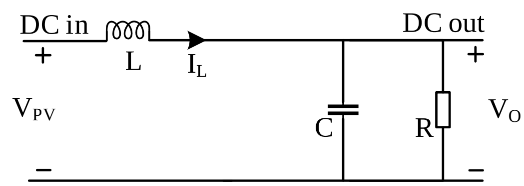

Fig. 4. Boost Converter (Switch S off State)

$$i_L = i'_{L_{initial}} + \frac{1}{L}\int_0^t V'_L(t)dt \tag{15}$$

Where,

$$V'_L(t) = V_{PV} - V_O \tag{16}$$

$$i'_{L_{initial}} = i_{L_{max}} \tag{17}$$

$$i_L = i_{L_{max}} - \frac{1}{L} * (V_O - V_{PV}) * (t_{switch} - d * t_{switch}) \tag{18}$$

$$\Delta i_L = \frac{(V_O - V_{PV})*(t_{switch} - d*t_{switch})}{L} \tag{19}$$

The relationship between output voltage and input voltage is

$$V_{PV} * t_{on} + (V_{PV} - V_O) * t_{off} = 0 \tag{20}$$

$$t_{on} = d * t_{switch} \tag{21}$$

$$t_{off} = t_{switch} - d * t_{switch} \tag{22}$$

$$V_{in} * d * t_{switch} = -(V_{in} - V_{out}) * (t_{switch} - d * t_{switch}) \tag{23}$$

$$\frac{V_O}{V_{PV}} = \frac{1}{1-d} \tag{24}$$

From these equations,

$$\Delta i_L = \frac{V_O*(d-d^2)*t_{switch}}{L} \tag{25}$$

In the on state the capacitor discharge and the output voltage is produced by capacitor. The capacitors voltage equation is:

$$V_O = V_{max} + \frac{1}{C} * (-I_o * d * t_{switch}) \tag{26}$$

$$\Delta V_O = \frac{I_o*d*t_{switch}}{C} \tag{27}$$

IV. TWISTING SLIDING MODE MPPT

Generally, algorithms such as P&O and IC are used for MPPT process. As an alternative to these methods, SMC-based MPPT can also be preferred. The SMC is a widely used method in nonlinear systems, known as robust controller. There are also higher order SMC structures available such as (T-SMC). In this study, T-SMC is designed for MPPT process.

The main difference between SMC and T-SMC is that the trajectories oscillate with twisting on the sliding surface instead of chattering. SMC consists of two basic steps: determining the sliding surface that will enable the boost converter circuit to work as desired and determining the control rule that directs the system to this sliding surface and enables it to operate on this surface. In order to perform the MPPT operation with the boost converter, firstly, the sliding surface can be defined as Eq.28. Here the sliding surface and its derivative are equal to zero. As long as the system trajectories reach and stay on the sliding surface, the system will operate at the maximum power point [43].

$$V(x,t) = \frac{\partial P_{PV}}{\partial V_{PV}} = V_{PV}\left(\frac{\partial I_{PV}}{\partial V_{PV}} + \frac{I_{PV}}{V_{PV}}\right) = 0 \tag{28}$$

The T-SMC contains two control laws named as switching and equivalent control. The equivalent control and T-SMC can be obtained by using the following expression.

$$x = \begin{bmatrix} I_L \\ V_O \end{bmatrix} \tag{29}$$

$$\dot{x} = f(x) + g(x)u \tag{30}$$

$$f(x) = \begin{bmatrix} \frac{V_{PV}-V_O}{L} \\ \frac{I_{PV}}{C_O} - \frac{V_O}{RC_O} \end{bmatrix} \quad g(x) = \begin{bmatrix} \frac{V_O}{L} \\ -\frac{I_{PV}}{C_O} \end{bmatrix} \tag{31}$$

$$\dot{V} = \left[\frac{\partial V}{\partial x}\right]^T \dot{V} = \left[\frac{\partial V}{\partial x}\right]^T \left(f(x) + g(x)u_{eq}\right) = 0$$

$$u_{eq} = \frac{\left[\frac{\partial V}{\partial x}\right]^T f(x)}{\left[\frac{\partial V}{\partial x}\right]^T g(x)} = 1 - \frac{V_{PV}}{V_O} \tag{32}$$

$$u_{T-SMC} = u_{eq} - \alpha_1 sign(V) - \alpha_2 sign(\dot{V}) \tag{33}$$

Lyapunov Stability Analysis

The basic logic of Lyapunov's theorem is that a continuously decreasing definite positive function must go to zero. If we can find the negative time derivative ($\dot{L}(x)$) of a strictly positive function $L(x)$, then the system is asymptotically stable.

$$L(x,t) = \frac{1}{2}\left(V(x,t)\right)^2 \tag{34}$$

$$\dot{L} = \left[\frac{\partial L}{\partial x}\right]^T \dot{x} = \left[\frac{\partial L}{\partial I_{PV}}\right]\left(-\frac{V_O}{L}(1-u) + \frac{V_{PV}}{L}\right) \tag{35}$$

$$\dot{V} = \left[\frac{1}{V_{PV}} - \frac{I_{PV}}{V_{PV}^2}\frac{\partial V_{PV}}{\partial I_{PV}} + \frac{q}{N_S \eta V_T}\frac{\partial I_{PV}}{\partial V_{PV}}\frac{\partial V_{PV}}{\partial I_{PV}}\right]\left(-\frac{V_O}{L}(1-u) + \frac{V_{PV}}{L}\right) \tag{36}$$

The first derivative of I_{PV} and V_{PV} are defined as in Eq.37 and Eq.38, respectively.

$$\frac{\partial I_{PV}}{\partial V_{PV}} = -\frac{q}{N_S \eta V_T} I_D \exp\left(\frac{q}{N_S \eta V_T}\right) < 0 \tag{37}$$

$$\frac{\partial V_{PV}}{\partial I_{PV}} = -\frac{N_S \eta V_T}{q} \ln\left(\frac{I_D}{I_{PH}+I_D-I_{PV}}\right) < 0 \tag{38}$$

The sign of the first term (Eq.35) is positive when $\frac{\partial V}{\partial I_{PV}} > 0$.

$$\dot{x} = -\frac{V_O}{L}\left(1 - \left(1 - \frac{V_{PV}}{V_O}\right) - u_{T-SMC}\right) + \frac{V_{PV}}{L} \tag{39}$$

$$V\dot{V} = V\left[\frac{\partial V}{\partial I_{PV}}\right]\frac{V_O}{L}\left(-\alpha_1 sign(V) - \alpha_2 sign(\dot{V})\right) \tag{40}$$

V and $\dot{V}$ always have different signs and Lyapunov stability criteria is ensured.

V. Simulation of Proposed System

The PV panel, boost converter and T-SMC based MPPT are simulated by using MATLAB/Simulink software. The simulation of the proposed system is shown in Fig.5.

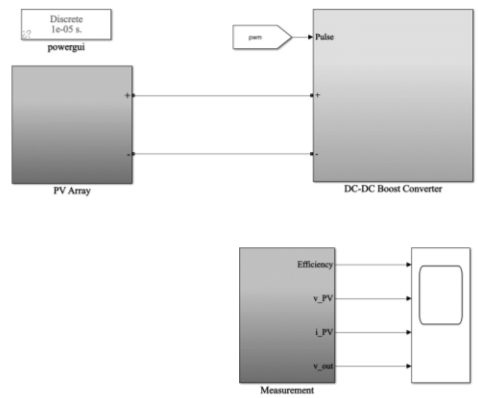

Figure 5. Simulation of proposed system

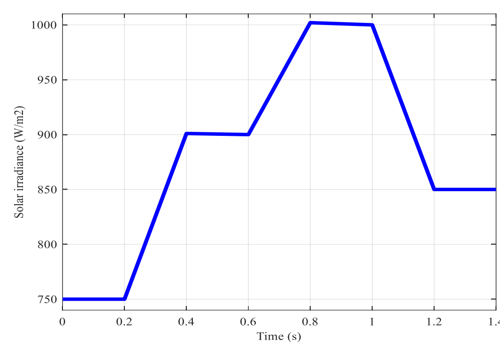

Figure 6. Solar irradiation profile

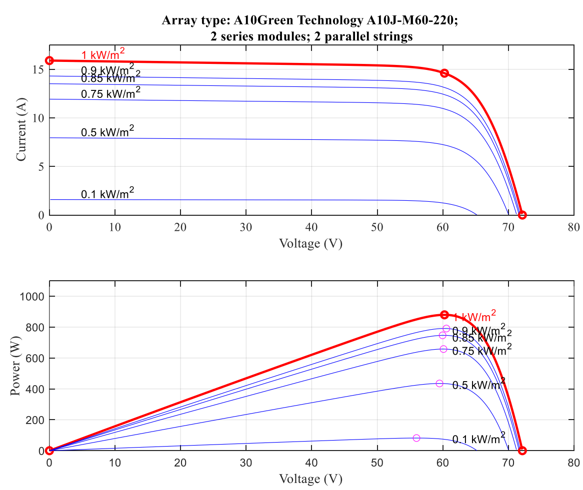

Figure 7. Characteristics of PV array

A variable solar irradiance profile is applied to the PV panel. 2 series and 2 parallel strings A10J-M60-220 solar panel is used on the proposed system. The solar irradiation profile and voltage-current, voltage-power characteristic of the PV array are shown in Fig.7.

The parameters of PV array, boost converter, SMC and T-SMC are given in Table.1.

TABLE 1. SIMULATION PARAMETERS

PARAMETERS OF PV ARRAY	
Parameter	**Value**
Maximum Power (W)	213.15
Cells per Module (N_{cell})	60
Open circuit voltage V_{OC} (V)	36.3
Short circuit current I_{SC} (A)	7.84A
Voltage at MPP V_{MP} (V)	29
Current at MPP I_{MP} (A)	7.35
Temperature (°C)	25
Parallel strings (N_P)	2
Series connected modules per string (N_S)	2
PARAMETERS OF BOOST CONVERTER	
Parameter	**Value**
Inductor L (mH)	2.2
Capacitor C (μF)	100
Resistance load (Ω)	25
Switching frequency (kHz)	10
Diode forward voltage (V)	0.8
IGBT forward voltage (V)	1
CONTROLLER PARAMETERS	
Parameter	**Value**
SMC (λ)	0.0487
T-SMC ($\boldsymbol{\alpha}_1$)	0.715
T-SMC ($\boldsymbol{\alpha}_2$)	0.014

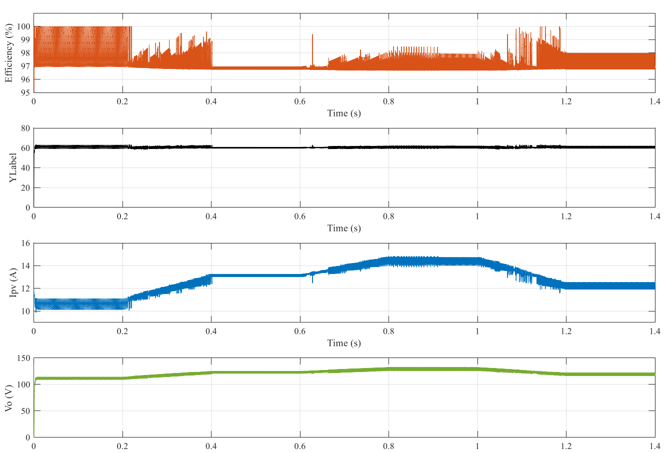

Figure 8. Simulation results of SMC based MPP

VI. RESULTS

There are two simulations are performed in this study. SMC based MPPT and T-SMC based MPPT algorithms are used to show and evaluate the performance of the proposed T-SMC based MPPT algorithm. The results are presented with efficiency, V_{PV}, I_{PV} and V_O of the boost converter. The results of SMC based MPPT and T-SMC based MPPT algorithms are shown in Fig.8. and Fig.9, respectively. The efficiency of SMC changes between 97%-98% for the high irradiation conditions. But this situation is improved as 97%-100% by using T-SMC. The efficiency of SMC and T-SMC based MPPT algorithms are shown in Fig.10. The efficiency performance of both algorithm is compared by presenting Fig.10. Also, the mean efficiency, maximum and minimum values are given in Table 2.

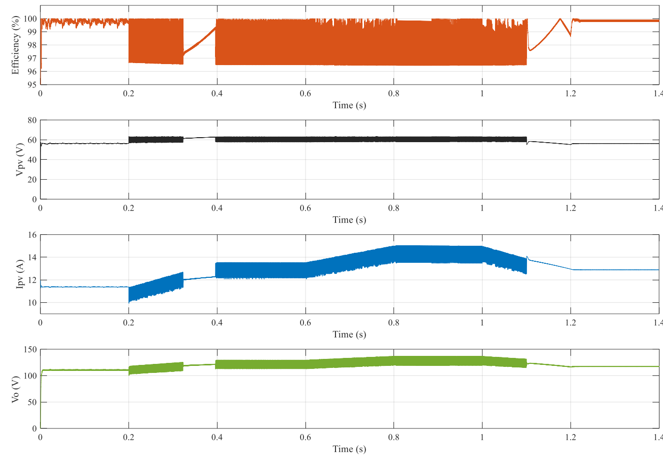

Figure 9. Simulation results of T-SMC based MPPT

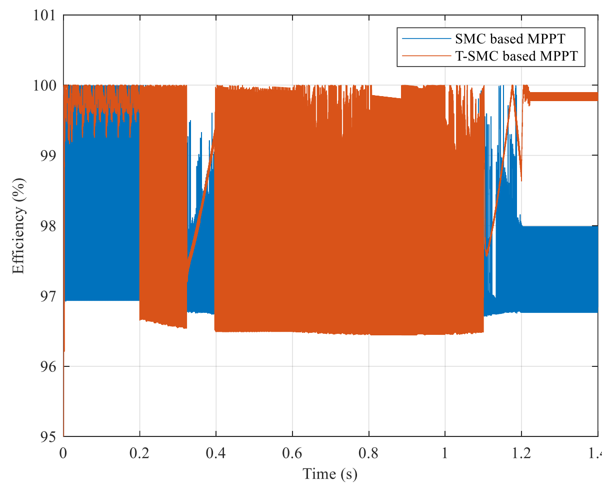

Figure 10. Efficiency of SMC and T-SMC based MPPT

TABLE 2. PERFORMANCE OF SMC AND T-SMC BASED MPPTS

	SMC MPPT	**T-SMC MPPT**
Efficiency (Eff.) (Mean)	97.1496%	98.8777%
Fluctuation on Eff. (Min-Max)	96.66%-100%	96.45%-100%
V_{PV} (Max)	62V	63V
I_{PV} (Max)	14.8A	15.02A
Fluctuation on V_O (Min-Max)	132.3V	136.8V

VII. CONCLUSION

In this study, T-SMC based MPPT algorithm is proposed and its performance is compared with the classical SMC based algorithm. The dynamic performance of T-SMC is better than SMC when the irradiation levels approach maximum value as

1000 W/m^2. This situation effects the mean efficiency of MPPT algorithms and T-SMC has 98.8777% efficiency. The efficiency performance is better than SMC based MPPT algorithm. Also, the proposed system cannot much be affected from the irradiation changes and the efficiency is generally higher than 97%. The dynamic response of the proposed MPPT technique is much sufficient especially irradiation changes. Also, mean efficiency is more than 98%. In future studies, efforts will be made to minimize the chattering problem and improve MPPT performance by adapting different control techniques and parameter optimization.

NOMENCLATURE

I_{SCR}	Short circuit current at reference temperature
K	Boltzmann constant
k_i	Cell's short circuit current temperature coefficient
n_{cell}	PV panel total cell number
q	electron charge
S	Sun irradiance
S_{ref}	Solar radiation reference
T	Cell temperature
T_{ref}	Cell's reference temperature
T_{STC}	Standard test condition temperature
V_d	Diodes terminals potential difference
V_L	Inductance voltage
$V_{thermal}$	Thermal voltage
d	duty cycle

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