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Enhancement of Solar PV Panel Efficiency Using Double Integral Sliding Mode MPPT Control

Immadisetty Rahul and Raju Hariharan*

Abstract: The extraction of maximum power from the solar panels, using the sliding mode control scheme, becomes popular for partial weather atmospheric conditions due to its effective dynamic duty cycle ratio. However, the sliding mode control scheme was sophisticated with single integral and double integral sliding mode control scheme, which offer enhanced maximum power extraction and support enhanced solar panel efficiency in partial weather conditions. The operation of the sliding mode control scheme depends on the selection of a sliding surface selection based on the atmospheric weather condition, which enables the effective sliding duty cycle ratio operation for the DC/DC boost converter. The duty cycle ratio of the sliding mode control resembles the usual dynamic behavior to achieve enhanced efficiency compared to the various maximum power point tracking (MPPT) schemes. The major limitation of the sliding mode control scheme is to achieve the steady state voltage error of the solar panel in minimum settling time duration. The single integral sliding mode control scheme achieves the expected steady state voltage error limit but fails to achieve minimum settling time duration. Hence, the single integral sliding mode control is extended to a double integral sliding mode control scheme to achieve both steady state voltage error limits within the minimum settling time duration. This double integral sliding mode control scheme allows us to obtain the higher sliding surface duty cycle ratio which acts as the input signal to the boost converter. This activates the enhanced stable and reliable system operation, and nullifies the lacuna of maximum solar panel efficiency under partial weather conditions. Hence, this paper aims to present the design and performance operation of the double integral sliding mode (DISM) MPPT control scheme. To validate the performance analysis of the proposed DISM MPPT control scheme, the MATLAB/Simulink model is designed and verified. Also, the performance analysis of the proposed DISM MPPT control scheme is compared with the sliding mode controller (SMC) scheme and single integral sliding mode controller (SISMC) scheme. The performance analysis of the proposed double integral sliding mode controller (DISMC) scheme attains 99.10% of efficiency and a very less settling time of 0.035 s when compared to other existing methods.

Key words: maximum power point tracking (MPPT) schemes; sliding mode controller (SMC); double integral sliding mode controller (DISMC); pulse width modulation (PWM); photovoltaic (PV) system

1 Introduction

Electrical energy utilization in recent years increased rapidly due to humans' smart lifestyle changes, digitalized industrialization, developments in technology, etc.

• Immadisetty Rahul and Raju Hariharan are with the Department of Electrical and Electronics Engineering, Saveetha School of Engineering, Saveetha Institute of Medical and Technical Sciences (SIMATS), Chennai 602105, India. E-mail: immadisettyrahul@gmail.com; harinov22@gmail.com.

∗ To whom correspondence should be addressed.

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The impediments such as insufficient fuel capacity, global warming conditions[1, 2], etc. in existing power plants necessitate supplementary power sources. Therefore, renewable energy-based electricity generation is playing a significant role in recent years due to its clean and socio-economic power generation[3]. Social factors are critical considerations for the development of every country. Renewable energy systems have the potential to give the following social benefits: local employment, improved health, job opportunities, and consumer choice. The socio-economic benefits of renewable energy initiatives, with three examples being solar, wind, and biofuel energy projects; data were collected systematically. Renewable energy projects' contributions to local sustainability include social, economic, and environmental factors, as well as determining the socio-economic benefits of renewable energy projects (REPs) through social integration. Social factors are fundamental concerns for every country's growth. Renewable energy systems have the potential to bring the following social benefits: local employment, improved health, career opportunities, and more consumer choice. Renewable energy schemes are economically advantageous since they use rural labor, local supplies and enterprises, local shareholders, and local bank services. Another way that renewable energy projects have benefited the local community is the development of a trust fund that aims to invest the money generated from selling power in the local economy. Renewable energy efforts have improved environmental outcomes along with reducing carbon dioxide emissions and increasing public awareness of climate change. Solar renewable energy is a clean and vivid energy source compared to all other renewable energy sources that offer socio-economic power generation. Producing energy from fossil fuels with no greenhouse gas pollutants while lowering some forms of air pollution, increasing energy supply diversity, decreasing reliance on imported hydrocarbons, and fostering economic growth and employment in production, construction, as well as other fields. Also, the application of solar renewable energy generation was growing rapidly compared to wind energy generation due to its availability of abundant amounts in nature[4–6]. Solar energy is utilized all over the world and is becoming more and more common for producing electricity or heating and desalinating water. This grid offers a well-organized architecture that improves the efficiency of turning energy from light into electricity. Nowadays, silicon-based solar cells offer a mix of high performance, relatively inexpensive, and high durability. Among the main issues with producing renewable power traditionally have been that resources are far more unpredictable than with conventional energy production methods. The availability of supply is less stable than that produced by fossil fuel facilities due to variations in the amount of wind and sunshine. Solar energy is used for a variety of purposes, including solar power, solar water heating, solar heating, solar ventilation, solar lighting, portable solar, and solar mobility. A scheduling-based heuristic method was proposed based on temperature and power for multi-core systems, which addressed the peak energy and power consumption issues[7]. A variety of complicated things can be designed or managed using heuristic optimization techniques, which are synthetic intellect-searching techniques. Moreover, to reduce the demands in energy consumption, an integrated heat and power design was developed based on a renewable energy system and to minimize the energy consumption, an energy storage system was designed[8]. To improve local energy production and forecast energy demand, a heuristic intelligent neural decision support system was presented through an optimized algorithmic method based on smart renewable energy systems[9]. Although, its abundant availability solar renewable energy is facing a major problem of intermittent nature. This intermittent nature of solar energy turns solar power generation into a supplementary power generation source only. To overcome this problem, various researchers proposed various maximum power point tracking (MPPT) schemes such as perturbation and observation (P&O)[6], incremental conductance (IncCond)[7], and variable step size open circuit voltage[8], and the short circuit current scheme (VSSOCV)[9] along with parasitic capacitance (PC)[10] were developed and employed. Maximum power point tracking (MPPT) techniques are used in photovoltaic (PV) arrays to maintain the PV array's operating point at its maximum power point (MPP) and acquire the maximum possible power. A key development in the solar power industry, MPPT increased system dependability as well as the power output from PV cells. Multilevel inverters or capacitors connected to the network utilize MPPT techniques to regulate the constant updating. In conclusion, the optimal methods are those created utilizing the SASV-MPPT technique and Lyapunov conceptual design, taking into account the PV program's ability to switch between different characteristics. The MPPT method is based on an intelligent perturb and observe methodology that makes use of an artificial neural network (ANN-P&O) to reduce oscillations at the maximum power point (MPP). The ANN provides the MPP's voltage and current values in advance for any solar irradiation and cell temperature. In PV systems, the incremental conductance (INC) technique is also extensively utilized. It computes the MPP by comparing the instantaneous and incremental conductance of the PV array. The difficulty with the INC technique is the same as it is with the P&O method. Executive function and MPPT accuracy are typically associated with one other. But all these schemes are limited to maximum power extraction in partial shading conditions. Sliding mode controller (SMC) schemes are designed to over this maximum power extraction under partial shading conditions also and become popular in recent years. SMC is a method that is useful for systems with disturbances and uncertainties. This technique offers a reliable strategy for achieving the desired performance. Further, the SMC approach is discontinuous, with the control input switching between two limits.

SMC schemes are designed to offer maximum power extraction by activating the effective sliding surface switching actions during partial shading conditions[11, 12]. Although the SMC schemes are meeting the maximum power extraction under partial shading conditions, these SMCs are also limited due to a few shortfalls such as maintaining incessant steady state voltage error, ineffective dynamic sliding surface duty cycle ratio, steady state settling time, etc. To overcome these shortfalls the design of SMC is extended to single integral sliding mode controller (SISMC) scheme. Electric drive device speed control currently employs sliding mode control. High transient reaction, lack of sensitivity to changes in plant factors, and resistance to outside interference are some of its appealing properties. Among the most reliable and nonlinear techniques is SMC. A simple resolution for the input signal is provided by the product's methodical construction process. The product's resistance against matching external disruptions and unanticipated variable alterations are just a couple of its benefits. The single integral implantation in SMC minimized the steady state error voltage by improving the sliding surface duty cycle ratio with improved settling time compared to the SMC scheme. The modulus criterion optimized controller's steady-state error is evaluated for the case of a sinusoidal input signal. Stable-state error reduction techniques include increased switching frequency and an integral element series in the controller[13]. But, the SISMC scheme is also limited to achieving the minimum steady-state error voltage settling time. Higher steady state error voltage settling time makes the system unstable running conditions in long run. This corresponds to failure in meeting the maximum power extraction in partial shading conditions. Hence, the concept of a double integral SMC scheme was designed and tested to overcome this shortfall steady state error voltage in minimum system settling time. The concept of the double integral sliding mode controller (DISMC) scheme achieves the effective dynamic sliding switching operation which improves the sliding duty cycle ratio so that it offers enhanced solar panel efficiency during partial shading conditions[14, 15]. Hence this paper is aimed to design and test the performance analysis of the SMC scheme, SISMC scheme, and proposed DISMC scheme and its comparisons to validate the proposed DISMC scheme. A prospective distributed Monte Carlo program's analysis is often validated by contrasting its findings with those from other computational methods or empirical studies. Defining the goals of the DISMC system, creating a standard, implementing the DISMC system, comparing the findings, conducting a risk assessment, and validating against many standards are a few actions that may undertake to verify the functional testing of the proposed DISMC system. The MPPT system, which alters the switching frequency, is used to manage the DC-DC converter. Matching the frequency response to the insertion loss observed by a DC-DC converter, or the resistance of solar PV, is the underlying idea of switching frequency adjustment.

The three ways that can be created and put into use to produce green hydrogen for refuelling stations utilising photovoltaic (PV) panels are examined in this research. Levelized hydrogen cost (LHC) is calculated using techno-economic methods, as well as the contrast between the three scenarios and choice of the best course of action is made possible by the optimizing outcomes of the net profit cost (NPC) or LHC. At an expense of 5.5 €/kg, a 3 MW grid-connected PV setup offered a potential sustainable gas generation[16]. A nanofluid was created by dispersing graphene oxide nanoparticles in freshwater at mole fraction of 0.10%, 0.15%, 0.20%, 0.25%, 0.35%, and 0.45%. At values of 25 °C, 30 °C, 35 °C, 40 °C, 45 °C, or 50 °C in the flat plate solar collector (FPSC)—riser tube, temperature distribution as well as viscous were computed. The entire spectrum of data was predicted using fuzzy systems and artificial neural networking systems, or help make decisions, we evaluated to identify errors and select the solution with the lowest error. Findings demonstrated that the fuzzy expert system accurately forecasted the feedback information[17].

The main contribution of the paper is discussed as follows:

- In this paper, the double integral SMC scheme is designed and tested to overcome the shortfall steady state error voltage in minimum system settling time.
- The DISMC scheme achieves an effective dynamic sliding switching operation which improves the sliding duty cycle ratio so that it offers enhanced solar panel efficiency during partial shading conditions.
- The MATLAB/Simulink model is designed to validate the performance analysis of the proposed DISM MPPT control scheme.

The paper is organized as follows: Section 1 discusses the introduction of the work; Section 2 indicates the DISMC; Section 3 indicates the results of the proposed methodology; Section 4 indicates the discussion of the work; finally, the conclusion of the work is discussed in Section 5.

2 Double Integral Sliding Mode Control

The DISMC scheme of the MPPT technique comprised a pulse width modulation (PWM) generator based DC-DC boost converter fed from a solar PV panel[14, 15]. A holding circuitry with integrators receives the PWM information. The integrator produces a ramping response that size is inversely proportionate towards the pulse duration whenever the affirmative side of the pulses occurs. The proposed DISMC scheme was designed to enable the enhanced sliding surface switching actions so that the effective sliding surface duty cycle ratio obtains the constant potential to the DC-DC boost converter and the schematic view of this proposed DISMC scheme operation is observed in Fig. 1. There are two types of direct current to direct current operation modes: linear and switching. DC-DC conversions come in two flavors: switching and continuous. A switched-mode DC-DC converter operates by regularly holding the energy required and then transferring it towards the outcome at a higher-voltages than a linear DC-DC conversion, which creates and regulates a production value via a resistance power dissipation. A linear DC-DC converter produces and regulates a certain output

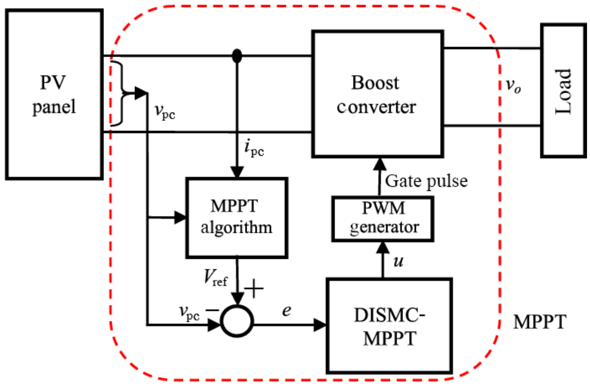


Fig. 1 Schematic view of solar PV system model with DISMC.

voltage through the use of a resistive voltage drop, whereas a switched-mode DC-DC converter converts by accumulating input energy periodically and then releasing it to the output at a variable voltage. High energy converting circuitry known as DC converters utilizes inductive loads, transducers, or capacitance to reduce voltage fluctuations and produce controlled DC outputs. Maximum power point (MPP) monitoring is among the crucial tasks that DC-DC conversion machines are capable of carrying out. The goal is to maintain the continuous operation of the solar energy system at its maximal power. The constant input-based DC-DC boost converter then generates the required power supply to the load under partial shading conditions with minimum settling time constraints. Therefore, the higher the effective dynamic sliding surface duty cycle ratio, the higher the solar panel efficiency observed. Enhanced cellular technologies, anti-reflective coverings, oxide layer coatings, reverse connection modules, concentrating solar cells, monitoring systems, along with thermal control, are some techniques to enhance and raise solar energy production. A nonlinear controller composite that combines backstepping and sliding mode controllers for DC-DC boost converters (DDBCs) fed by constant power loads (CPLs). A DC-DC converter's order to sustain the desired output voltage when the input voltage varies is known as voltage regulating. The inductance in the series resistance has an unanticipated variation in the input signal, which is how the DC-DC conversion functions. The inductor absorbs power from the input while the switching is on and retains electromotive force. The power escapes if the valve is engaged. The buck/boost conversion is employed to produce electrical outputs that are less than, higher than, or equivalent to the voltage source. The charge controller is employed to produce electrical outputs that are greater than the voltage being converted. In the interest of preserving the same load power, $P = VI$, a continuous power load is built to continuously regulate the power flow proportionally with the voltage waveform. In assessing the performance of models, like that of a changing type electrical supply, this inverted feature of a continuous power load is frequently helpful. Therefore, we need to provide energy to the feedback path to guarantee continuous power rather than supply current. The terminal voltage is then driven by the amplifier circuit to keep them identical after comparing a sampling of maximum output towards the standard. The nonlinear dynamical model is transformed into a simpler linear system with canonical form using an accurate feedback linearization technique[18]. Dynamic models use continuous translations or normal dynamical systems to model the time dynamics of a parameter value. The responses to these problems or transformations, as well as how they rely on the variables or beginning circumstances, are studied in the dynamical systems approach. A DC microgrid (DCMG) nonlinear decentralized double-integral sliding mode controller (DI-SMC). Ultimately, the DISMC program's utilization of two integral sections assures that every steady-state mistake that could exist can be eliminated, regardless if it is brought on by disruptions or modeling uncertainty. This DCMG comprises a hybrid energy storage system with a battery and supercapacitor energy storage technologies. Power generated by solar photovoltaic (SPV) devices meets the load requirement[19]. PWM does not decrease voltage or current; instead, it decreases averaging current as well as voltage by altering the ratio of on to off duration. This action lowers total energy, while immediate authority is determined by the combination of the two variables. The necessary action can be conducted to confirm the efficacy of the suggested DISMC-based MPPT system: modeling, comparing with other MPPT techniques, simulation results, and risk assessment. To contrast their performances and show the benefits of the SISMC system over the SMC system, the SISMC system has been evaluated alongside the SMC method mentioned previously. The proposed DISMC scheme uses two integral blocks to minimize the steady-state error voltage of the PWM generator and the corresponding equations related to this DISMC scheme are given below to obtain the constant potential and current for non-linear type of load consideration conditions.

PWM's primary benefit is the extremely low power loss in switching components. There is nearly no current when a switch is turned off, and almost no voltage drops across the switch when it is turned on and power is transmitted to the load. The output current of a solar panel is expressed as i_{pc} and is given by

$$\begin{aligned} i_{pc} = & I_{pc} - I_0 \left[\exp\left(\frac{v_{pc} + i_{pc} R_s}{N_{sc} V_{th}} \right) - 1 \right] - \\ & \frac{v_{pc} + i_{pc} R_s}{R_{sh}} v_{pc} \text{ with} \\ i_{pc} = & (I_{sc} + K_1 (T - 298)) \frac{H}{1000} \end{aligned} \tag{1}$$

$$V_{th} = \frac{a k_b}{e} T \tag{2}$$

$$I_0 = I_{0,\,ref} \left(\frac{T}{298} \right)^3 \exp\left(e E_g \frac{e E_g}{k_b N_{sc} V_{th}} \left(\frac{1}{298} - \frac{1}{T} \right) \right) \tag{3}$$

where $I_0, i_{pc}, T, k_b, R_s, H, R_{sh}, I_{sc}, K_1, N_{sc},$ and V_{th} are initial state current, solar panel current, temperature, Boltzmann's constant, series resistance, irradiation, shunt resistance, short circuit current and its coefficient, series connected cell count, and thermal voltage, respectively. I_{pc} is the photo generated current. v_{pc} is the voltage across diode or photo voltage across diode current. I_{sc} is the shunt current. a is the acceleration. e is the electron charge 1.602×10^{-19} C. $I_{0,\,ref}$ is the reference current at zero point. And E_g is the gate voltage. Boltzmann constant is used to expressing an atom's energy equipartition that represents the Boltzmann factor. It has a significant impact on the statistical definition of entropy and it is the term used to indicate thermal voltage in semiconductor physics. Among the most crucial ideas in both statistical mechanics and astrophysics is entropy. Entropy is an indicator of the level of chaos in a material or biological entity that is used casually. The less data we know about a process, the greater its volatility. Shunt resistance refers to a resistor with an extremely low resistance value. The shunt resistor is primarily comprised of a material with a low-temperature coefficient of resistance. It is parallel-connected to the ammeter whose range has to be improved. Additionally, the operating modes of the DC-DC boost converter to generate the required power supply for the nonlinear type of loads in circuit representation mode are presented in Fig. 2[5, 19]. Linear loads include transformers, motors, and capacitors. A non-linear process is one whereby such a proportionate connection between intake and outcome and does not at all exist. A linear load is an electromagnetic demand

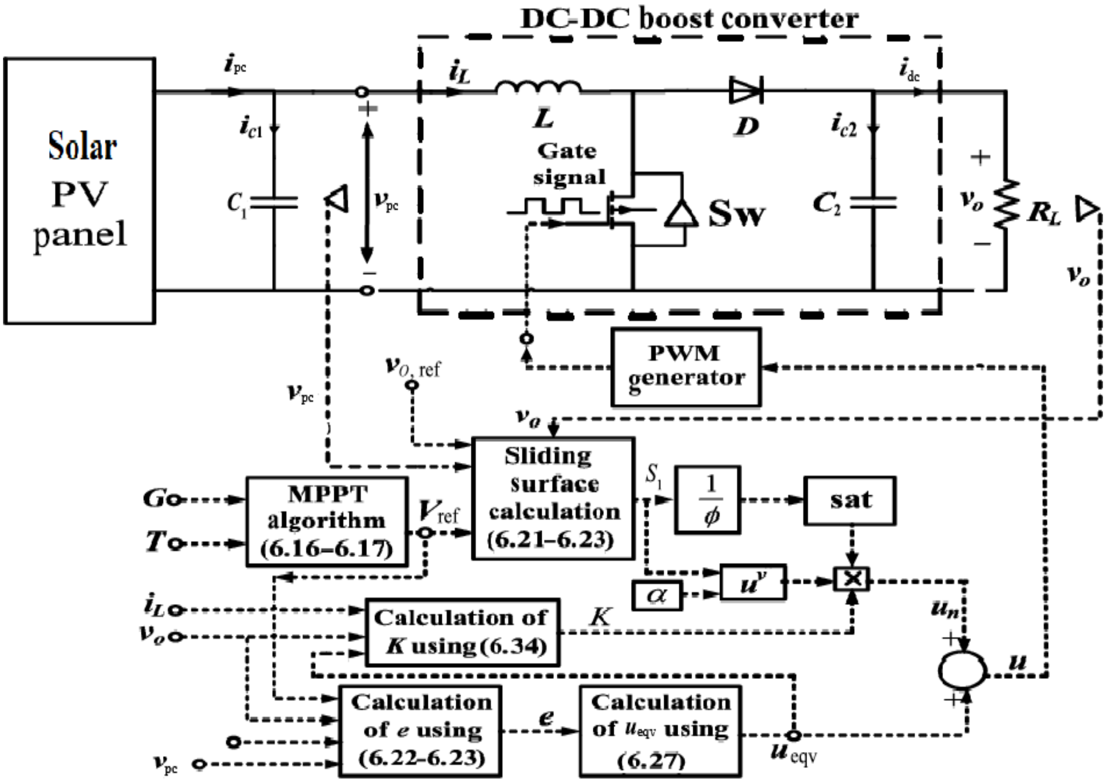


Fig. 2 DISMC-based MPPT design.

that uses AC energy with a voltage level of 1, using both actual and perceived electricity. The reactive power of a non-linear application is a little less than 1 Var, so it produces harmonic components in option to the initial AC current. The current in a non-linear load is not proportional to the voltage and varies depending on the intermittent load impedance. If the impedance of a load fluctuates with the applied voltage, it is a non-linear load. Owing to the element drops throughout the network characteristic impedance, the nonlinear load functions as a generator of current harmonics in the electrical network, resulting in voltage deformities at the multiple system bridges. Even though the non-linear load is connected to a sinusoidal voltage, the fluctuating impedance implies that the current drawn by the load will not be sinusoidal. Varying fatigued pressures are defined as loads that are of the identical sort (tension or compression) and range from a lower limit to the highest benefit. As the capacity (or resistance) is raised, the external load (or, you could say, impedance) is linked parallel to the previous weight since electricity charges are typically linked together. The comparable resistance is often decreased by a parallel connection. As a result, the current grows.

Six elements are commonly found in photovoltaic systems: a solar PV array, a charge controller, a battery bank, an inverter, an utility meter, and an electrical grid. Such variables involve the kind of PV substance, the amount of sunlight absorbed, the heat of the cells, freeloading defenses, the impacts of clouds as well as other types of coloring, the effectiveness of the alternator, sand, the alignment of the modules, the position of the modules, and so on. The effectiveness of solar panels is influenced by the proper installation of all of these components. The main elements of solar panel installation's efficiency are shading elements, location, time, the orientation of the Azimuth angle, pollution, etc.

It is possible to calculate the open circuit potential from the equivalent circuit given by

$$V_{oc} = N_{sc} V_{th}((\ln i_{pc} + I_0)/I_0) \tag{4}$$

The reference voltage for boost converter is calculated using open circuit voltage, and is given by

$$V_{ref} = M_{oc} \cdot V_{oc} \tag{5}$$

where M_{oc} is the solar PV panel material coefficient depending on the assembly of the proposed solar PV module and its material. Load impedance, sunshine strength (modules orientation and inclination), temperature difference, shadowing, dirtying, panel mismatches, transformer converter loss, and photovoltaic design are the main factors that determine a component's performance. Therefore, Eqs. (4) and (5) necessitate the design requirement of design panel open circuit potential and reference potentials are equal in magnitudes. Open circuit energy and corroded perspective are the same despite having different names. The perspective that an electrode has regardless of the outer power supplied is known as the oxidation potential. The term "open circuit potential" (OCP), also known as "open circuit voltage", "zero-current potential", "corrosion potential", "equilibrium potential", or "rest potential", refers to a passive method. To forecast whether different metals will take an interest in various electrochemical processes in a particular format, a knowledge of the potential for open circuits is essential in the corrosive sector. It is widely used to identify the resting potential of a system, on which further study is based. These organisms can have their passive membrane potential evaluated by inserting a sensor into the unit. Cardiomyocytes calculated remaining voltage is –90 mV. The quantity of particular potassium pathways is generally what matters most for controlling the reference voltage. Certain ion exchangers, like the Na+/K+-ATPase, cause electric polarization throughout the cell surface which may additionally actually impact membrane permeability. The sodium-potassium compressor as well as the sodium and potassium overflow streams are the two kinds of signaling pathways that keep relaxing cell wall possibilities stable. It is the voltage present when the terminal ends of a circuit are separated and there is no external load. To attain the same potential magnitudes, the proposed DISMC scheme was designed using Fig. 2[5]. Figure 2 demonstrates the intention of estimating the sliding surface duty cycle ratio signal as a gate signal for the IGBT-based boost converter switch. IGBTs are frequently used in inverter circuits (for DC-AC conversion) to power small to large motors. IGBTs are frequently utilized in inverter circuits (for DC-AC conversion) as swapping components to drive modest to big machines. To enhance their effectiveness, it is used in factory machines, automobile rotation speed regulators, or residential devices like air conditioning units and freezers. Appliances are put through tests to determine the amount of energy they consume regularly. This provides them a score on a range of A to G, with A regarded as the greatest effective item of its category, with G becoming the least effective. Compared to the power of MOSFET or BJT, the IGBT has benefits. It has superior conductance in the ON phase as well as a low ON-state power loss. This enables the use of a reduced die area with the potential for reduced production expenses. IGBT powering is straightforward and power-efficient. IGBTs are utilized in inverter applications to boost the efficiency of household appliances like air conditioners and refrigerators, as well as industrial motors and primary motor controllers for automobiles. There are various techniques to improve home appliance performance, that can aid in conserving energy and lower electricity costs. According to the location of the information relative to the sliding manifold in nonlinear adaptive systems, a switching function normally determines whether the component of the control method is to be utilized at a specific time moment. Therefore, the sliding switching surface $S_s(y)$ duty cycle ratio is given by

$$S_s(y) = \left\{\frac{\mathrm{d}}{\mathrm{d}t} + \beta\right\}^{j-1} e(y) \tag{6}$$

where s signifies the state space of the vector of the proposed solar PV system design, j is the sliding switch demand to accomplish the steady state error potential, β is a constant, and $e(y)$ is the controlling error representation. A steady-state error is related to three constants: the position constant (Kp), the velocity constant (Kv), and the acceleration constant (Ka). The disparity among a service's intake (request) or production in the maximum as duration approaches infinitely is known as a steady-state error. The steady-state error is dependent on the software configuration and the intake kind (0, I, else II). Users may establish if a system has a restricted steady-state error by knowing the values of these constants as well as the system type. The type of input used to stimulate the control system is the primary cause of the steady-state error. An additional component is the system type, as indicated by the structure of the transfer function. If

$$J = 1 \text{ obtains } S_s(y) = e(y) \tag{7}$$

The controlling error e given in the boost controller is

$$e(y) = e(y_1) + e(y_2) + e(y_3) \tag{8}$$

where $e(y_1) = V_{\mathrm{ref}} - v_{\mathrm{pc}}$, $e(y_2) = \int (V_{\mathrm{ref}} - v_{\mathrm{pc}})\mathrm{d}t$, $e(y_3) = \iint (V_{\mathrm{ref}} - v_{\mathrm{pc}})\mathrm{d}t$.

Therefore, the proposed DISMC MPPT scheme is envisioned to mitigate the steady state error voltage $e(x)$ using double integral concept arrangement projected from Eqs. (7) and (8).

3 Result

To validate the proposed DISMC MPPT control scheme, the DISMC scheme-based solar PV panel rated with 1 kW was designed in MATLAB/Simulink software. Simulink is a modeling and simulation tool for dynamic systems that includes a graphical editor, programmable block libraries, and solvers. It is MATLAB-compatible, which means that users may include MATLAB techniques in models and export simulation results to MATLAB for further analysis. Also, to validate the performance analysis of the proposed DISMC scheme, the SMC scheme and SISMC scheme are also designed and compared with the proposed DISMC scheme. Therefore, the MATLAB/Simulink designed model of the proposed DISMC MPPT scheme is presented in Fig. 3. The same design model control algorithm was altered and analyzed for both SMC and SISMC schemes.

The solar PV panel system configuration used in the simulation study is

PV array: 1 parallel and 1 series connected module per string;

Maximum rated power: 60.003 W;

Potential at open circuit terminal: 22 V;

Current at a shorted terminal: 3.8 A;

RL load: Load active power 1000 W; reactive power 200 Vars.

A photovoltaic array (PV array) is a full power-generation device made up of any number of PV modules and panels. PV modules and arrays are typically rated based on their maximum DC power output (W) under standard test conditions (STC).

Case study 1: Simulation results for sliding mode control MPPT scheme

To verify the proposed DISMC MPPT scheme, the simulation design model at the above-specified ratings is tested for SMC based MPPT scheme. To understand the performance efficiency of the SMC-based MPPT technique, the variations of the load output power and its source panel output power were presented in Fig. 4.

The load potential and solar panel potential variations are also observed in Fig. 5. The potential load is one of the factors that contribute to a body's second-order stress. It is the load caused by the second-order potential. It results in the complete QTF when added to the quadratic load. It is observed from Fig. 5 that, the efficiency was measured at 94.63% for a load output power magnitude of 41.78 W for the corresponding panel output power of 44.15 W. Similarly, the load potential and load current magnitudes are recorded at 46.26 V, and 0.9031 A, respectively. Additionally, the SMC-based MPPT scheme's settling time and sliding surface duty cycle ratio were measured at 0.1 s and 72.26%, respectively, which indicates the inefficiency of the sliding surface switching mode operation. Although the SMC-based MPPT scheme supports the dynamic performance of sliding surface switching actions under partial shading conditions, the measured magnitudes of sliding surface duty cycle ratio and settling time necessitate a lack of stable reliable operation in long run.

Case study 2: Simulation results for single integral sliding mode control MPPT scheme

To verify the proposed DISMC-based MPPT scheme performance, the SISMC scheme is tested along with the above SMC scheme. The efficiency of the SISMC scheme was measured at 96.8% for load and source panel

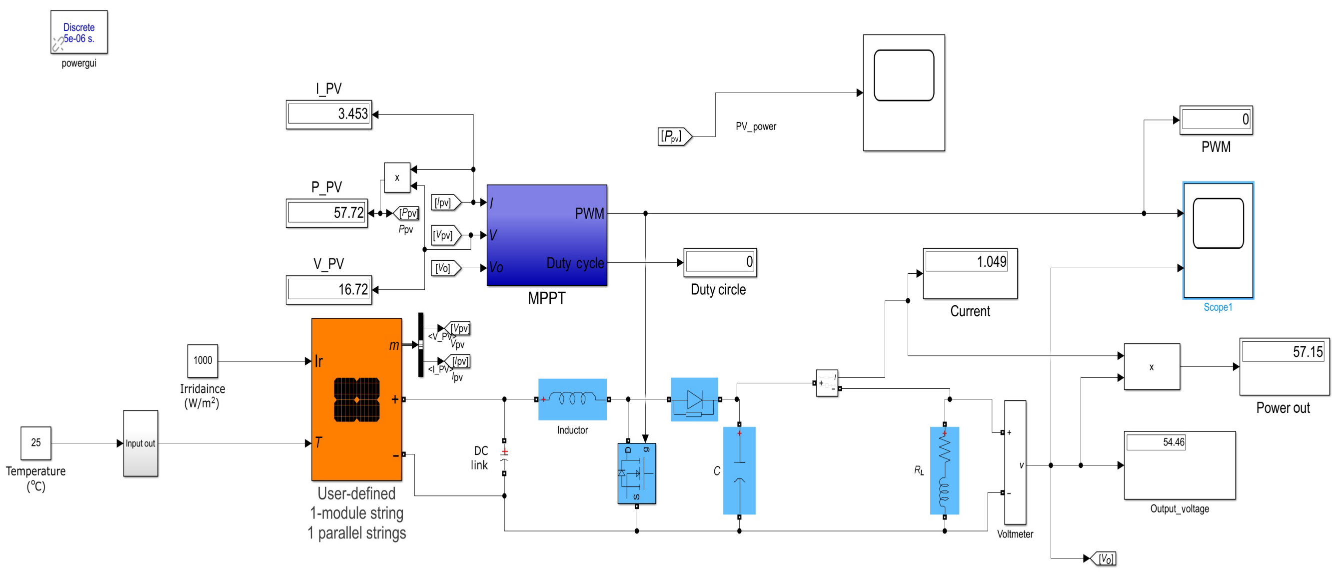
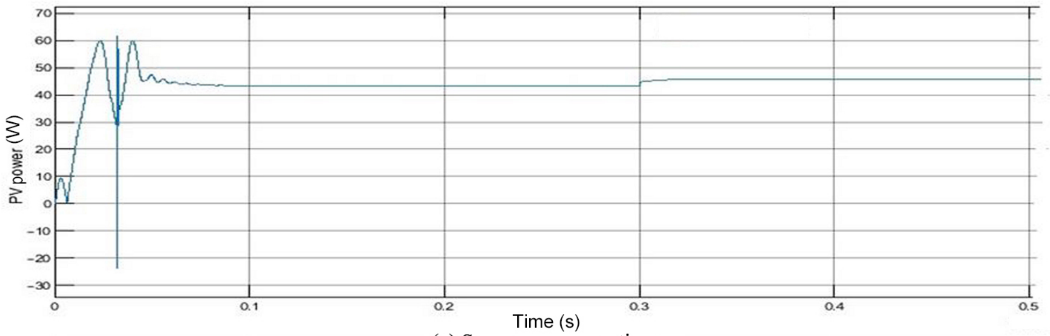
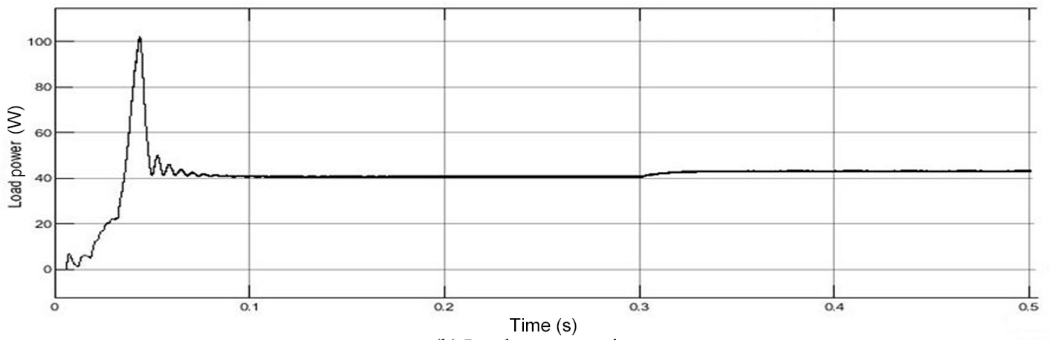


Fig. 3 MATLAB/Simulation design model of proposed DISMC MMPT scheme-based PV system.

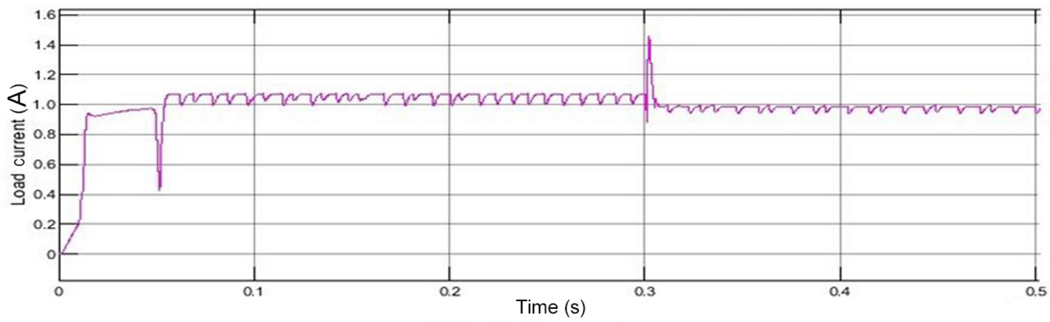


(a) Source power vs. time

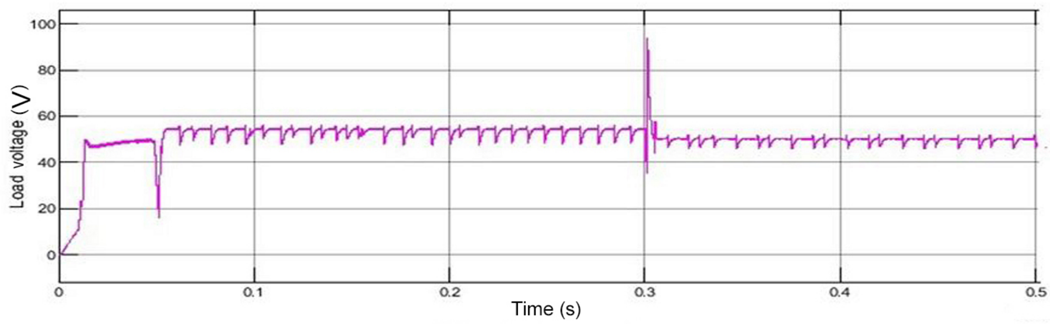


(b) Load power vs. time

Fig. 4 Source and load output power variations under SMC-based MPPT scheme.



(a) Load current vs. time

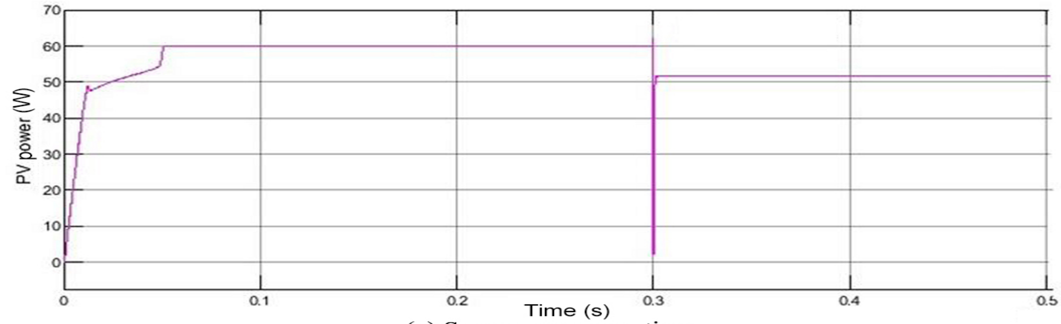


(b) Load voltage vs. time

Fig. 5 Voltage and current variations of the SMC-based MPPT scheme.

output powers of 55.92 W and 57.74 W, respectively, and the variations are given in Fig. 6. Similarly, the variations of load potential and current magnitudes under this SISMC scheme were observed in Fig. 7 and measured at 53.44 V, and 1.046 A, respectively.

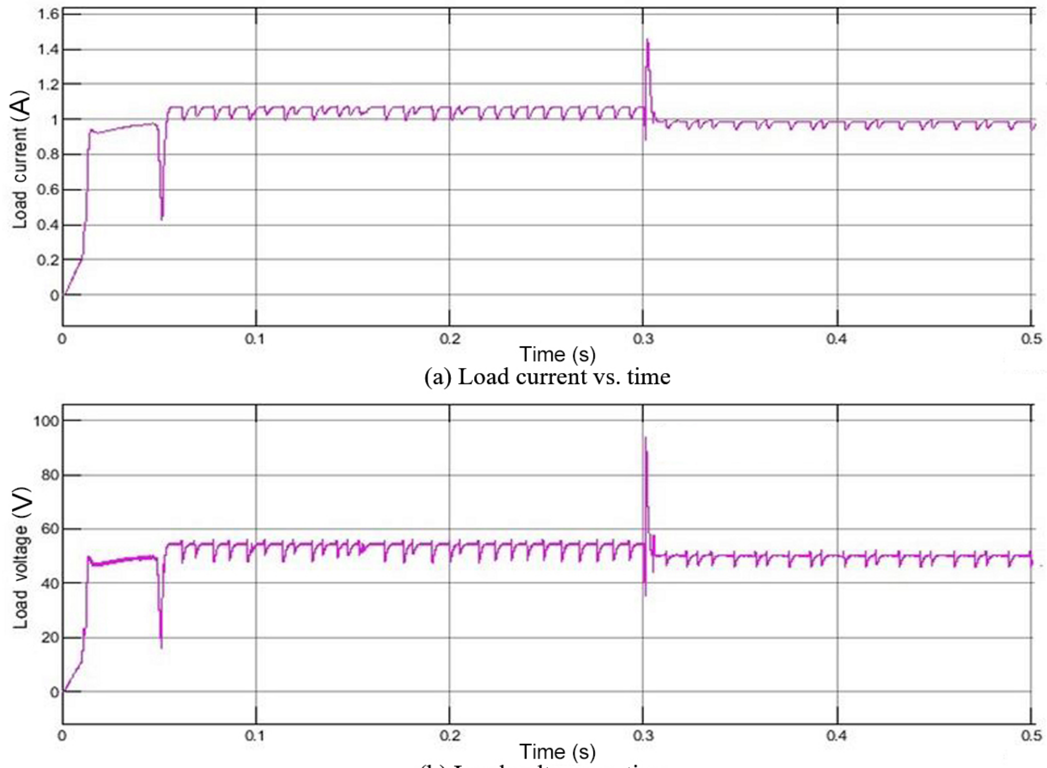
Additionally, the sliding surface duty cycle ratio also measured 0.921 which is improved significantly compared to the SMC scheme and confirms improved dynamic sliding surface switching operation with a reduced settling time of 0.05 s time duration only. Hence, it is clear from Fig. 6 to Fig. 7, the performance analysis of SISMC based MPPT scheme was improved compared



(a) Source power vs. time

(b) Load power vs. time

Fig. 6 Source and load output power variations under SISMC-based MPPT scheme.



(a) Load current vs. time

(b) Load voltage vs. time

Fig. 7 Voltage and current variations of the SISMC scheme.

to the previous SMC-based MPPT scheme.

Case study 3: Simulation results for double integral sliding mode control MPPT scheme

The proposed double integral sliding mode control scheme was designed for the same equipment configuration given in the above sections. The efficiency of the proposed DISMC MPPT scheme was calculated at 99.01% for the load and source panel output powers of 57.15 W and 57.72 W, respectively, and its variation waveforms are observed in Fig. 8. Correspondingly, load potential and current waveforms are observed in Fig. 8 and the magnitudes are recorded at 54.46 V and 1.049 A, respectively.

Additionally, the sliding surface duty cycle ratio was also verified and measured at a magnitude of 0.985 which is approximately equal to unity with a settling time of 0.02 s time duration only. The enhanced efficiency of 99% is achieved for the proposed DISMC MPPT scheme compared to the other two SMC and SISMC schemes. To validate the proposed DISMC MPPT scheme, the performance variations such as efficiency, settling time, sliding surface duty cycle ratio, etc. are compared in Table 1 with the SMC MPPT scheme, SISMC MPPT scheme, and P&O MPPT scheme given in the literature[22].

4 Discussion

It is observed from Fig. 3 to Fig. 8 and performance comparison in Table 1, the proposed DISMC MPPT scheme shows enhanced solar panel efficiency compared to SMC MPPT and SISMC MPPT schemes. However, the performance analysis of the P&O MPPT scheme presented in the literature[23, 24] shows enhanced efficiency performance compared to the SMC MPPT scheme, but it is limited to partial shading conditions. The sliding surface mode control switches to the concept of effective dynamic switching operation corresponding to partial shading conditions and shows acceptable reliable operation. Dynamic power is the most important component of switching losses in circuits, and it also contributes to peak power. It is determined by the supply voltage, switching frequency, and output load. The two main parts of dynamic power are switching

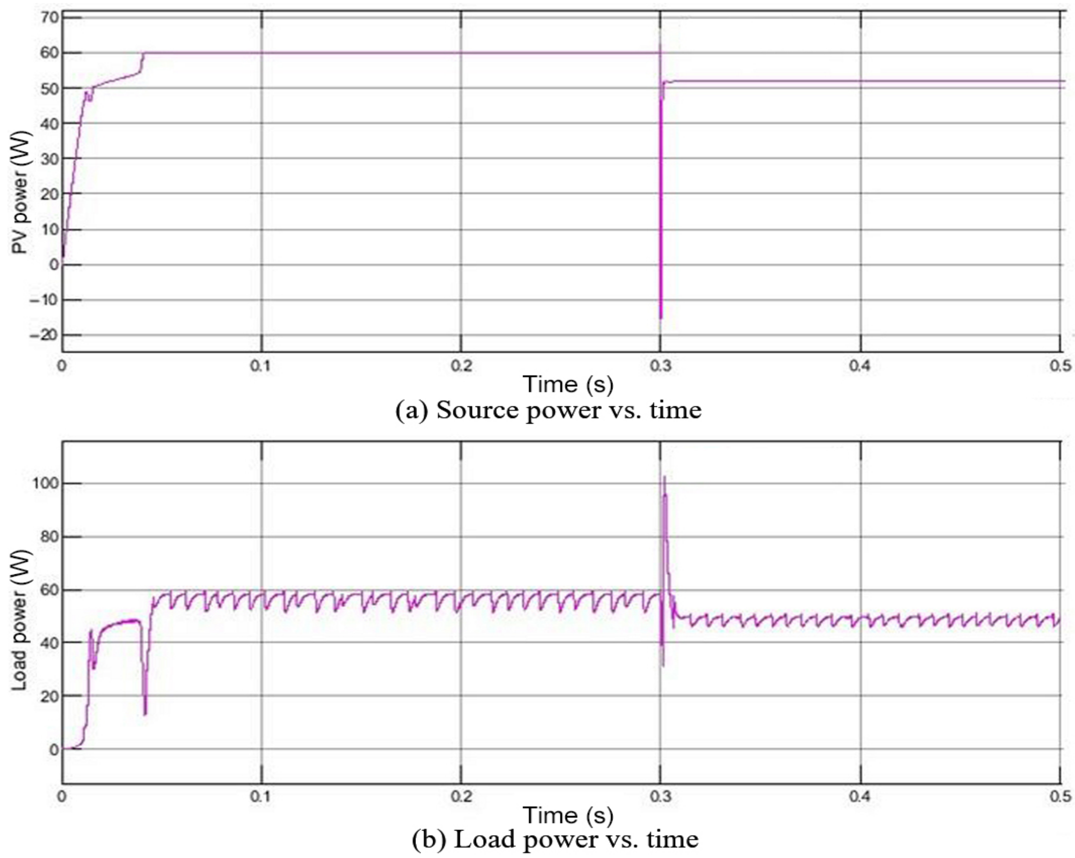


Fig. 8 Source and load output power variations under DISMC-based MPPT scheme.

Table 1 Comparison of performance analysis of DISMC with SISMC and SMC MPPT schemes and P&O scheme reported in the literature[20, 21].

Scheme	Settling time (s)	Efficiency (%)	Sliding surface duty cycle ratio	Load potential (V)	Load current (A)
P&O MPPT	0.3	96.16	–	–	–
SMC MPPT	0.07	94.60	0.7466	46.26	0.9031
SISMC MPPT	0.055	96.8	0.921	53.44	1.046
DISMC MPPT	0.035	99.10	0.985	54.46	1.049

power and short circuit power[25, 26]. Dynamic switching may be used by users to reduce average system power consumption and enhance the overall system thermal performance. This sliding mode surface control scheme is sophisticated with single integral sliding mode control scheme and double integral sliding mode control scheme, and becomes popular in recent years due to its effective dynamic sliding switching actions which comply with human-made dynamic switching operations. This is confirmed with a sliding surface duty cycle ratio of 0.985 at a very less settling period of 0.02 s time duration using the DISMC MPPT scheme. Hence, the proposed DISMC MPPT scheme offers effective dynamic sliding surface switching operations with enhanced solar panel efficiency under usual and partial shading conditions. In addition to this, the minimum settling time and higher sliding surface duty cycle ratio of the proposed DISMC MPPT scheme offer the enhanced reliable operation of the designed system.

5 Conclusion

The proposed DISMC MPPT scheme for a 1 kW rated solar PV model given in Fig. 1 is designed and analyzed using MATLAB/Simulink software. To validate the performance analysis of the proposed DISMC scheme, the SMC MPPT scheme and SISMC MPPT scheme are also designed and compared. From the comparison of performance analysis DISMC, SISMC, and SMC MPPT schemes, the following inferences are drawn:

(1) The proposed DISMC MPPT scheme is achieved enhanced solar PV panel efficiency for nonlinear load variations compared to SMC and SISMC MPPT schemes.

(2) The sliding surface duty cycle ratio of the proposed DISMC MPPT scheme achieves approximately unity which results in effective dynamic switching surface operations in partial shading conditions compared to other SMC and SISMC MPPT schemes.

(3) The settling time of the proposed DISMC MPPT scheme demonstrates the stable and enhanced reliable operation compared to the SMC MMPT scheme and SISMC MPPT scheme.

(4) Therefore, the proposed DISMC scheme offers enhanced solar PV panel efficiency under partial shading weather conditions compared to other existing MPPT schemes.

(5) As contrasted with other methods already in use, the suggested DISMC's performance assessment achieves 99.10% effectiveness. Moreover, it achieves a very fast 0.035 s settling time.

In future work, we may focus on improving the efficiency and settling time of the proposed method by adding novel techniques.

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Raju Hariharan received the BEng degree in electrical and electronics engineering from Anna University, Chennai, India in 2009, the MEng degree in embedded system and VLSI design from Dr. MGR Educational Research Institute, Chennai, India in 2012, and the PhD degree from Saveetha Institute of Medical and Technical Sciences, Chennai, India in 2018. He is currently an associate professor with the Department of Electrical and Electronics Engineering, Saveetha School of Engineering, Saveetha Institute of Medical and Technical Sciences (SIMATS), Chennai, India. He has published more than 45 Web of Science/Scopus indexed journal papers. His research interests include the artificial intelligence in real time applications and blackout restoration. He is a member of IET and IAENG. He has also served as a reviewer for various reputed journals such as *Journal of Electrical Engineering and Technology* and springer.

Immadisetty Rahul received the master degree from Aurora's Engineering College affiliated to JNTUH, India in 2012, and the bachelor degree from Jawaharlal Nehru Technological University Hyderabad (JNTUH), India in 2008. He is currently pursuing the PhD degree at the Saveetha School of Engineering, Saveetha Institute of Medical and Technical Sciences (SIMATS), Chennai, India. His area of interest includes power electronics and drives and renewable energy systems.