Abstract: Different tracking algorithms have been developed to obtain maximum efficiency from the PV power systems under changing atmospheric conditions. Some of these algorithms are effective under uniform irradiance, while the others are effective under partial shading conditions. In this study, a new MPPT method designed with System Identification-SI and named SI-based polynomial ARV is proposed for a PV system under uniform irradiance. The recommended method is also an adaptive reference voltage-ARV-based method. In this method, the model in which the reference voltage is obtained has a simple polynomial structure. This polynomial model has been obtained by assuming that the PV system is a nonlinear black-box type system. The input-output data, which are required for modeling, were created in MATLAB/Simulink environment. Then, by using these data with SI-Toolbox, the mathematical model of the PV system in polynomial structure giving the input-output relationship was obtained. Temperature information was used as model input, which was the generated reference voltage. Simulation studies were carried out under two different changing atmospheric scenarios; and the performance of the proposed method was analyzed. The obtained results were compared with perturb & observe-PO, incremental conductance-IC, constant voltage reference-CVR, artificial neural network-ANN-based ARV, and SI-based nonlinear ARV methods. All simulation results showed that the recommended method is simple structured, applicable, and has high performance.

Index Terms: Energy conversion, energy management, MPPT algorithms, photovoltaic energy, renewable energy, system identification.

Nomenclature:
- PO: Perturb & Observe
- IC: Incremental Inductance
- CVR: Constant Voltage Reference
- ARV: Adaptive Reference Voltage
- CC: Constant Current
- HC: Hill Climbing
- PC: Parasitic Capacitance
- FOCV: Fractional Open Circuit Voltage
- FSCC: Fractional Short Circuit Current
- RCC: Ripple Correlation Control
- ANN: Artificial Neural Network
- FLC: Fuzzy Logic Control
- PSO: Particle Swarm Optimization
- IPSO: Improved Particle Swarm Optimization
- GA: Genetic Algorithm
- GWO: Gray Wolf Optimization
- ABC: Artificial Bee Colony
- ACO: Ant Colony Optimization
- FFA: Firefly Algorithm
- DE: Differential Evolution
- BSA: Bat Search Algorithm
- CA: Cat Algorithm
- JA: Jaya Algorithm
- GSA: Gravitational Search Algorithm
- MKE: Monkey King Evolution
- CS: Cuckoo Search
- BOA: Butterfly Optimization Algorithm
- MFO: Moth-Flame Optimization
- SSA: Salp Swarm Algorithm
- SFLA: Shuffled Frog Leap Algorithm

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I. INTRODUCTION

Due to the usage of fossil fuels and the greenhouse effect occurring in the atmosphere, global warming is increasing rapidly, glaciers are melting, the ozone layer is pierced, natural disasters occur frequently, and people lose their lives due to diseases caused by air pollution. According to the 2019 report of the International Energy Agency (IEA), global energy-related CO₂ emissions increased by 1.7% in 2018 due to increased fossil fuel consumption [1]. Because of these disadvantages, fossil fuels are accepted not to be clean and sustainable. Due to the global environment problems caused by fossil fuels in energy production and the high costs of measures taken to solve these problems, the interest and tendency to renewable energy sources have increased in recent years.

Between 2009-2019, the share of renewable energy sources used in electrical energy production increased and reached 75% [2]. As of the end of 2019, the global scale utilization capacities of these resources are as follows: Hydropower 1150 GW, wind-power 651 GW, solar-power PV 627 GW, bio-energy 139 GW, geothermal-energy 13.9 GW, concentrating solar thermal power (CSP) 6.2 GW, ocean-power 0.5 GW.

PV power systems have advantages; for example, they are clean energy sources and environmentally friendly [3], lack of moving parts, cause no noise pollution, do not need long periodic maintenance periods, and have a life span of more than 20 years [4]. Contrary to these advantages, the efficiency of PV panels is low. To get a better result about this low efficiency, numerous studies have been carried out in the field of materials. The efficiency of silicon-based and monocristalline standard PV panels produced with current material technology is approximately 14-17.5% under standard test conditions (STC-1000 W/m², 25°C). Using the mineral called perovskite with crystal structure of ABX3, which is in the sub-class of oxide minerals, 31% efficiency was obtained [5]. By using gallium arsenide instead, the yield could be increased up to 40%. However, this is a very costly method. The optimum operating point is called as Maximum Power Point-MPP. Different Maximum Power Point Tracking-MPPT algorithms have been...
developed for the PV power system, which has low efficiency under changing conditions to operate with both high performance and maximum efficiency at the highest power point [4]. Advances in power electronics and microprocessors have made it possible to apply many different MPPT techniques.

In this study, a new MPPT method designed with System Identification-SI is proposed. The proposed method is also an Adaptive Reference Voltage-ARV-based method, and the model, in which the reference voltage is obtained, has a simple polynomial structure. Therefore, it is named SI-based polynomial ARV. The proposed method was compared with Perturb & Observe-PO, Incremental Conductance-IC, Constant Voltage Reference-CVR, Artificial Neural Network-ANN based ARV, and SI-based nonlinear ARV methods. Simulation studies in MATLAB/Simulink environment were performed under two different changing atmospheric scenarios. After that, performance analysis of the proposed method was made. All simulation results obtained are presented in graphs comparatively.

II. CLASSIFICATION OF MPPT METHODS AND LITERATURE REVIEW

MPPT controllers play a vital role in monitoring the maximum power-point to increase the efficiency of PV systems [6]. The first PV system with MPPT was designed in 1968 for a space system [7], [8]. Numerous MPPT algorithms have been proposed and used in PV systems until today [9]. However, the performance of these different techniques to carry out comprehensive comparison by various evaluation criteria such as efficiency [10], monitoring speed [11], accuracy [6], and implementation complexity [12] is difficult. The behavior of the PV system entirely depends on the operating conditions. Therefore, analyzes, comparisons, and classifications on MPPT techniques are insufficient without considering different operating conditions [13]. Examples include the lack of methods that can be adapted to all working conditions [14], inadequate analysis of various methods [15], and uncertain classification [16].

MPPT methods are classified in different ways in the literature. A total of 62 MPPT methods developed with their modifications in [13] are categorized into seven separate groups. These are conventional algorithms, meta-heuristic algorithms, hybrid algorithms, mathematics-based algorithms, artificial intelligence-AI algorithms, algorithms based on the estimation of characteristics curves, and other algorithms. However, in reference [17], it is classified in 3 separate groups as conventional, intelligent and optimization.

Conventional MPPT methods are basically structured also easily applicable methods. These methods only follow the MP point of PV systems under uniform insolation. Therefore, under rapidly changing atmospheric conditions and partial shading conditions (PSC), they cannot observe the global maximum power point (GMPP). They fall short. Even if they catch the GMP point, they cause large oscillations that can lead to power losses with low tracking accuracy over a long period. To overcome this disadvantage, more advanced and durable techniques have been developed. Perturb & Observe-PO [18], [19], Incremental Conductance-IC [20], [21], Constant Voltage-CV [22], [23], Adaptive Reference Voltage-ARV [24], Constant Current-CC [25], [26], Hill Climbing-HC [27], [28], Parasitic Capacitance-PC [7.29], Fractional Open Circuit Voltage-FOCV [30], Fractional Short Circuit Current-FSCC [31], Ripple Correlation Control-RCC [32], DC-Link Capacitor Drop [33], [34], On-Line MPP [35], Lookup Table [36], Linearization-based MPPT [37], [38] are the conventional MPPT methods [39], [17]. Among them, PO, IC, CV, and ARV methods are widely used.

The PO method has always been the focus of attention for researchers with its simplicity and easy applicability. Power fluctuations made by PO and similar methods at MP points are inevitable [40], [41]. In the source [42], [43], the oscillations at the MP point were reduced with a developed lock-on mechanism. The developed method was experimentally carried out under different irradiance values. A new method has been proposed by Abdel-Salam et al. In reference [18], it has been used for cases where PO method fails. The success of the technique under different atmospheric conditions has been demonstrated. With an extended adaptive PO algorithm proposed in [19], both steady-state power fluctuations were reduced, and also the maximum power point could be followed under partial shading conditions. In [44], a new PO method including current changes in the traditional PO method was proposed. The superiority of the proposed method was emphasized with the simulation studies. In [45], PO and IC methods were tested under dynamic environmental conditions. As a result of the tests carried out in EN 50530 standards, it was emphasized that IC method is slightly more efficient than PO method.

Regarding IC method, in [46], a modified IC method whose step changes are estimated by Fuzzy Logic was compared in detail with the traditional IC method. The superiority of the proposed method was proven by experimental studies. In [47], the success of a variable step IC method was demonstrated by simulation and experimental studies. In [48], an alternative to the variable step IC method was presented with a new technique consisting of tables. The success of the method was supported by experimental studies. In [49], a variable step IC algorithm that automatically adjusts the step size was proposed. This method, which is simple in structure and can be easily performed in digital signal processors, was confirmed by experimental studies and theoretical analysis. It has been observed that the proposed method increases MPPT speed and accuracy effectively. In [50], [51], a new IC method was proposed. It increased the monitoring speed by adjusting the duty period of DC-DC converter. For testing the effectiveness of the method, various simulation studies and experimental applications were carried out under partial shadowing and load change. The results showed that the proposed algorithm can accurately track GMP point under partial shading conditions and respond faster to changes in load and...
irradiance. In [52], the efficiency of the system was increased by reducing the fluctuations around the working point with an advanced IC algorithm based on the mathematical residue theorem. The method is independent of the system parameters. In [88], a modified incremental conductance algorithm, which could respond more accurately when the irradiance level increased, was proposed and experimentally verified. Thanks to the proposed algorithm, a smoother power was achieved and lower-amplitude oscillations occurred around the maximum power point. In [89], to allow PV system to respond quickly depending on solar irradiance and load resistance that show rapid change, a high-efficiency fast-converging MPPT method was proposed. In the proposed method, to achieve rapid response, the relationship between the load line and I–V curve was determined by the trigonometry rule. Extra control loop and intermittent disconnection were eliminated.

Regarding CV method, in the reference [22], the continuous and transient state behaviors of the method were analyzed; and the efficiency of the method was investigated in depth with simulations and experimental studies. Also, a new two-mode MPPT algorithm was obtained by combining it with IC method. In [23], a new method with high performance, whose PI controller coefficients are determined by a genetic algorithm, was proposed. The efficiency and time response of the method were examined. In [53], a compensation method was presented to improve the performance of CV method. With this method, a great improvement was achieved in the controller performance. In [54], a new MPPT method obtained by combining CV and IC methods was developed to eliminate the disadvantage of CV method. The superiority of the new method used was demonstrated by the simulation study. In [55], the performance of an induction motor fed by PV system was compared using CV and other methods. In [56], the effects of CV method on PV irrigation system performed experimentally with dSpace-DS1104 controller card were examined in detail. MP point was successfully followed without oscillation in the continuous regime.

Regarding ARV method, a reference voltage table was created for ARV according to temperature and irradiance values in reference [24]. The difference between the measured voltage and the reference voltage was processed by PI controller. As a result, the duty period of the switching element was obtained. In [57], a new SI-based ARV method with a nonlinear structure that works with high performance under changing atmospheric conditions was developed by Celikel and Gundogdu.

A new CC method was proposed in [25] where short circuit current was applied at short intervals to capture GMP point under partial shading. For validating the method, a state-space-based PV system model was created, and simulation results were presented. In [27], a method that determines the update frequency of HC algorithm was presented to monitor the continuously changing MP point depending on the changing atmospheric conditions. The proposed method also revealed the relationship between perturbation step size and energy loss. In [29], a new technique was proposed to find MP point and eliminate the parasitic capacitance effect by using the voltage fluctuations created by DC-DC converter.

Advanced MPPT methods have superior tracking performance, although they are more complex. They are preferred because they are robust, flexible, and reliable. They have been developed to overcome the disadvantages of conventional methods. Advanced methods generally include Soft Computing-SC, Evolutionary Algorithms-EA, and Artificial Intelligence-AI-based algorithms. Among these, the techniques that are widely used are as follows: Artificial neural network-ANN, fuzzy logic control-FLC, particle swarm optimization-PSO, improved particle swarm optimization-IPSPO, genetic algorithm-GA, gray wolf optimization-GWO, artificial bee colony-ABC, ant colony optimization-ACO, firefly algorithm-FFA, differential evolution-DE, bat search algorithm-BSA, cat algorithm-CA, Jaya algorithm-IA, gravitational search algorithm-GSA, monkey king evolution-MKE, cuckoo search-CS, butterfly optimization algorithm-BOA, moth-flame optimization-MFO, salp swarm algorithm-SSA, shuffled frog leap algorithm-SFLA, fish swarm algorithm-FSA, chicken swarm optimization-CSO, wind-driven optimization-WDO, beta algorithm-BA, chaotic search algorithm-CSA, fibonacci search algorithm-FSA, segmentation search method-SSM, random search method-RSM, pattern search-PS, gold section search-GSS, extreme seeking control-ESC, bayesian network-BN, memetic reinforcement learning-MRL, transfer reinforcement learning-TRL, maximum power trapezium algorithm-MPTA, enhanced scanning algorithm-EA, current source region detection algorithm-CSR, tabu search-TS, artificial vision-AV, optimal current control-Occ, stepped comparison search-SCS, simulated annealing-SA, fireworks algorithm-FWA, glowworm swarm optimization-GSO, flower pollination algorithm-FPA, teaching learning-based optimization-TLBO, mine blast optimization-MBA, whale optimization algorithm-WO, human psychology optimization-HPO [6], [13], [39]. In [58], the superiority of the FLC-based method over traditional methods is shown in comparison with the simulations made in PSIM and MATLAB/Simulink. ANN theory has increased its relevance with studies conducted in industry, PV systems, electric machines, and robotic systems [59], [60], [61]. An ANN-based MPPT algorithm has been developed for PV irrigation system with a PMSM motor in [62]. An MPPT method has been developed using Radial Basis Function Network-RBFN and Neural Network-NN algorithm in [63]. This developed method has been compared with traditional methods. It has been tested at different temperatures and irradiance values. MPPT algorithms using HC and ANFIS techniques have been examined in [64]. A hybrid MPPT algorithm has been developed using several different methods that work more efficiently in changing atmospheric conditions. Since the processing load of ANN algorithms is high, they force microprocessors in terms of processing time. For this reason, an ANN-based MPPT algorithm has been developed.
using FPGA in reference [65]. In [66], [67], the success of ANN algorithm has been shown in capturing GMP point under partial shading conditions. In SI technique in which a mathematical model of the system is obtained by using the input and output values of a system, photovoltaic power systems have been used in the modeling of many different systems such as Ankle Joint Dynamic Stiffness, Unmanned Surface Vessel and DC-DC converter [68], [73]. In [74], the mathematical model of the system was obtained for the design of the control algorithm developed by Bao et al. To control the voltage in a power distribution system using SI, in [75], an online-SI technique consisting of state estimation module, collision avoidance module, excitation module and parameter estimation module for underwater robotic vehicles has been developed by George et al. In [87], a fast-converging MPPT algorithm based on Modified Butterfly Optimization Algorithm was proposed. The proposed algorithm had the ability that could distinguish among partial shading patterns, uniform shading, solar intensity, and load change conditions. It was experimentally verified by using SEPIC converter. An improvement was achieved by 99.85% in partial shading, 47.20% in uniform shading, and 86.15% under sudden load variations.

Hybrid MPPT methods have been developed as a result of using conventional and advanced methods to increase the performance of existing methods. Some of the current hybrid methods are as follows: Firefly algorithm with incremental conductance (IC-FFA), perturb & observe with adaptive neural network (PO-ANN), fireworks algorithm with perturb & observe (FWA-PO), gray wolf with perturb & observe (GWO-PO), bat search algorithm with perturb & observe (BSA-PO), particle swarm optimization with perturb & observe (PSO-PO), simulated annealing with particle swarm optimization (SA-PSO), fish swarm algorithm with particle swarm optimization (FSA-PSO), jaya algorithm with differential evolution (JA-DE), whale optimization with differential evolution (WO-DE), particle swarm optimization with shuffled frog leaping algorithm (PSO-SFLA) [6], simulated annealing and perturb & observe (SA-PO) [12], differential evolution with particle swarm optimization (DE-PSO), ant colony optimization with perturb & observe (ACO-PO) [76], artificial neural network with sequential monte carlo (ANN-SMC), modified genetic algorithm and firefly algorithm (MGA-FFA), taguchi method and genetic algorithm (T-GA), augmented state feedback precise linearization and artificial neural network (AFL-ANN), artificial bee colony and perturb & observe algorithm (ABC-PO) [13].

The advantages and disadvantages of each MPPT algorithm in terms of complexity, oscillation, number of sensors, cost and dependency on PV Array are summarized in Table 1.

These developed methods differ in terms of application, accuracy, complexity, and efficiency. These techniques are also summarized in different sources numbered [6], [12], [17], [39], [77], [78], [79] in the literature.

III. THE BEHAVIOUR OF PV SYSTEM

MP point of PV power system is constantly changing depending on the atmospheric conditions [80], [81]. The angle of incidence of sunlight, dusting, partial shading, irradiance intensity, and temperature are among the reasons that create these changing atmospheric conditions. As the amount of irradiance increases under constant temperature, the current generation capacity of the panel increases significantly. However, this situation does not create the same increase in panel voltage. As the temperature increases under constant irradiance, the photovoltaic current generated by the panel increases slightly, but this significantly reduces the panel voltage. Monitoring MP point of PV system that exhibits nonlinear behavior under these variable conditions is inevitable in terms of efficiency. The variation of the power obtained from PV system concerning time is expressed by Eq.(1) [79].

\[
P_{PV}(t) = F[V_{PV}(t), I_{PV}(t), \gamma(t)]
\]

Here, \(V_{PV}\) stands for panel output voltage, \(I_{PV}\) for panel output current, and \(\gamma\) for all other PV system parameters and climatic variables. The dynamic behavior of PV systems is different under i) uniform irradiance and ii) partial shading. Therefore, PV system and MPPT algorithms to be developed should be analyzed and developed according to these two different concepts.

A. UNDER UNIFORM IRRADIANCE CONDITION

Large-scale PV systems consist of identical panels connected in series and parallel to each other. PV panels are connected in series to increase the voltage of the array and in parallel to increase the output current [13]. The same output current and output power are obtained from all identical panels exposed to the same irradiance. The characteristic behavior of a PV panel can be explained easily with the help of I-V and P-V curves. When PV system is under uniform irradiance, a single GMP point is formed on I-V and P-V curves. Fig.1 shows I-V and P-V curves under STC of a 10 kW PV system. All the panels in PV system are exposed to the same amount of irradiance. Because of this, a single GMP point is formed on both curves as shown in Fig.1. The system operates with higher efficiency at this point. It is easy to find MP point of PV system under uniform irradiance. If the measurements are correct, MP point can be found with high accuracy. Conventional MPPT techniques have higher performance under uniform irradiance.

B. UNDER PARTIAL SHADING CONDITION

Due to their large surface area, both PV panels and PV power systems can be exposed to different intensities of irradiance depending on dusting, clouding, and other atmospheric conditions. Different output currents and output power are obtained from each of the identical panels exposed to different irradiance. In this case, multiple local LMP points occur in PV system. In Fig.2, I-V and P-V curves of the 10 kW PV system under PSC are shown. Since all arrays in the PV system are exposed
### TABLE 1. Comparison of different MPPT algorithms.

| Classification | Algorithm | Reference | Complexity | Sensors | Oscillation | Cost | DPVA |
|----------------|-----------|-----------|------------|---------|-------------|------|------|
| Conventional   | PO        | [20, 22]  | Low        | $I, V$  | High        | Medium | No   |
|                | IC        | [50, 51, 52] | Medium   | $I, V$  | High        | Medium | No   |
|                | CVR       | [23, 53, 54] | Low       | $I$     | Medium      | Low   | No   |
|                | ARV       | [17, 24]  | Low        | $I, V$  | Medium      | Low   | No   |
|                | CC        | [25, 26]  | Low        | $V$     | Low         | Low   | No   |
|                | HC        | [27, 28, 58] | Low       | $I, V$  | High        | Medium | No   |
|                | PC        | [29, 34]  | Low        | $I, V$  | Medium      | High  | No   |
|                | FOCV      | [30, 77]  | Low        | $I, V$  | Low         | Low   | No   |
|                | FSCC      | [31, 77]  | Low        | $I, V$  | Low         | Low   | No   |
|                | RCC       | [32, 34]  | High       | $I, V$  | Medium      | High  | No   |
| Advanced       | ANN       | [65, 66]  | High       | $I, V$  | Low         | High  | No   |
|                | FLC       | [15, 17, 55] | Medium   | $I, V, P$ | Medium      | High  | No   |
|                | PSO       | [4, 16]   | Medium     | $I, V$  | Medium      | High  | No   |
|                | IPSO      | [6, 13]   | High       | $I, V$  | Low         | High  | No   |
|                | GA        | [23, 39]  | Medium     | $I, V$  | Medium      | High  | No   |
|                | GWO       | [12, 17]  | High       | $I, V$  | Low         | High  | No   |
|                | ABC       | [11, 12]  | Low        | $I, V$  | Medium      | Low   | No   |
|                | ACO       | [12, 15]  | Low        | $I, V$  | Medium      | Low   | Yes  |
|                | FFA       | [14, 16]  | Medium     | $I, V$  | Low         | Medium | No   |
|                | DE        | [11, 39]  | Medium     | $I, V$  | Medium      | Medium | No   |
|                | BSA       | [39]      | High       | $I, V$  | Low         | High  | No   |
|                | CA        | [39]      | High       | $I, V$  | Low         | High  | No   |
|                | JA        | [39]      | Medium     | $I, V$  | Medium      | Medium | Yes  |
|                | GSA       | [14]      | High       | $I, V$  | Low         | Medium | No   |
|                | MEK       | [13]      | High       | $I, V$  | Low         | Medium | No   |
|                | CS        | [9, 12]   | Medium     | $I, V$  | Low         | Medium | Yes  |
|                | BOA       | [13]      | Medium     | $I, V$  | Low         | Medium | No   |
|                | MFO       | [14]      | Medium     | $I, V$  | Low         | Medium | No   |
|                | SSA       | [14]      | Medium     | $I, V$  | Low         | High  | No   |
|                | SFLA      | [6, 13]   | High       | $I, V$  | Low         | High  | No   |
|                | FSA       | [9, 17]   | Medium     | $I, V, P$ | Low         | High  | No   |
|                | CSO       | [14]      | High       | $I, V$  | Low         | High  | No   |
|                | WDO       | [13]      | Low        | $I, V$  | Medium      | High  | No   |
|                | BA        | [14]      | High       | $I, V$  | Medium      | High  | Yes  |
|                | CSA       | [12, 15]  | High       | $I, V$  | Medium      | High  | No   |
|                | SSM       | [13]      | High       | $I, V$  | Low         | Medium | Yes  |
|                | RSM       | [13]      | High       | $I, V$  | Low         | Low   | Yes  |
|                | PS        | [13]      | Medium     | $I, V$  | Medium      | Medium | No   |
|                | GSS       | [13]      | High       | $I, V$  | Medium      | High  | Yes  |
|                | ESC       | [12]      | High       | $I, V$  | High        | Medium | No   |
|                | BN        | [14, 15]  | High       | $I, V$  | Low         | High  | Yes  |
|                | MRL       | [13]      | High       | $I, V$  | Low         | High  | No   |
|                | TRL       | [13]      | High       | $I, V$  | Low         | High  | No   |
|                | MPTA      | [14]      | High       | $I, V$  | Low         | Medium | Yes  |
|                | ESA       | [14, 19]  | High       | $I, V$  | Medium      | Medium | Yes  |
|                | CSR       | [13]      | High       | $I, V$  | Medium      | High  | Yes  |
|                | TS        | [13]      | Medium     | $I, V, P$ | Medium      | Low   | No   |
|                | AV        | [14]      | Medium     | $I, V, P$ | Low         | High  | No   |
|                | OCC       | [13]      | Low        | $I, P$  | Low         | Medium | No   |
|                | SCS       | [13]      | Low        | $I, V$  | Low         | Medium | No   |
|                | SA        | [10, 12]  | High       | $I, V$  | Medium      | Low   | Yes  |
|                | FWA       | [13]      | Medium     | $I, V$  | Low         | Medium | Yes  |
|                | FPA       | [76]      | Medium     | $I, V$  | Low         | High  | No   |
|                | TLBO      | [13]      | Medium     | $I, V$  | Low         | High  | No   |
|                | MBA       | [13]      | Medium     | $I, V$  | Medium      | Medium | No   |
|                | WO        | [13]      | Medium     | $I, V$  | Medium      | High  | No   |
|                | HPO       | [13]      | Low        | $I, V$  | Low         | High  | No   |
to different intensities of irradiance, more than one local LMP point has been formed as shown in the Fig. 2. The PV system works with lower efficiency at these points [80], [81]. It is much more difficult to find the GMP point since there is more than one MP point, local and global, in the PV system under PSC. Compared to uniform irradiance, more sophisticated MPPT techniques with higher technology are needed for partial shading. Advanced and hybrid MPPT techniques developed for this show high performance under partial shading conditions.

C. PV PANEL MODEL

PV cells have a nonlinear structure and act as a current source. The electrical circuit model of a PV cell is shown in Fig. 3. This model consists of a current source $I_{PV}$, a diode connected in reverse and parallel to this current source, and an $R_S$ resistor connected in series with a parallel $R_P$ resistor [82], [83]. This model is known as a single diode model.

$$I = I_{PV} - I_0(\exp(\frac{V + R_S I}{a}) - 1) - \frac{V + R_S I}{R_P} \quad (2)$$

Here, $I_{PV}$ represents the current produced in PV cell by the photoelectric effect depending on the $T$ temperature and $G$ irradiance and it is expressed as in Eq. (3).

$$I_{PV} = (I_{PV,n} + K_f(T - T_n))\frac{G}{G_n} \quad (3)$$
\[ I_{PV,n} \] refers to the current produced by \( n \) number of parallel cells, \( T_n \) refers to the nominal panel temperature in Kelvin, \( G \) refers to the irradiance value at the panel surface (W/m\(^2\)) and \( G_n \) refers to the nominal irradiance value (W/m\(^2\)). The saturation current of the diode \( I_0 \) is a function of the temperature. It is expressed as in Eq.(4).

\[
I_0 = \frac{I_{SC,n}}{\exp\left(\frac{V_{OC,n}+K_V(T-T_n)}{a}\right)} - 1
\]

(4)

\[
a = \frac{N_S k T}{q}
\]

(5)

Since equation (2) contains exponential terms, I-V and P-V curves of PV cell are also nonlinear. \( V_{OC} \) on I-V curve given in Fig.4 represents open circuit voltage of the cell, \( I_{SC} \) represents short circuit current of the cell and MPP represents the maximum power point. PV cell can only produce maximum power at this MPP point. All developed MPPT algorithms ensure that PV system operates with high efficiency at a steady state by continuously monitoring MP point.

**FIGURE 4.** I-V characteristic curve of PV cell.

### IV. SYSTEM IDENTIFICATION METHODOLOGY

The controller design is an important subject in control systems. The mathematical model of the physical system is needed for design. System Identification-SI is used for creating an approximate mathematical model of the system using real input-output data of physical systems. Since the mathematical model of linear systems with specific parameters can be easily obtained, it is easy to design a controller for these systems. However, mathematical modeling of physical systems with uncertain nonlinear parameters and the design of the controller for the control process through this non-linear model is more complex. Physical systems are divided into 3 in terms of parameter uncertainty. These are named white-box, gray-box, and black-box systems, as shown in Fig.5 [69], [84].

The model in which all system parameters are known is called the white-box system. In the model, some features of the system are known. However, some of them are determined by the data obtained from the system is the gray-box model. Black-box systems, on the other hand, are systems with uncertain parameters. However, they have no information about their contents. The mathematical model of black-box systems is created by analyzing the input-output data obtained from empirical studies on the system in the time-domain or frequency-domain level [85].

For black-box systems, different linear and nonlinear modeling techniques have been developed, classified as in Fig. 6 [69].

**FIGURE 5.** Dynamical system classifications by structures and parameters.

**FIGURE 6.** System identification modeling techniques.

These techniques are used in various systems for control and prediction. Different system identification techniques can be preferred for varying systems. With system identification, linear models such as transfer functions, process models, polynomial models, and state-space models can be obtained by using time-domain, time series, or frequency-domain data. Using only time-domain data, nonlinear models such as NARX and Hammerstein-Wiener can be predicted. The modeling process with system identification consists of the steps in the flow diagram given in Fig.7 [86].

In the first step, the input-output data obtained through the empirical way, are prepared. In the second step, a modeling technique suitable for the model is selected from the techniques given in Fig.6. Choosing the modeling technique is one of the most difficult steps in the modeling process. Since, there are many possibilities.

The best performing model structure is selected among these many possibilities by comparison. In the third step, the accuracy of the selected model structure is tested by evaluating its behavior with a validation data set that has not
been used before. In the fourth step, if the evaluation result is within acceptable limits, the system identification process is terminated. If not, the modeling process is reset with new test data.

V. PROPOSED SI-BASED POLYNOMIAL ARV-MPPT TECHNIQUE

In this study, a MPPT technique that is based on system identification was proposed. Modeling was carried out assuming that the analyzed PV system is a nonlinear black-box system. The input-output data required for modeling were created in the MATLAB/Simulink platform. Then, by using these data in the system identification toolbox platform, the mathematical model of PV system in a polynomial structure giving the relationship between temperature and voltage are shown together in Fig.8. These curves are T-V curve expressing the relationship between temperature and voltage and G-V curve expressing the relationship between irradiance and voltage are shown together in Fig.8. These curves are obtained when the system is open circuit and all the PV panels in the system are exposed to the same intensity of temperature and irradiance changes.

The change amount in $V_{PV}$, which is the open-circuit voltage of each PV array that constitutes the 10 kW PV power system used in this study, was obtained as follows with the help of Fig.8:

- The string voltage obtained at G-V curve / $G=1000\ W/m^2$ constant irradiance and temperatures [$-20^\circ C$, $+80^\circ C$] are $V_{PV-min}=303V$ and $V_{PV-max}=435V$. The change amount depending on the temperature is approximately 30.3%.

As you can see, because of $|V_{PV-max}-V_{PV-min}|_{G-V curve} < |V_{PV-max}-V_{PV-min}|_{T-V curve}$, for a simpler design, only the ambient temperature $T$ is used as input for the polynomial model. The estimated output of the polynomial model is the reference voltage called $V_{ref}$.

PV cells have a nonlinear structure. In this study, it was aimed to estimate the voltage at MP point by using both a simplified PV system model and a smaller number of sensors. For this purpose, a simplified polynomial model of a PV system with a nonlinear structure was obtained, and simulations were made. The obtained polynomial model has a “discrete-time output error (OE)” polynomial structure. Higher performance can be achieved by creating models with more complex structures. However, its ease of implementation and simple structure is the superiorities of this proposed polynomial model.

The purpose of this study is to develop a high-performance MPPT algorithm by simplifying the previously developed complex models. For this purpose, as a preliminary study, analyses were performed creating three and higher-order models with different polynomial structures by using System Identification. When the results obtained for the 10 kW PV system were examined, it was observed that the performance of the high-order polynomial models was not much higher or it was lower than the performance of the second-order polynomial model. In this regard, the second-order polynomial model structure was preferred due to both simplicity and high performance.

The polynomial model expresses the relationship between input-output and disruptive factors as a transfer function by using the mathematical structure of the system. The generalized polynomial model is expressed as in Eq.(6):

$$A(q)y(t) = \sum_{i=1}^{nu} B_i(q)u_i(t - nk_i) + C(q)\delta(t) \quad (6)$$
The variables $A$, $B$, $C$, $D$, $F$ in Eq. (6) are polynomials expressed in the time shift operator $q^{-1}$. Here, $u_i$ is the $i^{th}$ input, $n_k$ is the total number of inputs and $nk_i$ is the $i^{th}$ input delay. Also, $e(t)$ represents noise with the variance of $\lambda$.

The polynomial model obtained in this study has a discrete-time output error (OE) polynomial structure. The simplest form of this structure is given in Eq. (7).

$$y(t) = \frac{B(z)}{F(z)} u(t) + e(t)$$

Here $y(t)$ represents the output voltage $V_{ref}$ and $u(t)$ represents the system input temperature $T$. As a result, $B(z)$ and $F(z)$ terms were obtained with system identification toolbox as in Eq.(8) to obtain the $V_{ref}$ voltage:

$$B(z) = 0.7336z^{-1} + 0.743z^{-2}$$
$$F(z) = 1 - 1.006z^{-1} + 0.01293z^{-2}$$

The sampling time was determined as $0.01s$ and $15001$ pieces of data were used to obtain the terms, $B(z)$ and $F(z)$. The temperature-dependent polynomial transfer function model of the PV system is given in Fig.9.

![FIGURE 9. The temperature-dependent polynomial transfer function model of the PV system.](image)

This polynomial model has been used to obtain the reference voltage $V_{ref}$ within the proposed MPPT algorithm. The error obtained by comparing the output voltage of the PV system with this reference voltage is processed by a PI controller, hence the “duty” ratio is determined. Thus, the power produced by PV system under changing atmospheric conditions is transferred to the output with maximum efficiency, and the voltage at the ends of the load is kept constant by the boost converter driven with $d$ duty ratio. The block diagram of the proposed SI-based ARV-MPPT method is given in Fig.10. A polynomial transfer function block obtained by the system identification method consists of a PI controller and a different block.

The proposed method provides impressive performance in both fast and slow changes of temperature and irradiance. The reference voltage produced by SI-based ARV-MPPT method is also an adaptive method as it adapts to changing atmospheric conditions. Once the model is created, using only the temperature as input is sufficient to obtain the $V_{ref}$ voltage. While obtaining “$d$” duty ratio, it is sufficient to measure the panel output voltage.

Current measurement is not required in the method. In this respect, an advantage has been achieved in terms of the number of sensors compared to many studies. SI-based ARV-MPPT method proposed in this article is a hybrid method consisting of the synthesis of SI methodology with the conventional ARV method. Depending on the resolution and min-max values of temperature and irradiance data sets applied to the model input during the training phase, the optimum reference voltage is obtained at the model output.

The model proposed for a $10$ kW system in this study can also be easily improved for higher power PV systems where all input-output data can be monitored. Unlike other studies, using the system identification methodology, this article provides an opportunity to conduct feasibility studies of large-scale PV systems by modeling them in the computer environment before the installation stage to reduce the whole system to a single polynomial model, conduct performance tests, and reveal behavioral models for different climatic conditions.

VI. MODELING OF PV POWER SYSTEM

The modeled PV power system has the configuration shown in Fig.11. PV power system consists of 40 panels connected in series and parallel, DC-DC boost converter, and MPPT block. As shown in Table 2, PV arrays were connected in series with 10 Trina Solar TSM-250PA05.08 model PV modules, and 4 of these arrays were connected in parallel to create the power stage of the PV system. The panel, boost converter, and all other system parameters related to the PV power system are explained in Table 3.

VII. SIMULATION MODEL

The simulation model of PV system created in MATLAB/Simulink with MPPT method suggested in this study is given in Fig.12. The sampling frequency is determined as $5\mu s$, and the switching frequency for the boost converter is $20$ kHz. The fact that the sampling frequency of the simulation model is higher than the switching frequency allows obtaining results that are closer to reality.

To test the effectiveness of the proposed MPPT method, 2 separate simulations were carried out by creating 2 separate scenarios as shown in Fig.13a-b. Temperature and irradiance change graphs of scenario-2 are given in Fig.13b, and scenario-1 is shown in Fig.13a.

Scenario-1 represents atmospheric conditions in which temperature changes slowly and irradiance changes both rapidly and slowly, while scenario-2 represents atmospheric conditions in which temperature and irradiance change rapidly. In both scenarios, all 40 panels in PV system are simultaneously exposed to an equal amount of temperature and irradiance change. Depending on these changes, MP point is constantly changing. Although MP point is constantly changing, a single global MP point is formed on the power curve of the PV system because the entire PV system is exposed to a regular amount of temperature and irradiance.

In both scenarios, all simulation results obtained by testing the performance of the proposed SI-based polynomial ARV method and PO, IC, CVR, ANN-based ARV, and SI-based nonlinear ARV methods are comparatively given in graphs. The simulation model, where all MPPT methods are performed under equal conditions and the results are obtained, is given in Fig.14.
VIII. ANALYSIS AND COMPARISON

The graphs of current, voltage, and power obtained from the PV power system using all MPPT methods under changing atmospheric conditions in Scenario-1 are given in Figs. 15-21. Fig. 15 shows the change graphs of the output voltage $V_{PV}$ of the PV power system. In region 2, PO method followed MP point correctly by overexposing. The IC method, on the other hand, could not catch the MP point. In region number 1, where the irradiance shows a sinusoidal change, the excessive decrease in voltages obtained by PO and IC is shown in detail in Fig. 16. With the proposed SI-based polynomial ARV method, a more correct voltage has been obtained in the entire working range. SI-based polynomial ARV, SI-based nonlinear ARV, and ANN-based ARV graphics display similar behavior, although they have less fluctuation compared to other graphics. However, since the proposed method has a simpler structure than both methods, it can be easily performed with microprocessors in practice.

In Fig. 17, there are graphs of the change of $I_{PV}$ currents obtained from the PV power system. The current generation capacity of the PV system depends on the amount of irradiance and the form of change. In this respect, the current waveforms are in the same form as the irradiance change given in scenario 1. However, there are deviations in PO and IC currents in the 1st region, a decrease in IC and CVR

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**TABLE 2.** Configuration of the PV power system.

| Label | Module | $P_{max}$, W |
|-------|--------|--------------|
| Array-1 | 10 series-connected PV Modules, Trina Solar TSM-250PA05.08 | 2498.6 |
| Array-2 | 10 series-connected PV Modules, Trina Solar TSM-250PA05.08 | 2498.6 |
| Array-3 | 10 series-connected PV Modules, Trina Solar TSM-250PA05.08 | 2498.6 |
| Array-4 | 10 series-connected PV Modules, Trina Solar TSM-250PA05.08 | 2498.6 |
| Total Power | | 9994.4 |
TABLE 3. Parameters of PV power system.

| Symbol      | Quantity                        | Values |
|-------------|---------------------------------|--------|
| $P_{MPF}$   | Maximum power at MPP            | 250 W  |
| $V_{MPP}$   | Voltage at MPP                  | 31 V   |
| $I_{MPP}$   | Current at MPP                  | 8.06 A |
| $V_{OC}$    | Open-circuit voltage            | 37.6 V |
| $I_{SC}$    | Short-circuit current           | 8.55 A |
| $T_{C@VOC}$ | Temp. coefficient of Voc        | -0.35 °/C |
| $T_{C@ISC}$ | Temp. coefficient of Isc        | 0.06 °/C |
| $R_s$       | Series resistance of the PV cell| 0.247 Ω |
| $R_p$       | Parallel resistance of the PV cell| 301.814 Ω |
| $N_{cell}$  | Cells per module                | 60 -   |
| $N_{ser}$   | Number of series module         | 10 -   |
| $N_{par}$   | Number of parallel module       | 4 -    |

**PV Module**

**Boost Converter**

| Symbol | Quantity                        | Values |
|--------|---------------------------------|--------|
| $L$    | Boost inductor                  | 5e-5 H |
| $C$    | Boost capacitor                 | 2000e-6 F |
| $C_i$  | Boost input capacitor           | 3e-3 H |
| $f_{sw}$ | Switching frequency             | 20 kHz |
| $V_{IN}$ | Input voltage range of boost conv. | 355-375 V |

$P_{LOAD}$ Load value | 10 kW
$T_s$ Simulation step time | 5e-6 s

FIGURE 13. Variable atmospheric scenarios.

However, as shown in Fig. 18, the current waveform obtained with the proposed SI-based polynomial ARV during the simulation period [0-240s] is more correct.

In Fig. 19 and Fig. 20, the enlarged versions of voltage and current graphs obtained for Scenario-1 are given. As seen, the voltage and current obtained by the proposed SI-based polynomial ARV show a smooth change in the given range. Especially high oscillations occur in PO and IC graphs.

In Fig. 21, $P_{PV}$ power change graphs drawn from the PV power system are given. The waveforms are in the same
form as the irradiance change given in scenario-1. With the proposed method, a smoother power without oscillation was obtained by monitoring the MP point with high performance in all operating ranges. This situation can be seen more clearly in SI-based polynomial ARV-MPPT graph given in Fig. 22. In Fig. 23, the transient state graphs of $P_{PV}$ for 6 different regions in the range of [0-240s] are given in detail.

The graphs of current, voltage, and power obtained from the PV power system by using all MPPT methods under variable atmospheric conditions in the range of [0-3s] in Scenario-2 are given in Figs. 24-30. The temperature is decreasing steadily. Irradiance, on the other hand, has
increased and decreased in regions 1 and 2. Temperature change has occurred 3 times faster than Scenario-1. The change graphs of $V_{PV}$ output voltages obtained from the PV power system under this rapid change are shown in Fig. 24.

As can be seen from these graphs, $V_{PV}$ voltage obtained with SI-based polynomial ARV is stable and smooth, despite the rapid change of temperature and irradiance in both the 1st and 2nd regions. SI-based nonlinear ARV and ANN-based ARV methods have also behaved similarly. In SI-based polynomial
The photovoltaic effect and current generation capacity of panels are directly proportional to the amount of irradiance falling on the panel surfaces and their change. This situation is seen in the current graphs in Fig. 25. Despite the changes in atmospheric conditions, the maximum current was obtained from the PV power system with the proposed SI-based polynomial ARV, SI-based nonlinear ARV, and ANN-based ARV methods. The photovoltaic effect and current generation capacity of panels are directly proportional to the amount of irradiance falling on the panel surfaces and their change. This situation is seen in the current graphs in Fig. 25. Despite the changes in atmospheric conditions, the maximum current was obtained from the PV power system with the proposed SI-based polynomial ARV, SI-based nonlinear ARV, and ANN-based ARV methods. The change in irradiance that determines the waveforms of these currents. However, currents obtained by PO and IC methods could not react to the change in the increase and decrease in irradiance at the same rate. With these two methods, as in the proposed SI-based polynomial ARV method, the maximum current could not be obtained from the PV system. Due to their adaptive nature, currents obtained with SI-based polynomial ARV, SI-based nonlinear ARV, and ANN-based ARV are similar.

In Fig. 26 and Fig. 27, the enlarged versions of voltage and current graphs obtained for Scenario-2 are given. As seen, the voltage obtained by the proposed SI-based polynomial ARV shows a smooth change in the given range. Power charts drawn from the PV system are given in Fig. 28. It has a similar form to the current graphs, depending on the change of atmospheric conditions in Scenario-2. Maximum power was obtained from the PV system with the recommended method SI-based polynomial ARV at all points between these values with 1000 W/m² where the irradiance value is the highest and 400 W/m² where it is the lowest. However, the maximum power point could not be reached with PO and IC methods in 1000 W/m² irradiance. Therefore, the superior performance of the proposed SI-based

| Case       | Region   | t (s)  | G (W/m²) | T (°C) | Algorithm     | Power (W) | Voltage (V) | Current (A) |
|------------|----------|--------|----------|--------|---------------|-----------|-------------|-------------|
| Scenario-1 | Region-1 | 21.30  | 321      | 26.6   | PO            | 1560      | 142.40      | 10.955      |
|            |          |        |          |        | IC            | 1550      | 141.50      | 10.954      |
|            |          |        |          |        | CVR           | 3125      | 309.90      | 10.083      |
|            |          |        |          |        | ANN-ARV       | 3137      | 306.70      | 10.228      |
|            |          |        |          |        | SI-ARV        | 3138      | 307.90      | 10.191      |
|            |          |        |          |        | SI-pol ARV    | 3140      | 306.70      | 10.238      |
| Region-2   | 145      | 983.4  | 38.88    |        | PO            | 9364      | 291.30      | 32.145      |
|            |          |        |          |        | IC            | 8127      | 324.00      | 25.083      |
|            |          |        |          |        | CVR           | 9108      | 310.10      | 29.371      |
|            |          |        |          |        | ANN-ARV       | 9372      | 293.50      | 31.931      |
|            |          |        |          |        | SI-ARV        | 9374      | 294.60      | 31.819      |
|            |          |        |          |        | SI-pol ARV    | 9376      | 295.40      | 31.740      |
| Region-3   | 170      | 1000   | 37.75    |        | PO            | 9414      | 288.40      | 32.642      |
|            |          |        |          |        | IC            | 8062      | 322.70      | 24.982      |
|            |          |        |          |        | CVR           | 9070      | 310.20      | 29.239      |
|            |          |        |          |        | ANN-ARV       | 9448      | 290.40      | 32.534      |
|            |          |        |          |        | SI-ARV        | 9453      | 291.60      | 32.417      |
|            |          |        |          |        | SI-pol ARV    | 9455      | 292.70      | 32.302      |
| Region-4   | 235      | 1000   | 40       |        | PO            | 9318      | 285.80      | 32.603      |
|            |          |        |          |        | IC            | 9325      | 285.90      | 32.616      |
|            |          |        |          |        | CVR           | 8799      | 310.00      | 28.383      |
|            |          |        |          |        | ANN-ARV       | 9348      | 285.90      | 32.696      |
|            |          |        |          |        | SI-ARV        | 9355      | 287.20      | 32.573      |
|            |          |        |          |        | SI-pol ARV    | 9361      | 289.80      | 32.301      |
| Scenario-2 | Region-1 | 1      | 1000     | 34.67  | PO            | 8224      | 326.30      | 25.203      |
|            |          |        |          |        | IC            | 8255      | 326.00      | 25.322      |
|            |          |        |          |        | CVR           | 9362      | 310.10      | 30.190      |
|            |          |        |          |        | ANN-ARV       | 9570      | 295.20      | 32.418      |
|            |          |        |          |        | SI-ARV        | 9556      | 292.60      | 32.658      |
|            |          |        |          |        | SI-pol ARV    | 9573      | 296.90      | 32.243      |
| Region-2   | 2        | 600    | 34.33    |        | PO            | 4907      | 325.00      | 15.098      |
|            |          |        |          |        | IC            | 4884      | 325.40      | 15.009      |
|            |          |        |          |        | CVR           | 5614      | 310.20      | 18.098      |
|            |          |        |          |        | ANN-ARV       | 5754      | 295.50      | 19.472      |
|            |          |        |          |        | SI-ARV        | 5750      | 293.30      | 19.604      |
|            |          |        |          |        | SI-pol ARV    | 5757      | 297.40      | 19.357      |

* t: Time; G: Irradiance; T: Temperature

ARV method, the transition to perpetual state is smoother. Since PO and IC methods are not adaptive methods, the voltages associated with these methods are highly affected by the change of irradiance.

The photovoltaic effect and current generation capacity of panels are directly proportional to the amount of irradiance falling on the panel surfaces and their change. This situation is seen in the current graphs in Fig.25. Despite the changes in atmospheric conditions, the maximum current was obtained from the PV power system with the proposed SI-based polynomial ARV, SI-based nonlinear ARV, ANN-based ARV, and CVR methods. It is the change in irradiance that determines the waveforms of these currents. However, currents obtained by PO and IC methods could not react to the change in the increase and decrease in irradiance at the same rate. With these two methods, as in the proposed SI-based polynomial ARV method, the maximum current could not be obtained

from the PV system. Due to their adaptive nature, currents obtained with SI-based polynomial ARV, SI-based nonlinear ARV, and ANN-based ARV are similar.

In Fig.26 and Fig.27, the enlarged versions of voltage and current graphs obtained for Scenario-2 are given. As seen, the voltage obtained by the proposed SI-based polynomial ARV shows a smooth change in the given range.

Power charts drawn from the PV system are given in Fig.28. It has a similar form to the current graphs, depending on the change of atmospheric conditions in Scenario-2. Maximum power was obtained from the PV system with the recommended method SI-based polynomial ARV at all points between these values with 1000 W/m² where the irradiance value is the highest and 400 W/m² where it is the lowest. However, the maximum power point could not be reached with PO and IC methods in 1000 W/m² irradiance. Therefore, the superior performance of the proposed SI-based
polynomial ARV method in tracking MP point is seen in Fig. 29.

In Fig. 30, the transient state graphs of $P_{PV}$ for 4 different regions in the range of [0-3s] are given in detail. In all working areas under variable atmospheric conditions, the maximum utilization of the PV system was made with the proposed method.

Detailed power, voltage and current data for different regions in all two scenarios are shown in Table 4.

IX. CONCLUSION

In reference voltage-based MPPT methods, estimating the model of the PV system showing nonlinear behavior with high accuracy directly affects the performance of the method. In this respect, all PV system parameters must be known or measurable to obtain a high accuracy model. However, in practice, some of these parameters are not measurable. Therefore, different modeling techniques should be used for systems with parameter uncertainty.

In this study, an adaptive reference voltage-based MPPT method has been developed. The reference voltage is estimated with SI-based polynomial model created by the black box modeling method of the PV power system whose MP point will be monitored. The nonlinear model obtained is independent of the actual physical parameters of the PV system. Therefore, there is no need to estimate or measure the actual system parameters during the modeling process. While creating the model, only the input variables of the PV system, temperature, and the output variable, voltage data were used. Once the polynomial model is created in this way regardless of the system parameters, the only temperature is used as the model input. Also, there is no need for current measurement during model creation or application. This is an advantage of the proposed method in terms of the number of sensors and cost.

Also, the problem of capturing MP point, which occurs because of temperature change, has been eliminated. Therefore, the superior performance of the proposed reference voltage-based MPPT method in tracking the MP point under variable atmospheric conditions compared to other methods has been proven by the simulation results obtained. Current, voltage and power fluctuations around the MP point are minimized.

In industrial applications, there are many PV system installations with different parameters and different powers. In this study, this modeling method is suggested for a 10 kW system; and the obtained polynomial model can be developed for PV systems with the higher power. In the future, this modeling method will provide great convenience in large-scale PV systems. That is to say, the measured input-output data of large-scale PV systems can be monitored with central SCADA systems, modeling can be made on these data without the need for detailed field measurements, and MPPT and controller designs can be realized.

The proposed SI-based polynomial ARV-MPPT method is practically applicable since it includes a polynomial and a PI controller. Thanks to its simple and inexpensive structure, it can be easily performed with low-level microprocessors. A more effective system model can be developed by optimizing the coefficients and degree of the polynomial model.

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