WHALE OPTIMIZATION ALGORITHM BASED OPTIMAL MPPT OF PV POWER PLANT (REAL CASE STUDY)

By

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ABSTRACT

This study employs an advanced meta-heuristic optimization technique called Whale Optimization Algorithm (WOA) to adjust a novel Incremental Conductance (IC) based maximum power point tracking controllers for one section of a practical photovoltaic (PV) station with an overall capacity of 10 MW. Different scenarios of solar irradiance, temperature variation, and load fluctuations were used to check the feasibility of the proposed optimizer. The simulation analysis of Matlab™/Simulink results show that dynamic behavior enhancement of the overall PV system can be increased via PI/FOPI controllers tuned with in a shorter time.

Keywords: Incremental Conductance, Proportional-Integral, Fractional Order Proportional- Integral, Whale Optimization Algorithm, Perturb and Observe.

INTRODUCTION

The operation philosophy of photovoltaic (PV) systems is to track the Maximum Power Point (MPP) for achieving the maximum solar radiation conversion efficiency. Due to the variable nature of sun radiation and the ambient temperature, Distribution Network Operators (DNOs) have suffered from a lot of challenges, such like overvoltage, overloading, protection issues, increased losses, transformer and cables rating issues, and reverse power flow, which have affected the behavior of the traditional LV grid, specially in case of high penetrating ratio. As consequently, the role of Maximum Power Point Tracking (MPPT) controllers to attain maximum power from the solar radiation and achieve higher efficiency has become an urgent need (Tafti, Maswood, Konstantinou, Pou & Blaabjerg, 2018). Many optimization tools have been used and tested to guarantee the operation at the MPP under variable weather conditions and partial shading. This paper presents a step towards designing a novel MPPT controller (MPPTC) using simple, robust, flexible, and easy to implement optimization algorithm, which is the whale optimization algorithm (Kumar & Rao, 2016; Elazab, Hasanien, Elgendy, & Abdeen, 2017; Kumar, Hussain, Singh & Panigrahi, 2017; Keyrouz, 2018). In literature, Artificial Intelligence (AI), fuzzy logic control (FLC) (Al Badwawi, Issa, Mallick & Abusara, 2019; Samosir, Gusmedi, Purwiyanti, & Komalasari, 2018; Laagoubi, Bouzi, & Benchagra, 2018), Incremental Conductance Algorithm (Kumar, Hussain, Singh, & Panigrahi, 2018a; Al-Dhaifallah, Nassef, Rezk, & Nisar, 2018; Motahhir, El Ghzizal, Sebti & Derouich, 2018). Perturb and Observe (P&O) (Bijukumar, Raam, Ganesan, Nagamani, & Reddy, 2018; Ahmed & Salam, 2018; Husain, Khan, Tariq, Khan, & Jain, 2018), fractional open-circuit voltage (Hsu, Wu, Tsai, & Wei, 2019), in addition to several natural-inspired optimization techniques like, Whale Optimization with Differential Evolution algorithm (Chen, Vepa, & Shaheed, 2018), killer whale optimization algorithm, Artificial Bee Colony (ABC) (Gupta & Saurabh, 2017), Sperm Whale Algorithm (Ebrahimi & Khamehchi, 2016), Spider Monkey Optimization (SMO) (Behera, Behera, & Nayak, 2018), multi-objective dragonfly algorithm (MODA) (Wang, Yang, Du, & Li, 2018), Wind-Driven Optimization Technique (Mathew et al., 2018), parabolic extrapolation, modified incremental conductance technique, Grey Wolf Optimizer (GWO) (Cherukuri & Rayapudi, 2017; Xing, Wang, & Wang, 2018), flower pollination and differential evolution algorithms (Diab & Rezk, 2017), Enhanced Leader Particle Swarm Optimization (ELPSO) (Jordehi, 2018), Enhanced Adaptive Perturb and Observe (EA-P&O) (Ahmed & Salam, 2018), particle swarm optimization (Li, Yang, Su, Lü, & Yu, 2019; Anoop & Nandakumar, 2018), Artificial bee swarm optimization algorithm (Askarzadeh & Rezazadeh, 2013), discrete noise eliminating second order generalized integrator (DNSOGI) (Kumar, Singh, & Panigrahi, 2018b), Harmony Search (HS) in (Derick et al., 2017), Artificial Bee Colony (ABC) (Oshaba, Ali, & Elazim, 2017), and more novel techniques are used to fine tune the optimal PI/FOPI controller gains (Ramadan, 2017; Iftikhar et al., 2018). The major contribution of this paper is to apply an effective AI-based algorithm, which is the whale optimization algorithm (WOA) to adjust the practical gains of the fractional order proportional-integral (FOPI) and proportional-integral (PI) controllers of a real PV station, and proving the feasibility of the proposed scheme under different load changes and weather uncertainties by improving the tracking response of the MPP, the rise time, the settling time and the stability of the overall system. The WOA simulates the hunting behavior of humpback whales. The advantages of this optimization tool provide attaining optimal fine-tuning of FOPI and PI controllers (Mirjalili & Lewis, 2016).

1. Practical Case Study: Modeling and Configuration

In this paper, the WOA has used to fine-tune MPPTC gains of one section of an isolated off-grid hybrid solar-diesel power plant with a total installed PV capacity of about 2 MWp (while the total PV station capacity is 10 MW). This section namely section D (surrounded by a dashed blue rectangle in Figure 1) consists of 4 subsections (Table 1). It is worth

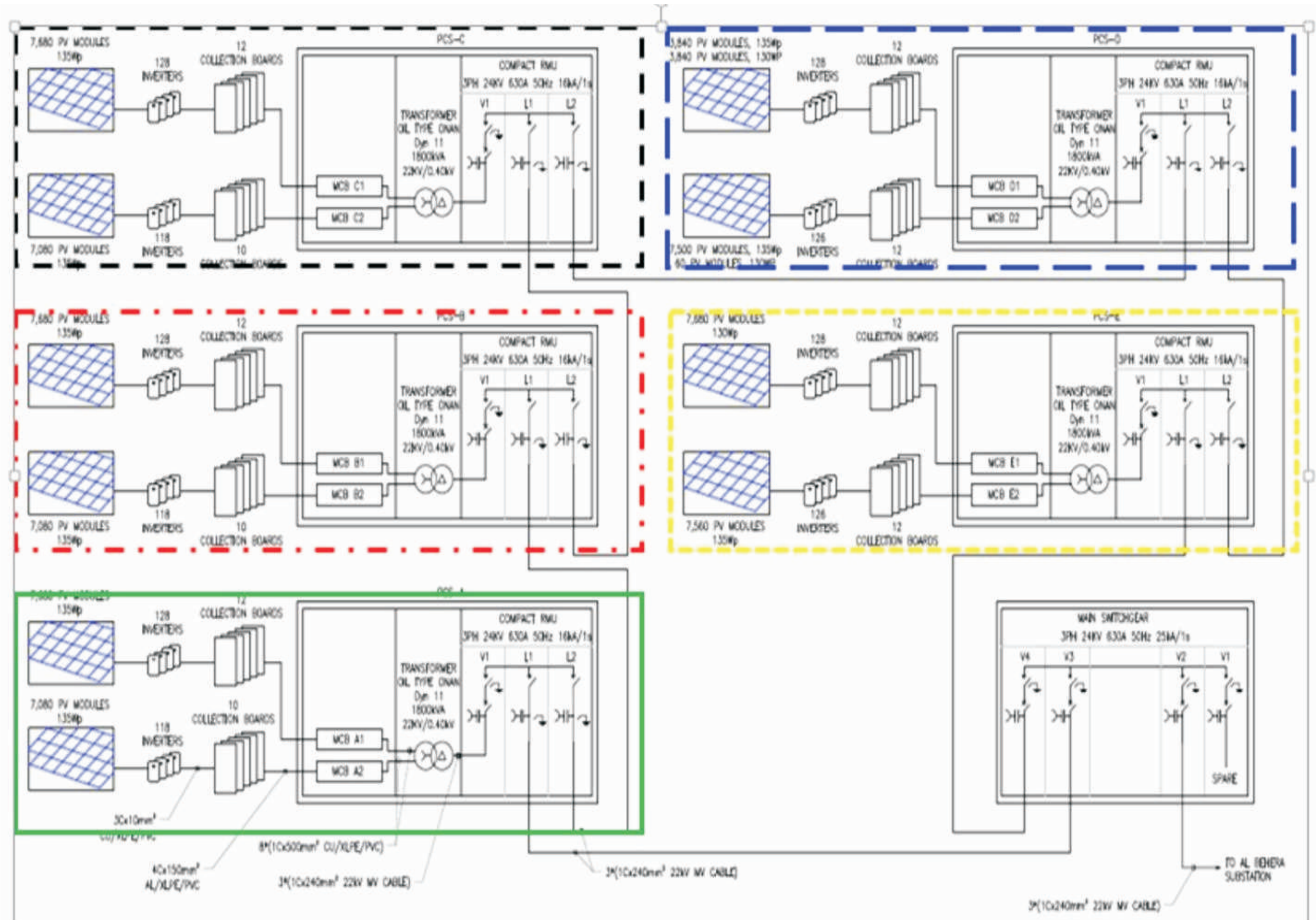


Figure 1. Siwa PV Station Configuration

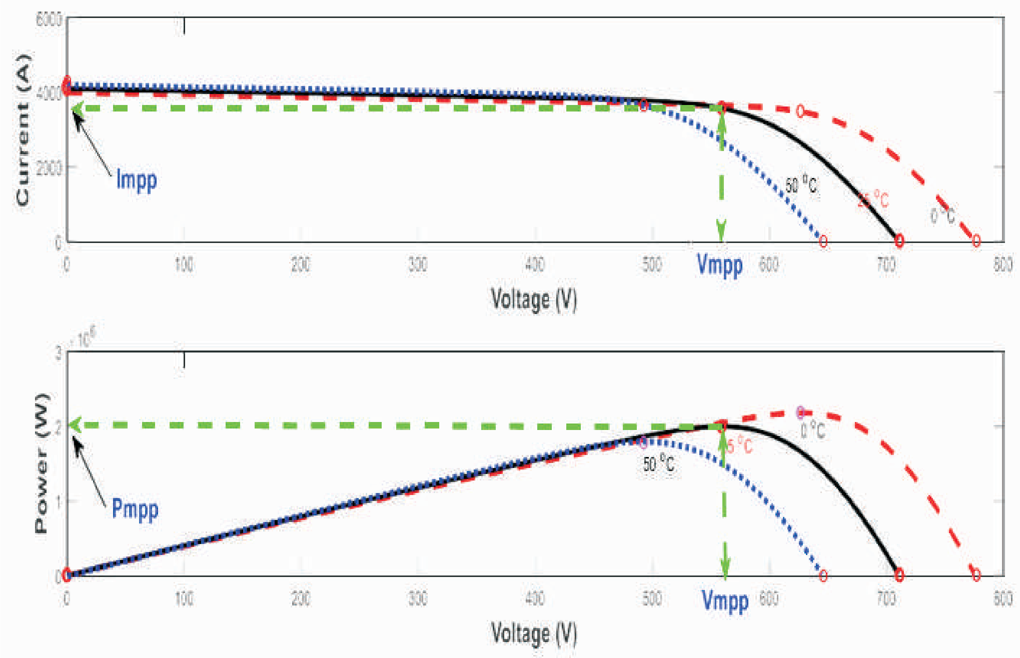


Figure 2. P-V and I-V Characteristics for Siwa PV Modules

stating that the PV modules usually linked with MPPTC to track MPP to maximize the harvest from the solar power, increase the PV module efficiency, suppress output power oscillation, and minimize the steady error in lesser time. In this section thin-film, PV modules are used. The technical properties of this module are shown in Table 1.

Figure 2 illustrates P-V and I-V characteristics of Siwa PV modules. It is worth mentioning that Siwa PV modules give their maximum outputs at STC as presented in Figure 2.

2. Mathematical Modeling of the PV System

2.1 Module Photo-current (I_{ph})

$$I_{ph} = [I_{sc} + \mu\,(T_k - T_{ref})]*G/1000 \qquad (1)$$

where, I_{sc} is PV short circuit current at 25 °C and 1000 W/m^2 and μ is the temperature coefficient of the short circuit current, T_k is the actual cell's temperature in Kelvin, T_{ref} is the reference temperature in Kelvin, and G is the Solar irradiation (W/m^2).

2.2 Module Reverse Saturation Current I_{rs}

$$I_{rs} = I_{sc}\,[(exp\,(QV_{oc})/\,(N_s kAT_k) - 1] \qquad (2)$$

where, Q is the electron charge $=1.6 \times 10^{-19}$ C, V_{oc} is the open circuit voltage, N_s is the number of series connected cells, K is the Boltzmann's constant $= 1.38 \times 10^{-23}$ J/k, and A is the Ideality factor (1.3) and depends on PV technology (Pandiarajan & Muthu, 2011).

2.3 Saturation Current Is or Diode Current

$$I_s = I_{rs}\left[\frac{T}{T_{ref}}\right]^3 exp\left\{\frac{Q*Eg}{AK}\left(\frac{1}{T_{ref}} - \frac{1}{T_k}\right)\right\} \qquad (3)$$

where E_g represents Bang-gap energy of silicon (1.1 eV).

2.4 The Module Output Current I_{pv}

$$I_{pv} = N_p I_{ph} - N_p I_s\left[exp\left\{Q\,\frac{Vpv+IpvRs}{NsAKT}\right\}-1\right] \qquad (4)$$

where N_p is the number of parallel connected cells, V_{pv} is the output voltage (v) and R_s is the series resistance of the module (Ω) (Soni & Bhatt, 2013). Figure 3 demonstrates Siwa PV module equivalent circuit.

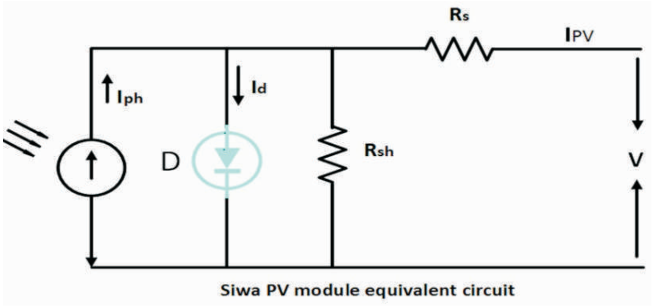
3. Whale Optimization Algorithm

The whale is a very intelligent and emotional animal. They have a very irregular hunting mechanism.

They go down about 12 m in the deep water then start to produce a chain of 9-shaped or spiral bubbles and move toward the water surface to hunt their prey as they prefer to hunt near the surface. They can recognize and encircle the prey if the best current solution is the optimum or the prey according to the following equations (Elazab et al., 2017; Ebrahimi & Khamehchi, 2016):

Parameter	Symbol	Subsection 1	Subsection 2	Subsection 3	Subsection 4
Subsection nominal output power	P (kW)	340	500	520	682
Panel maximum output power	Pmp (W)	135.278	130.626	135.278	135.278
Open circuit voltage	Voc (V)	142.2	140.4	142.2	142.2
Voltage at maximum power point	Vmp (V)	111.8	110.7	111.8	111.8
Short-circuit current	Isc (A)	1.41	1.39	1.41	1.41
Current at maximum power point	Imp (A)	1.21	1.18	1.21	1.21
Parallel strings	Np	5	5	5	5
Series-connected modules per string	Ns	12*6*7	12*8*8	12*8*8	12*7*12
dc-bus voltage	Vdc	800	800	800	800
Grid voltage	Vac	380	380	380	380
PV panel capacitor	Cpv	1 mF	3 mF	3 mF	4 mF
Diode saturation current	I0 (A)	6.24e-11	6.472e-11	6.24e-11	6.24e-11
Light-generated current	IL (A)	1.4011	1.4163	1.4011	1.4011
Temperature coefficient of V_{oc}	(%/deg.C)	-0.37	-0.37	-0.37	-0.37
Temperature coefficient of I_{sc}	(%/deg.C)	0.1	0.1	0.1	0.1
Shunt resistance R_{sh}	(ohms)	1013.846	707.0145	1013.846	1013.846
Series resistance R_s	(ohms)	10.597	10.233	10.597	10.597
Diode ideality factor		3.887	3.849	3.887	3.887

Table 1. PV System Simulation Parameters



Siwa PV module equivalent circuit

Figure 3. Equivalent Circuit of the PV Module

$$\vec{D} = |\vec{C}.\vec{X}^*(t) - \vec{X}(t)| \quad (5)$$

$$\vec{X}(t+1) = \vec{X}^*(t) - \vec{A}.\vec{D} \quad (6)$$

where A, C, and D are the coefficient vectors, t represents the current iteration, X* is the optimum solution that is updated periodically for each iteration in case of better solutions. The vectors of $\vec{A}$ and $\vec{C}$ can be calculated by:

$$\vec{A} = 2\vec{a}.\vec{r} - \vec{a} \quad (7)$$

$$\vec{C} = 2.\vec{r} \quad (8)$$

where, r is a random vector in [0, 1] and decreases linearly from 2 to 0 over the iteration course. For updating the whale and the prey position, a spiral equation is formed for mimicking the helix- shaped motion of the whale as follows:

$$\vec{X}(t+1) = \vec{D'}.\, e^{bl}.\cos(2\pi l) + \vec{X}^*(t) \quad (9)$$

where $\vec{D'} = |\vec{X}^*(t) - \vec{X}(t)|$ and indicates the optimum solution, b is a constant, l is a random number in the interval [-1, 1]. The whale position update whether in a shrinking encircling mechanism or along a spiral-shaped path can be achieved via the next equation:

$$\vec{X}(t+1) = \begin{cases} \vec{X}^*(t) - \vec{A}.\vec{D} & if\ p < 0.5 \\ \vec{D'}.e^{bl}.\cos(2\pi l) + \vec{X}^*(t) & if\ p \geq 0.5 \end{cases} \quad (10)$$

Moreover, p lies in [0, 1]

The exploration or searching for a prey can be performed by the following formula:

$$\vec{D} = |\vec{C}.\overrightarrow{Xrand} - \vec{X}| \quad (11)$$

$$\vec{X}(t+1) = \overrightarrow{Xrand} - \vec{A}.\vec{D} \quad (12)$$

where $\overrightarrow{Xrand}$ is a random whale chosen from the current population (Villalva, Gazoli, & Ruppert Filho, 2009). WOA flowchart is presented in Figure 4.

4. Practical Case Study

In this paper, a sector of 10 MW PV power plant is addressed. Loads of this system are nonhomogeneous, nonlinear, and rapidly changing during the day. The PV systems are characterized by its intermittent and fluctuating power generation nature, have no rotation part and no inertia. These characteristics affect the traditional power system during static and transient periods, thereby affected the traditional power system planning, operation,

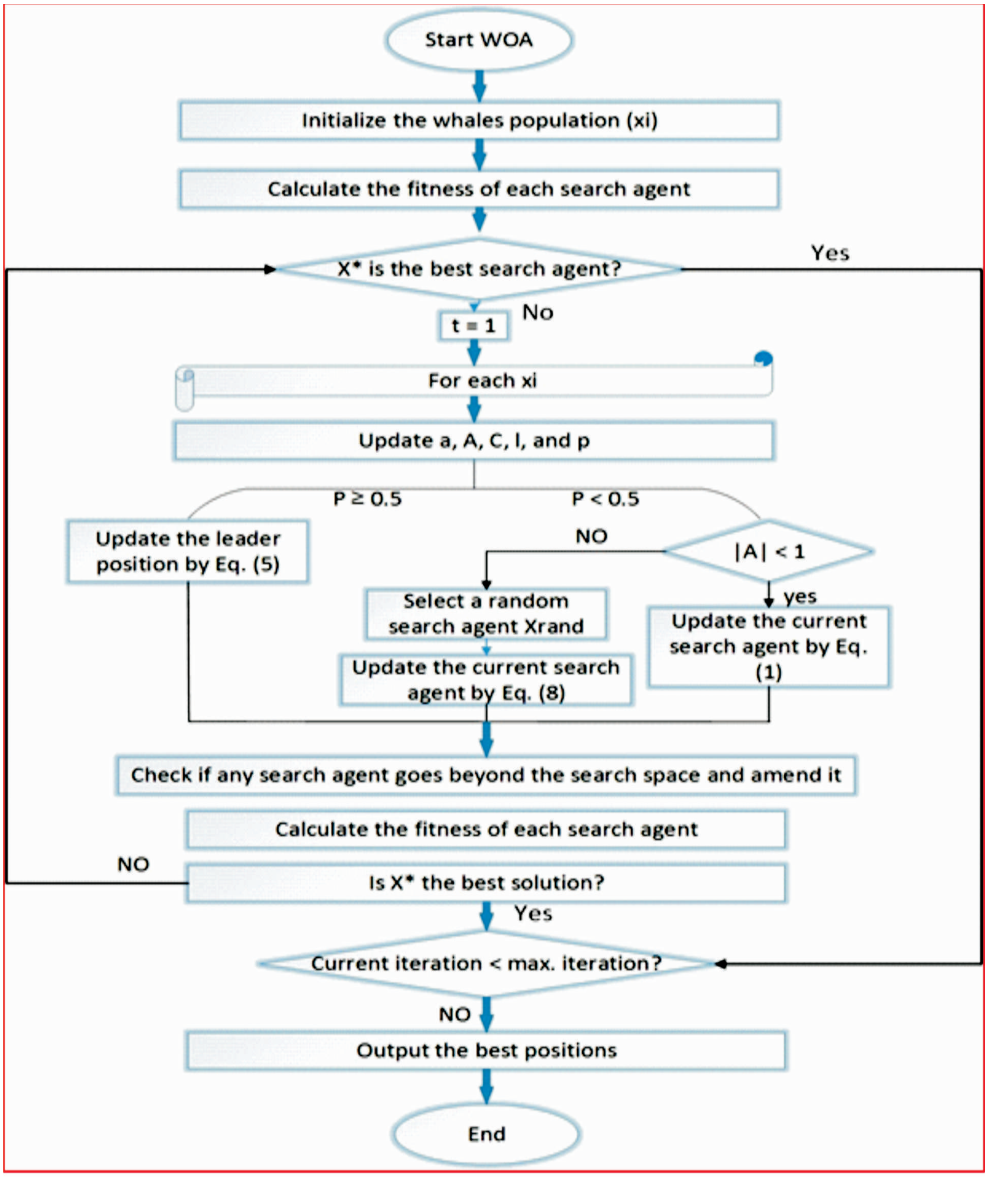


Figure 4. WOA Optimization Technique Flowchart

and control. These challenges motivated authors to employ the proposed MPPTC to maximize the extracted power, damp power variation, improve the voltage profiles and get rid of the steady state error rapidly.

The under-study prototype is simulated on Matlab™/ Simulink to accurately fine-tune the orders and gains of the Fraction Order Integral controller (FOI) to guarantee optimal dynamic MPP tracking performance during various patterns of climatic variations.

The overall capacity of the understudy sector is about 2030 kW (Table 1) and consists of 4 subsections of 340, 500, 510, 680 kW. The total number of inverters used is 254 of the sunny mini central 7000 HV type with 2 main collection boards feeding 1800 kVA 22/0.4 kV oil transformer.

In Siwa PV array, the power generated at 559 V DC and 10 kHz DC-DC boost converter is utilized to step up the voltage from 559 V to 800 V DC. The MPPTC control the DC-DC converter switch to obtain the desired output voltage to track the MPP via adapting the duty cycle to track the MPP. The filter minimizes the harmonics produced in the system. The VSC converts the 800 V DC into 380 V AC. Figure 5 shows the configuration of the under study section (section D) which is consisted of four subsections.

5. The Objective Function and Relevant Constraints

The best adjustment parameters for PI and FOPI-based MPPTCs are set taking into account the deviations of PV voltage and current. The most renowned used objective functions are utilized for tuning MPPTCs parameters as follow (Soni & Bhatt, 2013; Betti, Ebrahim & Hassan, 2018; Ebrahim, Aziz, Osman, & Nashed, 2018; Aouchiche, Aitcheikh, Becherif, & Ebrahim, 2018; Ebrahim, Becherif & Abdelaziz, 2018; Benmouna, Becherif, Depernet, & Ebrahim, 2018; Aouchiche, Cheikh, Becherif, Ebrahim, & Hadjarab, 2017; Osman, Mohamed, Ebrahim & Bendary, 2017; Mohamed, Ebrahim, Bendary & Osman, 2017; Soued, Ebrahim, Ramadan, & Becherif, 2017; Ebrahim, Elyan, Wadie, & Abd-Allah, 2017; Maher, Ebrahim, Mohamed, & Mohamed, 2017; Hussien & Mahmoud, 2017; Ebrahim, Ali, & Hassan, 2017; Mousa, Ebrahim, & Hassan, 2017; Ebrahim, AbdelHadi, Mahmoud, Saied, & Salama, 2016; Ali, Ebrahim, & Hassan, 2016; Omar, Ebrahim, Ghany, & Bendary, 2016; Jagatheesan, Anand, Dey, & Ebrahim, 2016; Mousa, Ebrahim, & Hassan, 2015; Ahmed, Ebrahim, Ramadan, & Becherif, 2015; Jagatheesan, Anand, & Ebrahim, 2014; Ebrahim, El-Metwally, Bendary, & Mansour, 2012; Ebrahim, Mostafa, Gawish, & Bendary, 2009; Ebrahim et al., 2011).

$$\mathrm{IAE} = \frac{1}{T}\int_0^T e(t).\,dt \qquad (13)$$

$$\mathrm{ISE} = \frac{1}{T}\int_0^T e^2(t).\,dt \qquad (14)$$

$$\mathrm{ITAE} = \frac{1}{T}\int_0^T |e(t)|.\,t.\,dt \qquad (15)$$

$$\mathrm{ITSE} = \frac{1}{T}\int_0^T e^2(t).\,t.\,dt \qquad (16)$$

For the fair comparison, the attained results by WOA are compared with that of a well-matured optimization algorithm such as a Genetic Algorithm (GA). The comparison aspects are the objective function value, computation time, overshoot, settling time, and rise time.

6. Simulation Results and Discussion

To evaluate the performance of the WOA approach, a Hybrid Microgrid System (HMS) is used. To achieve better benefits from this study and to avoid repetition only one section is put under study in this paper. The values surrounded by solid ovals is the optimal WOA gains obtained by I controller. While the values surrounded by dashed rectangular is the optimal WOA gains obtained by the PI controller. While the values surrounded by dotted rounded rectangular is the optimal WOA gains obtained by FOPI controller. The achieved gains using WOA are better than that of GA so more emphasis will be considered for WOA. Three test scenarios are used shown below:

It is worthy of emphasizing that the MPPTC input is the

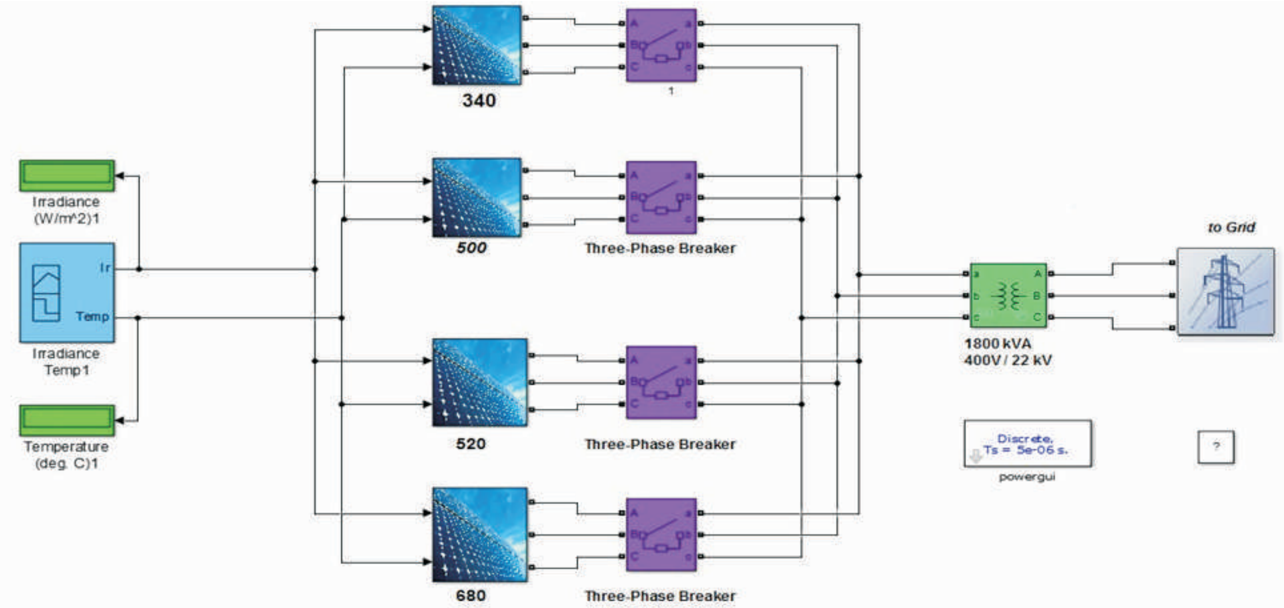


Figure 5. Simulink Model for the PV Section (Section D)

difference between the error ΔV & ΔI, and accordingly, the harvested PV power is maximized by applying PI and FOPI based MPPTCs to minimize this error. As four control variables for PI (has two parameters) and six control variables for FOPI (has three parameters) represent the controller gains for the selected PV array, WOA is used to decrease the objective function respecting all relevant inequality constraints. These MPPTCs are fine-tuned under different patterns of solar irradiance, temperature, and loads in various scenarios. Moreover, all the proposed MPPTCs are compared with classical P&O algorithm to verify the efficacy of the proposed controllers. Figure 6 presents the Simulink model for the under-study section that is employed to perform these scenarios.

Scenario (A): in this case study, the standard test conditions (STC) are presented in which a solar irradiance of 1 kW/m^2 with a temperature of 25 °C. The controllers are activated after 0.4 seconds. The output power time responses are shown in Figure 7. Table 2 reveals the MPPTC optimal gains of the PV array. Table 2 demonstrates that the minimum fitness function (FF) is IAE for I and FOPI controllers while ITSE for PI controller using WOA. The performance of the WOA is assessed after 100 repeated runs to confirm its efficiency. Figure 7 shows the performance superiority of the WOA-based FOPI under STC compared with I and PI controllers as well as classical P&O MPPTC.

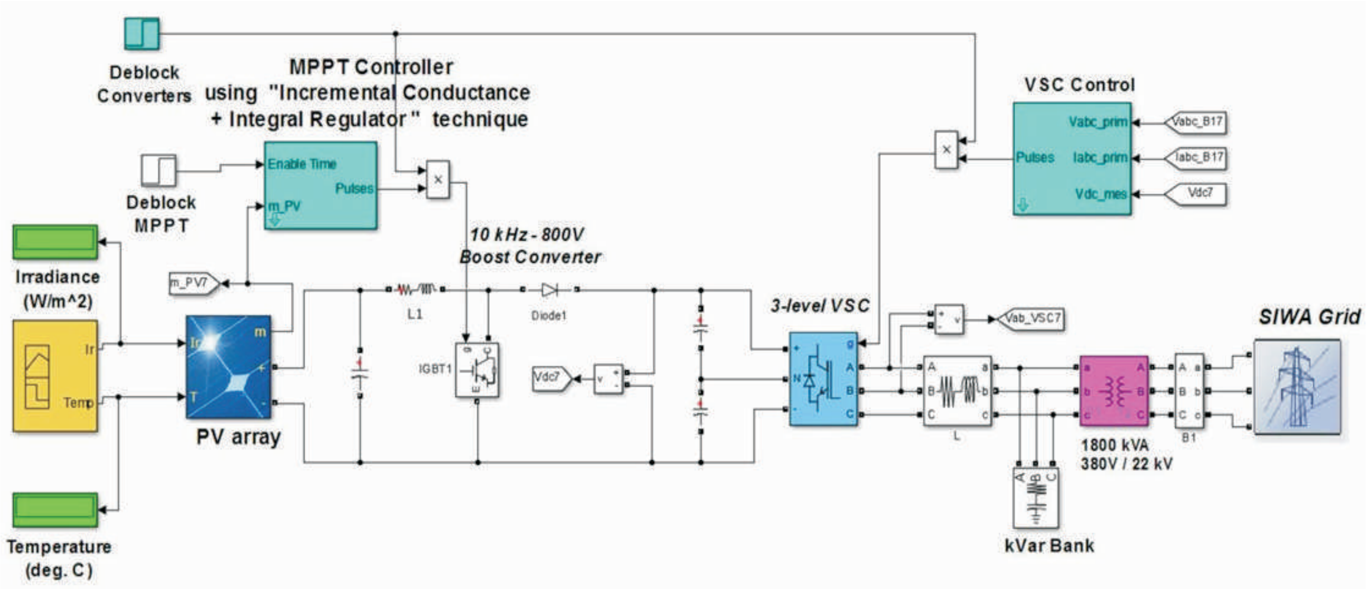


Figure 6. Simulink Model for the Under-study Section

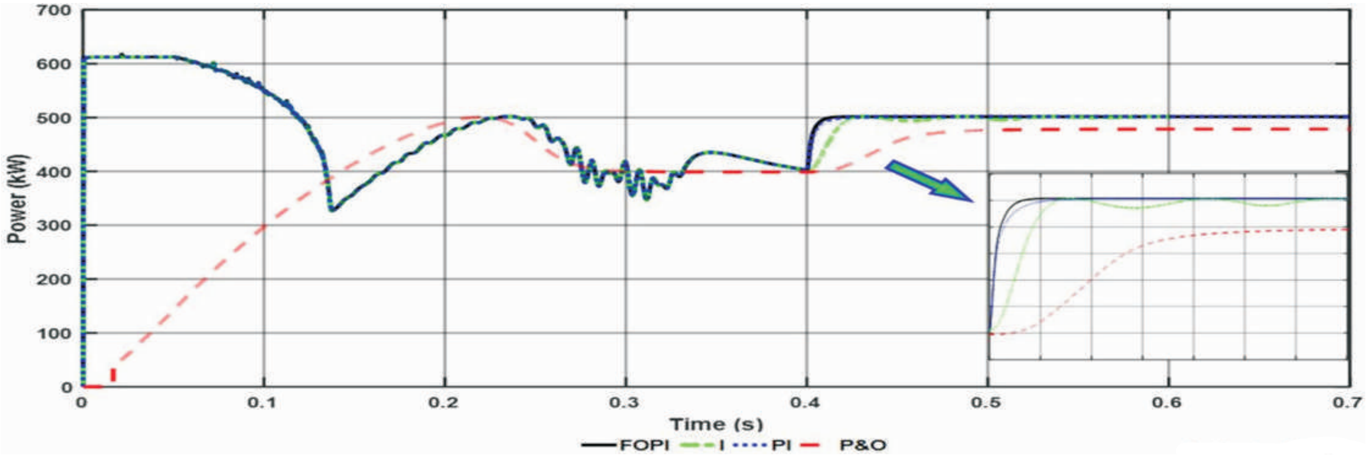


Figure 7. The PV Output Power for Scenario A

		IAE			ISE			ITAE			ITSE	
	I controller	PI controller	FOPI controller	I controller	PI controller	FOPI controller	I controller	PI controller	FOPI controller	I controller	PI controlle	FOPI rcontroller
Ki	9.88	18.78	5.938	7.463	2.666	7.695	7.893	16.10	5.477	6.732	6.295	8.166
Kp	NA	0.211	0.224	NA	0.191	0.115	NA	0.206	0.156	NA	0.216	0.214
lambda	NA	NA	0.728	NA	NA	0.851	NA	NA	0.754	NA	NA	0.933
Time	3.486	3.423	4.640	4.1203	3.422	5.102	4.154	3.377	5.214	3.518	3.363	5.04
FF value	36671	16833	16807	42296927	2.67E+08	2.67E+08	371551	198075	196230	3.44E+08	2.88E+08	2.88E+08

Table 2. Optimal WOA Gains with Indices Comparison

Scenario (B): in this scenario, it is assumed that the solar irradiance begins with 500 W/m^2 during the first 0.45 seconds before it decreases gradually to 300 W/m^2 during the next 0.1 second, then it remains constant at 300 W/m^2 for 0.1 second, during the next 0.2 second, irradiance increases to 1 kW/m^2 and then stabilizes at this value while the temperature value remains constant for the first 1.5 seconds at 25 °C and increases during 0.1 seconds to 50°C and remains at this value (see Figure 8). The desired goal of this scenario is to test the performance of the WOA under different conditions of weather changes. Figure 9 shows the dynamic responses of the PV system for the variations of the solar irradiance and the ambient temperature. The system performance is improved using FOPI-based MPPTC compared with I, PI and P&O based MPPTCs (Figures 8 and 9).

Scenario (C): this simulation scenario considers real site measurements of radiation and ambient temperature. The real site measurement taken out from the location is exemplified in Figure 10. The dynamic response of the prototype output power according to the real measurement is detected in Figure 11. The results concise the time domain dynamic response improvement of the system using FOPI as compared with I, PI, and P&O based MPPTCs.

From the above, it can be noticed that the proposed tracking technique has satisfactorily improved the system response compared to the traditional state of the art method P&O (the P&O results shown in red dashed lines in the above curves). It is clear that the harvest of the PV station is greater using WOA based MPPTCs compared with P&O. By performing the three study mentioned above cases, the performance of the WOA is validated effectively even in the scenario of considering real case

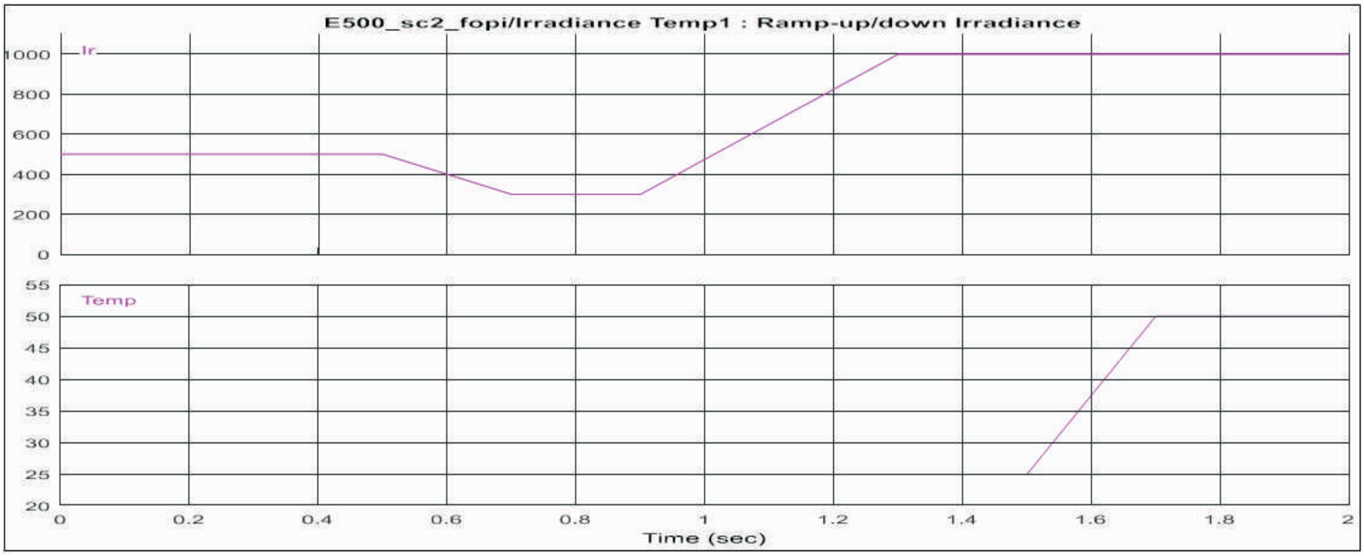


Figure 8. Irradiance and Ambient Temperature Patterns for Scenario B

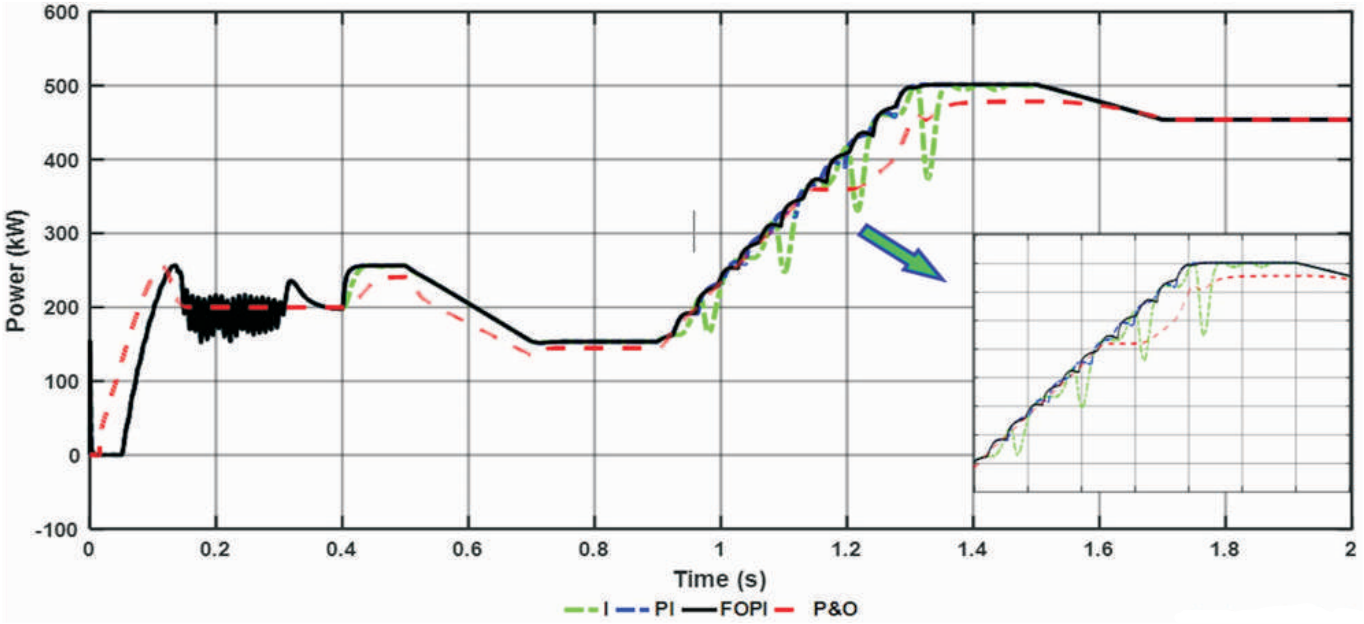


Figure 9. The PV Output Power under Scenario B

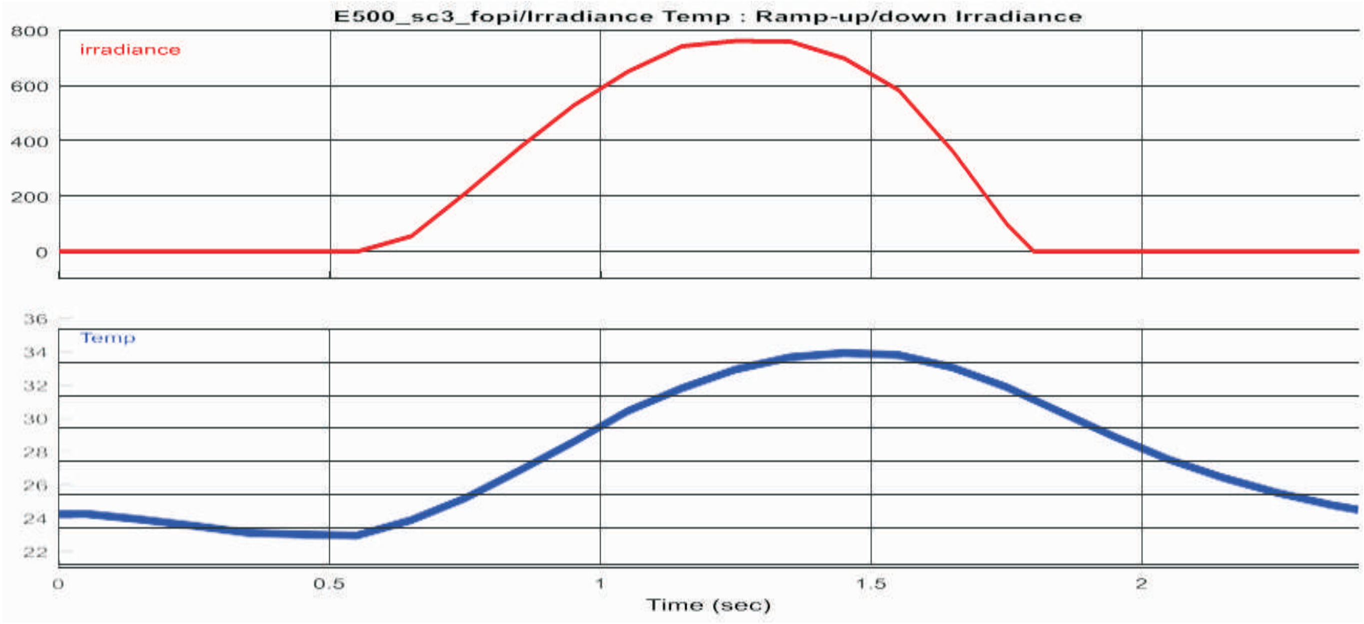


Figure 10. Realistic Irradiance and Temperature Measurements

measurements. The results are concise that a comprehensive assessment of the WOA is very competitive with the GA despite the impediments of finding the best gains of the meta-heuristic techniques to diminish the steady state error and power loss, and that the WOA is capable of dealing with high stochasticity grade of Renewable Energy Sources (RES) changes. As a future work for this research, the topologies, sizes, and types of multiple renewable energy resources can be extended.

Conclusion

In this paper, PI and FOPI based MPPTCs are adjusted to achieve the best dynamic performance of a practical hybrid PV-diesel system using WOA. The practical case study is addressed and simulated via Matlab™/Simulink software package. Different scenarios of Sun irradiance

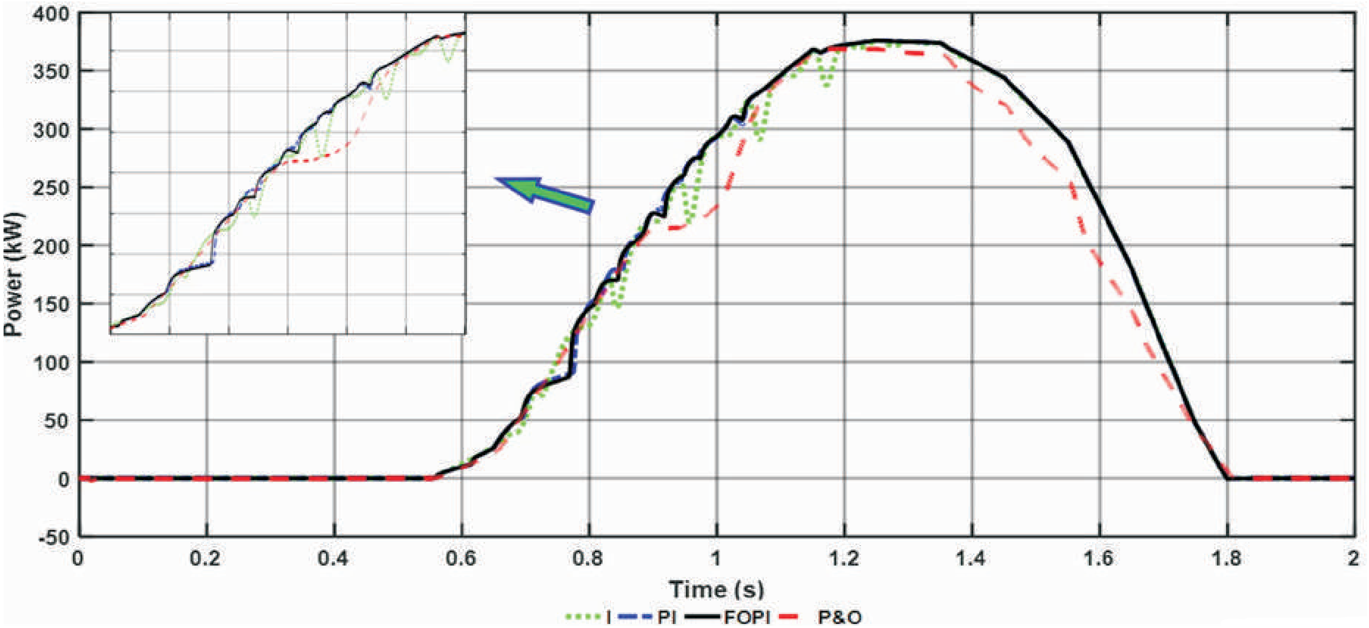


Figure 11. The Output Real Power of the PV System under Scenario C

and daily ambient temperatures variations are considered. Results confirm the superiority and validate the accuracy of the proposed scheme compared to the well-matured GA from the fast-tracking response, overshoot, settling time, and rise time point of view. In future work, the rest of the PV station and the diesel station will be entirely studied with novel strategies.

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