Maximum Energy Extraction in Partially Shaded PV Systems Using Skewed Genetic Algorithm: Computer Simulations, Experimentation and Evaluation on a 30 kW PV Power Plant

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Abstract

This paper presents an improved Genetic algorithm (GA) for Maximum Power Point Tracking (MPPT) in shaded Photovoltaic (PV) power generation systems. The proposed GA uses shrinking population wherein fitter chromosomes are retained for next generations while lesser-performing chromosomes are removed from the population sequentially. This methodology reduces convergence time while retains major advantages of GA. The method is explained lucidly and then computer simulations and experimental results on a prototype fabricated in the laboratory are presented. The practical feasibility of the new method is then showcased by applying the new theory on a 30-kW Photovoltaic (PV) power plant established in an educational institution premise. The PV plant undergoes partial shading conditions (PSC) during morning and afternoon hours due to branches of tall trees grown

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around the school building. The MPPT algorithm employed in the PV plant is Perturb and Observe (P&O) which fails to track global power peak at several shading conditions leading to loss of energy. The realistic shading patterns occurring on the PV plant were recorded and the new method is shown to exhibit enhanced energy yield.

Keywords: Photo voltaic (PV) power generation, maximum power point tracking (MPPT), genetic algorithms (GA), partial shaded condition (PSC).

List of Symbols and Abbreviations

I_{pv} – PV module output current
V_{pv} – PV module output voltage
P_{pv} – PV module output power
I_{ph} – photo current of PV module
I_o – diode saturation current
R_s – Series resistance
V_t – thermal voltage
I_{sc} – PV short circuit current
V_{oc} – PV open circuit voltage
ΔT – change in surface temperature of the panel
k_I – current temperature coefficient
λ – solar insolation
L – value of inductor
r_L – internal resistance of inductor
i_L – inductor current
C – value of capacitor
R – value of load resistance
v_o – output voltage
d – duty ratio of the boost converter
dmin – lowest value of duty ratio
dmax – highest value of duty ratio
k – iteration number

1 Introduction

Among the various renewable power sources, photovoltaic (PV) power generation is most sought after due to numerous merits such as omnipresence and free-availability of solar insolation, near-zero maintenance cost, financial aid from government agencies, absence of rotating parts etc [1]. However, the major drawbacks are the stochastic nature of PV power and non-linear power–voltage (P-V) characteristic [2, 3]. In roof top PV systems, shading on some PV modules occurs due to neighbouring tress, buildings, and towers and this is called partial shading condition (PSC). Under PSC, P-V curve exhibits several power peaks and the highest value is called global maximum power point (GMPP) and all other power peaks are termed as local maximum power points (LMPPs) [4–7]. When traditional methods such as Perturb & Observe (P&O) [8, 9] is employed for maximum power point tracking (MPPT), global convergence is not guaranteed, and the PV system works on in any one of the LMPP leading to energy loss.

Several methods are presented in the past to track GMPP in PV systems under PSC and one feasible scheme is the use of evolutionary and swarm intelligence techniques [10–16]. In [10], a comprehensive plant model incorporating PV with power converter for effective PV voltage control is developed; however, the effect of shading is not addressed. Hybridisation of adaptive perturb and observe method with particle swarm optimization (PSO) is seen in [11]. In [12], a comprehensive review on online, offline and hybrid MPPT techniques is well documented. In [13], a novel direct duty ratio control derived from power converter output ripples is introduced leading improved dynamic response. Logarithmic PSO is presented in [14], wherein the swarm is reduced to one particle during steady state leading to faster and smoother convergence. An improved grey wolf optimization is employed for MPPT [15] by incorporating pouncing behaviour of real wolves and the new method improves MPPT characteristics. Pigeon inspired optimization towards MPPT in shaded PV systems is introduced in [16] and is shown to be a better choice.

A closer examination of the above mentioned research works evidently shows that MPPT in shaded PV systems is a challenging task and researchers are continuously exploring newer MPPT techniques. Towards this goal, this research work presents a new Genetic Algorithm (GA) in which the population of chromosomes is skewed in such a way that the lesser-fit chromosomes are deleted one after the other in the later stages of MPPT. Population shrinking reduces computing as well as search durations with better chromosomes leading to speedy convergence to GMPP. The proposed strategy is first simulated and then experimentally verified. In order to showcase its potential on practical application, this scheme is then applied to 30-kW PV power plant located at an educational institution located at Kailasapuram town ship, Tiruchirappalli, Tamil Nadu, India which started functioning in 2015. The authors of this paper have recorded realistic shading patterns on the PV plant and new GA is applied for MPPT. It is shown through computer simulations and extensive computations that the new GA produces more energy from the PV plant than the existing P&O method; further MPPT characteristic curves exhibit improved dynamic response.

2 Description of the New GA Method

In this section, MPPT is first formulated as an evolutionary search process and application of new GA method is explained.

2.1 Maximum Power Point Tracking Through Evolutionary Search

The proposed power electronic interface along with associated components is shown in Figure 1. The microcontroller is the heart of the system wherein the modified GA program is downloaded and executed. For one generation of GA, one series of randomly generated gating signals of duty ratio in the range of 10%–90% are supplied to dc-dc converter. Once the transients are settled, PV voltage and current are sampled and the product is the PV power which is saved against each duty ratio. Thus, for one generation of GA, a set of duty ratio and associated PV power are stored.

In the proposed Genetic Algorithm method, randomly generated duty ratios are chromosomes and PV power is taken as fitness function. Each duty ratio undergoes selection, crossover and mutation in each generation. After a finite number of generations, population of chromosomes is skewed such that worst ones are deleted while better ones are preserved for further evolutionary process. The algorithm is described below:

Step 1
Generate random number of duty ratios equal to the population size, N. Here, each duty ratio is referred to as chromosome.

Step 2
Operate the boost type dc-dc converter for each duty ratio and measure PV voltage and current and then compute PV power under steady state conditions. PV power with respect to each chromosome is then stored.

Step 3
Generation of offspring

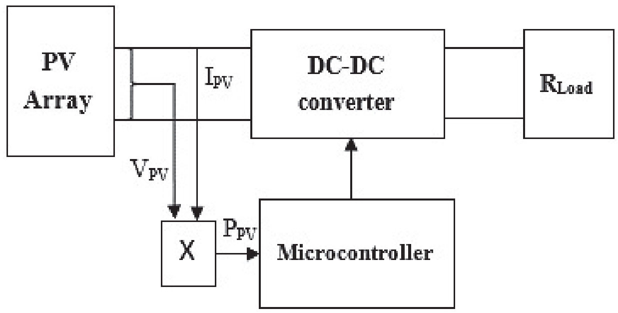


Figure 1 Block diagram of the experimental setup.

In this step, each chromosome undergoes, selection, crossover and mutation and new set of population of chromosomes is formed for next generation.

Step 4
Replace the current population with the new population.

Step 5
Execute steps 2, 3 and 4 for certain number of searches; else go to step 6.

Step 6 Remove the worst chromosome and follow steps 2, 3, and 4 with left out chromosomes.

Step 7 Stop the process if termination criterion is met and take the power as the GMPP and duty ratio as the optimal duty ratio.

2.2 Modelling of PV System

The single diode model of PV module [6] is used to calculate the power – duty ratio (P-d) curve. The relevant of PV modelling equations during non-uniform insolation are given below [10, 12]:

$$\mathrm{I_{pv}} = \mathrm{I_{ph}} - \mathrm{I_o}\left[\exp\left(\frac{\mathrm{V_{pv}} + \mathrm{R_s I_{pv}}}{\mathrm{V_t}}\right) - 1\right] \tag{1}$$

The following equation is used to compute the photo current, I_{ph} of a solar module:

$$\mathrm{I_{ph}} = (\mathrm{I_{sc}} + \mathrm{k}_I \Delta \mathrm{T})\lambda \tag{2}$$

PV module output voltage, V_{pv} can be written as

$$\mathrm{V_{pv}} = \mathrm{V_t}\left[\ln\left(\frac{\mathrm{I_{ph}} - \mathrm{I_{pv}}}{\mathrm{I_o}}\right) + 1\right] - \mathrm{R_s I_{pv}} \tag{3}$$

During partial shaded conditions, the power-duty ratio (P-d) curve contains multiple power peaks and it is very much essential to extract the highest power available. Hence, maximum power point tracking (MPPT) in photo-voltaic systems is perceived as an optimization task as given below:

$$\text{Maximize } \mathrm{P_{PV}} = f(\mathrm{d}) \tag{4}$$

$$\text{Subject to } \mathrm{d_{min}} \leq \mathrm{d} \leq \mathrm{d_{max}} \tag{5}$$

In the proposed MPPT scheme, evolutionary search continues till dc/dc converter operates to get GMPP.

2.3 Analytical Expressions for MPPT in PV Array with Boost Type dc/dc Converter

For a duty ratio of d, the ON period of the dc/dc converter is dT, while OFF period is (1-d)T where T is the period of one cycle of dc/dc converter.

The voltage across the boost converter inductance is taken from [17] and is given below:

$$\mathrm{L}\frac{\mathrm{di_L}}{\mathrm{dt}} = \mathrm{V_{pv}} - \mathrm{i_L r_L} - (1-\mathrm{d})\mathrm{v_o} \tag{6}$$

The capacitor current can be derived as

$$\mathrm{C}\frac{\mathrm{dv_o}}{\mathrm{dt}} = (1-\mathrm{d})\mathrm{i_L} - \frac{\mathrm{v_o}}{\mathrm{R}} \tag{7}$$

Taking Laplace Transform on both sides of Equations (6) and (7), we get

$$\mathrm{LsI_L(s)} = \mathrm{V_{pv}(s)} - \mathrm{I_L(s) r_L} - (1-\mathrm{d})\mathrm{V_o(s)} \tag{8}$$

$$\mathrm{CsV_o(s)} = (1-\mathrm{d})\mathrm{I_L(s)} - \frac{\mathrm{V_o(s)}}{\mathrm{R}} \tag{9}$$

Equation (10) is now derived by rearranging Equations (8) and (9):

$$\frac{\mathrm{V_{pv}(s)}}{\mathrm{I_L(s)}} = \mathrm{L}\left(\mathrm{s} + \frac{\mathrm{r_L}}{\mathrm{L}}\right) + \frac{(1-\mathrm{d})^2}{\mathrm{C}\left(\mathrm{s} + \frac{1}{\mathrm{RC}}\right)} \tag{10}$$

The concept of MPPT can be understood from the above equation: here, the ratio on the left-side term reflects input impedance of the PV plant for a given solar insolation and temperature while the right-side term is a variable depending on the duty ratio of the boost converter. With change in ambient conditions as well as shadings, left hand side ratio changes and MPPT is performed using duty ratio adjustment.

Table 1 PV module (Vikram Eldora 20P) features

Maximum Power (P_{max})	20W
Open Circuit Voltage (V_{oc})	21V
Voltage (V_{mp}) at P_{max}	17.2V
Short Circuit Current (I_{sc})	1.28A
Current (Imp) at P_{max}	1.2A
Voltage temperature co-efficient (Kv)	$-2.13e^{-3}$
Current temperature co-efficient (Ki)	$4.46e^{-3}$
Number of cells	36

2.4 Simulation Result

The proposed method is evaluated through computer simulations, experimental studies and finally application to an existing PV power plant. Towards this goal, a total of 12 shading patterns were employed and for better understanding these patterns are numbered and described in following section:

Patterns 1 and 2: These two patterns are exclusively considered for computer simulation study.

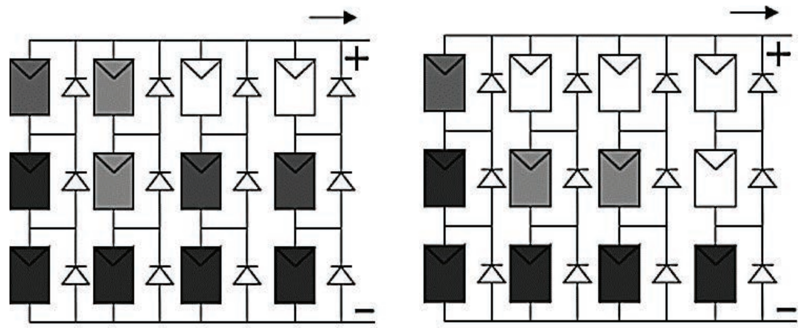
Patterns 3 and 4: These two patterns are artificially created on the prototype fabricated in the laboratory and are used for experimental verification.

Patterns 5 to 12: These are realistic shading patterns which occur on the 30kW PV power plant. Application of the new method towards increased energy yield and subsequent revenue income generated are computed using these patterns.

In order to validate the proposed method, computer simulations are carried out on a 3 series 4 parallel (3s4p) arrangement as given in Figure 2(a). Specifications of PV module are given in Table 1.

Two different shadings were made to exist on this system such that two power-duty ratio (p-d) curves as shown in Figure 2(b) are made available. The p-d curves exhibit multiple peaks and therefore suits the present study. Simulation results are now discussed.

An exclusive computer program is developed in MATLAB for the proposed GA s well as existing methods and is then applied to patterns 1 and 2. The details of GA parameters are shown in Table 2. Simulation results obtained are included in Figure 2. For pattern 1, which lasts for up to 6



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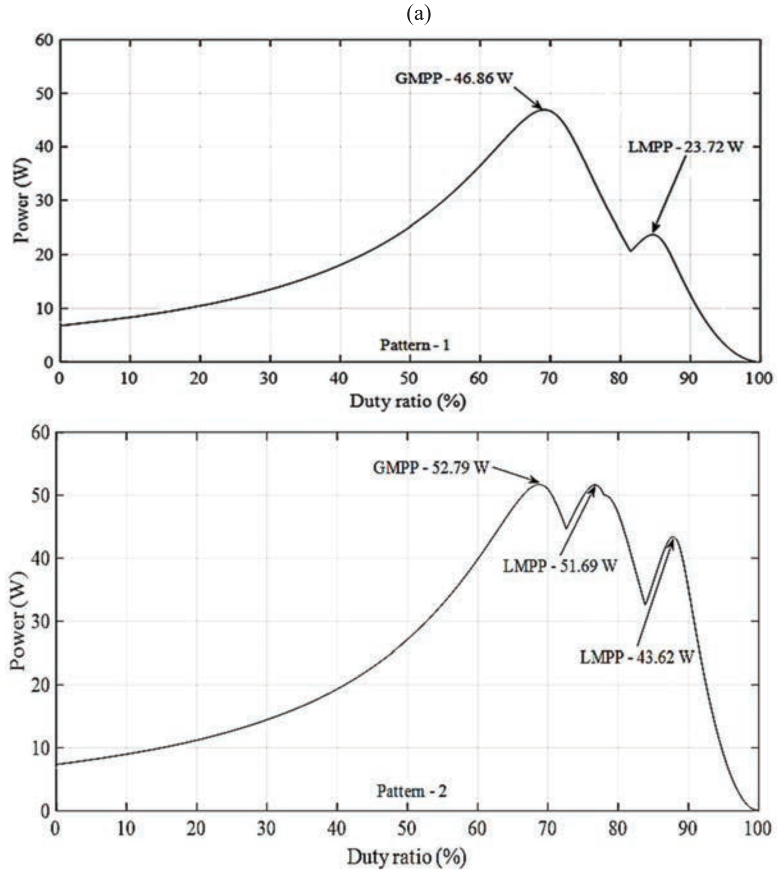

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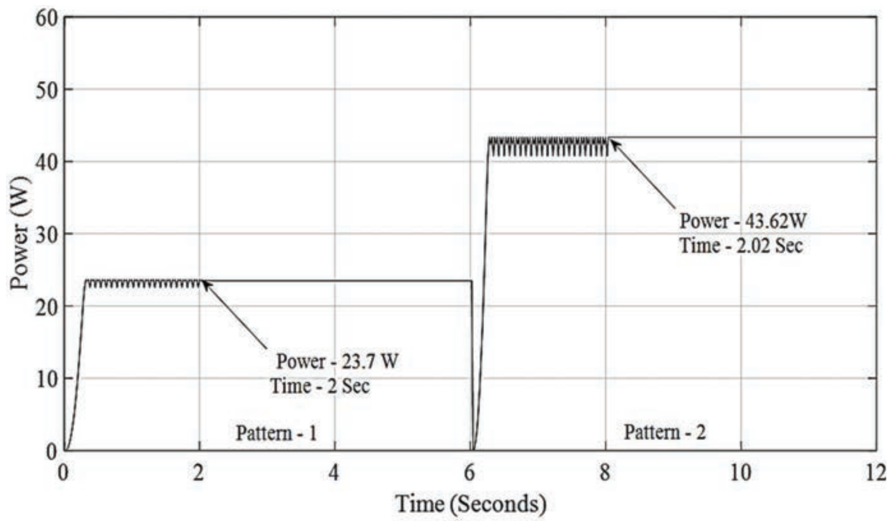

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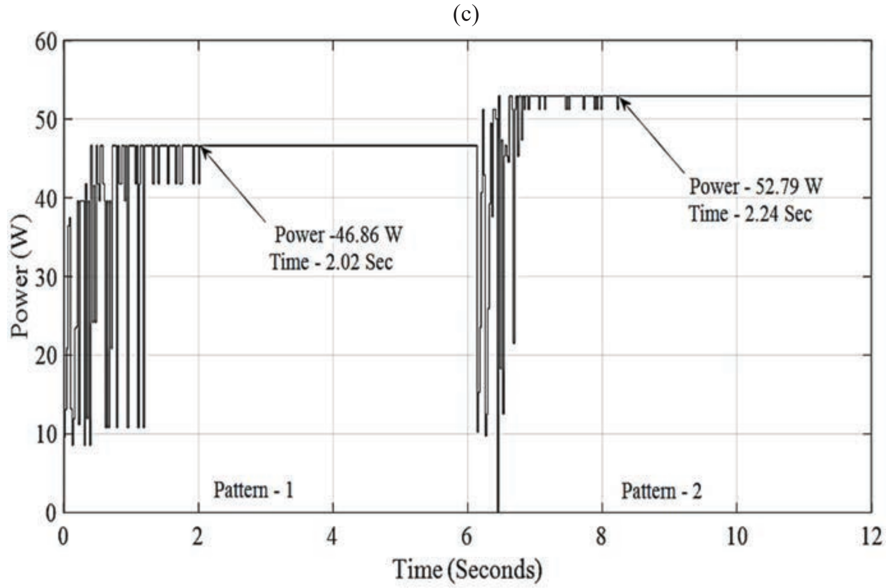


(d)

Figure 2 PV arrangements and simulation results. (a) Two types of shading on 3s4p PV arrangement and (b) corresponding P-d curves. MPPT curves using (c) P&O (d) Conventional GA and (e) new GA method.

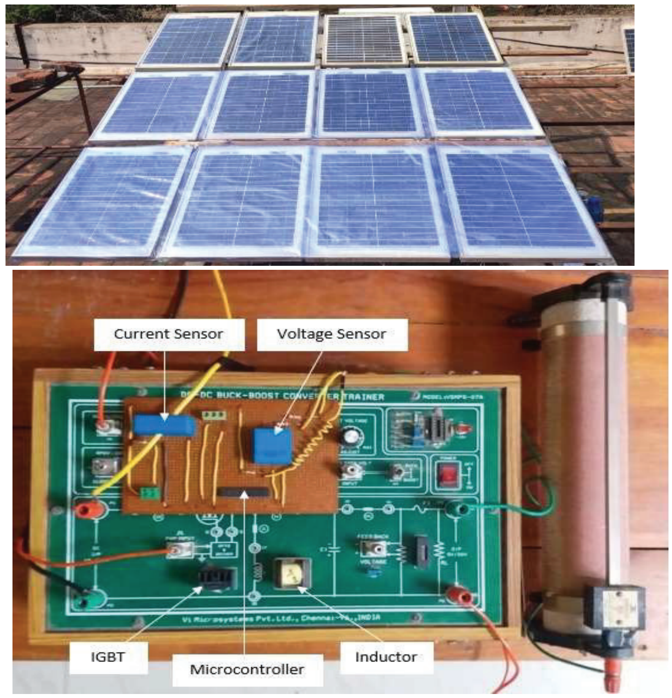
Table 2 Parameters of proposed Genetic Algorithm

Population size, N	12
Bit size of individual	7
Selection	Roulette wheel
Crossover	Single point
Crossover probability	0.8
Mutation probability	0.01
Number of iterations, k with fixed population size	5
Minimum chromosomes reserved during search	2
Number of chromosomes eliminated from population	1

Table 3 Performance evaluation MPPT methods (Simulation study)

PV Configuration	Shading Pattern with Max. Power From the P-V Curve (W)	Tracking Method	Maximum Power Tracked (W)	Convergence Time (s)	Tracking Efficiency (%)
3s4p	Pattern 1	New GA	46.86	0.98	99.99
	GMPP: 46.86 W	Conventional GA	46.86	2.02	99.97
	LMPP:23.72W	P&O	23.7	2	50
	Pattern 4	New GA	52.79	0.94	99.99
	GMPP: 52.79 W	Conventional GA	52.79	2.24	99.97
	LMPP: 51.69 W	P&O	43.62	2.02	100
	LMPP: 43.62 W				

seconds, P&O method settles at LMPP of 23.7W. The new and conventional GA methods track the GMPP of 46.84W, but skewed GA locates GMPP in in 0.98 seconds, while the conventional GA takes 2.02 seconds. Pattern 2 was made to exist from t = 6 seconds onwards and three MPPT algorithms restart tracking. For pattern 2, P&O method fails to reach GMPP, while both GA methods successfully tracks it; however, new GA method tracks the GMPP much faster compared to the conventional method. The simulation results evidently show that the proposed GA method gives better and efficient tracking performance. For ease of reference, the results are tabulated in Table 3. This table includes tracking efficiency [2] which is defined as the average output power under steady state and global maximum power. Accordingly, for pattern 1, P&O method settles to 23.7 watts which is LMPP and global power peak is 46.86 watts. Hence the ratio, 23.7/46.86 is 50%.



(a)

(b)

Figure 3 Photograph of prototype (a) PV roof top arrangement and (b) Hardware for MPPT.

2.5 Experimental Evaluation

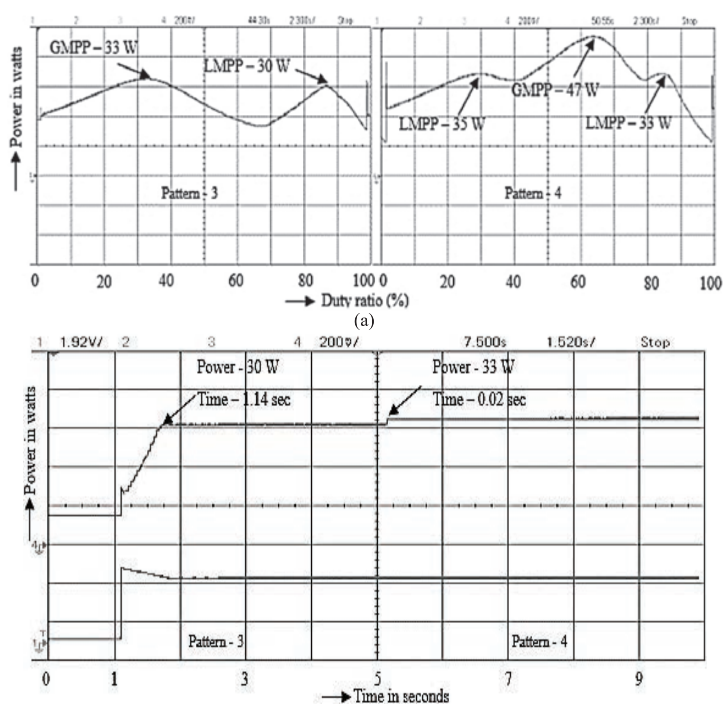
An experimental setup with 3s4p PV arrangement on the laboratory roof top together with microcontroller based MPPT controller was developed and measurements were taken. Figure 3 shows photographs of hardware set up developed in the laboratory. Here, intentionally, few PV modules are covered with transparent sheets to artificially create partial shading. The values of inductor, capacitor and switching frequency of the boost type dc-dc converter are designed for obtaining ripple-free output [17] which are listed in Table 4.

Two different shading patterns were artificially created on the roof top 3s4p configuration and a dedicated microcontroller program was executed to obtain the P-d curves which are labelled as patterns 3 and 4 and are given in Figure 4(a). Pattern 3 has two power peaks one at 33W as GMPP and 30W as LMPP. The GMPP of pattern 4 is at 47W and it has two LMPPs of values 35W and 33W. Software programs for MPPT based on P&O, conventional

Table 4 Experimental setup details

Microcontroller	PIC16F876A
PV Module	Vikram Eldora 20P
IGBT	1MBH15D060
Switching frequency, f_s	50 kHz
Capacitor, C	470 μF
Inductor, L	1.5 mH
Resistance component of Inductor, r_L	0.358Ω
Load (Resistance), R	150 Ω

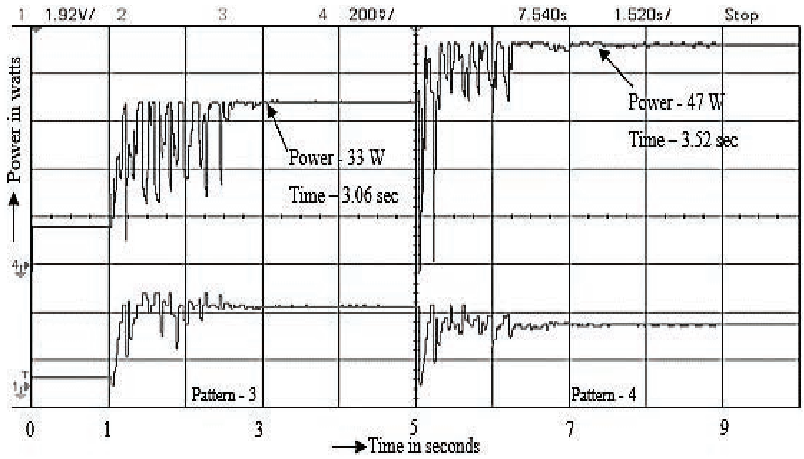
GA and proposed GA were first developed in MPLAB and then downloaded to the microcontroller. The PIC16F876A microcontroller was used for online MPPT of 3s4p arrangement. The pattern 3 was made to exist for the first 6 seconds and then the shading is physically changed to get pattern 4. The experimentally determined tracking curves employing the above mentioned MPPT methods are given in Figure 4(b), (c) and (d). The tracking curve



(a)

(b)

Figure 4 Continued



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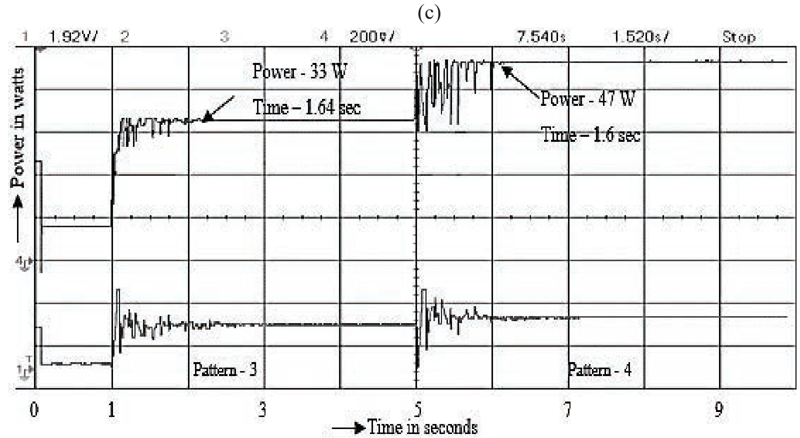

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Figure 4 Measured tracking curves with 3s4p architecture. (a) P-d curves (patterns 3 and 4). MPPT curves using (b) P&O, (c) conventional GA and (d) new GA methods.

shows that for pattern 3, P&O fails to recognize GMPP and settles at the LMPP of 30W. Conventional GA identifies the GMPP at 33W successfully; however, the convergence time is 3.6 seconds. The proposed GA is quicker to converge at the GMPP with 1.64 seconds. It is seen that PV power oscillates for increased duration in conventional GA whereas with the new GA the oscillations subside quickly.

When pattern 4 comes up after 6 seconds, all the three algorithms re-start the MPPT process. The P&O method settles at local peak of 33W. Both the

Table 5 Performance evaluation of MPPT schemes (Experimental results)

PV Configuration	Name of Pattern with PV Power Peaks	MPPT Scheme	Power (W)	Convergence Time (s)	Tracking Efficiency (%)
3s4p	Pattern 3	New GA	33	1.64	99
	GMPP: 33 W	Conventional GA	33	3.06	97
	LMPP: 30 W	P & O	30	1.14	90.9
	Pattern 4	New GA	47	1.6	99
	GMPP:47 W	Conventional GA	47	3.52	98
	LMPP: 35W	P & O	33	0.02	70.2
	LMPP: 33W				

conventional and proposed GA methods identify the GMPP at 47W. Here too, the proposed algorithm is faster to reach the GMPP than traditional GA. The dynamic performance indices of experimentally recorded tracking curves are given in Table 5.

3 Application to Existing PV Power Plant

This section explains the application of the proposed Genetic Algorithm towards MPPT in an existing PV power plant when it undergoes partial shading.

3.1 PV Plant Under Study

For implementing the proposed scheme on an existing plant, a 30-kW grid connected solar power plant at one educational building premises located in Kailasapuram, Tiruchirappalli, Tamil Nadu, India was taken up. The electrical wiring diagram of the plant is depicted in Figure 5 and consists of PV array, boost type dc-dc converter, inverter, grid and MPPT controller. At present P& O method is employed in the plant for energy harvesting and the following section describes application of the skewed GA based MPP.

The authors have closely monitored the PV plant for the past few months and observed that branches few tall trees cause partial shading in the plant during most part of day time. Based on the continuous observation, eight different shading patterns were identified throughout the day and are labelled as patterns 5 to 12 for convenience. The patterns were distinguished depending on the time of occurrence and are given in Table 6. As an illustration, Figure 6(a) shows the photograph of shading noticed at few modules of

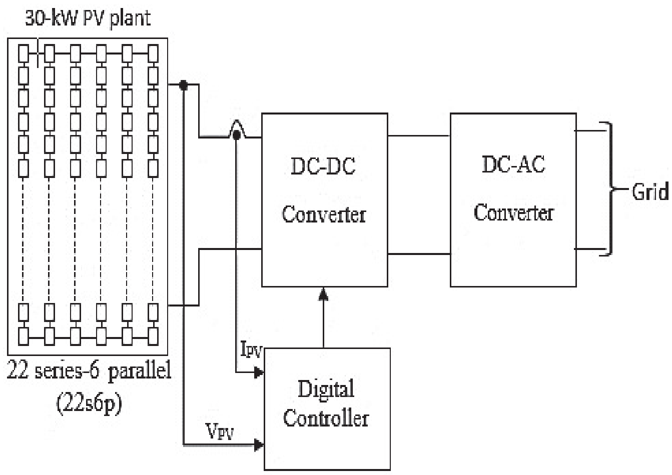


Figure 5 Circuit diagram of 30-kW PV plant.

Table 6 Patterns in the PV plant

Pattern Number	Time	Duration
5	08:31 – 08.53	23 minutes
6	08:54 – 10:06	73 minutes
7	10:07 – 10:38	32 minutes
8	10:39 – 10:52	14 minutes
9	10:53 – 02:13 (Uniform insolation)	201 minutes
10	02:14 – 02:37	24 minutes
11	02:38 – 03:27	50 minutes
12	03:28 – 04:30	63 minutes

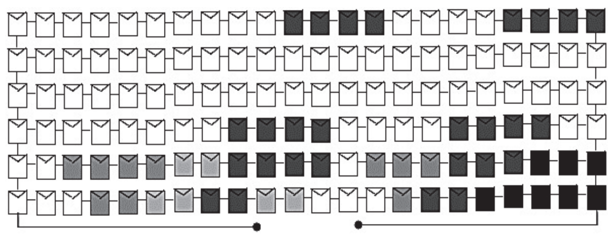
Table 7 Details of single PV module of the plant

Maximum Power (Pmax)	230Wp
Open Circuit Voltage (Voc)	37 V
Short Circuit Current (Isc)	8.8 A
Voltage (Vmp) at maximum power	30 V
Current (Imp) at maximum power	7.67 A

PV plant at 08.45 morning on 26/11/2019 and this is named as pattern 5 for further reference. Figure 6(b) shows PV arrangement corresponding to pattern 5. The specifications of PV panel are shown in Table 7.

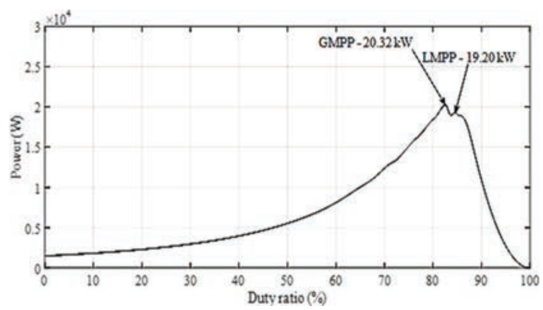
Equations (1), (3) and (10) are now used to calculate the P-d curve of pattern 5 and is given in Figure 7(a). This P-d curve has GMPP of 20.32 kW and

(a)



(b)

Figure 6 Picture and electrical circuit of grid connected plant. (a) Realistic shadings for pattern 1 and (b) corresponding PV array.



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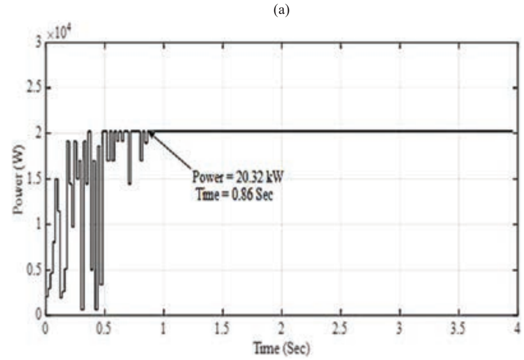

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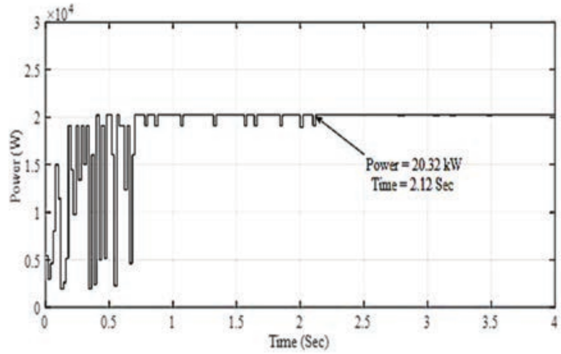

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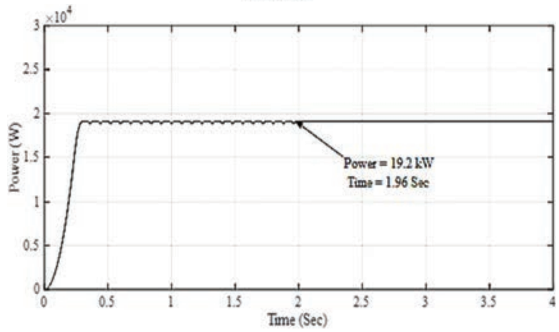


(d)

Figure 7 Calculated tracking curves of 30-kW (22s6p) PV plant. (a) Power-duty ratio(P-d) curve (Pattern 5). MPPT curves for pattern 5 using (b) new GA, (c) conventional GA and (d) P&O methods.

LMPP of 19.20 kW. A MATLAB program for skewed GA is developed and is applied to pattern 5 and MPPT curve thus obtained is given in Figure 7(b). It is seen that the new scheme converges to GMPP of 20.32 kW with 0.86 seconds. For comparison, conventional GA and existing P&O methods are also used to pattern 5 and the MPPT curves are given in Figure 7(c) and 7(d) respectively. The traditional GA also guarantees global convergence, but with increased time of 2.12 seconds. It is evident that conventional P&O method fails to identify GMPP and lands in LMPP of 19.2 kW. The new GA is then applied to all 8 patterns and it is observed that the proposed as well as conventional GA guarantees global convergence at all times, while P&O method fails to do so. The findings of the simulation results are tabulated in Table 8 which clearly demonstrate the superior performance of the new GA. As is established in the literature, P&O method does not guarantee

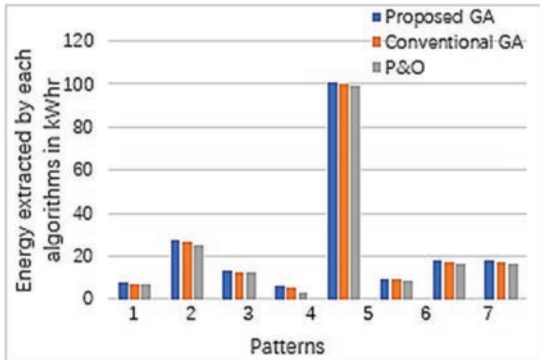
Table 8 Comparison of MPPT techniques

		Power tracked (kW) and tracking efficiency in brackets			Convergence Time (s)		
Pattern	GMPP (kW)	New GA	Conventional GA	P&O	New GA	Conventional GA	P&O
5	20.32	20.32 (100)	20.32 (100)	19.2 (LMPP) (94.48)	0.86	2.62	2.04
6	22.82	22.82 (100)	22.80 (99.91)	21.12 (LMPP) (92.55)	0.96	2.42	2.00
7	24.3	24.3 (100)	24.28 (99.91)	24.06 (LMPP) (99.01)	1.02	2.02	2.04
8	26.17	26.17 (100)	26.17 (100)	12.12 (LMPP) (46.31)	1.04	2.24	2.04
9	30	30 (100)	30 (100)	29.76(GMPP) (99.2)	0.96	1.84	2.06
10	23.79	23.79 (100)	23.79 (100)	23.79 (GMPP) (100)	0.7	2.32	2.06
11	21.8	21.8 (100)	21.8 (100)	20.7 (LMPP) (94.95)	1.06	2.36	2.02
12	17.23	17.23 (100)	17.23 (100)	16.27 (LMPP) (94.42)	0.94	2.02	2.02

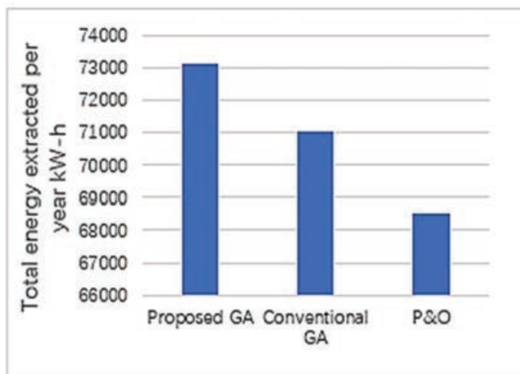
Table 9 Calculation of revenue generation in grid connected PV plant

Pattern Details and Time Span	New GA	Conventional GA	P&O
Pattern 5–23 minutes	7.7628	7.1251	6.9076
Pattern 6–73 minutes	27.6648	26.8963	25.15
Pattern 7–32 minutes	12.8928	12.2013	12.2406
Pattern 8–14 minutes	6.0536	5.4018	2.6501
Pattern 9–201 minutes	100.3968	99.8964	98.9969
Pattern 10–24 minutes	9.4672	8.9906	8.8787
Pattern 11–50 minutes	18.1321	17.0012	16.7066
Pattern 12–63 minutes	18.0858	17.1124	16.2643
Total energy extracted in a day (kW-h)	200.4559	194.6251	187.7949
Annual energy extracted (kW-h)	73166.4035	71038.1615	68545.1385
Annual income (Rs.) (at Rs. 8.05/kW-h as per LT-V Tariff)	588989.55	571857.20	551788.36

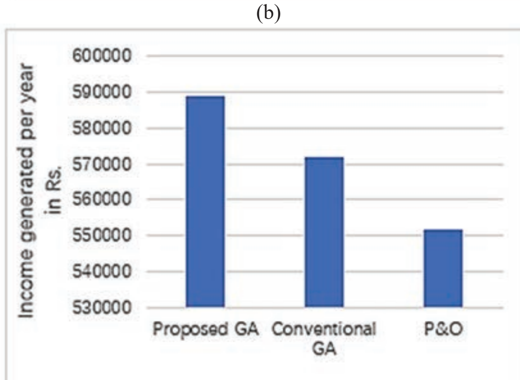
global convergence always. A dedicated MATLAB program is written and the tracking curve corresponding to each method is integrated to get energy generated per day. This value when multiplied by 356 days leads to annual energy generation in Kw-h. The energy value multiplied with electricity Tarif gives annual revenue generation in Indian Rupees. Assuming Rs. 8.05/kW-h as per LT-V Tariff, the revenue generation in Indian rupees is computed and is given in Table 9. The numerical values in Table 9 clearly suggest that proposed GA based MPPT is a promising procedure leading to enhanced revenue generation. The performance comparison of the proposed method and existing ones is further demonstrated in Figures 8(a), (b) and (c).



(a)



(b)



(c)

Figure 8 Performance comparison (a) energy extracted by each algorithm for patterns 5 to 12, (b) Energy extracted per year by each algorithm and (c) income generated per year by each algorithm.

4 Conclusion

This paper has focused on the development of a new Maximum Power Point Tracking (MPPT) algorithm on shaded photovoltaic (PV) systems. The proposed method is an improved version of Genetic Algorithm (GA)wherein population shrinking is intentionally introduced for faster convergence to global maximum power point tracking leading to enhanced energy yield. The major findings are listed below:

- MPPT in shaded PV system is framed as an optimization search and a modified GA is applied towards the solution search.
- The population of GA is systematically skewed such that chromosomes with worst performance are deleted from population and then GA is executed with better individual solutions. This methodology reduces computing time leading to faster convergence to GMPP.
- The new approach is first verified through computer simulations and subsequently verified on prototype fabricated in the laboratory under different shading conditions and further the new method shows improved performance over exiting MMPT alternatives.
- The new method is employed to an existing 30kW PV power plant in India and energy yield and the resulting revenue in Indian Rupees is calculated. It is shown that deployment of new MPPT algorithm leads to increased revenue income.

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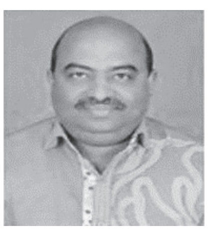
Biographies



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