

Table S1. Measured values of current and voltage for solar PV panel at different irradiance level.

Voltage (V)	Current (Amp)			
	1000 w/m ²	870w/m ²	@720 w/m ²	630 w/m ²
0.08448	1.169782	1.017777	0.842277	0.736977
0.255877	1.169753	1.017682	0.842182	0.736882
0.555023	1.16975	1.017653	0.842153	0.736853
1.089629	1.169752	1.01765	0.84215	0.73685
2.152909	1.16975	1.017652	0.842152	0.736852
2.878082	1.169754	1.01765	0.84215	0.73685
3.869691	1.169748	1.017654	0.842154	0.736854
4.583331	1.169751	1.017648	0.842148	0.736848
5.548299	1.169742	1.017651	0.842151	0.736851
6.278014	1.169738	1.017642	0.842142	0.736842
7.224307	1.169719	1.017638	0.842138	0.736838
8.050157	1.169684	1.017619	0.842119	0.736819
8.787816	1.169625	1.017584	0.842084	0.736784
9.768923	1.169502	1.017525	0.842025	0.736725
10.5181	1.169288	1.017402	0.841902	0.736602
11.3167	1.168853	1.017188	0.841688	0.736388
12.19018	1.16809	1.016753	0.841253	0.735953
12.99476	1.166352	1.01599	0.84049	0.73519
13.94578	1.163882	1.014252	0.838751	0.733451
14.65562	1.158313	1.011781	0.836281	0.73098
15.53478	1.147141	1.006212	0.83071	0.72541
16.43301	1.13126	0.995038	0.819535	0.714233
17.13243	1.090734	0.979155	0.80365	0.698347
18.08016	1.032567	0.938625	0.763114	0.657808
18.80656	0.890636	0.880451	0.704933	0.599622
19.74234	0.649391	0.738504	0.562967	0.457644
20.56286	0	0	0	0

Table S2. Comparison of WOAPSO with different parameter estimation methods for SDM.

Algorithms	I _{ph} (A) ± SD	I _{sd} (μA) ± SD	R _s (Ω) ± SD	R _{sh} (Ω) ± SD	a± SD	RMSE
HISA [61]	1.0324	2.6773	1.2317	748.4507	47.6575	2.0166 × 10 ⁻³
CS [62]	0.7605	0.3602	0.0349	43.8423	1.4929	2.0119 × 10 ⁻³
BLPSO [63]	0.7607	0.3662	0.0359	60.2845	1.4939	1.0272 × 10 ⁻³
SA [26]	0.762	0.4798	0.0345	43.1034	1.5172	1.7000 × 10 ⁻³
mGWO [64]	0.7606	0.3853	0.0356	64.6624	1.4991	1.1278 × 10 ⁻³
GOTLBO[65]	0.7608	0.3315	0.0362	54.1154	1.4838	9.8744 × 10 ⁻⁴
BMO [66]	0.7608	0.3248	0.0364	53.8716	1.4817	9.8602 × 10 ⁻⁴
MLBSA [67]	0.7608	0.3230	0.0364	53.7185	1.4812	9.8602 × 10 ⁻⁴
EHHO [68]	0.7607	0.3230	0.0363	53.7428	1.4812	9.8602 × 10 ⁻⁴
IJAYA [69]	0.7608	0.3228	0.0364	53.7595	1.4811	9.8603 × 10 ⁻⁴
GOTLBO [70]	0.7608	0.3315	0.0362	54.1154	1.4838	9.8744 × 10 ⁻⁴
WOAPSO	0.7597±0.0012	0.499±0.004	0.0342±0.0007	83.0131±0.027	1.5483±0.001	7.1700 × 10 ⁻⁴

Table S3. The calculated current and absolute error results of WOAPSO for SDM.

Observations	Measured data		Simulated current data		Simulated power data	
	V _L (V)	I _L (A)	I _{sim} (A)	IAE (A)	P _{sim} (W)	IAE (W)

1	0.0057	0.7605	0.7609	0.0004	0.0043	0
2	0.0646	0.76	0.7596	0.0004	0.0491	0
3	0.1185	0.759	0.7584	0.0006	0.0898	0.0001
4	0.1678	0.757	0.7574	0.0004	0.1271	0.0001
5	0.2132	0.757	0.7563	0.0007	0.1612	0.0002
6	0.2545	0.7555	0.7552	0.0003	0.1922	0.0001
7	0.2924	0.754	0.7536	0.0004	0.2204	0.0001
8	0.3269	0.7505	0.7513	0.0008	0.2456	0.0003
9	0.3585	0.7465	0.7472	0.0007	0.2679	0.0003
10	0.3873	0.7385	0.74	0.0015	0.2866	0.0006
11	0.4137	0.728	0.7273	0.0007	0.3008	0.0003
12	0.4373	0.7065	0.7069	0.0004	0.3091	0.0011
13	0.459	0.6755	0.6752	0.0003	0.3099	0.0002
14	0.4784	0.632	0.6307	0.0013	0.3017	0.0006
15	0.496	0.573	0.5718	0.0012	0.2836	0.0006
16	0.5119	0.499	0.4994	0.0004	0.2557	0.0003
17	0.5265	0.413	0.4134	0.0004	0.2177	0.0003
18	0.5398	0.3165	0.3273	0.0018	0.1767	0.0059
19	0.5521	0.212	0.2122	0.0002	0.1172	0.0002
20	0.5633	0.1035	0.1028	0.0007	0.0579	0.0004
Sum of IAE	-	-	-	0.0136	-	0.0117

Table S4. Comparison of WOAPSO with different parameter estimation methods for DDM.

Algorithms	I _{ph} (A)±SD	I _{sd1} (μA)± SD	I _{sd2} (μA)± SD	R _s (Ω)± SD	R _{sh} (Ω)± SD	a ₁ ± SD	a ₂ ± SD	RMSE
HISA [61]	1.03236	2.64194	1.00 × 10 ⁻⁹	1.2317	748.4507	47.6574	47.6325	2.0166 × 10 ⁻³
CS [62]	0.76223	0.02732	0.50832	0.0353	97.73242	1.70274	1.52893	2.4440 × 10 ⁻³
BLPSO [63]	0.76056	0.17895	0.3156	0.0355	64.79937	1.69574	1.48789	1.1042 × 10 ⁻³
SA [26]	0.7623	0.4767	0.01	0.0345	43.1034	1.5172	2	1.9000 × 10 ⁻²
mGWO [64]	0.76088	0.49333	0.17345	0.0346	62.17868	1.52522	1.94264	1.3163 × 10 ⁻³
GOTLBO[65]	0.7602	0.9889	0.0001	0.032	81.3008	1.6	1.192	1.52 × 10 ⁻²
BMO [66]	0.7608	0.0001	0.0001	0.0364	53.7185	1.3355	1.481	3.60 × 10 ⁻¹
MLBSA [67]	0.7608	0.22728	0.73835	0.0367	55.4612	1.4515	2	9.8249 × 10 ⁻⁴
EHHO [68]	0.76076	0.5861	0.2409	0.0365	55.6394	1.9684	1.4569	9.8360 × 10 ⁻⁴
IJAYA [69]	0.7601	0.00504	0.7509	0.0376	77.8519	1.2186	1.6247	9.8293 × 10 ⁻⁴
GOTLBO [70]	0.760752	0.80019	0.22046	0.03678	56.0753	1.9999	1.4489	9.8317 × 10 ⁻⁴
WOAPSO	0.7601±0.0007	0.5±0.0020	0.5±0.0027	0.0311±0.0005	100±0.4345	1.5755±0.0043	1.7314± 0.0015	9.8412 × 10 ⁻⁴

Table S5. The calculated current and absolute error results of WOAPSO for DDM.

Observations	Measured data		Simulated current data		Simulated power data	
	V _L (V)	I _L (A)	I _{sim} (A)	IAE (A)	P _{sim} (W)	IAE (W)
1	0.0057	0.7605	0.7588	0.0017	0.0043	0
2	0.0646	0.76	0.7582	0.0018	0.0489	0.0002
3	0.1185	0.759	0.7577	0.0013	0.0898	0.0001
4	0.1678	0.757	0.7571	0.0001	0.127	0
5	0.2132	0.757	0.7566	0.0004	0.1613	0.0001
6	0.2545	0.7555	0.7558	0.0003	0.1924	0.0001
7	0.2924	0.754	0.7546	0.0006	0.2206	0.0001
8	0.3269	0.7505	0.7524	0.0019	0.2459	0.0006
9	0.3585	0.7465	0.7484	0.0019	0.2681	0.0005
10	0.3873	0.7385	0.7409	0.0024	0.2869	0.0009
11	0.4137	0.728	0.7279	0.0001	0.3011	0.0001
12	0.4373	0.7065	0.707	0.0005	0.3092	0.0003
13	0.459	0.6755	0.6748	0.0007	0.3097	0.0004

14	0.4784	0.632	0.6298	0.0022	0.3013	0.001
15	0.496	0.573	0.5706	0.0024	0.283	0.0012
16	0.5119	0.499	0.4981	0.0009	0.2549	0.0005
17	0.5265	0.413	0.4122	0.0008	0.217	0.0005
18	0.5398	0.3165	0.3262	0.0097	0.1761	0.0053
19	0.5521	0.212	0.2117	0.0003	0.1169	0.0001
20	0.5633	0.1035	0.1027	0.0008	0.0578	0.0005
Sum of IAE	-	-	-	0.0308	-	0.0125

Table S6. The calculated current and absolute error results of WOAPSO for Solar PV Module.

Observations	Measured data		Simulated current data		Simulated power data	
	V _L (V)	I _L (A)	I _{sim} (A)	IAE (A)	P _{sim} (W)	IAE (W)
1	0.0845	1.1698	1.1707	0.0009	0.0989	0.0001
2	0.2559	1.1698	1.1707	0.0009	0.2996	0.0003
3	0.555	1.1698	1.1707	0.0009	0.6498	0.0006
4	1.0896	1.1697	1.1706	0.0009	1.2755	0.0009
5	2.1529	1.1696	1.1704	0.0008	2.5199	0.0015
6	2.8781	1.1697	1.1703	0.0006	3.3683	0.0017
7	3.8697	1.1698	1.1701	0.0003	4.5282	0.0016
8	4.5833	1.1697	1.1701	0.0004	5.3628	0.0015
9	5.5483	1.1697	1.1699	0.0002	6.491	0.0009
10	6.278	1.1697	1.1698	0.0001	7.344	0.0003
11	7.2243	1.1697	1.1696	0.0001	8.4498	0.0007
12	8.0502	1.1697	1.1695	0.0002	9.4146	0.0018
13	8.7878	1.1696	1.1694	0.0002	10.276	0.0029
14	9.7689	1.1696	1.1691	0.0005	11.4211	0.0048
15	10.5181	1.1695	1.1689	0.0006	12.2947	0.0062
16	11.3167	1.1692	1.1686	0.0006	13.2245	0.008
17	12.1902	1.1688	1.168	0.0008	14.2386	0.0099
18	12.9948	1.168	1.1672	0.0008	15.1673	0.0118
19	13.9458	1.1663	1.1654	0.0009	16.2517	0.014
20	14.6556	1.1638	1.1629	0.0009	17.0431	0.0143
21	15.5348	1.1583	1.1574	0.0009	17.9798	0.0143
22	16.433	1.1471	1.1464	0.0007	18.8385	0.0124
23	17.1324	1.1313	1.1308	0.0005	19.3732	0.008
24	18.0801	1.0907	1.0908	0.0001	19.722	0.0014
25	18.8066	1.0326	1.0332	0.0006	19.4314	0.0124
26	19.7423	0.8906	0.8919	0.0013	17.6081	0.0249
27	20.5629	0.6494	0.6503	0.0009	13.3722	0.0189
28	21.3013	0.2582	0.2564	0.0018	5.4626	0.0381
Sum of IAE	-	-	-	0.0184	-	0.2148

Table S7. The calculated current and absolute error results of WOAPSO for Solar PV Module (630 W/m²).

Parameters	Algorithms						
	GSA	SCA	GWO	PSO	WOA	PSOGSA	WOAPSO
I _{ph} (A)	0.6710 ± 0.0105	0.7399 ± 0.0113	0.7397 ± 0.037	0.7419 ± 0.252	0.7421 ± 0.0043	0.6706 ± 0.252	0.7382 ± 0.0008
I _{sd} (μA)	5.00 × 10 ⁻⁵ ± 5.697	2.80 × 10 ⁻⁸ ± 0.316	1.00 × 10 ⁻⁸ ± 0.858	1.00 × 10 ⁻⁸ ± 0.053	4.37 × 10 ⁻⁷ ± 0.522	1.18 × 10 ⁻⁵ ± 0.6745	0.0118 ± 0.023
R _s (Ω)	0.001 ± 0.0695	0.0249 ± 0.0412	0.0276 ± 0.59	0.0265 ± 0.054	0.0017 ± 0.0114	0.2810 ± 0.107	0.0273 ± 0.0176
R _{sh} (Ω)	1206.82 ± 12.31	768.387 ± 18.99	99.25 ± 14.24	1084.907 ± 21.61	54.124 ± 29.7363	657.23 ± 0.834	248.708 ± 0.1088
a	65.3725 ± 1.422	1.3298 ± 6.366	1.2552 ± 0.0217	1.2553 ± 1.352	1.5841 ± 4.708	99.77 ± 0.452	1.2665 ± 0.1106
RMSE	2.43 × 10 ⁻¹	9.54 × 10 ⁻²	9.48 × 10 ⁻²	1.30 × 10 ⁻¹	9.70 × 10 ⁻³	1.33 × 10 ⁻²	8.8226 × 10 ⁻³
CPU Time (s)	14.05	18.06	16.01	13.21	11.27	19.23	8.53

Table 8. The calculated current and absolute error results of WOAPSO for Solar PV Module (720 W/m²).

Parameters	Algorithms						
	GSA	SCA	GWO	PSO	WOA	PSOGSA	WOAPSO
I _{ph} (A) ±SD	0.7802±0.0044	0.8486±0.0179	0.8449±0.0206	0.9561±0.021	0.8487±0.0049	0.766±0.027	0.8421±0.0012
I _{sd} (μA) ±SD	$1.00 \times 10^{-8} \pm 0.237$	$5.60 \times 10^{-8} \pm 0.4365$	$6.98 \times 10^{-8} \pm 0.869$	$1.58 \times 10^{-8} \pm 0.301$	$1.50 \times 10^{-7} \pm 1.501$	$1.22 \times 10^{-5} \pm 0.234$	0.0022±0.043
R _s (Ω) ±SD	0.001±0.0212	0.0019±0.0123	0.00566±0.037	0.0028±1.052	0.0011±0.044	0.122±0.013	0.0117±0.0002
R _{sh} (Ω) ±SD	404.42±13.82	28.007±21.44	92.4964±17.699	91.882±1.431	38.915±44.49	122.4471±12.02	1870.72±4.924
a±SD	45.964±0.2528	1.3776±13.33	1.3954±0.1772	2.2658±1.352	1.4645±2.1847	6.0933±0.1420	1.3022±0.0402
RMSE	1.94×10^{-1}	7.16×10^{-3}	3.15×10^{-2}	6.54×10^{-3}	1.70×10^{-3}	9.29×10^{-3}	1.795×10^{-3}
CPU Time (second)	15.39	15.17	12	11.05	9.71	17.13	8.11

Table 9. The calculated current and absolute error results of WOAPSO for Solar PV Module (870 W/m²).

Parameters	Algorithms						
	GSA	SCA	GWO	PSO	WOA	PSOGSA	WOAPSO
I _{ph} (A)	0.9506 ± 0.0056	1.018 ± 0.0119	1 ± 0.064	0.883 ± 1.334	1.029 ± 0.019	0.943 ± 0.023	1.0179 ± 0.0014
I _{sd} (μA)	$5.00 \times 10^{-5} \pm 1.130$	$3.48 \times 10^{-8} \pm 0.634$	$1.00 \times 10^{-8} \pm 0.516$	$3.98 \times 10^{-5} \pm 1.165$	$6.91 \times 10^{-8} \pm 0.804$	$2.86 \times 10^{-5} \pm 0.623$	0.0689 ± 0.0852
R _s (Ω)	0.001 ± 0.0328	0.0012 ± 0.03	0.0038 ± 0.809	1.4099 ± 0.381	0.0015 ± 0.0294	0.6977 ± 0.034	0.001 ± 0.0201
R _{sh} (Ω)	670.255 ± 14.10	72.656 ± 16.02	100 ± 2.4565	1092.74 ± 1.33	21.489 ± 39.10	1027.49 ± 0.27	537.47 ± 0.0281
a	58.4639 ± 0.2469	1.3339 ± 2.342	1.2442 ± 0.0152	100 ± 0.707	1.391 ± 2.0765	33.859 ± 0.143	1.3882 ± 0.0124
RMSE	1.84×10^{-1}	3.59×10^{-3}	1.70×10^{-2}	503.01×10^{-2}	1.41×10^{-3}	4.02×10^{-3}	3.7957×10^{-4}
CPU Time (s)	16.02	14.25	9.25	12	15.005	8.16	8.05