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DYNAMIC CONDITION OF PARTIALLY SHADED PV SYSTEM BY TRACKING THE MAXIMUM POWER POINT USING WODE TECHNIQUE

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ABSTRACT

This paper introduces a humpback whale hunting behavior inspired whale optimization with differential evolution(WODE) technique based tracking algorithm for the maximum power point tracking in the dynamic as well as the steady-state conditions of a partially shaded solar photovoltaic (PV) system. This 'WODE' technique is used for quick and oscillation-free tracking of the global best peak position in a few steps. The unique advantage of this algorithm for maximum power point tracking (MPPT) in partially shaded condition is as, it is free from common and generalized problems of other evolutionary techniques, like longer convergence duration, a large number of search particles, steady state oscillation, heavy computational burden etc, which creates power loss and oscillations in output. This hybrid algorithm is tested in MATLAB simulation and verified on a developed hardware of the solar PV system, which Consists of multiple peaks in voltage-power curve. Moreover, the tracking ability is compared with the state of the art methods.The satisfactory steady-state and dynamic performances of the new hybrid technique under variable irradiance and temperature levels show the superiority over the state of the art control methods.

I.INTRODUCTION

Today Life and environment are the witnesses of pollution and energy crisis on a large scale. In this critical situation the world has a single option, 'understand and give emphasis to the renewable energy sources'. Out of all types of renewable energy sources, the solar photovoltaic (PV) and the wind energy sources have proven to be a good and easy solution on the large scale. The new technologies, new topologies, advanced devices, novel control strategies and good management systems are contributing to the success of these renewable energy sources. Due to static, quiet and movement free characteristic, solar PV system is

very popular, reliable and comfortable for users [1]. Therefore, it is highly desirable and to motivate to work with the maximum possible efficiency. Now, the PV power generation system is also commercialized for bulk power in grid-connected mode [2]. Therefore, huge numbers of market players are taking interest and establishing farms (PV Parks), and for maximizing the profit. All are trying to extract maximum power from the PV array or trying to run on the maximum power point (MPP). The MPP tracking (MPPT) is the process through which, the system runs and supplies maximum power to the load. However, the relation between voltage, current and power of the PV system is highly nonlinear. so to track the MPP needs MPPT algorithms. The basics of the MPPT are based on the current and voltage of the solar PV array. First of all, the current and voltage of PV array are sensed, then it calculates the instantaneous power, and after that by using an MPPT algorithm, it chooses a duty cycle or voltage reference for the converter, for matching the instantaneous power to the MPP. The structure of a solar PV panel is the series and parallel combination of several modules. The voltage and current ratings of the module are very less. Therefore, for achieving a certain range of output voltage, it needs to add a certain number of modules in series and the output of each module is bypassed from another module through a bypass diode. Similarly, for a certain range of output current, it needs to add a certain number of series of modules in parallel and the output of each series of the module is prevented from circulating current through blocking diode. This combined system is known as a PV array. When the solar irradiance on all modules are same, then the power- voltage(P-V) curve of the PV array consists of a single peak, but the solar irradiance on all modules are not uniform, then the P-V curve of a PV array consists of multiple peaks and this situation is known as a partially shaded condition [3][4]. In a practical situation, this

non-uniformity of solar irradiance on some module or on the some PV arrays of the PV park arises due to a shadow of clouds, tall buildings, trees etc. The pattern of the shadow decides the pattern of the P-V curve.

The global maximum power point (GMPP) tracking in the dynamic condition of the partially shaded PV system is a very difficult task. A literature review on solar PV array MPPT reveals that various traditional methods and soft computing techniques have been employed for tracking the GMPP, such as 'perturb and observe (P&O)' [5][6], 'incremental conductance [7][8]', and 'Hill Climbing [9]'. These are highly suitable for tracking the MPP, but the limitation is, only in uniform or without partially shaded condition. In the case of partial shaded condition, these techniques are not able to differentiate the difference between LMPP and GMPP, so stagnated at first peak, that is LMPP or GMPP, doesn't matter. Moreover, due to this the enormous amount of power loss occurs, because the GMPP exists at only a single point. Therefore, for searching the GMPP the researchers have 'fuzzy logic [10]' and 'neural network [11]' based control [12], but the 'excessive storage burden on the processor', a new type of problem comes in the picture. Because, in fuzzy logic control for fuzzification and defuzzification, as well as in neural network for training, a huge number of data are required. Therefore researchers tend towards evolutionary algorithms. Due to a simple structure and easy implementation, particle swarm optimization (PSO)[13] is employed for GMPP tracking. In standard PSO [13], the convergence occurs after a large number of iteration,which is the problem, due to high-velocity update or acceleration. Low acceleration follows the smooth trajectory but convergence speed is slow. A high acceleration leads or deviates from the trajectory and moves towards infinity. Thus, more numbers of iterations are conducted to bring the results in the optimum region. In view of these difficulties, some researchers have modified the classical PSO, which is called adaptive perceptive PSO (APPSO) [14], modified PSO[15][16]. This modification improves the performance, by providing the separate search space to all particles. However, it requires huge numbers of particles for covering the entire region, which creates complexity and additional computational burden on the processor. For further improvement, an improved PSO (IPSO) [17], novel PSO [18], P&O with PSO[19], differential evolution (DE) with PSO (DEPSO) [20], *et c*are proposed. These algorithms are the combination of PSO and direct updating process. The direct updating process updates the duty cycle according to the ratio of, the change in power and the change in duty cycle. This modification improves the performance in terms of searching ability, but initially, it creates

huge oscillations due to large random search. Moreover, these things are repeated again and again one very instant of insolation change in dynamic condition, which makes system oscillatory and unstable. Apart from PSO, firefly algorithm [21], numerical approach [22], and simulated annealing [23][24] have also used for GMPP tracking. Here, overall performance and searching ability have improved but not significantly. Therefore, for enhancing the searching ability with less oscillatory and computational burden, Mirjalil *et al.* [25] have developed a grey wolf optimization (GWO) and Mohanty *et al.* [4] have proposed GWO based MPPT algorithm. Grey wolf hunting behavior is based on tracking, encircling and attacking the prey. Since here, tracking process is decided by the linear variable, so encircling and attacking the prey is very similar to the local search behavior [26]. Diverge from the current prey and search a better and better prey is the behavior of global search. Therefore, sometimes, where the difference between GMPP and local MPP (LMPP) is very less or GMPP is on a very sharp point, in that condition GWO confuses and falls or stagnates on the LMPP (which is very closer to the GMPP).

Therefore, Mirjalili *et al* [27] again have proposed a 'Whale optimization (WO)' algorithm. Which is free from stagnating on the LMPP (which is extremely closer to the GMPP) problem. Moreover, this WO algorithm has proved to be the best technique for nonlinear objective function [27]. This WO algorithm is inspired by the bubble-net hunting strategy of the humpback whale. The trajectory path of the bubble-net attack mechanism of the WO is based on shrinking circling mechanism on the spiral track. In this mechanism, WO starts searching from the outer boundary of the search space and moving on the spiral path with shrinking circling mechanism, so it covers total search space. Since it covers total search space, so the probability of hitting the global best solution is extremely high. In WO algorithm (WOA), the motion of the whale is described in two parts: in a linear direction (for shrinking) with 50% probability and in circled spiral direction with 50% probability [27]. This probability is chosen or decided by a random number. Therefore, the granted probability for hit the global best target is equal to or more than 50%, due to the circled spiral motion of the whale and the probability of fall or stagnate on the LMPP is still equal to or less than 50%, due to local search based linear motion, similar to GWO algorithm.

Solar PV System under Partial Shading Condition

Due to the shadows by clouds, trees or tall buildings, a non uniformity in the insolation arises on the PV panel. In this situation, some modules receive direct irradiance and some are under partially shaded. The partially shaded modules generate less amount of current in comparisons to other modules. All modules in PV array are in series, so the current through the parallel resistance of partially shaded modules, leads to a voltage drop. This drop reduces the maximum output power and creates hotspots. This problem can be resolved by bypassing currents of all modules through a bypass diode. In the case of parallel connections of the string, the shaded string withdraws current from rest of the parallel connected strings. This circulating current reduces the efficiency of the PV panel. This problem can be resolved by using a blocking diode (DBL).

WODE ALGORITHM AND ITS APPLICATION The WODE algorithm is the hybrid of whale optimization (WO) and differential evolution (DE). WO searches the global best very efficiently and DE enhances the performance of the WO, by providing the best start point in each iteration, which enhances the searching ability, reduces the population size and globally maximizes the objective function. The objective function (f) is defined as, $f(D) = \max PPV(D)$ (4)

$PPV(D) = VPV(D) \times IPV(D)$ (5)

Where, $PPV(D)$, $VPV(D)$ and $IPV(D)$ are instantaneous power, voltage and current at duty cycle D.

The constraint is described as, $0 \leq D \leq 1$.

A. Whale Optimization

The WO algorithm is based on hunting method of a humpback whale. This hunting behavior is based on bubble-net feeding mechanism with shrink circled spiral motion [27]. The hunting of a prey is based on three processes, 1)Searching, 2) Encircling and 3) Bubble-net attack on the prey.

1) Searching for Prey

At initial position, humpback whales start searching randomly (according to initial position). After that, WOA forces to search on a global level by using a random coefficient vector(A). When |A| >1, humpback whales start searching in the entire region. This is mathematically described as, Dij(G+1)=Drand-A*dij (6)

Where, Drand is random duty cycle, Dij(G+1) is duty cycle for G+1th iteration, dij is a coefficient vector of jth whale and ith agent of DE. These, dij and A are calculated as,

dij=|C*Drand-Dij(G)| (7)

A=2*α*rand-α (8)

Where, 'rand' is a random number between 0 and 1. C is also a random number, which is defined as C=2*rand. 'α' is linear iteration dependent number, which is defined as,

2 2 $G g \alpha = - \times$ (9)

Where, G is current iteration number and g is a maximum number of iteration.

2) Encircling the Prey

In this step, humpback whale recognizes the prey and starts encircling. During encircling, the whale updates its position towards the global best prey. This action takes place when |A|<1. Mathematical description of it is as follows,

dij=|C*Dbest(G)-Dij(G)| (10)

Dij(G+1)=Dbest-A*dij (11)

Where, Dbest(G) is the best duty cycle after the Gth iteration.

3) Bubble-net Attack on the Prey

During bubble-net attacking mechanism, the motion of the whale is divided into two parts with 50-50% probability: linear motion along the shrinking circle and circular motion along the spiral path [27] as,

Where, b is a shape constant, L is a random number between -1 and +1, *Pc* is a random number, d'ij is a new coefficient vector of jth whale and ith agent of DE. This is described as,

dij'=|Dbest(G)-Dij(G)| (13)

B. Differential Evolution

DE is a probabilistic based global search optimization. In this work, the role of the DE is to enhance the performance of WO. For this purpose, DE selects 3 target vectors (Di1(G), Di2(G) and Di3(G)) from the whale population and passes through the searching process of the DE, which is completed in three steps: mutation, crossover and selection [28].

1) Mutation

DE mutation process generates a trial vector (Ui(G)) from the parent vector (Di1(G), Di2(G) and Di3(G)) by using weighted differential coefficients or scale factor of mutation (ξ). This generation process is mathematically described as, Ui(G)=Di1(G)+ξ*(Di2(G)-Di3(G)) (14)

Where, 'i' is the current population number.

2) Crossover

During crossover, DE generates child (D'i(G)) from the trial vector (Ui(G)) and best parent (Di1(G)) of the parents vector by using crossover probability (ρ).

Where, 'rand' is a random number between 0 and 1.

3) Selection

DE selects the best option (Di(G+1)) for next generation, from the parent and child on the basis of the best value of the fitness function (f). The selection process is described as [28],

Hybridizing and Application of WODE Algorithm WO has very efficient searching and solving ability of nonlinear problem, but it requires a large number of whales or iterations and in some cases, it is stagnated on LMPP (which is extremely closer to the GMPP) due to linear motion of whale during shrinking circle with 50% probability. Moreover, DE has strong comparative studies and optimal location searching or generating ability in defined region. These merits of the DE are very suitable for reducing the number of iteration as well as for forcing to the jump out from the stagnation on LMPP problem by discovering an optimal locatio for whale at the end of every iteration. In detail, it is discussed in section I. The combined effect of both algorithms can be found by hybridizing of both, known as WODE algorithm. Here, DE is integrated into series with WO. Where, WO starts searching on a circular path and at the end of each round of the searching, it passes all information to the DE. DE analyses and finds a single best place and optimal accelerating speed of the whale by using three sets of location information, which is decided by WO. This combined performance reduces the effects of random constants and meta heuristic nature of the algorithm by increasing the convergence speed. Moreover, computational burden and stagnation problems are removed through mutation, crossover, and selection process of the DE. As well as, it drastically reduces the number of iteration.

The different stages and steps of the WODE for problem solving are described as:

1st step;

- Define objective function (by using (4) and (5)),
- Provide algorithm constants (b, ρ, ξ), upper (DU) and lower (DL) limit of the variable at initial stage, initial error constant (εo) and number of population (Po).

2nd Step;

- Set, flag=1, Sf = 1, Dmin=DL, Dmax=DU, ε = εo. 3rd Step;
- Randomly create 4 duty cycles (3 for WO and 1 for DE) within upper (Dmax) and lower (Dmin) limit,

- Find power for duty cycle of WO,
- By using the Dmax and Dmin find Pmax and Pmin. 4th Step;
- Find power for duty cycle of DE,
- According to power choose best 3 duty cycles,
- Find Dbest according to Pbest,
- Find ΔP (=Pi -Pi-1) for selected all 3 duty cycles. 5th Step; Check, P is in between [Pmax , Pmin] ?
- If, yes, go to step 6,
- If, no, go to step 2.

6th Step; Check, ΔP is less than ε ?

- If, yes, go to step 7,
- If, no, go to step 8. 7th Step;
- flag=flag+1,
- Sf=Sf/flag,
- Dmin=(1-Sf)*Dbest,
- Dmax=(1+Sf)*Dbest,
- Ɛ = Sf*Ɛ 0,
- Go to step 3.

8th Step; Pass all 3 duty cycles from WO.

- Search for prey (by using (6)-(9)),
- Encircle the prey (by using (10) and (11)),
- Bubble-net attack on the prey (by using (12)and(13)).

9th Step;

- Find power for all duty cycle and arrange in descending order.

10th Step; Pass all 3 duty cycle from DE.

- Mutation (by using (14)),
- Crossover (by using (15)),
- Selection (by using (16)).

11th Step; Update duty cycle and go to step 4.

This is an online process, so the cyclic process is repeated again and again. The uniqueness of this process is, at the end of every iteration, the performance of all whales are summarized and, a best place for a starting the new iteration is decided. Another best part is, it has extremely less steady state oscillation and quick dynamic performance. The steady state oscillation is controlled by 'step 7', which exponentially reduces the oscillation in every iteration. Moreover, the dynamic condition is sensed by 'step 5' and controlled by 'step7'. Here the population size is only 4. Therefore, the small population, quick dynamic performance and negligible steady state oscillations enhance the searching ability tremendously, as well as the computational burden is very less so, it can be easily implemented on a cheap microcontroller.

C. Selection of Control Parameters

The control parameters are the key of every algorithm,because the performance of the algorithm is directly influenced by the control parameters. In WODE, the control variables are, shape constant of the logarithmic spiral (b),scaling factor (ξ) and crossover probability (ρ).

1) Shape constant of the logarithmic spiral (b)

This 'b' defines the shape and radius of the spiral net in WO. In general, a small value is taking for 'b', so its accuracy level improves. However, a very small value, decreases the convergence rate [27]. Therefore, it takes an optimum value for 'b' in the range of [0.1, 1].

2) Scaling factor (ξ)

This 'ξ' controls the amplification of the differential variations in DE. The smaller value of ξ, reduces the differential variations but, it takes a long time to converge and larger value facilitates exploration. But it may lead to overshoot optimum results [28][29]. Therefore, the optimum range is [0,5], 5 is the maximum range, because in MPPT problem, more than 5 times differential variations amplification, abruptly enhances the values, and it goes beyond the range (>1).

3) Crossover probability (ρ)

Crossover probability (ρ) is also known as recombination probability. It directly influences the diversity of DE. It's higher value increases diversity, exploration and convergence rate, but the search robustness decreases.

II.RESULTS AND DISCUSSION

The performance evaluation of the proposed WODE method is performed over the 'SPV fed battery load by using a boost converter'. Here, variations in solar insolation and temperature, both are considered. Its superiority is proven through comparison with the most recent technique 'GWO' [4] and highly popular 'IPSO' [11] algorithm.

1) Simulation Results

The performance of the SPV system is simulated by using MATLAB 2010a software on Dell computer with Intel core i3, 2.4 GHz processor, 2 GB of RAM memory and windows 7 operating system. For simulation, a PV array of Voc=480 V, Isc=11.26 A, Pmpp=4 kW at 25oC with irradiation 1000 W/m2 in without shaded condition, and as a load, the battery bank of 480 V is considered. Moreover, in each pattern, the change in dynamics on every 10s is considered and 3D representation of PV characteristic or all patterns.The simulations for all 3 patterns by WODE, GWO and IPSO methods are performed in similar circuit conditions and results are plotted over each other for detail comparative study. The power and duty cycle waveforms for pattern 1 are

Similarly, for pattern 2 and pattern 3, the waveforms Moreover, all results are summarized in Table IV. From all waveforms and Table IV, it can be seen clearly, the WODE is tracking the GMPP very quickly and efficiently, on all patterns. During pattern-1, the average GMPP tracking times of the IPSO and GWO are 7.673s and 3.016s. However, the WODE is taking only 1.296s to reach the GMPP. Similarly, on pattern-2 and pattern-3, IPSO is taking 8.01s and 7.93s as well as GWO is taking 3.416s and 3.92s but WODE is taking only 1.423s and 1.363s

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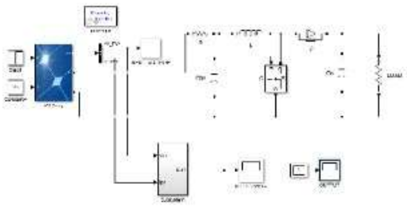


to reach the GMPP. It means,

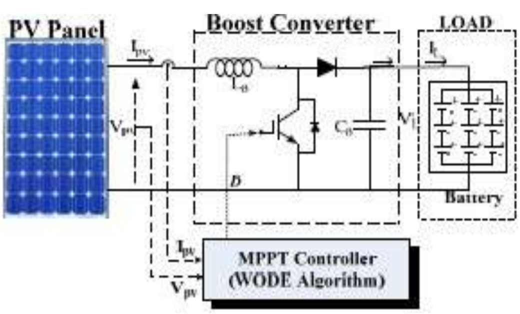
on an average, WODE is more than 2 times faster

w.r.t. GWO and more than 5 times faster w.r.t. IPSO. Moreover, the overall efficiency of the WODE is also better w.r.t. GWO and IPSO algorithm.

2) Hardware Implementation

A solar PV array simulator (AMETEK ETS600x17DPVF) is used to generate the required P-V and I-V characteristics. The power of the SPV simulator is supplied to the load (battery) by using a boost converter. The Hall Effect current (LA-55p) and voltage (LV-25) sensors are used for sensing the voltage and current signal of the SPV array. The

outputs of the sensors are given to the 'Analog to Digital converter (ADC)' of the 'Digital Signal Processor (d Space Micro Lab Box)' board. The processor is used for executing the MPPT algorithms and generating the PWM signals for the power switch of the boost converter. Moreover, the signals (Ppv, Ipv,Vpv) are obtained from the DSP-d Space and displayed on DSO. Here, the solar panel rating, shading pattern, load, solar insolation and temperature variation, all are same, which have been used during simulation. The steady state response and achieved % MPPT on patterns-1, 2 and 3 at 1000 W/m2 irradiation by IPSO, GWO and WODE.



These figures and Table V reveal that, the steady state performance of the WODE is good in each case w.r.t.

IPSO and GWO. The achieved %MPPT is highlighted by the red boundary on every figure. These figures also show the information about the rating of Pmpp, Vmpp, Impp and error in Vmpp and Impp. Moreover, the obtained experimental results for Pattern-2 by IPSO, GWO and WODE algorithm. The experimental results for all patterns, achieved by all algorithms, in summarized form are shown in Table VI. In the experimental results, the time division on the X-axis is 5s/dev the results of IPSO algorithm for pattern-2. Where in dynamic change condition, IPSO takes 7.97s for insolation change 1000 W/m2 to 500 W/m2 and 8.11s for insolation change 500 W/m2 to 800 W/m2 to track the GMPP. In the case of GWO, the performance is slightly improved for both insolation changes, it takes 3.25s and 3.61s to reach the GMPP. This tracking time is also too much. In this situation, the WODE has performed extremely good and tracked the GMPP only in 1.43s and 1.35s. These experimental results again show that, the tracking capability of WODE is approximately 5 to 6 times faster from IPSO and 2 to 3 times faster from GWO. Moreover, here, the load voltage is equal to the open-circuit voltage of the PV panel, so the permissible range of duty cycle variation is from 0 to 1.However, the random variation, random motion or oscillation during searching in WODE are very less in comparison to the IPSO and GWO, which can be seen in duty cycle.

III.CONCLUSION

A new evolutionary technique called WODE has been proposed for MPPT under partial shading condition. ThisWODE algorithm is the hybrid of WO and DE evolutionary techniques. WO has the strong searching ability in a wide area and DE reduces the effect of random constants and meta heuristic nature by increasing (accelerating) the convergence speed of the algorithm Therefore, the searching ability of the proposed WODE algorithm is quicker, reliable, system independent and free from the initial condition as well as the computational burden is also very less, for MPPT in all types of weather and shading condition on the PV panel. The performance of the WODE in GMPP tracking under partial shading in steady state and dynamic conditions has been compared to the performance of some recent techniques (GWO and IPSO) in the same irradiance, temperature and hardware condition on high power rating. The simulated and test results of the WODE in both conditions: change in the shadow pattern in a similar fashion and different fashion in a dynamic condition, show the superiority over all existing methods. This proposed method (WODE) can track GMPP very accurately and more than 2 to 5 times faster in comparison to the state of the art methods with a good dynamic as well as steady-state responses in every type of environmental condition.

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