Optimization of PV Array & Inverter Parameters For Grid Connected Applications Using Particle Swarm Optimization

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Abstract- *Renewable energy is the energy produced from natural resources like sunlight, wind, tides, waves & geothermal heat. Solar energy is that technology of obtaining useful energy from the sun solar power is currently employed in a number of applications like heat, electricity generation, and desalination of seawater. A recent trend in solar energy technology is 1) Micro grid & Artificial intelligence 2) Solar energy harvesting trees. A Co-design method is presented, where the best design parameters of the PV array and inverter are calculated simultaneously through a unified design process. The suggested technique enables to optimally match the PV array configuration and inverter structure. A study has been performed; The PV arrays and inverter parameters are designed separately, through different optimization methodsbased on various alternate optimization objectives. At the same time, co-designing the PV array and inverter enables to derive PV system parameters that are capable to inject more energy into the electric grid compared to the PV systems formed by merging independently designed subsystems (arraysand inverters).*

Keywords- Photovoltaic (PV) generation systems, DC-AC power conversion, transformer less inverter topology optimization methods, particle swarm optimization (PSO)

I. INTRODUCTION

The installation of grid-connected photovoltaic (PV) systems has followed an exponential growth during the last years. However, the global installed capacity of PV systems is expected to be further increased in the following years to further pave the way, additional advancements in PV materials, power converters, and control strategies should be achieved. Simultaneously, design for high reliability and high efficiency is also an important.

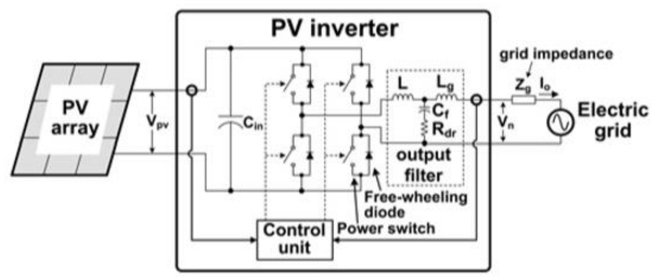

Fig 1 A block diagram of a grid-connected PV system

A general diagram of a grid-connected PV system is illustrated in Fig. 1. A PV array is formed by relating numerous PV cells/modules in series and parallel. The PV array is then attached to a DC/AC inverter that interfaces the energy into the electric grid. Transformer less DC/AC inverter topologies (e.g., Neutral Point Clamped-NPC and H6) are recently used in PV applications due to their small volume, light weight, low leakage currents and high efficiency. An output filter, comprising of passive components (i.e., inductors, capacitors, and damping resistors), is used to decrease the harmonic distortion of the current injected into the electric grid.

A microelectronic control unit is also employed in the PV inverter structure for implementing processes, such as the Maximum Power Point Tracking (MPPT) of the PV power source and the synchronization with the electric grid.The target of a grid-connected PV system is to inject the maximum possible amount of energy into the electric grid, in order to maximize the corresponding economic benefit achieved during its operation. As illustrated in Fig. 1, in order to develop a grid-connected PV system, two sets of parameters must be considered during the design phase:

1) The PV array design factors, such as its tilt angle and the arrangement of PV cells in series/parallel connection.
2) The PV inverter design parameters, such as the switching frequency and the values of the passive components of output filter.

II. OBJECTIVE

The continuous growth of global PV market necessitates Grid-connected PV system to inject maximum possible amount of energy into electric Grid.Co-design technique needed to design parameters

PV array:

1. Tilt angle
2. Numberof series connected cell
3. Number of parallel-connected cell

PV inverter:

1.Switching frequency
2. Values of passive component of output filter

To derive PV system configurations using particle swarm optimization, which are capable to inject more energy into the electric grid.

III. THE PROPOSED OPTIMIZATION METHODALOGY

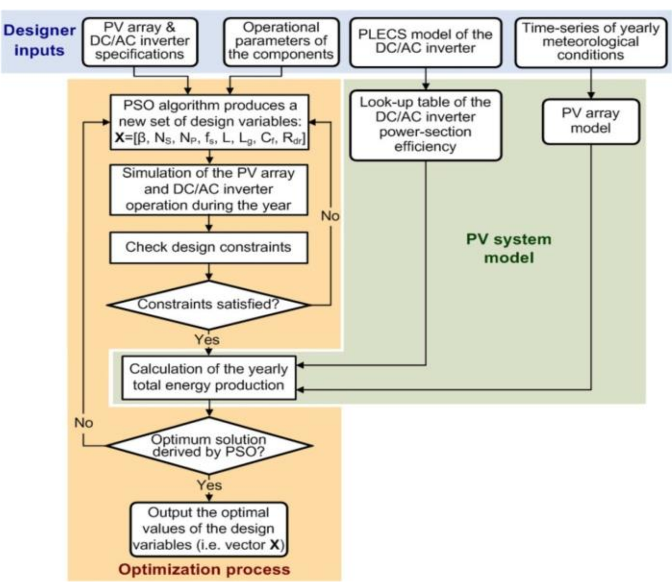

Fig.2Flowchart of the proposed optimization process

Aflowchartoftheproposedcodesigntechniqueisillustratedin Fig.2.Thecontributionparametersprovidedbythedesignerinclude The PV system terms: the nominal powerrating, the latitude and Longitude of the installation site, as well as the nominal frequency and Root-Mean-Square (RMS) voltage of the electric grid

The operational characteristics (under Standard Test Conditions, STC) of the PV cells, which will be used to creäte the PV array.The operational factors of the PV inverter components (i.e., power switches and diodes of the power section and output-filter inductors and capacitor), which will be used in the design of the PV inverter power losses during the year

The time-series of the hourly-mean values of solar irradiance on the flat plane and ambient temperature which succeed at the installation site during the year.

A. PLECS MODEL OF DC/AC INVERTER

A circuit model of the PV inverter, which has been working in the PLECS software program (www.plexim.com), is used to calculate the efficiency of the PV inverter as a function of its switching frequency f_s, DC input voltage and DC input power. The resulting values are kept in a look-up table, which is then used in the optimization process.

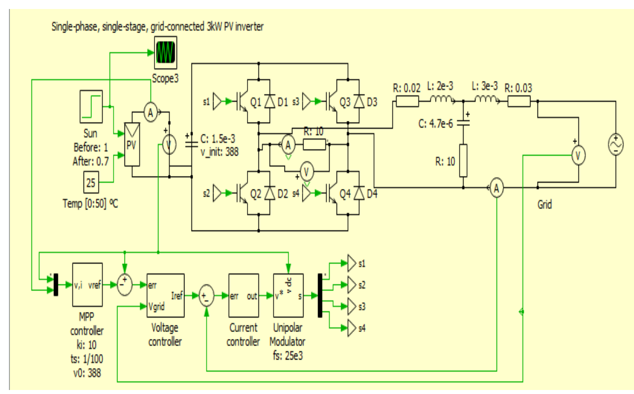

Fig.3 Grid Connected PV System

B. OPTIMIZATION OBJECTIVE

The target of the recommended optimization process is to derive the optimal values of the following design parameters of PV array &inverter**.** The PV array tilt angle, β (o), The number of PV cells connected in series, N_S, the number of PV strings connected in parallel,N_P,The switching frequency of the DC/AC inverter power semiconductors, f_s (Hz), L-Inverter-side inductor of the output filter,L_g- Grid-side inductor of the output filter.,C_f-Output-filter capacitor,R_{dr}-Damping resistance

The ideal values of the design variables are designed such that the total energy injected into the electric grid throughout the year E_y(WH) is maximized

$$\text{maximize}_x \{E_y(X)\} \qquad (1)$$

Where $X = [\beta, N_s, N_p, f_s, L, L_g, C_f, R_{dr}]$ is the vector of the above-mentioned design parameters. It is observed in (1) that the design vector, X, consists of both the PV array associated and PV inverter associated design parameters.

C. PV ARRAY MODELLING FOR OPTIMIZATION

The total of parallel PV strings $N_P$is calculated allowing to the nominal power rating of the PV system P_n(W) and the number of series-connected PV cells, as follows

$$N_p = floor\left(\frac{P_n}{N_s.P_{pvc,STC}}\right) \quad (2)$$

Where $P_{pvc,STC}$(W) is the power at the Maximum Power Point (MPP) of separately PV cell under STC.

$$N_s \le N_{s,max} = floor\left(\frac{V_{mpp,max}}{V_{pvc,STC}}\right) \quad (3)$$

The maximum allowable value of $N_s$which is calculated during the implementation of the proposed optimization process,$V_{mpp,max}$ (V) during the yearly process of the PV system.

$$V_{pvc,max} = \max_{1\le t\le 8760}\{V_{pvc,t}(\beta, G_t, T_{A,t})\} \quad (4)$$

The annual energy production E_y(WH) in (1) is designed by summing the differences among the power produced by the PV array and the total power loss of the inverter with a time of 1 hour during the year:

$$E_y(X) = \sum_{t=1}^{8760}(P_{pv,t} - P_{l,t})\,\Delta t \quad (5)$$

Where

$P_{pv,t}$(W) is the power produced by the PV array throughout hour t of the year

$P_{l,t}$ (W) is the total power loss of the PV inverter at hour t and Δt = 1 h is the

Period step of the energy-production calculations. , for each time t of the year, the input power of the PV inverter, $P_{in,t}$ (W), is designed as follows

$$P_{in,t} = \begin{cases} 0 & if\ V_{pv,t} = Ns.V_{pvc,t}(\beta, G_t, T_{A,t}) < V_{mpp,min} \\ Ns.Np.P_{pvc,t}(\beta, Gt, T_{A,t}) & else \end{cases} \quad (6)$$

Where

$V_{pv,t}$(V) is the MPP voltage of PV array

$P_{pvc,t}$(W) is the MPP power of PV cells and is calculated as a function of β, G_t, and $T_{A,t}$

$$P_{pv,t} = \begin{cases} P_n & if\ P_{in,t} > P_n \\ P_{in,t} & else \end{cases} \quad (7)$$

The whole power loss of the PV inverter at hour t is designed according to the following equation

$$P_{l,t} = [1 - \eta_{ps}(P_{pv,t}, V_{pv,t}, f_s)] * P_{pv,t} + P_{LCL,t} + P_c \quad (8)$$

The total power losses of the output filter

$$P_{LCL,t} = P_{L,c,t} + P_{L,r,t} + P_{Rdr,t} \quad (9)$$

The power loss owing to the parasitic resistance of the filter inductor windings, $P_{L,r,t}$(W), is found as follows

$$P_{L,r,t} = I_{r,t}^2 * \eta * L + I_{0,t}^2 * \eta * (L + L_g) \quad (10)$$

D. PV INVERTER MODELLING FOR OPTIMIZATION

During the execution of the recommended optimization process, the components of the output filter are selected such that the ha0rmonic alteration of the current injected into the electric grid fulfills the corresponding constraint set by the designer. For this, the ripple factor of the DC/AC inverter output current, *RF* (%), is designed as

$$RF = RF_{sw}.R_a \le RF_{max} \quad (11)$$

$$RF_{sw} = \frac{I_{r,t}.V_n}{P_n} \le RF_{sw,m} \quad (12)$$

To avoid resonance, the values of the LCL-filter modules are selected such that the resonant frequency of the filter, f_{res} (Hz), is constrained to be within the following bounds

$$10.f \le f_{res} \le \frac{f_{s,r}}{2} \quad (13)$$

Where

$$f_{res} = \frac{1}{2\pi}\sqrt{(L + L_g)/(L_g.C_f.L)}$$

f is the nominal fundamental grid frequency (i.e., f=50Hz)

E. OUTPUT FILTER OPTIMIZATION

The following constraints are executed on the selection of the values of the output filter components

$$L + L_g \leq 0.1. L_b \quad (14)$$

$$C_f \leq 0.05 * C_b \quad (15)$$

Where

$L_b = V_n^2 / 2\pi f_{res}$ is the Base Inductance

The LCL filter-damping resistor Rdr is set to be equivalent to the impedance of the filter capacitor at the resonant frequency

$$R_{dr} = \frac{1}{C_f \, 2\pi f_{res}} \quad (16)$$

The switching frequency of the PV inverter is constrained to be fewer than the maximum $f_{s,max}$ (Hz), specified by the constructers of the power device

$$f_s \leq f_{s,max} \quad (17)$$

As illustrated in Fig. 2, during the execution of the proposed co-design optimization process, other values of design variables (i.e., X=$[\beta, N_s, N_p, f_s, L, L_g, C_f, R_{dr}]$) are created by using the Particle Swarm Optimization (PSO) algorithm.

During its implementation, the PSO algorithm produces iteratively not the same sets of values of the design vector X, which constitute the particles of the swarm under evolution. For each value of the design vector X, which has been produced, the PV system process is simulated for a time of one year in order to:

1) Verify that the optimization constraints defined by (3), (6), (7), (11), (13)–(16) and (17) are satisfied

2) Calculate the yearly energy injected into the electric grid by the PV system If any of the limits is not satisfied the equivalent vector X is not considered as a potentially optimal solution of the design optimization Problem. This procedure is repetitive until it reaches the optimal (i.e., the maximum) annual energy yield E_y in (1).

F. ALTERNATIVE DESIGN OPTIMIZATION OBJECTIVE

For comparison with the proposed co-design technique, the presentation of alternative PV system configurations has also been investigated, which have been made by merging a PV array and a PV inverter that have been considered separately through distinct optimization processes. In the design of the PV array and DC/AC inverter in these PV systems, the following optimization objectives has engaged alternatively instead of (1)

Optimization objective 1:

The optimal tilt angle of the PV array, β (o) is designed such that the total solar irradiance that is occurrence on the PV array during the year is maximized

$$maximize_{X}\left\{\sum_{t=1}^{8760} G_{\beta,t}\right\} \quad (18)$$

Optimization Objective 2:

The best values of the filter components are calculated such that the power efficiency of the PV inverter is maximized when operating at the nominal DC input power and voltage levels

$$\underset{X1}{\text{maximize}} \quad \{\eta(X2, V_{mpp,max}, P_n\} \quad (19)$$

IV. DESIGN OPTIMIZATION RESULT

The proposed method has been applied to optimally co-design the PV array and DC/AC inverter of the PV scheme shown in Fig. 1 with the nominal power rating being P_n = 1.6.kW. The PV system is connected to an electric grid with V_n= 220 V (RMS) and f = 50 Hz. The operational characteristics of the PV cells that were used by the optimization algorithm to manufacture the PV array of the PV system are shown in Table 1. The MPP voltage range of the PV inverter is from $V_{mpp,min}$= 350 V to $V_{mpp,min}$ = 600v

The power unit of the PV inverter consists of IGBT type power switches and power diodes with $f_{s,max}$= 15 kHz. The power intake of the control unit in (4) has been set as Pc = 5 W. The proposed optimization process has applied in the MATLAB software platform.

A typical of the PV inverter in the PLECS software program has been used to compute the efficiency of the power section of the PV inverter as a function of its DC input power, DC input voltage and switching frequency with steps of 1.6 KW, 388V and 14.5 kHz, respectively.

The resulting values were then used to build up a look-up table for the finishing of the proposed co-design optimization process.The planned co-design optimization process has been implemented by using the built in function of the PSO algorithm that is presented in the Global Optimization Toolbox of MATLAB.

The PSO algorithm was set to operate with a swarm size of 250 particles and a extreme number of 3000 iterations. In addition, in order to reduce the performance time of the optimization process, the PSO algorithm operation was set to finish when the relative change in the best value of $E_y$in (1), which was resultant during the last 50 iterations, was less than 10−6.

The similar MATLAB function and PSO algorithm settings were also used for the expansion of objective functions (18)–(19), in order to implement the PV system design according to the alternative optimization objectives. The separately optimized PV systems are designed by implementing two different optimization algorithms. It is described in table 4

The results presented in Fig.4 demonstrate that the total energy manufacture of the PV systems designed by employing the proposed co-design methodology is advanced by 0.18–1.64% for the installation site.

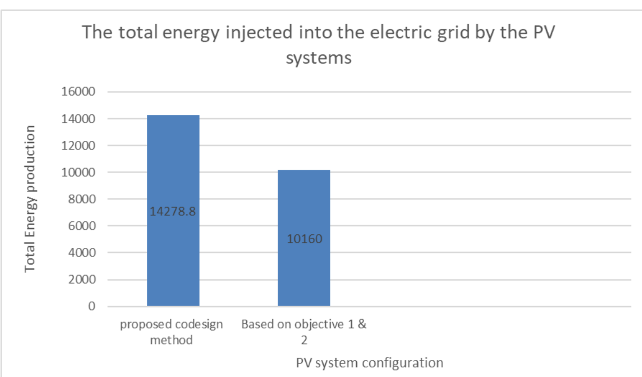

Fig.4 The Total energy injected into the electric grid

PSO MATLAB OUTPUT:

MATLAB Command

Objective_Function

X =1.0e+04 *

Columns 1 through 6
0.0027 0.0960 0.0003 1.4900 0.0000 0.0000

Columns 7 through 8
0.0000 0.0003

X=27.000000 960.000000 3.000000 14900.0000000. 0014720. 0000480. 000005
2.969000 85.000000

Ans =71394/5=14278.8

Iteration 50; Best fitness = 14278.8

TABLE 1
OPERATIONAL CHARACTERSTICS OF PV CELL UNDER STC

MPP Power	0.556 W
Open circuit voltage	0.583 V
Short circuit current	1.29A
Temperature coefficient of open circuit voltage	-0.0021 °C/V
Temperature coefficient of short circuit current	0.0013545 A/°C
Nominal operating temperature	47 °C

TABLE 2 PV INVERTER EFFICIENCY

N_s	N_p	$fs(khz)$	DC INPUT VOLTAGE	DC INPUT POWER	EFFICIENCY
960	2	5	535	3522	92.7
720	4	25	570	7432	72.7
960	2	5	520	3420	84.5
22	2	5	389	2859	86.5
90	10	10	560	5488	44.49

TABLE 3
DESIGN OPTIMIZATION RESULTS FOR 1.6-kW PV SYSTEMS

OPTIMIZED PV SYSTEM THROUGH CODESIGN METHOD							
Optimal values of design variables (i.e., X=$[\beta, N_s, N_p, f_s, L, L_g, C_f, R_{dr}]$)							
β	N_s	N_p	f_s (KHZ)	L(mH)	$L_g(\mu h)$	$C_f, (\mu f)$	$R_{dr}\,(\Omega)$
27.093	960	3	14.95	1.472	47.812	5.261	2.967
43.284	960	3	14.95	1.559	47.802	5.261	2.967

TABLE 4

Separately Optimized PV System Based on Optimization objective 1& 3							
Optimal values of design variables							
β	N_s	N_p	f_s (khz)	L(mH)	$L_g(\mu h)$	$C_f, (\mu f)$	$R_{dr}\,(\Omega)$
28.073	960	3	10	2.485	107	5.261	4.415

- The values of N_S= 720 and N_P= 4 had been selected for satisfying eqn (2), then the model results indicate that the energy production of the PV system would drip by 68.3% compare to using N_S= 960 and N_P= 3 so it has been adopted to synthesize the size of separately optimized PV system
- The proposed co design technique provided additional energy production compare to separately optimized PV system

PV STRING VOLTAGE, CURRENT, POWER WAVEFORM:

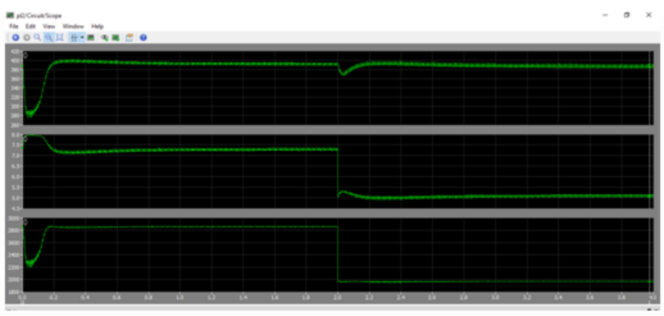

Fig.5 PV String Voltage ,Current,Power WaveForm

V. CONCLUSION

The continuous development of the global PV market expected in the following years necessitates further development of the PV systems efficiency in order to promote their effectiveness over alternative energy production technologies.

In this project, a co-design technique has been presented, where the optimal values of the design limits of the PV array and DC/AC inverter in a grid-connected PV system are calculated simultaneously in a unified design process. Compared to the existing design methods of PV systems, the proposed optimization technique enables the ideal matching of the PV array configuration and the DC/AC inverter structure. Concurrently co-designing the PV array and DC/AC inverter enables to derive PV system configurations, which are capable to inject additional energy into the electric grid

A proportional study has been performed, where other PV system configurations have also been considered, which include PV arrays and DC/AC inverters that have been designed independently, through distinct optimization processes based on various alternative optimization objectives.

Co-designing the PV array and DC/AC inverter enables to derive PV system configurations which are capable to inject more energy into the electric grid compared to the PV systems formed by merging distinctly designed subsystems (arrays and inverters), even if these subsystems have been previously calculated through individual optimization processes.

VI. APPENDIX

PARTICLE SWARM OPTIMIZATION CODES IN MATLAB

1)Save the following codes in MATLAB script file (*.m) and save as objective_function

```
function f= objective_function(X)
% objective function maximiztion
syms kx
f = -symsum(1.63,k,1,8760);
% designer input
beta=27;
vn=220;
pn=1.6e3;
ppvc=0.556;
vmmax=600;
vmmin=350;
vpvc=0.625;
nsmax=1104;
fsmax=20e3;
rfmax=20*100;
vpv=388;
ns=960;
np=floor((pn)/(ns*ppvc));
l=1.472e-3;
lg=47.812e-6;
cf=5.261e-6;
cb=(pn)/(2*3.14*50*vn^2);
lb=(vn^2)/(2*3.14*50*pn);
rdr=2.969;
efficiency=85;
fs=14.9e3;
if vpv<vmmin
   disp ('pin=0')
else
   disp ('pin=65')
end
pin=0;
if pin>pn
   disp('pn')
else
   disp('0')
end
X=[beta ns np fs l lg cf rdr]
fid = fopen('lookup.m', 'a');
```

```
fprintf(fid,'%f',X)
fprintf(fid,'%f ',efficiency);
fprintf(fid,'\n');
fclose(fid);
fid = fopen('lookup.m')
b=fscanf(fid,'%f  %f',[2,1]);
% a1= fscanf(fid,'%f  %f');
b=b';
fclose(fid);
% it is constrained to
c0=[];c=[];
c0(1)=l+lg-0.1*lb;
c0(2)=cf-0.05*cb;
u=[Inf; 3; Inf]
for i=1:length(c0)
if c0(i)>0
        c(i)=1;
else
        c(i)=0;
end
end
penalty=10000;          % penalty on each constraint violation
f=f+penalty*sum(c);     % fitness function
return
```

2) Save the following main program codes in MATLAB script file (*.m) as run_pso.m (any name can be used) and run.

```
clc
Clear all
close all
%% Problem
nVar = 8; % number of variables
VarMin = 0; % lower bound of variable
VarMax = 500; % upper bound of varible
%% PSO parameters
MaxIter =50; % max number of iterations
nPop = 250; % population size
w = 1; % inertia
d = 0.99; % damping ratio of the inertia
c1 = 2; % acceleration 1
c2 = 2; % acceleration 2
%% Initial
x0.position = [];
x0.velocity = [];
x0.fitness = [];
x0.best.position =[];
x0.best.fitness =[];

x = repmat(x0,nPop,1); % Make a population
global_best.fitness = -inf;
% Generate initial population
for i = 1: nPop
    x(i).position = unifrnd(VarMin,VarMax,[1 nVar]); % generate random solutions
    x(i).velocity = zeros([1 nVar]); % initial velocity
    x(i).fitness = objective_function(x(i).position); %calculate the fitness
    x(i).best.position = x(i).position; % update the local best
    x(i).best.fitness = x(i).fitness;   % update the local best
if x(i).best.fitness > global_best.fitness
        global_best = x(i).best;
end
end
B = zeros(MaxIter,1); % Save the best fitness in each iteration
C=zeros(MaxIter,nVar);
%% Main program
for j = 1:MaxIter
for i=1:nPop
        x(i).velocity = w*x(i).velocity + c1*rand([1 nVar]).*(x(i).best.position - x(i).position)...
            + c2*rand([1 nVar]).*(global_best.position - x(i).position); % update velocity
        x(i).position = x(i).position + x(i).velocity; % update position
        x(i).fitness = objective_function(x(i).position);
if x(i).fitness > x(i).best.fitness
            x(i).best.position = x(i).position; % update the personal best
            x(i).best.fitness = x(i).fitness;
if x(i).best.fitness > global_best.fitness
                global_best = x(i).best; % update the global best
end

end
end
    w = w*d; % update the damping ration
% Save best fitness
    B(j)=global_best.fitness;
    C(j,:)=global_best.position;
    disp(['Iteration ' num2str(j) '; Best fitness = ' num2str(B(j)) '; Optimal solution (x, y) = ' num2str(C(j,:))]);
    plot(B(1:j,1),'r.'); drawnow
end
```

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