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Abstract **HTML**

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A Differential Evolution Tuned Nonlinear Backstepping Controller for Three-Phase Grid-Connected Photovoltaic System

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***Abstract*—This paper presents an alternative technique to improve the gain tuning of nonlinear backstepping controller applied to three-phase grid-connected photovoltaic (PV) system in order to control active and reactive power fed into the grid. Gain parameters of nonlinear backstepping controllers play a key role in the convergence of currents corresponding to active and reactive power in grid-connected PV systems. The use of Differential Evolution (DE) optimization technique is proposed in this work, to obtain the optimised gain parameters while ensuring the fast convergence of errors associated with currents and this is done by minimizing the fitness function. Meanwhile, the gains are also optimised using an effective DE variant, differential evolution with composite trial vector generation strategies and control parameters (CoDE). The control parameter selection plays a vital role in the efficient performance of DE algorithm. However, the best choice of control parameters for optimum performance varies from problem to problem. Simulation studies are carried out to validate the effectiveness of the proposed scheme in terms of time responses (e.g., rise time, settling time, peak time, etc.)**

***Index Terms*—Differential evolution, gain optimization, nonlinear backstepping controller, grid-connected photovoltaic systems.**

I. INTRODUCTION

Solar photovoltaic (PV) systems are considered as the most popular renewable energy source due to their different distinct features [1]. Since solar PV units generate DC power, it is important to convert into AC power using Voltage Source Inverter (VSI) for the integration with existing power grids which poses several challenges due to uncertainties in solar irradiations and changes in power requirements for the grid. As a result, the VSI needs to be controlled in such a way that the desired active and reactive power are delivered into the grid in order to maximize the benefits of solar PV units. For this reason, it is essential to control the switches for the VSI.

Traditionally, linear controllers had been designed and implemented for grid-connected solar PV systems. However, these linear controllers have extremely limited operating regions as these are designed based on linearized models and their performance significantly deteriorate with abrupt changes in operating conditions which are very common. Nonlinear controllers are used to overcome these challenges as these controllers have the ability to cope up with any changes by capturing nonlinearities at both source-side and grid-side [2]. However, the performance of nonlinear controllers for grid-connected PV systems rely on gain parameters and there are no systematic ways for selecting these parameters. These parameters are currently chosen using the trial and error approach which is time consuming as well as requires prior experience about the system. Hence, the gain tuning is a significant problem and this is still uncovered.

Differential Evolution (DE) algorithm has been widely used meta heuristic optimisation technique by researchers because of its conceptual simplicity, ease of implementation and good convergence characteristics. It can optimize non-linear and non-differentiable continuous space functions. Earlier DE has been used in various applications where tuning controller gains is challenge. In [3]–[7] DE and other metaheuristic algorithms are used for tuning the gains of controllers applied to various electrical systems. Since, DE and its variants have been proven to show remarkable performance in optimizing non linear functions, it can be used to optimise the gains of nonlinear backstepping controller applied to grid connected solar PV system.

This paper focuses on optimizing the gain parameters of a nonlinear backstepping controller, as proposed in [2], for grid-connected PV systems using a differential evolution (DE) scheme and its variant, differential evolution with composite trial vector generation strategies and control parameters (CoDE) [8]. Based on above study the research objectives of this paper are as follows.:

- To investigate application of DE and CoDE on designing backstepping controller by estimation of I_d and I_q for a solar PV.
- To analyze the proposed scheme with the help of time domain specification analysis and to calculate several time domain specifications such as rise time, settling time, peak overshoot, undershoot and peak time.
- To present comparative analysis of the performance of DE and CoDE based controller on the basis of gains stability and convergence of objective function.

Rest of the paper is organized as follows: in section 2, overview of modelling of solar PV system is presented. In section 3, a control scheme based on DE is proposed. In section

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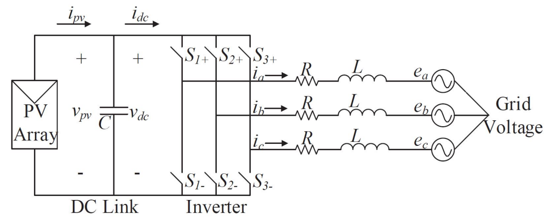

Fig. 1: Three phase grid connected PV system

4, simulation and results of the study are presented. Major conclusions and future directions have been depicted in section 5.

II. BRIEF OVERVIEW OF MODELLING GRID-CONNECTED PV SYSTEM

The schematic diagram of a three-phase grid-connected solar PV system is shown in Fig. 1 in which there are two stages. In the first stage, a maximum power point tracking (MPPT) system is used to extract the maximum power from the solar PV unit and maintain a constant voltage across the DC-link capacitor at the input of the VSI.

In the second stage, the VSI inverter is used along with relevant control actions to convert the DC power into AC power where the main control objectives are to ensure the injection of desired active and reactive power into the grid with minimum distortions in the current. An output L filter is used for reducing distortions in the current and in this paper, the controller is designed only for the VSI and hence, it is assumed that the MPPT system is always ensuring the constant voltage across the DC-link capacitor. In this work, the dynamic model is used only for capturing the dynamics of the current as presented in the following subsection.

A. Brief overview of modeling grid-connected PV systems

The well-established model of grid-connected PV system is used in this work. The detailed dynamical modeling of grid-connected PV system considering the dynamics of currents and DC-link voltage are clearly presented in [9]. The dynamical model of grid-connected PV systems in abc-frame can simply be derived by employing circuit theory. However, the model in abc-frame represents the instantaneous values of currents in three-different phases, i.e., time varying. The controllers are usually designed based on the time-invariant model which can be obtained by using abc to dq transformation, also know as Park's transformation. The dynamics of currents in dq-frame can be written as [9]:

$$\begin{aligned} \dot{I}_d &= -\frac{R}{L}I_d + \omega I_q - \frac{E_d}{L} + \frac{V_{dc}}{L}M_d \\ \dot{I}_q &= -\omega I_d - \frac{R}{L}I_q - \frac{E_q}{L} + \frac{V_{dc}}{L}M_q \end{aligned} \tag{1}$$

where I_d and I_q are currents in d- and q-frame, respectively; R and L are combinations of filter and line resistance and inductance, respectively; E_d and E_q are grid voltages in d- and q-frame, respectively; V_{dc} is the DC-link voltage; and M_d and M_q are switching signals of the VSI in d- and q-frame, respectively. The corresponding active (P) and reactive (Q) power for this system can be written as [9]:

$$\begin{aligned} P &= \frac{3}{2}E_dI_d \\ Q &= \frac{3}{2}E_dI_q \end{aligned} \tag{2}$$

which clearly demonstrate that P and Q can be controlled by controlling I_d and I_q, respectively as E_d is constant. A brief overview to design backstepping controller is provided in the following subsection.

B. Brief overview of a nonlinear backstepping controller design for grid-connected PV systems

The control objectives for the nonlinear backstepping controller are I_d and I_q such that the control signals, M_d and M_q stabilize errors e_1 and e_2 where these errors are defined as:

$$\begin{aligned} e_1 &= I_d - I_{dref} \\ e_2 &= I_q - I_{qref} \end{aligned} \tag{3}$$

where I_{dref} and I_{qref} are desired or reference values of I_d and I_q, respectively whose values might change depending on the desired values of P and Q, respectively.

For analyzing the convergence of e_1 and e_2, the Control Lyapunov Function (CLF) can be chosen as:

$$W = \frac{1}{2}e_1^2 + \frac{1}{2}e_2^2 \tag{4}$$

for which $(e_1, e_2) \to 0$ if $\dot{W} < 0$ or $\dot{W} \leq 0$. Thus, $\dot{W}$ can be written as

$$\begin{aligned} \dot{W} = e_1\dot{e}_1 + e_2\dot{e}_2 = e_1 &\left(-\frac{R}{L}I_d + \omega I_q - \frac{E_d}{L} + \frac{V_{dc}}{L}M_d\right) \\ +e_2 &\left(-\omega I_d - \frac{R}{L}I_q - \frac{E_q}{L} + \frac{V_{dc}}{L}M_q\right) \end{aligned} \tag{5}$$

The value of $\dot{W}$ will be $\dot{W} \leq 0$ for any value of e_1 and e_2, i.e., errors will be converged to zero if and only if the following conditions hold:

$$\begin{aligned} -\frac{R}{L}I_d + \omega I_q - \frac{E_d}{L} + \frac{V_{dc}}{L}M_d &= -k_1e_1 \\ -\omega I_d - \frac{R}{L}I_q - \frac{E_q}{L} + \frac{V_{dc}}{L}M_q &= -k_2e_2 \end{aligned} \tag{6}$$

where k_1 and k_2 are positive gain parameters, i.e., $k_1 > 0$ and $k_2 > 0$ whose values define the convergence speed of e_1 and e_2, respectively. With the conditions in equation (6), equation (5) can be simplified as:

$$\dot{W} = -k_1e_1^2 - k_2e_2^2 \leq 0 \tag{7}$$

Using this backstepping approach, M_d and M_q can be determined from equation (6) as:

$$\begin{aligned} M_d &= \frac{L}{V_{dc}}(\frac{R}{L}I_d - \omega I_q + \frac{E_d}{L} - k_1e_1) \\ M_q &= \frac{L}{V_{dc}}(\omega I_d + \frac{R}{L}I_q + \frac{E_q}{L} - k_2e_2) \end{aligned} \tag{8}$$

From equation (8), it can be seen that the gain parameters appear in the backstepping control law and the selections of appropriate values for these gains are major challenges which are solved in this paper by employing a DE scheme as discussed in the following section.

III. PROPOSED DE SCHEME FOR TUNING GAIN PARAMETERS

This section is focused to tune gain parameters using the proposed DE scheme. A detailed study of the DE algorithm is presented in [10] which is employed to optimize gain parameters for the backstepping controller used for grid-connected PV systems.

The DE algorithm which is used to estimate gain parameters of a nonlinear backstepping controller for a three-phase grid-connected PV systems that fulfils the system requirements is explained in this subsection. As indicated in [10], the population set comprises N_p members. For the backstepping controller, two gain parameters need to be tuned which can be expressed as:

$$P_i{}^k = (k_1, k_2) \;\; \text{with} \;\; i = 1,\ 2,\ 3,\ \cdots,\ N_p \tag{9}$$

and the objective function which is used for tuning these gain is defined as:

$$W = \frac{1}{2}(\overline{e_1}^2 + \overline{e_2}^2) \tag{10}$$

where $\overline{e_1}$ and $\overline{e_2}$ are mean absolute errors for I_d and I_q, respectively. The minimization of W ensures the minimum value of errors, i.e., appropriate tracking of pre-defined values of I_d and I_q. The algorithm is developed by considering all these facts as shown in the Algorithm 1. Also, Algorithm 2 is developed for CoDE [8] employed for tuning backstepping controller gains. Based on these algorithms, simulation studies are shown in the following section.

Algorithm 1 DE-based gain tuning for a nonlinear backstepping controller

```
Generate an initial population of size $N_p$ consisting of each vector with dimension $D = 2$. Each vector consists of random combination of $k_1$ and $k_2$.
gen=0
while gen<max gen do
    Evaluate fitness for each member.
    for i = 1 to $N_p$ do
        Perform mutation and crossover for the target vector $i$.
        if trail vector satisfies constraint then
            Evaluate fitness of the newly generated trail vector.
        end if
        if fitness of trail $<$ fitness of target then
            Trail replaces target.
        end if
    end for
    gen=gen+1
end while
Output P
```

IV. SIMULATION RESULTS

The simulations are carried out on a similar grid-connected PV system as shown in Fig. 1 and the values of different components in this figure are similar to that as presented in [2].

Algorithm 2 CoDE-based gain tuning for a nonlinear backstepping controller

```
INPUT: Strategy candidate pool: ”rand/1/bin”, ”rand/2/bin” and ”current-to-rand/1”. Parameter candidate pool: [F=1.0,Cr=0.1], [F=1.0,Cr=0.9] and [F=0.8,Cr=0.2].
gen=0
Generate an initial population size of $N_p$ and each vector of dimension $D = 2$. Each vector consists of random combination of $k_1$ and $k_2$.
while gen<max gen do
    Evaluate fitness for each member.
    for i = 1 to $N_p$ do
        For the target vector $i$ use the the three trail vector generation strategies, each with control parameter setting randomly selected from parameter candidate pool to generate three trail vectors $u_{i_1}$,$u_{i_2}$ and $u_{i_3}$.
        if all the trail vectors satisfy the constraints then
            Evaluate fitness of all the newly generated trail vectors.
            Choose the best trail vector.
        end if
        if fitness of trail $<$ fitness of target then
            Trail replaces target.
        end if
    end for
    gen=gen+1
end while
Output P
```

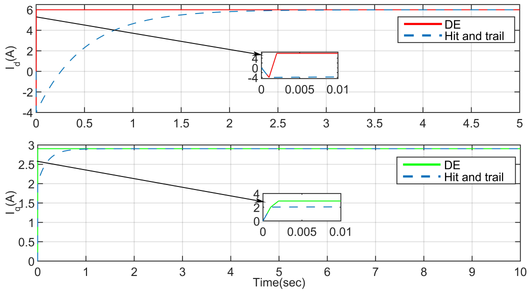

Fig. 2: I_d and I_q with time

Simulations are performed using the values of gain parameters employing the proposed DE scheme and compared with that of in [2] as well as with a successful variant of DE i.e., CoDE as presented in [8]. For the proposed DE scheme, the relevant parameters are considered as $F = 0.6$, $Cr = 0.6$, $gen = 1500$ and $N_p = 30$. The values of k_1 and k_2 is constrained in interval of $(0, 2000)$.

The convergence of objective function w.r.t generations for DE and CoDE is shown in Fig 3. The change of gain parameters

TABLE I: GAIN PARAMETERS

Parameters	Without DE	DE	CoDE
k_1	2	1004	1004
k_2	5	1043.5	1045.1

TABLE II: COMPARISON OF TIME RESPONSES OF I_d WITH PARAMETERS FROM DIFFERENT APPROACHES

Step Response	Without DE	DE	CoDE
Rise Time	1.1019	0.0004	0.0004
Settling Time	1.9629	0.0020	0.0020
Settling Min	5.3966	5.9956	5.9956
Settling Max	5.9956	5.9956	5.9956
Overshoot	0	0	0
Undershoot	66.5225	66.5225	66.5225
Peak Time	15.5340	0.0070	0.0050
Peak	5.9956	5.9956	5.9956

TABLE III: COMPARISON OF TIME RESPONSES OF I_q WITH PARAMETERS FROM DIFFERENT APPROACHES

Step Response	Without DE	DE	CoDE
Rise Time	0.2296	0.0015	0.0015
Settling Time	0.5706	0.0019	0.0019
Settling Min	2.6137	2.9024	2.9038
Settling Max	2.9038	2.9039	2.9039
Overshoot	0	0.0200	0.0018
Undershoot	0	0	0
Peak Time	15.5360	0.0030	0.0020
Peak	2.9038	2.9039	2.9039

k_1 and k_2 w.r.t the generations for DE and CoDE is shown in Fig 4 and Fig 5 respectively.

The values of k_1 and k_2 without using DE (i.e., as presented in [2]), with DE as proposed in this paper, and with CoDE in [8] are shown in Table I. These values are used to analyse different time responses for step response of I_d and I_q as indicated in Table II and Table III from where it can be seen that the gain parameters obtained from the proposed DE and CoDE ensure better performance as compared to existing trail and error method. The corresponding time-domain step response is shown in Fig 2. The gains obtained by DE and CoDE are almost same due to which there is not much difference in their step responses. Although, comparing the convergence graphs for DE and CoDE it is evident that CoDE converges faster than DE. Moreover, comparing Fig 4 and Fig 5 it is proven that CoDE gives stable gain values than DE. This ensures that CoDE gives better results in tuning the gain parameters than DE and traditional trail and error method.

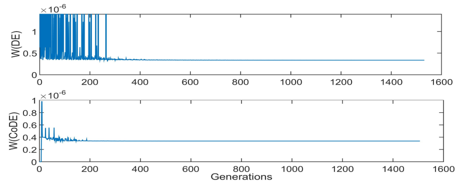

Fig. 3: Convergence graph for DE and CoDE

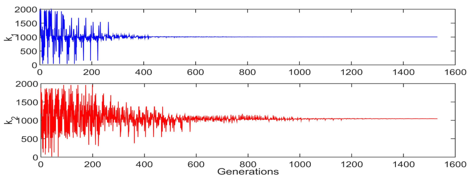

Fig. 4: k_1 and k_2 in DE

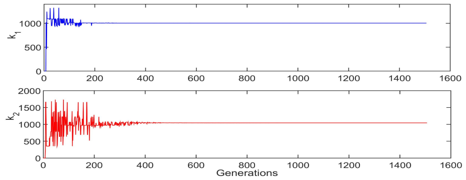

Fig. 5: k_1 and k_2 for CoDE

V. Conclusion

Controller gain tuning is a critical task for grid connected PV systems. Nonlinear backstepping control algorithm is a powerful and robust algorithm also it serves as an alternative way to control direct axis and quadrature axis currents. In this work, an attempt has been made to access the optimal values of I_d and I_q by tuning the gain parameters of nonlinear backstepping controller. A control scheme based on DE and CoDE has been proposed and evaluated on the basis of time domain specifications namely peak time, rise time, settling time, overshoot and undershoot of the response of I_d and I_q. Different analysis have been conducted to showcase the efficacy of the control scheme such as comparative analysis of time domain response of DE, CoDE and without controller, convergence property analysis on the controller gain (sensitivity analysis). From the obtained results, it has been concluded that the proposed scheme is robust and shows better results as compared to other schemes. Uncertainty in DC link voltage and parametric sensitivity analysis of grid have been kept for future analysis.

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