Nonlinear adaptive control of PV inverter for maximum solar energy harvesting using democratic joint

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Abstract. This study designs a novel nonlinear adaptive controller (NAC) of photovoltaic inverter in order to generate the maximum energy of solar power under different condition. Inverter nonlinearities, uncertain grid/inverter parameters, as well as inverter modelling uncertainties are aggregated into a perturbation. Then, a linear extended state observer (ESO), is applied for estimate the perturbation online. Meanwhile, a state feedback controller is used to calculate the perturbation in the real-time. Particularly, its optimal control parameters are effectively and efficiently tuned by a novel meta-heuristic algorithm, called democratic joint operations algorithm (DJOA), such that a satisfactory control property could be resulted in. Case studies verifies the effectiveness and advantages of NAC compared to conventional linear control, e.g., PID controller, and typical nonlinear control, e.g., feedback linearization controller (FLC), under solar irradiation variation and temperature variation.

1. Introduction
Renewable energy applications are prevailing around the globe to resolve the energy crisis and protect the environment [1,2]. In the past decade, plenty of solar energy has been globally deployed due to its prominent advantages of resource inexhaustibility, free air pollution, noiseless operation, insignificant tear-and-wear, easy installation and allocation, and low overall maintenance burden [3]. In practice, it is paramount to ensure PV systems to consistently generate the optimal solar energy under different atmospheric conditions, which is a well-known concept and task called MPPT [4]. As PV system generates DC current which cannot directly supply to AC power grids, PV inverters are always employed for a successful power grid connection.

In general, linear controllers associated with conventional PID loops are commonly used in PV inverter control system. It is easily control and has high reliability [5]. However, a natural drawback of PID control is that it can only achieve a discordant control manifestation under complicated environment as the PID control parameters are chosen at a specific operation point via local linearization. More specifically, when the operation condition varies the contented control property of PID control may be dramatically degraded or sometimes might even result in the collapse of the closed-loop system stability. What’s worse, such issue will become even severer in PV system applications as the atmospheric conditions, e.g., temperature and solar irradiation, often vary significantly and unpredictably.
In order to resolve the above obstacle, many nonlinear control schemes have been developed. In references [6] and [7], feedback linearization controller (FLC) was used for both three-level PV inverters and two-level PV inverter for optimal power production, which completely remove the system nonlinearities to achieve the global coincident control property under different operation points. Nevertheless, FLC need the accurate PV system model, hence it is invulnerable to any uncertain system parameters or external disturbances.

As a consequence, a higher power generation property can be realized in the presence of system imperfections [8]. In addition, based on the pole placement method [9], a novel digital predictive current controller using disturbance estimator was developed, which could significantly reduce the effect of parameter uncertainties and efficiently improve the grid-side disturbance reject capability. Besides, a passivity-based controller (PBC) based on Hamilton equation was presented for PV system connected to main power grid [10]. Based on perturbation observer, work [11,12] designed advanced robust controllers for PV inverter to acquire the ideal solar energy without the need of an accurate system model, and just few states are required to be measured.

This study develops a nonlinear adaptive controller (NAC) of PV inverters in different conditions, such that the maximum solar energy could be produced. Inverter nonlinearities, uncertain grid/inverter parameters, as well as inverter modelling uncertainties are aggregated into a perturbation. As a result, NAC is robust to various modelling uncertainties and external disturbances. Two case studies, e.g., solar irradiation variation and temperature variation, are investigated. Simulation results demonstrate the validity and merits of NAC against PID control and FLC, respectively.

2. AC power grid connected PV inverter modelling

Figure 1 show the diagram of a single-line PV inverter connected to AC power grid, which includes PV array for solar energy harvesting, PV inverter for DC/AC conversion, DC-link capacitor for voltage regulation, and AC power grid for solar energy supply to various power demanders [4]. The PV cell generates the DC current which flow into the PV inverter to be converted into AC current, which then supplies to power grid.

![Diagram of a typical PV inverter connected to AC power grid](image)

Figure 1. The diagram of a typical PV inverter connected to AC power grid.

\[ I_{pv} = N_p I_{gp} - N_p I_s \left( \exp \left[ \frac{q}{N_a T_C} \left( \frac{R_a}{N_a} + \frac{R_{gp}}{N_p} \right) \right] - 1 \right) \] (1)

where \( I_{gp} \) is the generated photocurrent which is determined by the solar irradiation, it gives as


\[ I_{sp} = \left( I_{sc} + k_i(T_c - T_{ref}) \right) \frac{s}{1000} \]  \hspace{1cm} (2)

In addition, \( I_{sc} \) denotes the saturation current of PV cells which varies with the temperature, as

\[ I_{sc} = I_{sc0} \left( \frac{1}{\frac{T_{ref}}{T}} \right)^3 \exp \left( \frac{Q_s}{k} \left( \frac{1}{T_{ref}} - \frac{1}{T} \right) \right) \]  \hspace{1cm} (3)

The PV inverter dynamics described in dq rotational coordinate is described as [6,7]

\[
\begin{align*}
V_d &= e_d + R_i d + L \frac{di_d}{dt} + \omega Li_q \\
V_q &= e_q + R_i q + L \frac{di_q}{dt} - \omega Li_d
\end{align*}
\]  \hspace{1cm} (4)

where \( e_d, e_q, V_d, V_q, i_d, i_q \) denote the dq-axis grid voltages, dq-axis PV inverter voltages and dq-axis grid currents, respectively; the resistance and inductance of AC power grid is denoted by \( R \) and \( L \), respectively; meanwhile, the synchronous frequency of AC power grid is denoted by \( \omega \). Ignore the power balance between the DC generation, the switching power losses produced in PV inverters and the AC output is as follows

\[ e_d i_d + e_q i_q = V_{dc} i_{dc} \]  \hspace{1cm} (5)

where \( i_{dc} \) and \( V_{dc} \) mean the DC-side input current and DC-side input voltage of the PV inverter, separately.

According to Kirchoff’s current law, one can obtain the DC side dynamics by

\[ C \frac{dV_{dc}}{dt} = I_{pv} - I_{dc} = I_{pv} - \frac{e_d i_d + e_q i_q}{V_{dc}} \]  \hspace{1cm} (6)

where \( C \) denotes the DC-bus capacitance.

3. Democratic joint operation algorithm

DJOA is the latest modification of the human society inspired joint operations algorithm (JOA). As a member of meta-heuristic algorithm, JOA needn’t the accurate optimization model and just require the system input and output for the optimization, which is capable of resolving various type of optimization tasks, particularly for ‘black-box’ problems from which only system input and system output are available to designers. The main improvement of DJOA can be summarized as follows:

(1) A deeper optimum seeking can be achieved by introducing an extra deputy officer into each military unit. This mechanism is called democratic defensive operations;

(2) By adopting the regroup strategy of shuffled frog leaping algorithm (SFLA), the possibility of local optimum trapping can be considerably reduced. This mechanism is called shuffling regroup operations.

The offensive operations are depicted below:

\[ y_{m,j}^k = \begin{cases} 
y_{m,j}^k + RA[0,1] \times (R_{j}^k - y_{m,j}^k), & \text{if } y_{j}^C > y_{m,j}^k \\
y_{m,j}^k + RA[0,1] \times (L_{j}^k - y_{m,j}^k), & \text{otherwise}
\end{cases} \]  \hspace{1cm} (7)

\[ \begin{align*}
L_j^k &= y_{k,j}^0 + S_t \times (L_j - y_{k,j}^0) \\
R_j^k &= y_{k,j}^0 + S_t \times (R_j - y_{k,j}^0)
\end{align*} \]  \hspace{1cm} (8)

\[ S_t = \lfloor \cos (t \times g \times \pi) \rfloor \]  \hspace{1cm} (9)

where \( y_{j}^C \) is the commander’s jth position while \( y_{k,j}^0 \) means the officer’s jth position of the kth military unit; \( S_t \) is a dynamic cycle parameter which can adjust the balance between exploration and exploitation; \( t = (1, 2, \ldots, T) \) is the current iteration and \( T \) represents the number of maximum iterations; and \( g \) is a user-specified constant to examine the frequency of the cosine function, respectively.

Some of the soldiers new positions will be chosen as the equation given below. If they do not relate to a military unit leading under a commander,

\[ y_{m,j}^k = \begin{cases} 
y_{m,j}^k + RA[0,1] \times (R_{j}^k - y_{m,j}^k), & \text{if } y_{j}^C > y_{m,j}^k \\
y_{m,j}^k + RA[0,1] \times (L_{j}^k - y_{m,j}^k), & \text{otherwise}
\end{cases} \]  \hspace{1cm} (10)

The democratic defensive operations are expressed as
where $y_{m,j}^i$ and $v_{m,j}^k$ is the $j$th defensive position of the $m$th soldier's deputy officer and in the $k$th military unit respectively.

$v^k_m$ and $v^k_m$ are the position of generated candidate defensive and fitness function of the current of new location of soldier in the next iteration is described blow:

$$y_{m,j}^k = \begin{cases} v_{m,j}^k, & \text{if } f(v_{m,j}^k) < f(y_{m,j}^i) \\ y_{m,j}^i, & \text{otherwise} \end{cases}$$

(14)

Shuffling regroup operations are written as

$$2^k = \left[ (B(m))^k, f(m)^k \mid B(m)^k = B(K + N(m - 1)) \right]$$

(15)

$$f(m)^k = f(k + N(m - 1)), m = 1, ..., M; k = 1, ..., K$$

(16)

where set $\{(i), f(i), i = 1, ..., N\}$ is the total stored positions and fitness functions of all soldiers ranked in the descending order, with $i=1$ is tells performance value the soldier ; $K$ is the number of military units; $M$ is the population size of each military unit; and $N=M*K$ is the total population size of all the military units, respectively.

Figure 2. illustrates the schematic structure of DJOA . More data of DJOA literature is referred at [13] for interested readers.

4. Nonlinear adaptive controller (NAC) of photovoltaic (PV) inverter to generate the optimal solar energy DJOA

Define the state vector as $x = (x_1, x_2, x_3)^T = (i_d, i_q, V_{dc})^T$, control input $u = (u_1, u_2)^T = (v_d, v_q)^T$ and system output $y = (y_1, y_2)^T = (i_q, V_{dc})^T$.

Differentiate the system output $y$ until the control input $u$ appears

$$\begin{align*}
y_1 &= -\frac{R}{L}i_q + \omega l_d - \frac{q}{L} + \frac{u_2}{L} \\
y_2 &= \frac{i_v}{C} - \frac{e_d}{C(V_{dc})} + \frac{e_q}{C(V_{dc})} - \frac{e_d}{C(V_{dc})} u_4 - \frac{e_q}{C(V_{dc})} u_2
\end{align*}$$

(17)
Equation (17) show by matrix as below,

\[
\begin{bmatrix}
\dot{y}_1 \\
\dot{y}_2
\end{bmatrix} = \begin{bmatrix}
g_1(x) \\
g_2(x)
\end{bmatrix} + D(x) \begin{bmatrix}
u_1 \\
u_2
\end{bmatrix}
\]

(18)

while

\[
g_1(x) = -\frac{R}{L} i_q + \omega i_d - \frac{e_q}{L}
\]

\[
g_2(x) = \frac{L \psi_{pv}}{c} e_d \left( \frac{e_{d1} - \omega i_q - \frac{e_d}{L}}{c^2 v_{dc}^2} + \frac{e_{d2} + \omega i_q - \frac{e_d}{L}}{c^2 v_{dc}^2} \right) - \frac{(e_{d1} + e_{d2})^2}{c^2 v_{dc}^2} I_{pv} + \frac{(e_{d1} + e_{d2})^2}{c^2 v_{dc}^2} I_{pv}
\]

(19)

and

\[
D(x) = \begin{bmatrix}
0 & \frac{1}{L} \\
-\frac{e_d}{L C v_{dc}} & -\frac{e_q}{L C v_{dc}}
\end{bmatrix}
\]

(20)

The control gain matrix \(D(x)\) is received as

\[
\det[D(x)] = \frac{e_d}{L^2 C v_{dc}} \neq 0
\]

(22)

Describe the perturbations \(\Phi_1(\cdot)\) and \(\Phi_2(\cdot)\) for PV system (7), as given:

\[
\begin{bmatrix}
\Phi_1(\cdot) \\
\Phi_2(\cdot)
\end{bmatrix} = \begin{bmatrix}
g_1(x) \\
g_2(x)
\end{bmatrix} + \left( D(x) - D_0 \right) \begin{bmatrix}
u_1 \\
u_2
\end{bmatrix}
\]

(23)

The constant control gain matrix \(D_0\) is written as

\[
D_0 = \begin{bmatrix}
d_{11} & 0 \\
0 & d_{22}
\end{bmatrix}
\]

(24)

where \(d_{11}\) and \(d_{22}\) are the constant. Matrix \(D_0\) is to completely decouple the control of q-axis current \(i_q\) and DC voltage \(V_{dc}\).

Define the tracking error \(e = [e_1, e_2]^T = [i_q - i_q^*, V_{dc} - V_{dc}^*]^T\), where \(i_q^*\) denotes the q-axis current reference while \(V_{dc}^*\) represents the DC voltage reference. The control input \(u\) will appear by altering the tracking error \(e\), it gives

\[
\begin{bmatrix}
\dot{i}_q \\
\dot{V}_{dc}
\end{bmatrix} = \begin{bmatrix}
\Phi_1(\cdot) \\
\Phi_2(\cdot)
\end{bmatrix} + D_0 \begin{bmatrix}
u_1 \\
u_2
\end{bmatrix} = \begin{bmatrix}
\dot{i}_q^* \\
\dot{V}_{dc}^*
\end{bmatrix}
\]

(25)

A second-order high-gain perturbation observer (HGPO) calculate perturbation \(\Phi_1(\cdot)\) as

\[
\begin{cases}
\dot{i}_q = \tilde{\Phi}_1(\cdot) + o_{11} i_q + d_{11} u_1 \\
\dot{\dot{i}}_q = \tilde{\Phi}_1(\cdot)
\end{cases}
\]

(26)

where observer gains \(o_{11}\) and \(o_{12}\) are all positive constants.

A third-order high-gain state and perturbation observer (HGSPO) is put to measure perturbation \(\Phi_2(\cdot)\) as

\[
\begin{cases}
\dot{\dot{V}}_{dc} = \tilde{\Phi}_2(\cdot) + o_{21} i_q + d_{21} u_2 \\
\dot{\dot{\dot{V}}}_{dc} = \tilde{\Phi}_2(\cdot)
\end{cases}
\]

(27)

where observer gains \(o_{21}\), \(o_{22}\), and \(o_{23}\) are all positive constants.

The NAC for PV system (17) is designed as

\[
\begin{bmatrix}
u_1 \\
u_2
\end{bmatrix} = D_0^{-1} \begin{bmatrix}
\dot{i}_q^* - \tilde{\Phi}_1(\cdot) - p_1 e_1 \\
\dot{V}_{dc}^* - \tilde{\Phi}_2(\cdot) - p_2 e_2 - p_3 e_2
\end{bmatrix}
\]

(28)

Clearly, from NAC (28), one can see that the combinatorial effect of PV inverter nonlinearities, parameter uncertainties, and unmodelled dynamics are aggregated into perturbations \(\Phi_1(\cdot)\) and \(\Phi_2(\cdot)\),
which are then estimated by HGSPOs (26) and (27), and then fully compensated to realize an adaptive control performance with only the measurement of q-axis current and DC voltage.

Now, the control parameters of NAC (28), e.g., \(p_{11}, p_{21}, \text{ and } p_{22}\), are optimized by DJOA. The optimization model is as given.

\[
\text{Minimize } f(x) = \sum_{\text{Two cases}} \int_0^T \left[ |i_q - i_q^*| + |V_{dc} - V_{dc}^*| + \omega_1 |u_1| + \omega_2 |u_2| \right] dt \\
0 \leq p_{11} \leq 50 \\
0 \leq p_{21} \leq 50 \\
0 \leq p_{22} \leq 50 \\
-500 \leq d_{11} \leq 500 \\
-500 \leq d_{22} \leq 500 \\
-100 \leq u_1 \leq 100 \\
-100 \leq u_2 \leq 100
\]

subject to

where \(T\) is the total running time. And the weights \(\omega_1\) and \(\omega_2\) are selected as 0.25 which used to evaluate the control costs. The two cases are the solar irradiation variation and temperature variation.

The convergence standard of DJOA is given as

\[
|y_k - y_{k-1}| \leq \varepsilon
\]

where \(\varepsilon\) is selected as \(10^{-4}\), \(y_k\) and \(y_{k-1}\) denote the fitness function value at the \(k\)th iteration and the \((k-1)\)th iteration.

The overall optimization flowchart of DJOA for PV inverters is illustrated in Figure 3.

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5. Case studies

Applying the NAC to get the MPPT under multiple conditions for assessing the control property. And PID control \([5]\) and FLC \([7]\) take part in the comparison. Here, PV system parameters are given on the Table 1. Besides, the rated values of solar irradiation and temperature are 1 kW/m\(^2\) and 25℃, separately. And q-axis current \(I_q=0\) for a unit power factor. Under the above running condition, the DC link voltage \(V_{dc}=539.5\) V, PV output current \(I_{pv}=3.46\) A and PV output power \(P=1867\) W, separately.

PID control, FLC, and NAC are all optimally tuned by DJOA, every control method run 10times and
the attained perfect results are shown in Table 1. The simulation is undertaken via Matlab/Simulink 2016b.

Table 1. A table with headings spanning two columns and containing notes. The optimal control parameters of PID control, FLC, and NAC obtained by DJOA in 10 runs.

| Algorithm | q-axis current | DC-link voltage |
|-----------|----------------|-----------------|
| PID       | $K_{P1}=33$    | $K_{D2}=44$     |
|           | $K_{I1}=67$    | $K_{P2}=44$     |
|           | $K_{D1}=0.8$   | $K_{I3}=89$     |
|           | $K_{P3}=148$   | $K_{D3}=1$      |
| FLC       | $k_{11}=40$    | $k_{21}=46$     |
|           | \              | $k_{22}=35$     |
| NAC       | $k_{11}=45$    | $k_{21}=37$     |
|           | $b_{11}=385$   | $k_{22}=28$     |
|           | \              | $B_{22}=448$    |

Two cases are carried out to assess the property of NAC. Firstly, three successive step variations in solar irradiation are implemented to the PV system. The solar irradiation reduces between 1 kW/m² and 0.5 kW/m² at $t=0.2$ s, raises to 0.8 kW/m² at $t=0.7$ s, and returns to 1 kW/m² at $t=1.2$ s. The temperature retains at 25°C during the all test period. And q-axis current $I_q$ is raised to 50 A at $t=0.2$ s and reduced to -30 A at $t=1.2$ s. Here, Figure 4 denotes the simulation results of different control methods. Apparently, the time of NAC converge to the maximum PV out power point in the thrice solar irradiation varying period are 0.06 s, 0.12 s and 0.15 s which are the smallest than PID control and FLC. Obviously, both PID control and FLC have significant DC link voltage and q-axis current oscillations in each solar radiation varying period. Especially, when the solar radiation is reduced, the DC link voltage first overshoot acquired by PID control attains about 400V, which is about 13.42% lower than the steady state voltage. When the solar radiation is raised for the second time, the DC link voltage first overshoot acquired by PID control attains about 570V, which is 27% higher than the steady state voltage. Moreover, the DC link voltage and power point during the twice temperature varying period. The same as PID control and FLC than other control methods. As is shown in the results, NAC can realize the most fast and stable MPPT compared to PID control and FLC after the convergence power point during the twice temperature varying period. The same as solar radiation varying period, PID control have conspicuous DC link voltage and q-axis current oscillations in each temperature varying period. Because the parameters of the PID control are acquired by linearizing the original nonlinear system at a operating point. When the operating point of the system variations, its control property will be reduced, so it is difficult to achieve global consistent control property. Particularly, when the temperature is raised, the DC link voltage first overshoot acquired by PID control attains about 470 V, which is about 6.12% lower than the steady state voltage. And when the temperature is recovered, the DC link voltage first overshoot acquired by PID control attains around 555 V, which is about 3.27% higher than the steady state voltage. Moreover, the DC link voltage and q-axis current oscillations of FLC is more acute than PID control obvious during each temperature varying period as it requires a precise system model. And the parameters of NAC are optimized by DJOA, so that a well-pleasing control property could be achieved.
6. Conclusions
A novel DJOA optimized NAC is designed under various atmospheric conditions to get the available highest solar energy of PV systems. The contributions of this paper can be concluded as below:

(1) The PV inverter nonlinearities, parameter uncertainties, and unmodelled dynamics are collected into a perturbation, which is evaluated by an HGSPO and then completely compensated in the real-time;

(2) NAC only needs to measure the q-axis current and DC-link voltage, and the precise PV inverter model is not required;

(3) DJOA is used to optimize the NAC parameters, so that a satisfactory control property could be obtained;

(4) Simulation results verify that PID control and FLC is not as good as NAC that can track the PV out power at the fastest rate, together with the least DC-link voltage and q-axis current overshoot.
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