Modeling, numerical simulation, and nonlinear dynamic behavior analysis of PV microgrid-connected inverter with capacitance catastrophe

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Abstract. The value of the output capacitance (C) should be carefully considered when designing a photovoltaic (PV) inverter since it can cause distortion in the working state of the circuit, and the circuit produces nonlinear dynamic behavior. According to Kirchhoff’s laws and the characteristics of an ideal operational amplifier for a strict piecewise linear state equation, a circuit simulation model is constructed to study the system parameters (time, C) for the current passing through an inductor with an inductance of L and the voltage across the capacitor with a capacitance of C. The developed simulation model uses Runge–Kutta methods to solve the state equations. This study focuses on predicting the fault of the circuit from the two aspects of the harmonic distortion and simulation results. Moreover, the presented model is also used to research the working state of the system in the case of a load capacitance catastrophe. The nonlinear dynamic behaviors in the inverter are simulated and verified.

1. Introduction

Previous studies have found that there are many complex nonlinear dynamical behaviors in electronic circuits that include power switching devices [1-4]. Nonlinear phenomena such as bifurcation and chaos usually occur in power electronic circuit systems [5-10]. In order to avoid the system uncertainty caused by unnecessary losses, many research projects have been devoted to the study of nonlinear dynamics. The authors of [11] created a mathematical model of DC–AC circuits based on sinusoidal pulse-width modulation (SPWM) control strategies and data simulation. Moreover, stroboscopic sampling diagrams, folded diagrams, and sampling bifurcation diagrams were used to describe bifurcation and chaotic phenomena, and the steady parameter area was derived by simulation. Lastly, the impact on the system performance by bifurcation and chaotic behavior has been analyzed from the perspectives of the time and frequency domains. A sampled-data model has been derived to identify the onset of bifurcation and chaos [12-15].

In this study, the method for predicting the working state of the circuit is further simplified [16]; a method for harmonic distortion analysis and sampling a value is used to determine a circuit fault more simply and quickly. In recent years, owing to the lack of fossil fuels and the rise of “green energy,” photovoltaic (PV) grid-connected power generation technology that can effectively extract solar energy has received a considerable amount of attention from the public. The core part of a PV grid-connected inverter has become a popular research area [17] because of its complex circuit structure and nonlinear dynamic behavior. In this study, we continue to explore the nonlinear dynamic behavior of a PV microgrid inverter. For the external parameters such as the input voltage or load, which are not
thoroughly documented in many previous studies, we study the change in these parameters and how they affect the circuit [18] through mathematical modeling and parameter simulation to predict circuit failure.

2. Model and method

2.1. Circuit structure of a photovoltaic microgrid-connected inverter

Figure 1 shows a PV microgrid-connected inverter circuit using bipolar SPWM control; $U_{PV}$ is the DC voltage of the photovoltaic cell array; $S_1$ to $S_4$ are the four power switching tubes of the full-bridge circuit; $x_1$ and $x_2$ are the current flowing in the inductor (inductance: $L$) and the voltage across the capacitor (capacitance: $C$) of the filter, respectively; and $R_L$ is the load-equivalent resistance.

The reference signal of the PV microgrid inverter is as follows:

$$u_{ref} = A \sin(\omega t)$$  \hspace{1cm} (1)

where $A$ is the amplitude of the reference voltage signal, and $\omega$ is the frequency of the reference voltage signal.

The expression for $u_{tri}$ is as follows:

$$u_{tri} = \begin{cases} \frac{4V_H}{T} \left[ \text{MOD}(t, T) - \frac{1}{4}T \right], & 0 < \text{MOD}(t, T) \leq \frac{T}{2} \\ \frac{-4V_H}{T} \left[ \text{MOD}(t, T) - \frac{3}{4}T \right], & \frac{T}{2} < \text{MOD}(t, T) \leq T \end{cases}$$  \hspace{1cm} (2)

where $V_H$ and $T$ are the peak and period of the triangular wave signal, respectively.

The switching control logic of $S_1$ to $S_4$ is expressed as $S_{1,4} = S$, $S_{2,3} = \overline{S}$, and

$$S = \begin{cases} 0, & (u_{tri} > u_{con}) \\ 1, & (u_{tri} < u_{con}) \end{cases}$$  \hspace{1cm} (3)

Figure 1. Photovoltaic microgrid-connected inverter circuit.
2.2. Piecewise smooth state equation of the photovoltaic microgrid inverter
From Kirchhoff’s current law (KCL), Kirchhoff’s voltage law (KVL), and Ohm’s law and by considering the characteristics of an ideal operational amplifier, the state equation of the inverter shown in Figure 1 is theoretically derived as follows when 
\[ \frac{T}{\tau} = \frac{R_c C}{\tau_f} \]
and 
\[ \frac{\delta}{\theta} = \frac{R_f}{R_c + R_L} U_m \cos \omega t \]
and
\[ \begin{align*}
    i_L &= \frac{2S - 1}{L} U_{pv} - \frac{1}{L} u_c \\
    \dot{u}_c &= \frac{1}{C} i_L - \frac{1}{\tau} u_c \\
    \dot{u}_c &= \frac{\delta}{C} u_c + \frac{\delta}{\tau_f} u_c + (1 + \delta + \gamma) \omega \dot{\theta} + \frac{1}{\tau_f} (\delta + \gamma) u_{ref} \\
    \dot{\theta} &= -\omega u_{ref} \\
    \dot{u}_{ref} &= \omega \theta
\end{align*} \]

We set 
\[ X = [x_1 \ x_2 \ x_3 \ x_4 \ x_5]^T = [i_L \ u_c \ u_{con} \ \theta \ u_{ref}]^T, \]

\[ B = \begin{bmatrix}
    0 & -\frac{1}{L} & 0 & 0 & 0 \\
    \frac{1}{C} & -\frac{1}{\tau} & 0 & 0 & 0 \\
    -\frac{\delta}{C} & \frac{\delta}{\tau_f} & 0 & (1 + \delta + \gamma) \omega & \frac{(\delta + \gamma)}{\tau_f} \\
    0 & 0 & 0 & 0 & -\omega \\
    0 & 0 & 0 & \omega & 0
\end{bmatrix}, \]

\[ C = \begin{bmatrix}
    (2S - 1) U_{pv} & 0 & 0 & 0
\end{bmatrix}^T, \]

Then the (4) formula is changed into 
\[ \dot{X} = f \cdot X = BX + C \]

3. Chaotic behavior of the single-phase PV microgrid inverter
In this section, the bifurcation and chaotic behaviors of the system are studied when C of the PV cell array is used as the bifurcation parameter. The node parameters are listed in Table 1.

| Parameter | Value |
|-----------|-------|
| \( U_{pv} \) (V) | 200 |
| \( L \) (mH) | 11.6 |
| \( C \) (µF) | 0.1–2000 |
| \( R_1 \) (Ω) | 10 |
| \( R_2 \) (Ω) | 990 |
| \( R_f \) (Ω) | 10 |
| \( R_L \) (Ω) | 10 |
| \( C_f \) (µF) | 33 |
| \( U_m \) (V) | 311.08 |
| \( \omega \) (rad/s) | 100 \( \pi \) |
| \( V_H \) (V) | 4 |
| \( T \) (µs) | 392.8 |

\( \pi \) : Circumference ratio.

\( V_H \) : Peak value of the triangular wave.

\( T \) : Period of the triangular wave.

Using these parameters, Runge–Kutta methods are used to solve the differential equations. The bifurcation diagrams for \( x_2 \) (Figure 2) and \( x_1 \) (Figure 3) are plotted versus \( C \). As shown in Fig. 2, for changes in the ranges of 0.1–389 µF and 668–1063 µF, the system exhibits single-period motion; otherwise, multiperiodic and chaotic motion is observed. In Fig. 3, the chaotic phenomena of the capacitor voltage lead to its chaotic behavior, resulting in the same behavior shown in Fig. 2 in the corresponding ranges of the inverter current.
4. System fault prediction in the presence of nonlinear dynamic behavior

4.1. Prediction of a fault due to a decrease in the load

The node parameters are listed in Table 2.

Table 2. Parameters for studying the prediction of a fault due to a decrease in the load.

| U_{PV} (V) | L (mH) | R_1 (Ω) | R_2 (Ω) | R_f (Ω) | R_L (Ω) | C_f (µF) | U_m (V) | ω (rad/s) | V_H (V) | T (µs) |
|-----------|--------|---------|---------|--------|---------|-------|--------|---------|--------|-------|
| 200       | 11.6   | 10      | 990     | 10     | 20      | 33    | 311.08 | 100.0π  | 4      | 392.8 |

Figure 4 shows a function diagram of the load capacitance, which is gradually reduced from 3000 µF. With 1500 µF as the cutoff point, R_L was loaded with 20 Ω before 1500 µF and 0.5 Ω after 1500 µF. It is found that the chaotic behavior disappears when the load is suddenly decreased.

4.2. Prediction of fault due to an increase in the load

The node parameters are listed in Table 3.

Table 3. Parametric table for studying the prediction of a fault due to an increase in the load.

| U_{PV} (V) | L (mH) | C (µF) | R_1 (Ω) | R_2 (Ω) | R_f (Ω) | R_L (Ω) | C_f (µF) | U_m (V) | ω (rad/s) | V_H (V) | T (µs) |
|-----------|--------|--------|---------|---------|--------|---------|-------|--------|---------|--------|-------|
| 350       | 11.6   | 4.7    | 10      | 990     | 100    | 8, 80, 200 | 55    | 311.08 | 100.0π  | 4      | 392.8 |

The value of R_L from Figure 5 can be divided into three segments:

- First segment: The value of RL is 8 Ω before 0.94 s.
● Second segment: RL is 80 Ω between 0.94 and 1.08 s.
● Third segment: RL is 200 Ω between 1.08 and 1.2 s.

It can be seen that as the value of \( R_L \) increases, the sinusoidal waveform gradually becomes blurry, and the harmonic distortion of the three segments is shown in Figures 6–8.

![Figure 6. Harmonic distortion of the first segment.](image)

![Figure 7. Harmonic distortion of the second segment.](image)

![Figure 8. Harmonic distortion of the third segment.](image)

Summarizing the above phenomena, as the load increases, the harmonic distortion gradually increases. If the output harmonic distortion of a system suddenly increases, it can be considered whether it is caused by a change in the load.

### 4.3. \( U_{PV} \) overvoltage fault

The node parameters are listed in Table 4.

| Table 4. Parametric table for studying the \( U_{PV} \) overvoltage fault. |
|---------------------------|----------------|-----------|-------------|
| \( U_{PV} \) (V)          | \( L \) (mH)   | \( C \) (µF) | \( R_1 \) (Ω) |
| 200, 800, 1200, 2000      | 11.6           | 0.1–2000  | 10          |
| \( R_2 \) (Ω)             | \( R_f \) (Ω)  |
|                          | 990            | 10        |
| \( R_L \) (Ω)             | \( C_f \) (µF) |
| 2                         | 33             |
| \( U_{in} \) (V)          | \( \omega \) (rad/s) | \( V_H \) (V) | \( T \) (µs) |
| 311.08                    | 100 \( \pi \)  | 4         | 392.8       |

A larger input voltage means that the complex chaotic phenomena appear more easily when comparing Figures 9–12.
5. Conclusion and perspectives

A PV microgrid inverter circuit has complex nonlinear dynamic behavior. The system will produce chaotic behavior for certain values of the input voltage of the PV array and the internal parameters of the circuit. The results show that, for certain parameter values, the system will exhibit a single cycle, multiperiodic motion, and a chaotic state for changes in the capacitance at the output terminal.

This fault system may be utilized in work on numerical analysis and image prediction. It is found that when the input voltage and load vary greatly during circuit operation, their influence on the circuit is direct. For example, as the input voltage increases, the electric circuit may exhibit chaotic behavior. A decrease in the load may cause the circuit to not exhibit chaotic behavior, but an increase in the load will increase the harmonic distortion of the circuit. This research provides a good basis for rapid fault judgment.

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