Modeling and Faults Analysis of Distributed Rooftop PV Grid-Connected Power Generation System

John Maynard Keynes*[1, a1], Michael Jackson [2, b], and Adam Smith [2, c]
[1]School of Management, Harvard University, Cambridge, MA 02138, USA;
[2] Business School, National University of Singapore, Singapore.

ABSTRACT

In the background of the energy and environment strategies of "carbon neutrality" and "emission peak ", increasing the installed capacity of new energy power generation has become an inevitable trend. Among them, distributed photovoltaic power generation is flexible and efficient, and its installed capacity is increasing year by year. Rooftop photovoltaic grid-connected power generation systems are particularly popular in rural areas, and are connected to the power system through the distribution network.

This article analyzes the composition of the rooftop photovoltaic grid-connected power generation system and develops the Matlab/Simulink modeling model of the rooftop photovoltaic grid-connected power generation system. By simulating the model, the faults of grid side are set up and the responses of system grid-side and source-side like the voltage, current and DC-side components are summarized.

Keywords: PV generation system; Matlab/Simulink modeling; Fault analysis.

1. INTRODUCTION

In the context of the China's strategies of " carbon neutrality" and " emission peak ", increasing the installed capacity of new energy power generation has become an inevitable trend. Among them, distributed photovoltaic power generation is flexible and efficient, and its installed capacity is increasing year by year. In June 2020, China's photovoltaic installed capacity totaled 216 million kW, and distributed photovoltaic power generation installed capacity totaled 67.07 million kW, accounting for 31.1% of it.

Among them, the rooftop photovoltaic(PV) system that has been promoted in rural areas belongs to the spontaneous self-use surplus grid mode[1]. The rooftop PV grid-connected power generation system is connected to the power grid through low-voltage distribution lines, meeting user needs while delivering power to the grid. Studies have shown that even if the government does not introduce subsidy policies, rooftop PVs in rural areas of China will still generate huge economic benefits [2,3]. In order to maximize economic benefits, the control strategy commonly used in rooftop PV grid-connected power generation systems is that the PV output power according to the maximum power point tracking (MPPT) algorithm, and the grid-connected inverter generates power according to the constant DC-side capacitor terminal voltage unit power factor strategy. The switching device controls the signal to deliver all the maximum PV power to the user in the form of active power, and the remainder is sent to the grid. However, distribution networks in rural areas lack maintenance, are prone to damage, and lack protection equipment [4]. In this case, when users of the multi-user rooftop PV grid-connected power generation system are connected to the distribution network, a failure will cause serious consequences.

The main research object of this article is a single rooftop PV grid-connected power generation system and its fault conditions. It mainly includes the analysis of the system composition and the working principles of each component and the Matlab/Simulink modeling of the system. The rooftop PV grid-connected power generation system outputs a five-level voltage wave from the grid-connected inverter under the control signal, which needs to be connected to the grid through a three-phase filter inductor. Therefore, for rooftop PV grid-connected power generation systems, the part from the PV to the filter inductor is called the source side of the system, and the side from the filter inductor to the grid is

[1*a] UserID@u.nus.edu, [b] xxx@harvard.edu, [c] yyyy@mail.tsinghua.edu.cn

The International Conference Optoelectronic Information and Optical Engineering (OIOE2024), edited by Yang Yue, Lu Leng, Proc. of SPIE Vol. 13513, 135133Y · © 2025 SPIE · 0277-786X · © The Authors.
Published under a Creative Commons Attribution CC-BY 3.0 License · doi: 10.1117/12.3056622

called the grid side. This article uses simulation to explore and analyze the impact on the system when ground faults and phase-to-phase short circuit faults occur on the source and grid sides respectively.

2. MODELING OF PV GRID-CONNECTED POWER GENERATION SYSTEM AND SIMULATION VERIFICATION

The rooftop PV system mainly consists of PV and a grid-connected inverter, and the PV, including PV panels and a BOOST chopper circuit that tracks and controls the output voltage of the PV according to the maximum power point tracking algorithm (MPPT). The inverter is composed of a three-phase inverter bridge circuit, a control loop that generates corresponding control signals, and a three-phase filter inductor. The DC-side capacitor plays a connecting role between the PV and the grid-connected inverter. This capacitor and the three-phase inverter bridge circuit form a voltage source inverter [5].

According to the SPR-305-WHT model PV setting parameters listed in Table 1, the measured I-U and P-U curve simulation characteristics under the standard conditions of irradiance 1kW/m2 and temperature 25 ℃ are shown in Figure.1.

Table 1. SPR-305-WHT PV parameters.

Parameter	Value	Parameter	Value
Maximum power point current	5.58A	Current-temperature coefficient	0.015
Maximum power point voltage	54.7V	Voltage-temperature coefficient	0.7
Open-circuit voltage	64.2V	Series resistance	2Ω
Short-circuit current	5.96A		

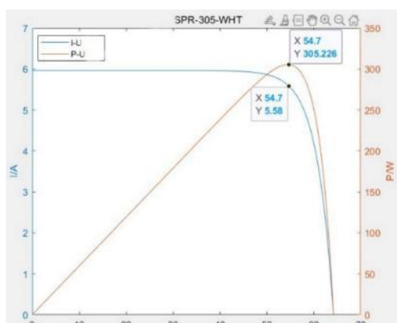

Figure 1. Output characteristic under standard working conditions.

From Figure.1, it can be found that the I-U and P-U curves of the PV panel exhibit nonlinear characteristics: when the terminal voltage of the PV panel is below the maximum power point voltage, the output current value of the PV panel hardly changes with the terminal voltage of the PV panel. The output power of the PV panel changes with the change of the voltage value. At this time, the output power of the PV panel is basically proportional to the terminal voltage value of the PV panel. After the terminal voltage of the PV panel exceeds the maximum power point voltage value, the output current decreases rapidly as the voltage increases. The output power of the panel also drops rapidly until the output current drops to 0 when the PV panel is open circuit.

The output power of the PV panel changes non-linearly with the voltage change. Therefore, in order to send out as much power as possible, it is necessary to set up a circuit to keep the terminal voltage of the PV panel at the maximum power point voltage under the current irradiance and temperature conditions. The MPPT strategy is adopted to adjust the control signal duty cycle of BOOST chopper to maintain the PV output voltage near the maximum power point voltage under current working conditions.

The topology of the two-stage PV grid-connected power generation system is shown in Figure.2. After the electric energy is generated by the PV array panels and passed through the BOOST chopper to achieve maximum DC power transmission, it needs to be sent to the distribution network lines through the three-phase inverter bridge circuit.

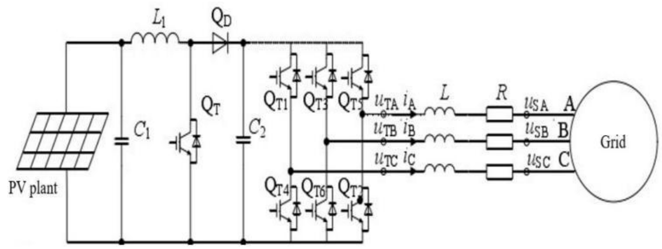

Figure 2. Structure of two-stage PV grid-connected power generation system.

In order to convert all PV current into active power and send it to the grid, PV systems adopt unit power factor control. The PV power generation grid-connected system was modeled in Matlab/Simulink, and a 10kV infinite ideal grid was used as the distribution network bus. Therefore, by setting up a measurement module on the grid side and using the measured voltage signal as the input signal of the third-order phase-locked loop, the corresponding oscillating voltage phase signal can be generated. The specific parameters of the model are shown in Table 2.

Table 2. Simulation parameter settings.

Parameter	Value	Parameter	Value
L_{inv}	3 mH	Filter inductor L_g	1 mH
C	50μF	DC-side capacitor voltage U_{dc}	700 V
Grid phase voltage	380 V	Grid frequency	50 Hz
Output voltage of PV system	300 V-350 V	DC-side capacitor C_{dc}	3200μF
Rated power	100 kW	Inverter switching frequency	20 kHz

The voltage and current waveforms of PV A phase are shown in Figure.3 and the output of PV are shown in Figure.4. When the system working conditions remain unchanged, the control reaches stability. At this time, it is observed that the PV terminal voltage and output current waveform remain stable, while the output power is always maintained at the rated 100kW. This shows that the MPPT algorithm operates effectively and the PV outputs electric energy at its maximum power under standard conditions.

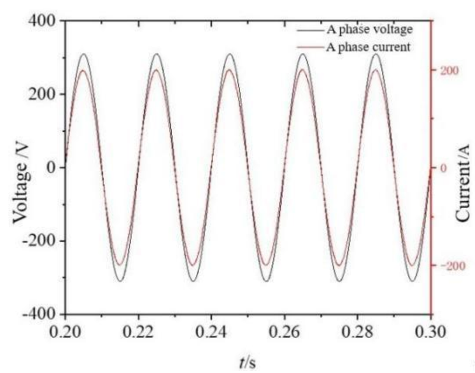

Figure 3. Voltage and current waveforms of PV A phase.

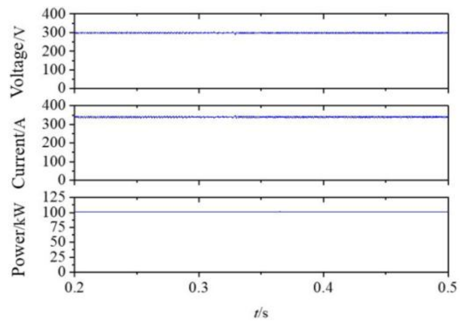

Figure 4. The output of PV plant.

3. IMPACT OF GRID-SIDE FAULTS ON ROOFTOP PV GRID-CONNECTED POWER GENERATION SYSTEMS

Since the rooftop PV grid-connected power generation system adopts a grid-following control strategy, when a fault occurs on one side of the distribution network, the voltage and current amplitude information obtained by the system from the grid side cannot be used to generate control signals required for normal operation. At this time, under the action of the inverter circuit control signal generated by the unit power factor control strategy of the constant DC-side capacitor terminal voltage, the output current and voltage of the grid-connected inverter will be abnormal, and the MPPT algorithm of the PV will also fail. The response of the source side to the grid-side fault will in turn affect the power flow of the distribution network.

The controlling strategy of constant DC-side capacitor voltage and unit power factor is adopted here. On the basis of the established model, different ground faults and phase-to-phase short circuit faults were set up on the grid side. According to the responses of source and grid side three-phase grid currents and voltage, the impact of grid-side faults can be analyzed. The simulation is carried out under the condition that the irradiance is 1000W/m2 and the temperature is 25℃

3.1 Ground Faults

When rooftop PV is installed, the PV panels are directly fixed on the roof of the user's house through rivets, etc., and connected to the switch network through overhead lines. The height of the overhead line from the ground is usually lower than that of the regular switching network overhead line, and because it is close to the user's house, it is easy to be hung up on common floating objects or damaged. In the case where the line connecting the rooftop PV grid-connected power generation system to the AC distribution network generally has a higher outlet ground fault occurs in the general distribution network line. PV grid-connected power generation systems in rural areas are generally constructed using power generation systems, while those in rural areas Power grid lines are often aged and damaged due to economic and environmental factors. The situation in urban power grids is more serious, so the accident rate is also higher.

By setting single-phase and two-phase ground faults at the Simulink model connection point of the rooftop PV grid-connected power generation system, the voltage and current waveforms on the source side and grid side of the system, as well as the PV terminal voltage and output power are recorded and analyzed. Research Network The impact of side ground faults on the grid connected to the PV rooftop concurrent grid system.

3.1.1 Single-phase ground faults

In order to simulate a single-phase ground fault in the grid-side line, the grid-side A-phase ground fault occurrence time is set to 0.1s in the simulation model. The fault disappears after 0.1s. The results are shown in Figure.5-7.

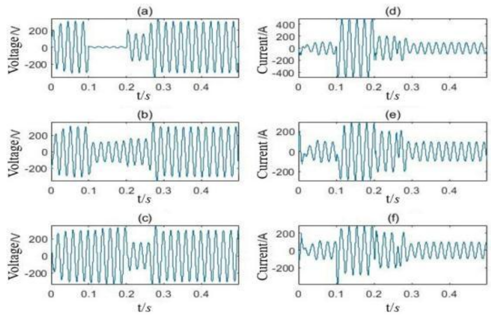

Figure 5. The grid-side three-phase voltage and current.

(a)~ (c) grid-side voltage of phase A,B and C

(d)~ (f) grid-side current of phase A,B and C

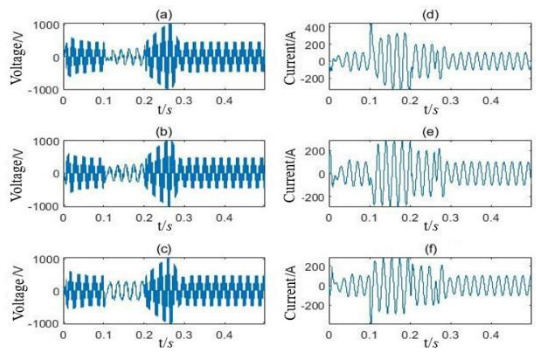

Figure 6. The source-side three-phase voltage and current.

(a)~ (c) source-side voltage of phase A,B and C

(d)~ (f) source-side current of phase A,B and C

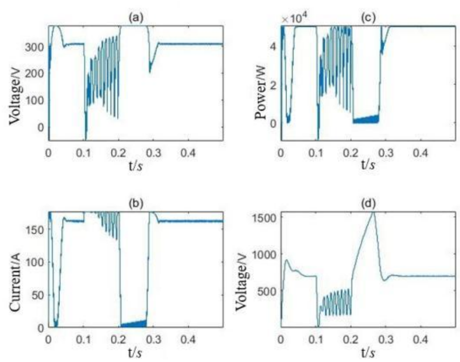

Figure 7. The output voltage, current and power of PV plant and the voltage of DC-side capacitance.

(a)~ (c) output voltage, current and power of PV plant

(d) voltage of DC-side capacitance

After a single-phase ground fault occurs in phase A on the grid side of the system, it can be seen that the voltage on phase A on the grid side immediately drops to 0, and the voltage on phase B drops to 0.53pu. At the same time, the current amplitude on the A-phase grid side suddenly increased to 5.01pu, and the B and C phase currents suddenly increased to 3.04pu respectively.

When a single-phase ground fault occurs, the three-phase output voltage on the source side is a distorted waveform instead of the five-level inverter voltage wave when the system is operating normally. The current amplitude of the A-phase source side suddenly increased to 3.23pu, and the current of the B and C phases suddenly increased to 2.82pu.

During the fault, the MPPT algorithm on the DC side of the rooftop PV grid-connected power generation system failed: the PV output current and terminal voltage both oscillated, causing the PV DC output power to also oscillate and unable to output power to the grid at the maximum power. During this process, no PV terminal voltage and output power are always non-negative, indicating that no power backfeed occurs.

The fault disappeared after 0.2 seconds. From the PV DC power and source-side inverter voltage and current waveforms, it can be seen that the system restored the control of the DC side by the MPPT algorithm about 0.05 seconds after the single-phase ground fault disappeared, and reappeared within 0.1 seconds. Constant DC side voltage unit power factor control for the inverter and DC-side capacitor voltage. However, during this recovery period, the DC-side capacitor terminal voltage experienced an overcharge situation similar to a two-phase ground faults or phase-to-phase short circuit fault on the source side. The highest voltage value reached 2.25pu of the original 700V.

3.1.2 Two-phase ground faults

In the Simulink model of the rooftop PV grid-connected power generation system, a two-phase ground fault lasting 0.1 seconds occurs in the two-phase lines A and B on the source side for simulation.

The simulation results showed that when a two-phase ground fault occurs on the A and B phases of the system grid side at 0.1 seconds, the voltage on the two-phase grid side immediately drops to 0, while the voltage amplitude of phase C without a ground fault drops to 0.4pu. During the fault, the grid-side current amplitude in the A and B phase lines suddenly increased to 5.01pu, and the C-phase current amplitude increased to 3.04pu.

When a two-phase ground fault occurs, the three-phase output voltage on the source side is a distorted waveform instead of the five-level inverter voltage wave when the system is operating normally. The current amplitude of the A and B phase source sides suddenly increased to 5.42pu, and the current of the C two-phase source side suddenly increased to 2.29pu.

During the two-phase ground fault on the grid side, the PV terminal voltage, output current and DC power waveforms showed oscillation phenomena similar to those under the action of a single-phase ground fault, but the oscillation amplitude was larger but the PV power never showed negative values, indicating that there was no This occurs when power is sent back from the grid to the PV. The oscillation amplitude of the voltage waveform at the DC-side capacitor is similar to that of a single-phase ground fault.

The two-phase ground fault on the grid side ends at 0.2 seconds. At this time, the three-phase source side voltages of A, B, and C begin to output an approximately five-level inverter voltage wave. After a transient process that lasts for more than 0.1 seconds, it returns to the normal five-level voltage wave. Level inverter voltage output, the total time to return to normal working state is about 0.18 seconds. During this period, the voltage at the DC-side capacitor terminal was overcharged by 2.36pu. In addition, after the two-phase ground fault is eliminated, the PV voltage suddenly increases and the output current drops suddenly. It does not return to the maximum power output under the MPPT algorithm until the transient process is over.

3.2 Phase-to-phase Short Circuit Faults

In the distribution grid system, due to the close distance between different phase lines, in some cases, conductors or arc connections between phases lead to short-circuit faults, which are called phase-to-phase short-circuit faults [6]. In order to explore the impact of grid-side phase-to-phase short circuit fault on the rooftop PV grid-connected power generation system, two-phase and three-phase phase-to-phase short circuit faults were set up at the Simulink model grid connection point for simulation research.

3.2.1 Two-phase phase-to-phase short circuit fault

In the model, the phase-to-phase short circuit fault of phase A and phase B on the grid side is set to start at 0.1 seconds and last for 0.1 seconds for simulation analysis. The results are shown in Figures 8-10.

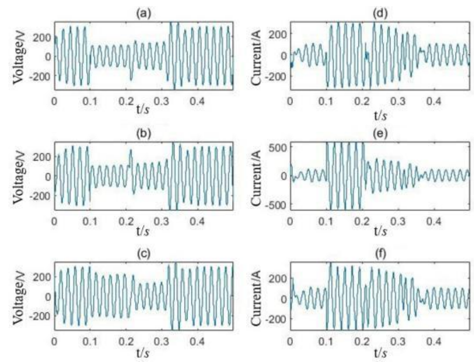

Figure 8. The grid-side three-phase voltage and current.

(a)~ (c) grid-side voltage of phase A,B and C

(d)~ (f) grid-side current of phase A,B and C

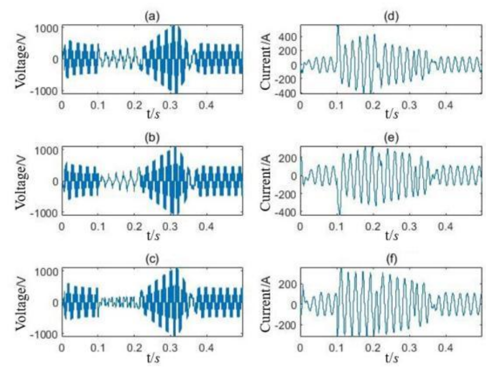

Figure 9. The source-side three-phase voltage and current.

(a)~ (c) source-side voltage of phase A,B and C

(d)~ (f) source-side current of phase A,B and C

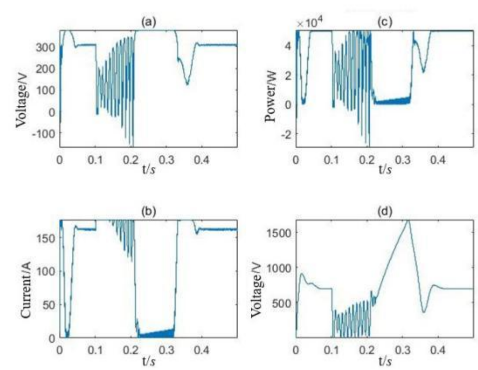

Figure 10.The output voltage, current and power of PV plant and the voltage of DC-side capacitance.

(a)~ (c) output voltage, current and power of PV plant

(d) voltage of DC-side capacitance

When a two-phase short-circuit fault occurs between phases A and B on the system grid side at 0.1 seconds, the voltage amplitude of the two-phase grid side drops to 0.35pu, while the voltage of phase C that does not fail drops to 0.69pu. In addition, the three-phase current on the grid side of the system, the three-phase voltage and current on the source side, and the PV terminal voltage, output current and power waveforms under the action of a two-phase short-circuit fault are similar to those under a two-phase ground fault on the grid side A and B. The fault ended at 0.2 seconds, and the system also showed a transient process similar to that after the two-phase ground fault ended in about 0.1 seconds. It takes a total of about 0.21 seconds to return to normal working status. Different from the two-phase ground fault on the grid side, under the action of the two-phase short-circuit fault, the PV terminal voltage and output current will have negative values during the oscillation process, indicating that reverse power transmission has occurred.

3.2.2 Three-phase phase-to-phase short circuit fault

By setting a three-phase phase-to-phase short-circuit fault on the grid side A, B, and C in the model that starts at 0.1 seconds and lasts for 0.1 seconds, the impact of the three-phase phase-to-phase short circuit fault on the grid side on the system is analyzed.

It is known from the results that when a three-phase short-circuit fault occurs in the grid-side line of the system at 0.1 seconds, the three-phase grid-side voltage immediately drops to 0, and the grid-side current amplitude suddenly changes to 5.14pu.

When a grid-side three-phase short-circuit fault occurs, the three-phase source side voltage amplitude output amplitude is smaller than the distorted waveform of the five-level inverter voltage wave under normal operating conditions, while the source side three-phase current amplitude suddenly increases to 5.23pu.

After the fault occurs, the DC-side capacitor voltage oscillates. No power feedback occurs in the PV.
The grid-side three-phase short-circuit fault ended 0.2 seconds later, and the system gradually returned to normal operating status after experiencing a transient process from the fault state. During this process, the voltage at the DC-side capacitor terminal was overcharged, but the maximum overcharge voltage was only 1.78pu of the original target of 700V, which was smaller than the voltage overcharge caused by the disappearance of the two-phase short circuit fault on the grid side. Compared with the system that takes about 0.4 seconds to return to normal after the source-side three-phase short-circuit fault disappears, the system returns to normal working state faster after the grid-side three-phase short-circuit fault ends, with a recovery time of about 0.1 seconds.

Tables 3 to 6 list the impact of the occurrence and end of grid-side faults on the source and grid sides of the system, including the changes in source and grid-side fault/non-fault phase voltage and current, and whether PV reverse power transmission occurs during the fault or whether the DC-side capacitor voltage is overcharged after the fault is over, etc. All data in the table are written in per unit form. In addition, the time it takes for the system to return to normal after the fault is over is also calculated and listed in Table 6.

Table 3. Impact on the source side of the system.

Fault category	Voltage of fault phase	Current of fault phase	Voltage of non-fault phase	Current of non-fault phase	PV reverse power transmission
Single phase grounded	drop to 0.50pu	increase to 3.23pu	drop to 0.53pu	increase to 2.82pu	No
Double phase grounded	drop to 0.35pu	increase to 5.42pu	drop to 0.32pu	increase to 2.29pu	No
Short circuit between 2 phases	drop to 0.49pu	increase to 2.71pu	drop to 0.22pu	increase to 2.89pu	Yes
Short circuit between 3 phases	drop to 0.79pu	increase to 5.23pu	——	——	No

Table 4. Impact on the grid side of the system.

Fault category	Voltage of fault phase	Current of fault phase	Voltage of non-fault phase	Current of non-fault phase
Single phase grounded	drop to 0	increase to 5.01pu	drop to 0.40pu	increase to 3.04pu
Double phase grounded	drop to 0	increase to 5.08pu	drop to 0.88pu	increase to 2.66pu
Short circuit between 2 phases	drop to 0.35pu	increase to 3.02pu	drop to 0.69pu	increase to 3.16pu
Short circuit between 3 phases	drop to 0	increase to 5.14pu	——	——

Table 5. Impact on the source side of the system when the fault ends.

Fault category	Voltage of fault phase	Current of fault phase	Voltage of non-fault phase	Current of non-fault phase	Overcharged voltage of DC-side capacitor
Single phase grounded	increase to 2.25pu	increase to 1.94pu	increase to 2.15pu	increase to 1.92pu	increase to 2.25pu
Double phase grounded	increase to 2.27pu	increase to 2.01pu	increase to 2.34pu	increase to 1.96pu	increase to 2.36pu
Short circuit between 2 phases	increase to 2.28pu	increase to 2.69pu	increase to 2.38pu	increase to 2.57pu	increase to 2.40pu
Short circuit between 3 phases	increase to 1.74pu	increase to 1.98pu	——	——	increase to 1.78pu

Table 6. The impact on the grid side of the system when the network side fault ends and the time to restore normal working status.

Fault category	Voltage of fault phase	Current of fault phase	Voltage of non-fault phase	Current of non-fault phase	the time to restore normal working status /s
Single phase grounded	drop to 0.50pu	increase to 2.09pu	drop to 0.51pu	increase to 2.09pu	0.1
Double phase grounded	drop to 0.57pu	increase to 2.08pu	drop to 0.79pu	increase to 2.08pu	0.18
Short circuit between 2 phases	drop to 0.49pu	increase to 2.51pu	drop to 0.45pu	recover to1pu	0.21
Short circuit between 3 phases	drop to 0.77pu	increase to 2.04pu	——	——	0.1

According to the data in Tables 3-1 to 3-4, it can be summarized as follows:

1. When a ground fault or phase-to-phase short circuit fault occurs on the grid side of the system, the voltage of the fault phase source and grid side drops and the current increases;

2. A two-phase ground fault on the grid side will also cause PV power to be sent back, which may cause damage to PV;

3. When single-phase ground faults, double-phase ground faults and two-phase short circuit faults on the grid side end, the DC-side capacitor terminal voltage will exceed 2.3pu and the voltage will be overcharged, which may damage the DC-side capacitor or cause other accidents;

4. When a two-phase ground fault occurs on the grid side, the magnitude of the sudden change in voltage and current during and after the fault is greater than that caused by a single-phase ground fault, and it takes longer for the system to return to normal operating conditions. However, the impact caused by a three-phase phase-to-phase short circuit fault is less than that of a two-phase phase-to-phase short circuit fault.

4. SUMMARY

This paper studied the Matlab/Simulink modeling and grid-side fault simulation of the rooftop PV system, confirms the effectiveness of the control strategy of the rooftop PV system, and also obtains the system's fault response when the distribution network fails under this strategy. In the future, further simulation research can be conducted to explore the impact of faults in larger-scale, high-proportion distributed PV access systems. In addition, the grid-side voltage and current waveforms under the action of faults can also be used as input conditions, and the response of various equipment in the distribution network, including distribution transformers, under the influence of this influence can be analyzed through multi-physics simulation.

5. ACKNOWLEDGMENTS

This work was funded by the Science and Technology Project of State Grid Jiangxi Electric Power Co., Ltd(Development and application of a new type of distribution transformer with rapid and wide range voltage regulation on secondary side, 5218A023000L).

REFERENCES

[1] Chaohui Hou. Research on grid connection of rooftop power generation photovoltaic system[D]. Hebei Agricultural University, 2016.

[2] Yang Y, Campana P, Yan J. Potential of unsubsidized distributed solar PV to replace coal-fired power plants, and profits classification in Chinese cities[J]. Renewable and Sustainable Energy Reviews, 2020, 131:109967.

[3] Minli Yu, Fu Sheng Tsai, Hui Jin, et al. Digital finance and renewable energy consumption: evidence from China[J]. Economic Modelling,2020,86:317-326.

[4] Jinghao Zhang. Research on friendly access and operation and maintenance technology of high-proportion distributed poverty alleviation photovoltaic power stations in weak rural distribution networks [D]. Wuhan: Huazhong University of Science and Technology, 2021.

[5] Deming Wang. Fault analysis and protection research on distribution network containing distributed photovoltaic power supply[D]. Xi'an: Xi'an Petroleum University, 2021.

[6] Chaojun Jiang. Measures for locating phase-to-phase short circuit faults in 10kV distribution network [J]. Electrical Technology,2020(21):78-79.DOI:10.19768/j.cnki.dgjs.2020.21.020.