FAULT LEG DETECTION FOR OPEN-CIRCUIT FAULTS IN PWM VOLTAGE-SOURCE INVERTERS OF RENEWABLE ENERGY VIA THE FUZZY LOGIC DIAGNOSTIC METHOD

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ABSTRACT

An inverter is a critical piece of equipment for connecting green energy to a power grid, and whether the inverter equipment works normally will influence if the electrical energy generated by green energy can be smoothly transmitted to the power grid. This study explores the influence of a single thyristor and transistor open-circuit faults of an inverter on the output current waveform of the inverter. A computer is used to simulate the fault symptoms of the inverter, and the fault features are discussed, Clarke’s transformation is used to transform a three-phase current signal into stationary coordinates in order to observe the distributional characteristics. An expert system is constructed using fuzzy logic to analyse and evaluate the running state of the inverter, and a testing machine is used in the laboratory to test the feasibility of the proposed method. The results show that this method can implement analysis and evaluation of the running state of an inverter.

I. INTRODUCTION

Many countries have invested large amounts of research labour in developing new energy sources in response to the energy crisis and the goal of low carbon emissions. Green energy is a research emphasis in many countries, and at present, the mature power generation technologies include solar and wind electric power generation. Although these are adequate sources of clean energies, they are still unstable energy sources. For example, the electrical energy generated by wind power is AC voltage, and the frequency and electric quantity of the voltage varies with the amount of wind energy, while the electrical energy generated by solar panels is DC voltage.

Therefore, for solar power and wind electric power generation, a DC power supply or unstable AC power supply must be converted by an electrical energy conversion device into a stable AC power supply. A common electrical energy conversion device is an inverter.

The inverter is a key piece of equipment for solar power and wind electric power generation. As such energy sources may be located in isolated island operations, whether the operating function of the inverter is normal can influence the
Current studies on the diagnostic techniques for inverter faults can be summarized according to parameter types and techniques, as follows:

1. Use cross-voltage on a thyristor [2, 3].
2. Use pole voltage and time behavior [4].
3. Use the error values between the upper thyristor current and lower thyristor current of an inverter for diagnosis [5].
4. Intermittent misfiring faults in an inverter switch are detected based on the time domain response of the stator current [2, 6].
5. The current vector trajectory [1-2, 7-9] and instantaneous frequency of the current vector are used to identify the inverter fault pattern [2, 7].
6. The error values between the measured current value and the current value, as estimated at the load end, are used for diagnosis [10].
7. The manipulator workspace residuals are regarded as the standard of diagnosis. In normal conditions, the residuals are close to zero. In case of open-circuit faults, the residuals will be greater than the predetermined threshold [11].
8. Three-phase waveforms are reconstructed by using time displacement, and the differences are compared and the type of fault is identified through correlation coefficients [12].

II. FEATURE ANALYSIS FOR OPEN-SWITCH INVERTER FAULTS

An inverter is a device that converts DC voltage into AC output voltage with a stable frequency. A three-phase inverter consists of six transistors or thyristors and six diodes, and the output voltage and frequency of the inverter are changed by controlling the width of the trigger pulse wave. This study uses the controlled inverter trigger pulse wave signal to simulate open-circuit faults in six transistors or thy-
risors. The load characteristics and capacities are changed to discuss the characteristics of the three-phase current waveform when an open-circuit fault occurs in any arm of the inverter.

1. Using Matlab/Simulink to Build and Simulate an Open-Circuit Fault in an Arm of the Inverter

A simulation system for a three-phase inverter is constructed using the SimPowerSystem tools of Matlab/Simulink. The gate trigger signal of the three-phase inverter is generated using discrete PWM generator six pulses, and different load conditions are generated by a three-phase series RLC load, as shown in Fig. 1.

An inverter operating in isolated island operation mode can be simulated by changing the load impedance parameter of the three-phase series RLC load, where the power grid for the inverter may be an unbalanced load or a load with a lower power factor.

In the common inverter control mode, a current transformer is used to extract the output current waveform of the inverter, thus, using Park’s transformation, the extracted three-phase current waveform is transformed into D-Q axis coordinates, which rotates synchronously with the power supply frequency before control operations. This study reduced the complexity and equipment costs by using Clarke’s transformation to transform the extracted three-phase current waveform into stationary $\alpha-\beta$ axis coordinates, as expressed in (1).

$$\begin{bmatrix}
i_a \\ i_b \\ i_c\
\end{bmatrix} = \frac{2}{3} \begin{bmatrix}
1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ 1 & 1 & 1
\end{bmatrix} \begin{bmatrix}
i_x \\ i_y \\ i_z\
\end{bmatrix}$$

(1)

In order to avoid the influence of capacity value, as caused by varying degrees of load resulting in different distribution ranges on the $\alpha-\beta$ coordinate plane, this paper standardizes the data of the $\alpha-\beta$ axis coordinates.

2. Normal State

Fig. 2 shows the output waveform of the inverter when the six gate trigger signals of the simulated inverter are normal. Fig. 2(a) shows the inverter output waveform before being processed by a 100 Hz low pass filter, while Fig. 2(b) shows the inverter output waveform after being processed by a 100 Hz low pass filter. Fig. 2(c) shows the kinematic trajectory of the waveform in Fig. 2(a) on the $\alpha-\beta$ axis coordinates, and Fig. 2(d) shows the kinematic trajectory of the waveform in Fig. 2(b) on the $\alpha-\beta$ axis coordinates.
Fig. 3 Current waveform when an open-circuit fault occurs in the upper arm of the $R$ phase

Fig. 4 Simulation results of the fault feature on the $\alpha$-$\beta$ map when the open-circuit fault occurs to: (a) the upper switch of the $R$ phase (left side) and the lower switch of the $R$ phase (right side); (b) the upper switch of the $S$ phase (left side) and the lower switch of the $S$ phase (right side); (c) the upper switch of the $T$ phase (left side) and the lower switch of the $T$ phase (right side)

Fig. 2 shows that the inverter output waveform before processing contains many harmonic components, and the kinematic trajectory on the $\alpha$-$\beta$ axis coordinates is hexagonal. When the inverter output waveform was processed by a 100 Hz low pass filter, the kinematic trajectory on the $\alpha$-$\beta$ axis coordinates was circular.

3. Change in Characteristics of the Inverter Disconnection Fault on the $\alpha$-$\beta$ Axis

When an open-circuit fault occurs in the upper arm of the $R$ phase, the output current waveform will have an unbalanced distortion, as shown in Fig. 3. It was observed that, when an open-circuit fault occurs in the upper arm of the $R$ phase, the positive half-cycle amplitude value of the $R$ phase current waveform was about -0.25 p.u., while the negative half-cycle amplitude value was about 1 p.u. Although the other two phases can maintain a sinusoidal waveform, the amplitude value was unbalanced. Fig. 3(b) shows that, when a low pass filter filters signals above 100 Hz, the $R$ phase current has an offset of sine wave plus DC. As
the $R$ phase current was a waveform with an average not equal to 0, meaning the current waveform contains a DC offset, the temperature of the $R$ phase thyristor will rise and the residual workable thyristors of the $R$ phase will receive heavier stress, thus, accelerating the aging of the thyristors.

Fig. 4 shows that, when an open-circuit fault occurs in the various arms, the current in the open-circuit fault period will be processed by the low pass filter, the filtered signals will be standardized, and the distribution on the $\alpha-\beta$ plane of the stationary coordinate axes will be obtained by Clarke’s transformation. It was observed that the distribution areas on the $\alpha-\beta$ plane were different in the open-circuit fault period of each arm.

In order to easily describe the distribution areas, the distribution areas on the $\alpha-\beta$ plane are converted into the gravity center of distribution using Eqs. (2) and (3).

\begin{align}
I_\alpha &= \frac{1}{n} \sum_{k=1}^{n} i_\alpha(k) \\
I_\beta &= \frac{1}{n} \sum_{k=1}^{n} i_\beta(k)
\end{align}

where $n$ is the amount of data measured in the experiment.

4. Influence of the Electric Power Factor on the Characteristic Gravity Center on the $\alpha-\beta$ Axis

In order to discuss whether the power factor of the load influences the center of the distribution area of the current on the $\alpha-\beta$ plane, this study began with a simulated pure resistive load with a power factor of one. The power factor was changed into an R-L load with a power factor of 0.7, which gradually lagged by changing the power factor by 0.01 each time. The simulation result is as shown in Fig. 5.
Open-circuit fault occurs to Q1
Open-circuit fault occurs to Q2
Open-circuit fault occurs to Q3
Open-circuit fault occurs to Q4
Open-circuit fault occurs to Q5
Open-circuit fault occurs to Q6

**Fig. 6** Trajectory of change in the centre of the distribution area on the \( \alpha-\beta \) plane when an open-circuit fault occurs in the upper and lower arms of the \( R \) phase, \( S \) phase, and \( T \) phase, respectively.

The left and right figures show the trajectory of changes in the center of the distribution area when the power factor was changed from 1 to 0.7, and open-circuit faults occur in both the upper arm and the lower arm, respectively. Figs. 5(a)-(c) show the trajectory changes in the center of the distribution area on the \( \alpha-\beta \) plane when open-circuit faults occur in the upper and lower arms of the \( R \) phase, \( S \) phase, and \( T \) phase, respectively.

It was observed that, whichever arm the open-circuit fault occurs in, the trajectory of change in the center of the distribution area on the \( \alpha-\beta \) plane will extend outwards as the power factor decreases.

However, the spacer regions among the centers of the distribution areas on the \( \alpha-\beta \) plane, as resulting from different fault types, remain apparent, as shown in Fig. 6, in which Q1 represents the upper arm thyristor of the \( R \) phase, Q2 represents the lower arm thyristor of the \( R \) phase, Q3 represents the upper arm thyristor of the \( S \) phase, Q4 represents the lower arm thyristor of the \( S \) phase, Q5 represents the upper arm thyristor of the \( T \) phase, and Q6 represents the lower arm thyristor of the \( T \) phase.

5. Influence of Capacity on the Characteristic Gravity Center on \( \alpha-\beta \) Axis

The circuit shown in Fig. 1 is used to simulate load balancing, namely, the capacity of the three-phase load is changed to simulate the influence of the process of load growth on the characteristic gravity center on the \( \alpha-\beta \) axis when load balancing is increased by degrees. The simulation analysis results show that the process of load growth has slight influence on the characteristic gravity center on the \( \alpha-\beta \) axis.

6. Influence of Load Unbalance on the Characteristic Gravity Center on the \( \alpha-\beta \) Axis

The circuit shown in Fig. 1 is used to simulate load unbalance, namely, a variable resistor was inserted in the \( R \) phase wire to simulate the influence of the degree of load unbalance on the characteristic gravity center on the \( \alpha-\beta \) axis when the load was unbalanced. The simulation analysis results show that the load unbalance produces an insignificant impact on the distribution areas of the center of gravity of the fault trajectory.

III. PROPOSED FAULT DIAGNOSIS ALGORITHM

According to the simulation analysis of Section II, when the inverter was working in the normal state and an open-circuit fault occurs in any arm of the six-arm thyristor of the three-phase inverter, if the output current of the inverter is standardized by a low pass filter, after Clarke’s transformation, the distribution areas on the \( \alpha-\beta \) plane will be different; therefore, the present running state of the inverter can be identified according to the situation marked on the \( \alpha-\beta \) plane.

According to the above discussion, when the distribution area of the output current trajectory of the inverter on the \( \alpha-\beta \) plane is used for diagnosis, it is very important to define the boundary regions of the various states in order to avoid misrecognition. However, it is difficult to specify boundary regions.

The method for analyzing the inverter running state, as proposed in this paper, uses fuzzy logic to define the boun-
Fig. 8  Input-output surface of the fuzzy inference system and the membership functions, as based on diagnostic variables $\alpha$ and $\beta$

dary region according to the aforesaid phenomenon, in order to implement evaluation of the inverter running state, as shown in Fig. 7.

1. Fuzzy Logic

Fuzzy logic combines fuzzy and probability theories with a knowledge base, which can simulate and implement the uncertainties of actual states and human thinking behavior patterns by converting expertise into specific and realizable rules through language listings.

The fuzzy theory consists of the three steps of fuzzification, fuzzy rule base inference, and defuzzification.

2. Fuzzification

The purpose of fuzzification is to convert data, which is explicitly measured by the system using a membership function, into the required fuzzy values for simulation calculation. The fuzzy set uses the concept of membership function, and the numerical range of the membership function was $[0, 1]$. In a fuzzy set, the greater the membership of an element to a set is, the closer to 1 the membership grade will be; otherwise, the closer it will be to 0. The membership function is made as required, and without any hard rules.

The spacer regions among the centers of the distribution areas on the $\alpha$-$\beta$ plane, as resulted from the various fault types, are apparent in Fig. 6. Therefore, the $\alpha$-axis and $\beta$-axis are divided into four or five fuzzy sets, namely, I to IV and I to V fuzzy sets, respectively, according to experience, as shown in Figs. 8(a) and (b). The output of class is classified into seven classes, including the normal class and the Q1-Q6 classes, as shown in Fig. 8(c). The relationship between the input $\alpha$-axis and $\beta$-axis variables and the output variable of the fuzzy inference system is as shown in Fig. 8(d).

3. Inference Engine

The appropriate semantic diagnosis rule is selected from the fuzzy rule base by simulating a logic operation that simulates human thinking, and the imported fuzzified variable is calculated in the parallel mode to obtain the fuzzified output.

4. Rule Base

The fuzzy rule base represents the thinking rule of the overall diagnostic system. The stored diagnosis rule is combined with expert intelligence in order to express the various probable states of the diagnostic equipment as a fuzzy algorithm containing expert judgment in the if-then line format. Nine rules can be obtained from the conclusions of the simulation study and practical experience, which are described, as follows:

R1: If the $\beta$-axis is I and the $\alpha$-axis is II, then the output is Q1.
R2: If the $\beta$-axis is II and the $\alpha$-axis is I, then the output is Q4.
R3: If the $\beta$-axis is II and the $\alpha$-axis is IV, then the output is Q6.
R4: If the $\beta$-axis is III and the $\alpha$-axis is II, then the output
is normal.

R5: If the $\beta$-axis is IV and the $\alpha$-axis is I, then the output is Q5.

R6: If the $\beta$-axis is IV and the $\alpha$-axis is IV, then the output is Q3.

R7: If the $\beta$-axis is V and the $\alpha$-axis is II, then the output is Q2.

R8: If the $\beta$-axis is I and the $\alpha$-axis is III, then the output is Q1.

R9: If the $\beta$-axis is IV and the $\alpha$-axis is III, then the output is normal.

5. Defuzzification

The fuzzy set is transformed into specific output through the reasonable and appropriate calculations of the results of the fuzzy inference.

IV. LABORATORY MEASUREMENTS AND DISCUSSION

1. Experimental results

This study used a set of miniature DC motor-DC generating sets to simulate the power generation characteristics of a wind turbine. The generated DC voltage was step-up boosted and transmitted to the inverter to be converted into a three-phase AC power supply, and this three-phase supply was transmitted to the Y-connection load with a variable resistance value, and the generated energy was consumed.

This paper used a host PC to control the rotation speed of the DC motor, the status commands of the inverter, and the commands for changing the load impedance value. These commands were sent to the real-time PC, which measured and recorded the various parameter values, and then, fed back the observed trajectory of the parametric variations to the host PC. The structure is as shown in Fig. 9.

Fig. 10 shows the running trajectories on the $\alpha\beta$ plane when an open-circuit fault occurs in the various arms of the inverter. It is observed that the running trajectories on the $\alpha\beta$ plane are similar to the simulation results shown in Fig. 4. The distribution areas of the running trajectories on the $\alpha\beta$ plane of the open circuit of each arm are different, meaning that the distribution gravity centers on the $\alpha\beta$ plane of the open circuit of each arm are different.

2. Discussion

In order to discuss the applicability of the fuzzy logic evaluation rule, as proposed in Section III, and the smallest data length for operation, this paper gives the host PC commands for two balanced load impedance values (case 1: $ZR = 1000 \Omega$, $ZS = 1000 \Omega$, $ZT = 1000 \Omega$; case 2: $ZR = 1500 \Omega$, $ZS = 1500 \Omega$, $ZT = 1500 \Omega$) and four unbalance load impedance values (case 1: $ZR = 2000 \Omega$, $ZS = 1500 \Omega$, $ZT = 1500 \Omega$; case 2: $ZR = 3000 \Omega$, $ZS = 1500 \Omega$, $ZT = 1500 \Omega$; case 3: $ZR = 3000 + j0.0075 \Omega$, $ZS = 1500 + j0.0075 \Omega$, $ZT = 1500 + j0.0075 \Omega$; case 4: $ZR = 3000 + j0.02 \Omega$, $ZS = 1500 + j0.0075 \Omega$, $ZT = 1500 + j0.0075 \Omega$). There are seven commands for the on-off state of the inverter: normal, Q1 open, Q2 open, Q3 open, Q4 open, Q5 open, and Q6 open.

The data lengths for the tests were one cycle and two cycles, respectively, and each state was tested 20 times.

It was found that, when the tested data length was one cycle, the state of the inverter can be accurately diagnosed, with the exception of one instance, when the unbalance load impedance values ($ZR = 3000 \Omega$, $ZS = 1500 \Omega$, $ZT = 1500 \Omega$) misidentified Q1 open as a normal state. When the tested data length was two cycles, the state of the inverter was accurately diagnosed in 20 tests.
Fig. 10 Experimental results of the fault feature on the $\alpha$-$\beta$ map when the open-circuit fault occurs on (a) the upper switch of the $R$ phase (left side) and the lower switch of the $R$ phase (right side); (b) the upper switch of the $S$ phase (left side) and the lower switch of the $S$ phase (right side); (c) the upper switch of the $T$ phase (left side) and the lower switch of the $T$ phase (right side)

V. CONCLUSIONS

An inverter is a key piece of equipment for solar power and wind electric power generation; therefore, the performance of the operating characteristics of the inverter will influence the generating efficiency of renewable energy. If a fault occurs in the inverter, the power supply quality will be influenced and the load will be damaged.

In order to shorten the time required for a maintenance firm to evaluate the running state of an inverter, and thus, avoid changing the hardware architecture of the inverter, the waveform characteristics of the output current of the inverter are applied. The current waveform signals of the output current of the inverter are extracted by a current transformer and processed using a low pass filter. The current waveform data, with a data length of one or two cycles, are normalized using Clarke’s transformation in order to obtain the normalized $\alpha$ and $\beta$ parameters, which are substituted using fuzzy logic to obtain the present running state of the inverter.

The proposed method has proven feasible by digital simulation and laboratory testing, and is a simple method that can be implemented at a low cost. Moreover, it can be used to diagnose the running state of an inverter and detect open-circuit faults in any thyristor. Thus, it can help engineering personnel recognize and maintain the state of an inverter during operation.

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