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Fault diagnosis of star-connected auto-transformer based 24-pulse rectifier

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ABSTRACT

This paper proposes a fault diagnosis method for star-connected auto-transformer based 24-pulse rectifier unit (ATRU) by integrating artificial neural networks (ANN) with wavelet packet decomposition (WPD) and principal component analysis (PCA). The WPD is employed to extract the features of different fault waveforms of the output voltage of the rectifier. PCA is adopted to reduce the dimensionality of the extracted feature vectors, which leads to fast computation of the algorithm. Back Propagation (BP) neural network is adopted to classify the fault types and determine the fault location according to the extracted features. These faults are simulated in real-time simulation platform and the obtained data are then analyzed with MATLAB toolbox, and finally verified with digital signal processor. Compared with other diagnosis methods, the proposed method shows better performance and faster computing speed.

1. Introduction

As a result of the transition to "more electrical", aircraft [1,2] power systems will substitute a significant amount of mechanical and hydraulic power required for actuation and environmental control with electrical power [3]. As a result, aircraft power systems will be based on the interconnection of a wide range of components, resulting in a significantly more complex electrical distribution system with multiple distributed loads supplied and controlled by power electronic converters.

However, the interconnection of the relatively high-impedance aircraft generators, and the large number of power converters and motor controllers have strong side effects on the power systems [4]. The rectifier front end of the power converter has nonlinear characteristic that conducts currents at multiple harmonic frequencies of the fundamental line current, which results in distortion of the generator output voltage. Moreover, this distorted waveform, rich in reactive components, makes the system operate at a lower power factor and consequently lowers efficiency as loads and sources circulate undesirable reactive power.

Among all the available literatures, one popular, efficient and low cost approach is to increase the number of rectification pulses, as shown in Fig. 1. In [5], the authors presented a compact autotransformer topology suitable for 12-pulse rectification. Then an improvement has been made, thus a compact autotransformer suitable for 18-pulse rectification was proposed in [6]. In 2009, a 24-pulse rectifier based on a hexagon-connected autotransformer feeding a vector controlled induction motor drive was reported in [7]. These schemes can considerably reduce the size and weight of the transformer. The focus of this paper is a star-connected autotransformer based 24-pulse rectifier, due to the fact that it is more compact and has lower weight, which is important for aircraft applications [8].

On the other hand, with pervasive power electronic devices inside the multi-pulse rectifier circuit, the output voltage waveform will be distorted when fault occurs, such as short-diode faults (SDF) or diode open-circuit faults (DOF), which may threaten the safety of whole aircraft power systems. However, the available literature on the topic of fault diagnosis for multi-pulse rectifier is still rear.

Fast Fourier Transform (FFT) and wavelet packet decomposition (WPD) are among the commonly used signal analysis methods for fault detection. However, the intrinsic drawback of FFT is the lack of information in the time domain [9–11], thus they are unfit for detecting transients or short spikes contained in the signal. WPD can decompose wideband and non-stationary signals into specific time-frequency resolutions. In particular, WPD can be used to extract the energy features of the signals, which are the representation of the signal dynamics [12–14]. Because of its great

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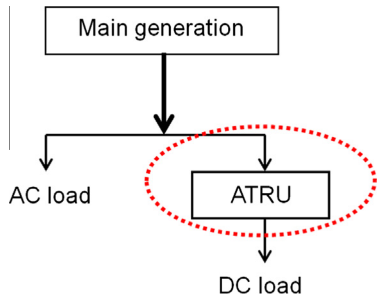

Fig. 1. Position and application of ATRU.

resolution characteristics, WPD has been proposed extensively for fault detection and classification [15].

Artificial neural network (ANN), expert systems, and fuzzy mathematics have been successfully applied as classifier in fault diagnosis in recent years. Ref. [4] diagnoses the three-phase rectifier thyristor open-circuit fault by a combination of neural networks and rough set. But due to the lack of expansion, the rough set is not suitable in complex fault analysis. Ref. [16] studies the fault classification and diagnosis method for the double-bridge 12-pulse waveform controlled rectifier circuit based on pattern recognition. However, the accuracy of pattern recognition turns out to be affected by disturbances or noise easily. ANN is capable of finding complex and hidden relationships among the presented data [17,18], and shows better real time execution capability in [15], which is very suitable for complex fault diagnosis system.

This paper proposes a fault diagnosis method for star-connected auto-transformer based 24-pulse rectifier by integrating artificial neural networks (ANN) with wavelet packet decomposition (WPD) and principal component analysis (PCA). The WPD is employed to extract the features of different fault waveforms of the output voltage of the rectifier. PCA is adopted to reduce the dimensionality of the extracted feature vectors, which leads to fast computation of the algorithm. Back Propagation (BP) neural network is adopted to classify the fault types and determine the fault location according to the extracted features. Previous results of the proposed method were presented in [13], in this extended version, the structure of the auto-transformer based 24-pulse rectifier was illustrated with a thorough theoretical analysis. A comparative study of the proposed method with other diagnosis methods for fault detection and classification of 24-pulse rectifier is provided based on the data obtained from real time platform.

The proposed fault diagnosis structures for 24-pulse rectifier systems are shown bellow in Fig. 2.

Compared with the previous research on fault diagnosis, the innovative contributions of this paper can be summarized as follows.

(1) This paper first combines WPD, PCA and ANN together for fault detection and classification in 24-pulse rectifier circuit, which improves the computing speed and simplifies the diagnosis system with better accuracy.
(2) In order to achieve a trade-off between the accuracy and computing efficiency, Daubechies wavelet basis (Db10) and wavelet decomposition scale 10 are selected in this paper.
(3) The simulation results of the extracted fault waveforms are based on the analysis of real-time (RT) simulated data (SpeedGoat RT Simulator), which sets the conditions for a more realistic scenario and for easy further transition.

The rest of this paper is divided into four parts. Section 2 introduces the structure of 24-pulse rectifier in detail. Section 3 discusses the fault types of star-connected auto-transformer based 24-pulse rectifier and then presents a method to verify the correctness of fault model. Section 4 introduces the proposed fault diagnosis method, with a detailed description of WPD theory as well as the procedures to select wavelet basis and decomposition scale, the PCA theory, and finally the structure of BP neural network. Section 5 presents the classification results based on the data obtained from the real time simulator, and comparisons with other methods to show the improvement of the proposed method. The paper is concluded in Section 6.

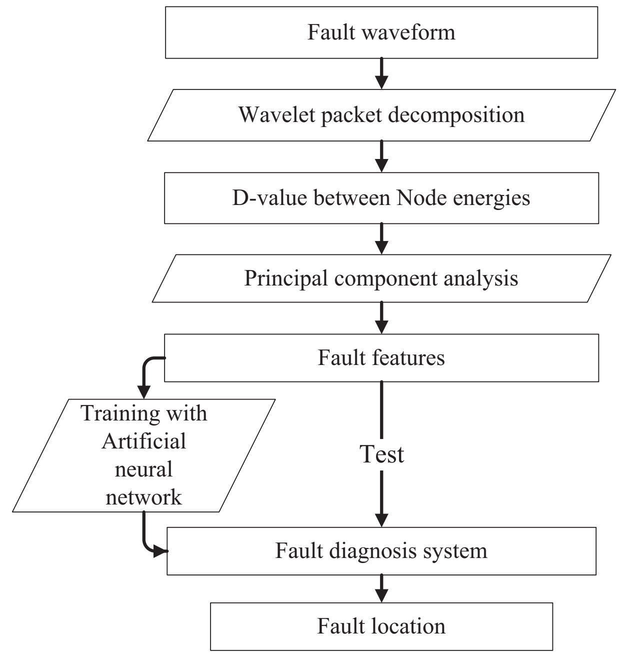

Fig. 2. Flow chart of fault diagnosis.

2. Introduction of the auto-transformer based 24-pulse rectifier

The studied 24-pulse rectifier (rated power 18 kW, output voltage 270 V, input voltage 115 V/400 Hz), is under consideration for future high voltage direct current (DC, 270 V) aircraft power systems. The schematic of the proposed 24-pulse rectifier is shown in Fig. 3. This topology adopts a star-connected autotransformer that feeds four 6-pulse diode bridge converters which are connected on DC side by interphase reactors [8]. The completed circuit consists of autotransformer, diode rectifiers, interphase reactors, and load.

An auto-transformer based n-pulse ac–dc converter operates on the principle of harmonic elimination. The minimum order of harmonics is $nK \pm 1$, where K is a positive integer and n is the number of rectification pulse per cycle of the fundamental voltage.

For harmonic elimination, the required minimum phase shift is given by:

$$\theta = 60^{\circ}/N \tag{1}$$

where θ is the shifting phase and N is the number of 6-pulse converters.

For achieving 24-pulse rectification, the phase shift required between any two nearby set of voltage is 15°.

The winding connection arrangement of the proposed autotransformer is shown in Fig. 4. Corresponding secondary windings of phase A are c1, c2, b4, b3; corresponding secondary windings of phase B are c3, c4, a2, a1; corresponding secondary windings of phase C are b1, b2, a4, a3. When the star-connected autotransformer is fed from three-phase input voltages (V_a, V_b, V_c) displaced