A Power Electronic Fault Diagnosis Method Based on Bond Graph Model

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Abstract: Propose a fault diagnosis method which combines analytical redundancy with bond graph model for electrolytic high power rectifier system. Firstly, using the software 20-sim, the author builds a bond graph model of the system and established a diagnostic bond graph model through adding virtual sensor in bond graph model; then, according to the causal relationship in the components, analytical redundancy relationship and its fault characteristic matrix are set up; finally, comparing the observed characteristics matrix and fault characteristic matrix, fault can be detected and isolated quickly. The simulation results demonstrate that the method is convenient and effective for Power electronic fault diagnosis.

Keywords: Rectifier circuit, Bond graph, Analytical redundancy, Fault signature.

1. Introduction

Along with the development of science and technology and the requirement of industrial expansion, rectifying power supply system is developing toward the direction of complication and automation, which also increases the risk of system failure. Once failure occurs, the loss is huge. Rectifier circuit fault diagnosis has been under the spotlight. Many of the new fault diagnosis method have been sprung up, such as the literature [1, 2] where neural network used to fault diagnosis of power electronic is mentioned. The literature [1] introduces quantum computing, in which the traditional neural network diagnosis method is improved. Although compared with traditional neural network fault diagnosis it saves time, but the training time is too long for the complicated system of rectifier, it appears easily fitting phenomenon problems and fault characteristics. The literature [3] uses wavelet and Elman neural network for electric excitation rectifier circuit of double generator fault diagnosis. This method utilizes the advantage of wavelet in signal feature extraction and the features of neural network classification automatically. However, when inheriting the advantages of these, it also has such problems, the diagnosis time is long, the noise is bigger, the error diagnostic rate is higher. Literature [4] uses the method of the fuzzy theory, which is applied to the inverter pulse width speed regulation of motor to the fault diagnosis. It has not yet established effective method to analyze and design fuzzy system. So it mainly relies on the expert experience and trial and error, which makes study harder.

The above methods work well in the fault diagnosis of simple rectifier circuit, but there are some drawbacks in using these methods in the high
power rectifier circuit, such as long diagnosis time and slow isolation. This paper studies the fault diagnosis method of combining analytical redundancy with bond graph model. It can be concluded that using thyristor as the single checkpoint can avoid tedious fault sorting work, and using break over current with more obvious fault signatures as fault detection can find and isolate fault more quickly. As a result, the huge loss caused by fault can be avoided.

2. Modeling

2.1. Fundamental Principles of Bond Graph and Building Model

2.1.1. Bond Graph Theory

Bond graph theory is mainly about the computer automatic modeling and simulation. It was founded by H. M. Payter, Professor in the Massachusetts institute of technology in 1959, and then his students Professor D. Karnopp, Professor D. Margolis and Professor R. Rosenberg introduced the concept of bond graph into the system modeling. Since then, the bond graph theory has flourished in the academia and engineering field [5].

Bond graph theory is a method about modeling and simulating of system which has muti-energy. The model is simple in structure but rich in its information, and it’s easier to recognize the relationship between the internal structure and system. The model mainly uses energy transfer in the system to describe the dynamic behavior of the system. In the bond graph, energy flow will be treated as power flow, as is shown in Fig. 1. In this diagram, the end of half arrow indicates the reference direction of power flow; the perpendicular stroke represents the causal relationships between variables. In Fig. 1(a) effort causes flow, on the contrary, flow is the result of effort. However, in Fig. 1(b), flow is the cause, effort is the result [6].

![Fig. 1. Causal relationship between expressions of key.](image)

2.2. Modeling

2.2.1. Power Rectifier Circuit

High power rectifier system has always been an essential part in the field of electric power, chemical industry, smelting. Thus, the security of the electrolytic rectifier system is one of the key points in the production. This article studies 36 pulse high power rectifier, the circuit is shown in Fig. 2.

![Fig. 2. Diagram of thyristor rectifier stand-alone group circuit.](image)

2.2.2. Bond Graph Model

There is a lot of dynamic analysis software of bond graph modeling in foreign countries, such as ENPORT, TUTSM, CAMP-G, 20-sim etc. The software in power electronic circuit modeling is 20-sim developed by the University of Twente in the Netherlands. It contains the components library and a special language SIDOPS+, which can be used to write equations and establish submodel [6].

According to the structural characteristics of thyristor, the rule of bond graph modeling and the
20-sim components model in the components library, thyristor will be equivalent a rheostat. When the thyristor turns on, the resistance is zero; when the thyristor cuts off, then it is equivalent to infinity. We can obtain the bond graph model of high power rectifier system by the software 20-sim, as is shown in Fig. 3.

3. Fault Diagnosis

3.1. Analytical Redundancy Relation

Analytical Redundancy Relations plays an important role in the fault diagnosis based on modeling. Analytical Redundancy Relations are kinds of constraint relation between variables and known variables. If ARRS is equal to zero, works well; otherwise, the model break down. In practice, the result of an ARR will be within certain small error bounds due to numerical inaccuracies, sensor noise or process parameter uncertainties. As is mentioned above, Analytical Redundancy Relations in bond graph model-based fault diagnosis framework is shown in Fig. 5. In the 20-sim software, according to the causal relationship between system and element, system diagnosis model is established. Then, through the establishment of analytical redundancy relations between the normal model and the diagnosis model, the failure point can be known and the fault can be isolated quickly [7-9].

3.2. Diagnosis Model

In the bond graph model, real sensors are replaced by virtual sensors, which are transferred according to the node equation and causality. After that, we can achieve the diagnosis model. The effort sensor is equivalent of 1-junction, and the flow sensor is equivalent of 0-junction (Fig. 4) [11].

Fig. 3. The bond graph model of high power rectifier system.
According to the conversion relation of virtual flow sensor, we can get diagnosis model of system, the paper selects the two phase thyristor in any normal work. For convenience, the equivalent model was adopted. R1, C, C1, R3 is the equivalent of protective circuit, R, R4 is the equivalent of thyristor.

3.3. Fault Signature Matrix

Each thyristor is regarded as a test point in diagnosis model. When the thyristor is open, the flow is zero in the whole cycle; if a thyristor is short, the current flows appear in the opposite direction form the reference current.

In practice, the type of failure can be divided into thyristor short-circuit FSj(i=1,2,3,4……,36), open-circuit FOi(j=1,2,3…….,36). From Fig. 5, fault sets are got, \( F = \{ \text{Fo1, Fo18, FS1, FS18} \} \).

The analytical redundancy relationships are got from Fig. 5. Take thyristor 1 for example. Its analytical redundancy relations are as follows.

**ARR1:**

\[
D^*_e = e_4 - e_5 - e_6 - e_7 - e_8 = 0 \\
\frac{d e_7}{d t} = c \\
f_5 = f_6 = e_5 / R = e_6 / R_1 \\
f_{10} = (e_8 - e_{11}) / R_2 \\
f_5 = f_4 = f_5 = f_6 = f_7 = f_8 \\
\text{ref}_1 = f_1 - f_4
\]

According to the causality, diagnosis model shows causal pathways of residual. Causal pathways of ARR1: R→f5→res1; R1→f6→res1; c→f7→res1; R2→f10→res1. According to the value of voltage output is changed by the failures of thyristor, using 1, 0 indicates direction of residual error, 0 normal, 1 open circuit, -1 the short circuit of thyristor. Since all the thyristor structures are the same, Causal pathways
of Analytical redundancy are the same. So, the fault observation matrix is got from Fig. 5.

Table 1. Fault observation matrix.

<table>
<thead>
<tr>
<th>Failure</th>
<th>ref1</th>
<th>ref18</th>
<th>Det</th>
<th>Iso</th>
</tr>
</thead>
<tbody>
<tr>
<td>FO1</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>FO18</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>FS1</td>
<td>-1</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>FS18</td>
<td>0</td>
<td>-1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

If the fault of each thyristor is recorded into fault observation matrix, it will be a huge data table. It is not convenient to observe and contrast. Because the parameters of each thyristor in high-power rectifier system are the same, we coded from number 1 to number 36 and used 0, 1, -1, to show the direction of the residual. There are four kinds of faults of number 1 and number 18 in Table 1. The code is as follows.

- FO1 indicates open circuit of number 1.
- FS1 indicates short circuit.
- FO18 and FS18 indicate the fault of number 18.

FO1 = [100000, 000000, 000000, 000000, 000000, 000000]
FS1 = [-100000, 000000, 000000, 000000, 000000, 000000]
FO18 = [000000, 000000, 000001, 000000, 000000, 000000]
FS18 = [000000, 000000, 00000-1, 000000, 000000, 000000]

3.4. Experiment

We suppose failure to detect the validity of the method. The signal of the number 1 disconnect, the signal of the number 18 connect. Then observe the waveform of residual. Through observing the residual direction, the code of thyristor 1 is [100000, 000000, 000000, 000000, 000000, 000000] form the ref1. The code of thyristor 18 is [000000, 000000, 0000-1, 000000, 000000, 000000]. Finally, compared with fault observation encoding, it is open circuit. Thyristor 1 appears opening fault and thyristor 18 is shorting.

4. Conclusions

This article combines bond graph theory with analytical redundancy relations and applies them to the fault diagnosis of high power rectifier system. It also puts forward a model-based fault diagnosis method of power electronics. Through adding virtual sensors, diagnosis model of high power rectifier circuit is established, and then we can establish its analytical redundancy relations for diagnosis model and obtain coding of residual. Finally, by comparing the encoding of residual and encoding of fault feature, if not consistent, coding fault set can be obtained from the residual direction. It can be concluded that it is effective and feasible to use bond graph theory and analytical redundancy relations diagnosis ideas, via diagnosing high power rectifier system.

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References

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