Transformer Turn-to-Turn Fault Detection Using Hybrid Parameters

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Abstract—Transformer protection is of vital concern to the relay engineer. This paper presents the study of frequency domain based models to determine if a fault condition may be detected from the model parameters. By comparing the nature of the parameters with and without the presence of a fault, it is hoped that a pattern may be observed which may distinguish the two cases.

INTRODUCTION

Transformer protection is complicated by the device's non-linear nature. When a transformer is switched on, it will experience inrush current. Frequency domain analysis of inrush current indicates that the second harmonic component is dominant during switching. The magnitude of the second harmonic component is a function of the residual magnetism and the voltage switching angle [1].

This paper attempts to model the transformer as a two port network. By examining the two port network parameters, it is hoped that the transformer status (internal fault or no fault) may be determined.

ABCD PARAMETERS

One of the most familiar frequency domain techniques is the application of ABCD parameters [2]. The general form of the ABCD equations is

\[ V_1 = A V_2 + B I_2 \]

\[ I_1 = C V_2 + D I_2 \]

where \( V_1 \) and \( V_2 \) are the primary and secondary voltages, respectively, and where \( I_1 \) and \( I_2 \) are the primary and secondary currents, respectively. The complex parameters ABCD provide the relationship between the primary and secondary phasors. Consider a symmetrical pi network as shown in Figure 1.

![Figure 1. Equivalent pi network.](image)

Another possible network configuration is the equivalent T network. For either the symmetric pi or T network, the following relations are valid. The parameters \( A \) and \( D \) are equivalent and the determinant of the ABCD matrix is 1.0. This may be shown as

\[ A = D \]  

(3)

\[ AD - BC = 1. \]  

(4)

Use of these relations results in four unknowns (ABCD) and four equations (1,2,3,4). Equations 1 and 2 may be used to solve for \( A \) and \( C \) as

\[ A = [V_1 - B I_2]/V_2 \]

(5)

\[ C = [I_1 - A I_2]/V_2. \]

(6)

Substitution of equation 5 into 6 yields

\[ C = [I_1 - ([V_1 - B I_2]/V_2) I_2]/V_2 \]

(7)

Use of equations 3 and 4 allows \( B \) to be determined as

\[ B = [V_1^2 - V_2^2]/[V_1 I_2 + V_2 I_1]. \]

(8)

The parameters \( A \) and \( C \) may be determined by using equations 5 and 6. Since the phasor estimates will change with the assimilation of each new measurement, the estimates for the ABCD parameters will change also. Thus, the ABCD algorithm may be illustrated in a flowchart as shown in Figure 2.

![Figure 2. Flowchart of the ABCD parameter study.](image)
Kalman filtering is discussed in detail in reference 3.

**ABCD RESULTS**

Results of the ABCD parameter estimation are shown here. The algorithm was tested using actual recorded data [4]. The transformer is a specially designed 120/120 V single-phase transformer with taps on the secondary. In some test cases, the taps were shorted to obtain data for turn-to-turn faults. The parameters were calculated for a variety of inrush conditions. Inrush with and without the presence of a fault were tested, as well as turn-to-turn faults of varying values.

**SWITCHING THE TRANSFORMER WITH LOAD**

The transformer was energized with rated load on the secondary. Upon detection of the energization, the algorithm estimates the voltage and current phasors. These values are used to determine the ABCD parameters. Only the magnitude of the complex ABCD parameters are shown here. Results are shown for switching the transformer on at zero and ninety degrees on the phase A voltage, as shown in Figure 3 and Figure 4, respectively. Maximum inrush occurs when the transformer is energized at zero degrees.

**SWITCHING THE TRANSFORMER WITH LOAD AND TURN-TO-TURN FAULT**

The transformer was energized with rated load and a turn-to-turn fault on the secondary across a 12 volt tap. Results are shown for switching the transformer on at zero and ninety degrees on the phase A voltage, as shown in Figure 5 and Figure 6, respectively. Results for switching on the transformer with a turn-to-turn fault with a 60 volt tap faulted on the secondary are shown in Figure 7 and 8 for energization at zero and ninety degrees, respectively.

![Figure 3](image1.png)  
**Figure 3.** ABCD parameters for switching at zero degrees.

![Figure 4](image2.png)  
**Figure 4.** ABCD parameters for switching at ninety degrees.

![Figure 5](image3.png)  
**Figure 5.** ABCD parameters for switching at zero degrees with 12 volt tap faulted.

![Figure 6](image4.png)  
**Figure 6.** ABCD parameters for switching at ninety degrees with 12 volt tap faulted.

![Figure 7](image5.png)  
**Figure 7.** ABCD parameters for switching at zero degrees with 60 volt tap faulted.

![Figure 8](image6.png)  
**Figure 8.** ABCD parameters for switching at ninety degrees with 60 volt tap faulted.
SWITCHING THE TRANSFORMER WITH LOAD AND INTERNAL FAULT

The transformer was energized with rated load and an internal fault on the secondary. Results are shown for switching the transformer on at zero and ninety degrees on the phase A voltage, as shown in Figure 9 and Figure 10, respectively.

\[ I_2 = Y_{12} V_1 + Y_{22} V_2 \]

where \( V_1 \) and \( V_2 \) are the sending and receiving voltage phasors, respectively. \( I_1 \) and \( I_2 \) are the sending and receiving current phasors, respectively. The complex parameters \( Y \) provide the relationship between the primary and secondary phasors and may be expressed in terms of the circuit parameters \( y_{10}, y_{20}, \) and \( y_{12} \). This relationship is given by:

\[ Y_{11} = y_{10} + y_{12} \]

\[ Y_{12} = -y_{12} \]

\[ Y_{21} = -y_{12} \]

\[ Y_{22} = y_{20} + y_{12}\]

Given \( y_{12} \), the unknowns \( Y_{11} \) and \( Y_{22} \) may be expressed in terms of the estimated phasors as

\[ Y_{11} = \frac{I_1 - y_{12} V_2}{V_1} \]

\[ Y_{22} = \frac{I_2 - y_{12} V_1}{V_2} \]

The circuit parameters \( y_{10} \) and \( y_{20} \) may be determined using Equations 11 through 14. The parameter \( y_{12} \) is assumed to be known from transformer short circuit test.

ADMITTANCE PARAMETERS

The model studied does not have to be symmetric. A familiar unsymmetric model is the unsymmetric pi model, as shown in Figure 11.

This model may be expressed in terms of the admittances \( y_{10}, y_{20}, \) and \( y_{12} \). The general form of the admittance equations is

\[ I_1 = Y_{11} V_1 + Y_{12} V_2 \]

Figure 9. ABCD parameters for switching at zero degrees with internal fault.

Figure 10. ABCD parameters for switching at ninety degrees with internal fault.

Figure 11. Unsymmetric pi model.

Figure 12. Magnitude of \( y_{10} \) and \( y_{20} \) parameters for switching at zero degrees with rated load on the secondary.

ADMITTANCE RESULTS

Results of the admittance parameter estimation are shown here. As in the ABCD study, upon detection of energization, the program estimated the voltage and current phasors and used these values to calculate the admittances parameters. Several cases are shown here. As before, only the magnitudes of the complex parameters are plotted.

SWITCHING THE TRANSFORMER WITH LOAD

The transformer was energized with rated load on the secondary. Results are shown for switching the transformer on at zero and ninety degrees on the phase A voltage, as shown in Figure 12 and Figure 13, respectively.
SWITCHING THE TRANSFORMER WITH LOAD AND TURN-TO-TURN FAULT

The transformer was energized with rated load and a turn-to-turn fault on the secondary across a 12 volt tap. Results are shown for switching the transformer on at zero and ninety degrees on the phase A voltage, as shown in Figures 14 and 15, respectively. Results for switching on the transformer with a turn-to-turn fault with a 60 volt tap faulted on the secondary are shown in Figures 16 and 17 for energization at zero and ninety degrees, respectively.

SWITCHING THE TRANSFORMER WITH LOAD AND INTERNAL FAULT

The transformer was energized with rated load and an internal fault on the secondary. Figure 18 and Figure 19 show results when the transformer is switched on at zero and ninety degrees on the phase A voltage, respectively.
SUMMARY

The study of the ABCD parameters suggests that the parameters are a function of the switching angle, the residual magnetism, and fault condition. The magnitude of the A and B parameter seem to be fairly constant in all of the test cases, while the parameter C varied in the test. It may be seen from the plots that C initially attains a high magnitude in all of the test cases when the switching angle is zero degrees. In the low turn-to-turn fault cases, the magnitude of C is much lower when the angle is ninety degrees. However, difficulty exist in determining if a fault is present using only the magnitudes of the variables. The switching angle and residual magnetism need to be studied further to determine their impact on the parameters. Also, it appears difficult to distinguish low turn-to-turn faults from the normal inrush case.

The study of the admittance parameters in the unsymmetric pi model also indicates that the y10 and y20 parameters are a function of the switching angle and the residual magnetism. However, the parameter y10 approaches a lower value for the inrush cases than in the fault cases. Both of the parameters approached higher values in the external fault cases.

Both studies need further analysis. In both cases, faults should be applied on the primary side of the transformer to study the effect on the parameters. Monitoring the residual flux and switching angle may suggest a protection function utilizing these quantities. Further analysis may suggest techniques for adaptive protection algorithms [5].

REFERENCES