Determination method for zero-sequence impedance of 3-limb core transformer

J. S. Song, J. S. Kim, G, J. Cho, C. H. Kim, N. H. Cho

***Abstract* — Most of the distributed generations are interconnected with the distribution system through the 3-limb core transformers for economical reasons. However, the zero-sequence impedance depends on the core structure and 3-limb core transformers have very different zero-sequence impedance with other core structure type transformer. Since accurate fault analysis is essential for proper protection system design, determining the correct impedance for transformers which link distributed generation to the distribution system becomes more important. However, since some 3-limb core transformer manufacturers do not provide zero-sequence testing data, it is difficult to do fault analysis on distribution system interconnected with distributed generations through 3-limb core transformers. Therefore, this paper proposes a method to estimate the typical values of zero-sequence impedance parameters of 3-limb core transformer using IEC 60076-8 standard. In addition, it introduces a zero-sequence testing method to measure the zero-sequence impedance of a 3-limb core transformer. At last, the comparison and verification of the estimated value and the actual testing value of the zero-sequence impedance of 3-limb core transformer are performed.**

***Keywords*: zero-sequence impedance, zero-sequence flux, 3-limb core transformer, distributed generation, zero-sequence test.**

I. Introduction

The penetration level of the distributed generations is gradually increased to a distribution system. In addition, it is predicted that more distributed generation will be interconnected in the future. In Korea, for example, the government decided to increase the ratio of distributed generation to renewable energy to 20% until 2030 [1]. As the penetration of the distributed generation increases, an impact of the distributed generation to power system also increases. One of the impacts of the interconnection of distributed generations is a power system protection problem such as blinding protection and sympathetic protection [2]. Presence of the distributed generation reduces the fault current seen by the upstream protection relay, making the protection relay fail to detect the fault or prolong the operation time of the protection relay (Blinding Protection). And also reverse current of the distributed generations in the healthy feeder can cause a nuisance trip of the circuit breaker in the same feeder due to the fault in another feeder (Sympathetic Protection). Since interconnections of the distributed generations cause malfunction of the protective relay, it is required to set the protection system considering the fault contribution of the distributed generation. For that reason, it is necessary to understand the fault contribution of the distributed generation precisely.

One of the factors affecting the fault contribution of the distributed generation is the transformer for interconnection. Most of the distributed generations are interconnected through the 3-limb core transformers due to economical reason [3]. However, due to the unique core structure of the 3-limb core transformer, it has a different zero-sequence characteristic from transformers with another core structure [4]. But, several 3-limb core transformer manufacturers do not often provide the zero-sequence testing data of transformer. So, this paper introduces two determination method for zero-sequence impedance of the 3-limb core transformer. First method uses IEC 60076-8 standard to determine typical value of zero-sequence impedance parameter and second method uses zero-sequence test data to determine actual value of zero-sequence impedance parameter. And also several equations are derived to calculate the zero-sequence impedance parameter in this paper.

The paper is organized as follows. 3-limb core transformer and 5-limb core transformer are compared to illustrate the zero-sequence impedance characteristic of 3-limb core transformer in section II. Section III introduces two methods of determining the zero-sequence impedance parameters of the 3-limb core transformer. Section IV compares two zero-sequence impedance values calculated by both determination methods. At last, Section V is the conclusion.

II. Comparison Between Core Type Transformers

A. 3-limb core Transformer

Fig. 1 shows the core structure of the 3-limb core transformer. It consists of three limbs wound with three-phase windings and two yokes connecting each limb. When three-phase voltage is applied to each winding, three-phase magnetic fluxes are induced in each limb. These fluxes are summed to zero in the yoke under three-phase balance condition. However, if the unbalancing voltage is applied to the transformer due to occurrence of the ground fault, the zero-sequence flux is induced and the three-phase fluxes are not sum to zero in the yoke any longer. Therefore, the residual

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flux which is named as the zero-sequence flux needs a return path through the air gap and tank.

The air-gap means a space composed of insulation outside the transformer core, and transformer tank enclose the air-gap. The zero-sequence flux gets out of one side yoke and flows through air-gap and tank (or only air-gap) to the other side yoke. The permeability of the air gap is considerably lower than the permeability of the core. Thus, a larger magnetizing force is consumed to generate the zero-sequence magnetic flux, which appears as a lower zero sequence inductance. Equation (1) represents the magnetic reluctance of the 3-limb core transformer. The magnetic reluctance is inversely proportional to the permeability and the cross-sectional area of the path through which the zero-sequence flux flows, and is proportional to the length of the path. Because the zero-sequence magnetic flux flows through both air gap and core, magnetic reluctance is represented by sum of magnetic reluctance of the air gap and the core.

$$R_{m(0)} = R_{m(ag)} + R_{m(core)} = \frac{l_{ag}}{\mu_{ag} A_{ag}} + \frac{l_c}{\mu_{core} A_c} \tag{1}$$

where,

$R_{m(0)}$: zero-sequence magnetic reluctance
$R_{m(ag)}$, $R_{m(core)}$: magnetic reluctance of air gap and core
μ_{ag}, μ_{core} : permeability of air gap and core
l_{ag}, l_c : length of air gap and core
A_{ag}, A_c : cross sectional area of air gap and core

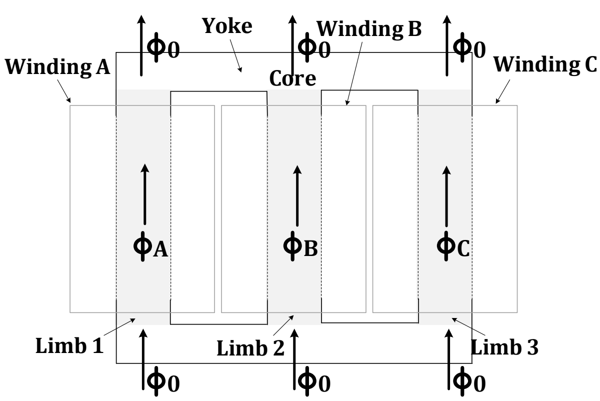

Fig. 1. Core structure of 3-limb core transformer [5]

Since the permeability of the air gap is much lower than that of the core, the magnetic reluctance of the 3-limb core transformer is dominated by the air gap permeability.

The magnetizing inductance is expressed by (2). The magnetizing inductance is inversely proportional to the magnetic reluctance and proportional to the permeability. So, the magnetizing inductance is also highly dependent on the air gap of the transformer and is smaller than magnetizing inductance of transformers with another core structure.

$$L_{m(0)} = \frac{N^2}{R_{m(ag)} + R_{m(core)}} \approx \frac{\mu_{ag} A_{ag} N^2}{l_{ag}} \tag{2}$$

where,

$L_{m(0)}$: zero-sequence magnetizing inductance
N : turns ratio of winding

B. 5-limb core Transformer

Fig. 2 shows the core structure of the 5-limb core transformer. It has two outer limbs to which the zero-sequence flux can return unlike the 3-limb core transformer. Therefore, the zero-sequence magnetic flux dose not flow through the air gap, resulting in a much lower zero-sequence magnetic reluctance and higher magnetizing inductance. The cross-sectional areas of yoke and outer limbs of 5-limb core transformer are smaller than inner limb for reducing transformer dimensions. Typically, the cross-sectional area of yoke (A_{yoke}) is 0.7 times of inner limb (A_{inner}) and the cross-sectional area of outer limb (A_{outer}) is 0.57 times of inner limb [5]. Equation (3) and (4) represent the zero-sequence magnetic reluctance and the magnetizing inductance respectively. Comparing between (2) and (4), difference of the magnetizing inductance between two transformers can be confirmed. The difference between two inductances is mainly caused by difference between the permeability of the air gap and core, which is about several hundreds of times different.

$$\begin{aligned} R_{m(0)} &= R_{m(inner)} + \left(\frac{1}{2}\right) R_{m(outer)} \\ &= \frac{l_{limb}}{\mu_{core} A_{inner}} + \frac{1}{2}\left(\frac{2 l_{yoke}}{\mu_{core} A_{yoke}} + \frac{l_{limb}}{\mu_{core} A_{outer}}\right) \end{aligned} \tag{3}$$

$$L_{m(0)} = \frac{N^2}{R_{m(0)}} = \frac{\mu_{core} A_{inner} N^2}{1.43 l_{yoke} + 1.88 l_{limb}} \tag{4}$$

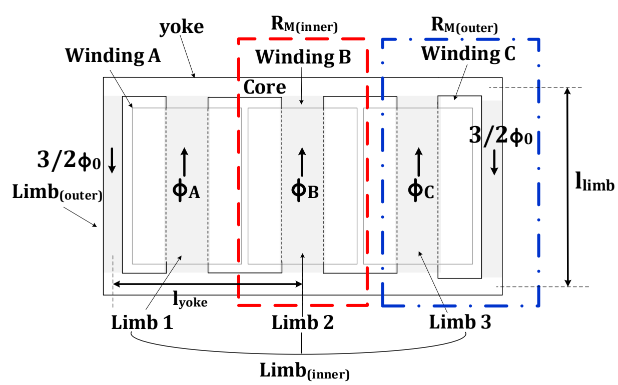

Fig. 2. Core structure of 5-limb core transformer [6]

C. Comparison of Zero-sequence Fault Current Between 3-Limb and 5-Limb Core Transformer

Fig. 3 shows a test system to observe how the differences in magnetizing impedance between 3-limb and 5-limb core transformers affect the zero-sequence fault current. 10 MW distributed generations are interconnected through 22.9kV/380V 20% 3-limb or 5-limb core transformer (Yg-Yg) to the test system with (30+j5) MVAR load and single-phase ground fault in another feeder is simulated at 0.05s. And impedance parameter of line is 0.1835+j0.4064 ohms/km. Fig. 4 shows zero-sequence contribution from both transformers with distributed generation. As shown in Fig. 4, 3-limb core transformer contributes more zero-sequence fault current due to lower magnetizing impedance and its zero-sequence fault contribution causes relay to malfunction. Therefore, it is necessary to analyze the accurate fault analysis for the 3-limb core transformer. For this purposes, the method of determining the zero-sequence impedance of the 3-limb core transformer should be preceded.

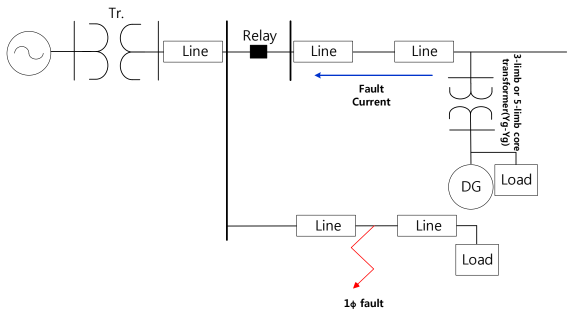

Fig. 3. Test system interconnected with distributed generation through 3-limb or 5-limb core type transformer

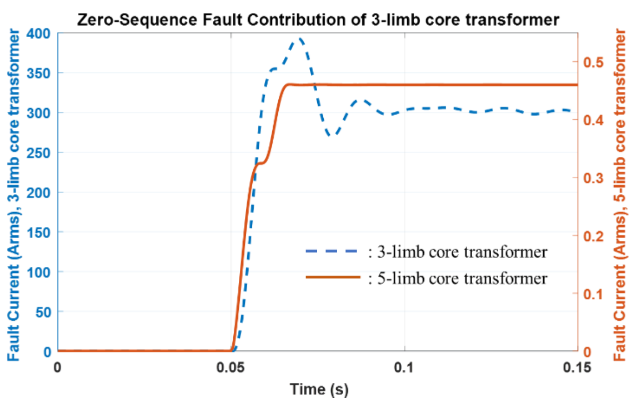

Fig. 4. Fault Current Contribution of 3-limb and 5-limb core transformer

III. Determination Method of Zero-Sequence Impedance of 3-Limb Core Transformer

A large amount of distributed generations is interconnected to distribution system around the world. Also, in the Republic of Korea, many distributed generations are being interconnected to the distribution system. Since the interconnections of the distributed generations affect the fault current flow and the protection system of the distribution system, proper fault analysis for the distribution system connected to the distributed generation is essential for the protection of it.

When interconnecting distributed generation to the distribution system, 3-limb core transformer is preferred. However, as described in section II, 3-limb core transformer has a different zero-sequence impedance from that of the other core type transformer. Therefore, in order to analyze the effect on the grid connection of the distributed generation, a study on the zero-sequence impedance (especially zero-sequence magnetizing inductance) of the 3-limb core transformer should be preceded.

In this section, we introduce two methods to determine the zero-sequence impedance of the 3-limb core transformer.

A. IEC Standard 60076-8

In IEC Standard 60076-8, typical values of zero-sequence impedance of 3-limb core transformer and 5-limb core transformer are summarized as shown in Table I [7]. However, this table shows the overall zero-sequence impedance for each winding, but does not show the zero-sequence leakage impedance (Z_H, Z_X, Z_Y) and zero-sequence magnetizing impedance (Z_M) which are required in transformer modeling. Therefore, it is necessary to deduce each value for more accurate fault analysis using values in Table I.

Table II shows equivalent circuits of transformer for each connection. Using equivalent circuits in Table II, the zero-sequence impedance in Table I can be represented as (5)-(8).

$$Z_{0(Yg-Y)} = Z_H + Z_M = 0.5\ per\ unit \tag{5}$$

$$Z_{0(Y-Yg)} = Z_X + Z_M = 0.6\ per\ unit \tag{6}$$

$$Z_{0(Yg-\Delta)} = Z_H + Z_X || Z_M = a_1 Z_{HX} \tag{7}$$

$$Z_{0(\Delta-Yg)} = Z_X + Z_H || Z_M = a_2 Z_{HX} \tag{8}$$

where, $Z_{0(Yg\text{-}Y)}$, $Z_{0(Y\text{-}Yg)}$, $Z_{0(Yg\text{-}\Delta)}$, $Z_{0(\Delta\text{-}Yg)}$: Zero-sequence impedance of Yg-Y, Y-Yg, Yg-Δ, Δ-Yg connection.

Equation (5)-(8) are consisted of five unknown values (Z_H, Z_X, Z_M, a_1, a_2). If one of the unknown values is given, other four values can be calculated based on the given value. In this paper, to estimate the typical values of Z_M based on Table I, four unknown values are calculated by substituting Z_M values one by one in (5)-(8). IEC 60076-8 sets the range of a_1 and a_2 between 0.8 and 1.0, and also a_2 is bigger than a_1. Therefore, if the calculated values of a_1 and a_2 by the given value of Z_M belongs to the range, it can be confirmed that the given value of Z_M is one of the typical values.

Based on (5)-(8), the typical value of the magnetizing impedance value can be deduced as 0.43-0.5 per unit. For example, when the magnetizing impedance value is 0.45 per unit, Equation (9)-(12) are derived from (5)-(8) and zero-sequence leakage impedance (Z_H, Z_X) and constants (a_1, a_2) are calculated as 0.05 per unit, 0.15 per unit, 0.8125, 0.9750 respectively. Notice the calculated constants a_1 and a_2. The values are within the range specified in the standard IEC 60076-8 shown in Table I, and they support fact that one of the typical values of the magnetizing impedance is 0.45 per unit.

$$Z_{0(Yg-Y)} = Z_H + 0.45 = 0.5 per\ unit \tag{9}$$

$$Z_{0(Y-Yg)} = Z_X + 0.45 = 0.6 per\ unit \tag{10}$$

$$Z_{0(Yg-\Delta)} = 0.05 + 0.15||0.45 = a_1(0.05 + 0.15) \tag{11}$$

$$Z_{0(\Delta-Yg)} = 0.15 + 0.05||0.45 = a_2(0.15 + 0.05) \tag{12}$$

Table III shows the calculated values under each magnetizing impedance values using (5)-(8). As shown in table III, if the zero-sequence magnetizing impedance is lesser than 0.43 per unit, a_1 gets out of the lower limit (0.8). And if the zero-sequence magnetizing impedance is higher than 0.5, a_2 gets out of the higher limit (1.0). Therefore, the typical value range of the magnetizing impedance values should be higher than 0.43 and lower than 0.5 according to the range of a_1 and a_2.

TABLE I
TYPICAL VALUES OF ZERO-SEQUENCE IMPEDANCE OF TWO-WINDING CORE TYPE TRANSFORMER IN IEC 60076-8

Connection of Transformer		3-limb core transformer		5-limb core transformer	
primary	secondary	primary	secondary	primary	secondary
Yg	Y	≈ 50%	-	≈ 10^4%	
Y	Yg	-	≈ 60%	-	≈ 10^4%
Yg	Yg	$a_1 Z_{HX}$	$a_2 Z_{HX}$	Z_{HX}	Z_{HX}
Yg	Δ	$a_1 Z_{HX}$	-	Z_{HX}	-
Δ	Yg	-	$a_2 Z_{HX}$	-	

• Z_{HX} : short circuit positive impedance
• $0.8 < a_1 < a_2 < 1$

TABLE II
EQIVALENT CIRCUIT FOR TRANSFORMER CONNECTION

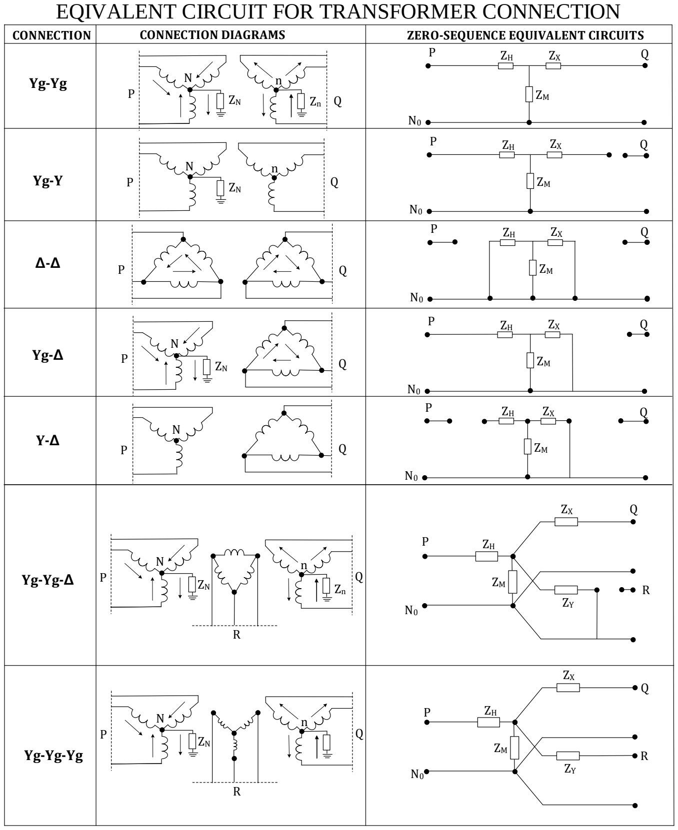

TABLE III
CALCULATED VALUES UNDER DIFFERENT MAGNETIZING IMPEDANCE VALUES

Z_M	Z_H	Z_X	a_1	a_2
0.43 per unit	0.07 per unit	0.17 per unit	**0.7993**	0.9592
0.45 per unit	0.05 per unit	0.15 per unit	0.8125	0.9750
0.50 per unit	0 per unit	0.1 per unit	0.8333	**1**

This approach can be used for three-winding transformers as well as two-winding transformers. For example, the typical value of zero-sequence impedance of Yg-Yg-Δ connection transformer, which is well used in Korea is written in IEC standard as $a_1(Z_H+Z_X||Z_Y)$ on the primary side and $a_2(Z_X+Z_H||Z_Y)$ on the secondary side. Using the equivalent circuit of the Yg-Yg-Δ transformer shown in Table II and typical values of 3-limb core transformer in the IEC standard, we can derive (13) and (14). If the magnetizing impedance is 0.45 per unit, which is one of the typical values, the impedance values (Z_H, Z_X, Z_Y) and constants (a_1, a_2) can be calculated by (13) and (14) as shown in Table IV.

$$Z_H + Z_X||Z_Y||Z_M = a_1(Z_H + Z_X||Z_Y) \tag{13}$$

$$Z_X + Z_H||Z_Y||Z_M = a_2(Z_X + Z_H||Z_Y) \tag{14}$$

TABLE IV
CALCULATED VALUES OF THREE-WINDING TRANSFORMER

Z_M	Z_H	Z_X	Z_Y	a_1	a_2
0.45 per unit	0.05 per unit	0.15 per unit	0.25 per unit	0.8876	0.9816

B. Zero-sequence Impedance Testing

The approach proposed in section III.A is to obtain a typical value of the zero-sequence impedance of the 3-limb core transformer. However, the typical value is different from the actual zero-sequence impedance of the 3-limb core transformer, and there is a limitation that accurate fault analysis results can not be derived with typical value. Because, more accurate fault analysis is essential for proper protection system, zero-sequence impedance testing is needed to obtain the accurate zero-sequence impedance of transformer. And typical values can only be used for approximate analysis if the zero-sequence impedance testing data is not provided.

Fig. 5 shows the circuit diagram for the zero-sequence impedance testing of Yg-Yg connection transformer. As shown in the Fig. 5, the zero-sequence impedance testing is performed by shorting the three-phase bushings of Y connection terminal together and applying voltage between the neutral point and the point where the three-phase are shorted. After the testing, zero-sequence impedance (Z_0), resistance (R_0) and reactance (X_0) are calculated by using the measured voltage (V_0) and current (I_0) with (15)-(17) [3].

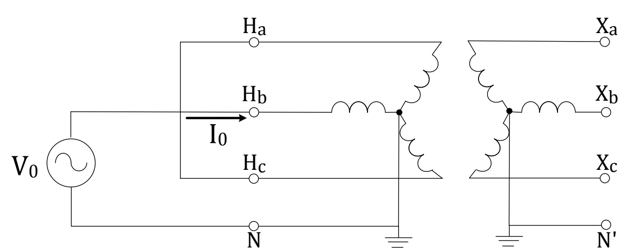

Fig. 5. Zero-sequence Impedance Testing

$$Z_0 = \frac{V_0}{I_0} = R_0 + jX_0 \tag{15}$$

$$R_0 = \frac{P_0}{3I_0^2} \tag{16}$$

$$X_0 = \sqrt{(\frac{V_0}{I_0})^2 - (R_0)^2} \tag{17}$$

The zero-sequence impedance of (15) is the impedance value of the whole transformer seen by the winding which the voltage is applied. The impedance parameters of the equivalent circuit like Z_H, Z_X, Z_M can not be derived by only the impedance value from one testing data. Therefore, various kinds of tests must be performed in parallel. For example, in case of Yg-Yg transformer shown in Fig. 5, the equivalent circuit parameters can be calculated from the zero-sequence impedance obtained from the open circuit test and short circuit test from high-voltage side and the open circuit test from low-voltage side [3]. The detailed procedure will be introduced in following section by using a three-winding transformer of Yg-Yg-Yg connection as an example.

C. *Zero-sequence Impedance Testing of Three-winding Transformer*

Determination method of the impedance parameters of three-winding transformer is well known. The following impedance values are obtained through three transformer tests and impedance parameter value can be calculated by using (18) [8].

- Z_{HX}: leakage impedance measured from '*H*' winding with '*X*' winding short and '*Y*' winding open
- Z_{XY}: leakage impedance measured from '*X*' winding with '*Y*' winding short and '*H*' winding open
- Z_{HY}: leakage impedance measured from '*H*' winding with '*Y*' winding short and '*X*' winding open

$$\begin{aligned} Z_H &= \frac{1}{2}(Z_{HX} + Z_{HY} - Z_{XY}) \\ Z_X &= \frac{1}{2}(Z_{HX} + Z_{XY} - Z_{HY}) \\ Z_Y &= \frac{1}{2}(Z_{HY} + Z_{XY} - Z_{HX}) \end{aligned} \tag{18}$$

This calculation is valid only for a transformer having an iron core structure other than a 3-limb core transformer in which the magnetizing impedance is large and the parallel shunt can be ignored. In case of 3-limb core transformer, additional tests are required to clarify all impedance parameters. The additional tests and the measured zero-sequence impedances are as follows.

- Z_{Hopen}: leakage impedance measured from '*H*' winding with '*X*' and '*Y*' winding open (= $Z_H + Z_M$)
- Z_{Xopen}: leakage impedance measured from 'X' winding with '*H*' and '*Y*' winding open (= $Z_X + Z_M$)
- Z_{Yopen}: leakage impedance measured from 'Y' winding with '*H*' and '*X*' winding open (= $Z_Y + Z_M$)

The impedance parameters of the Yg-Yg-Yg connection 3-limb core transformer are calculated by using the zero-sequence impedances measured from the tests as shown is (19) [3].

$$\begin{aligned} Z_M &= \sqrt{Z_{Xopen}\,(Z_{Hopen} - Z_{HX})} \\ Z_H &= Z_{Hopen} - \sqrt{Z_{Xopen}\,(Z_{Hopen} - Z_{HX})} \\ Z_X &= Z_{Xopen} - \sqrt{Z_{Xopen}\,(Z_{Hopen} - Z_{HX})} \\ Z_Y &= Z_{Yopen} - \sqrt{Z_{Xopen}\,(Z_{Hopen} - Z_{HX})} \end{aligned} \tag{19}$$

where, $Z_{HX} = Z_H + Z_X || Z_M$

IV. Comparison Between Typical Values with Testing Data

To verify the typical values of zero-sequence magnetizing impedance (0.43-0.45 per unit) determined by IEC 60076-8 standard, the typical values are compared with the actual zero-sequence impedance testing data of 3-limb core transformer. Table V shows a part of 3-limb core transformer data. The zero-sequence impedance of Yg-Δ connection transformer is calculated as (20) due to equivalent circuit shown in table II. Assuming each leakage impedance (Z_H, Z_X) is the same, the value of each leakage impedance is half of the leakage impedance of the 3-limb core transformer and it is 0.05635 per unit. If the zero-sequence magnetizing impedance of transformer is 0.45 per unit, which is one of the typical values, the zero-sequence impedance is calculated as 0.1064 per unit. The calculated value is similar with the testing data and the error is only 3.80%.

$$Z_0 = Z_H + (Z_X || Z_M) \tag{20}$$

TABLE V
Specifications of 3-limb core transformer [9]

Quantity	Value
Rated voltage	220/13.8 kV
Rated power	105MVA
Connection	Yg-Δ
Leakage Impedance	0.1127 per unit
Zero sequence impedance (testing data)	0.1025 per unit

V. Conclusion

As the penetration of the distributed generation increases, the influence of the distributed generation on the fault current also increases. Since accurate fault analysis is essential for proper protection system design, the study for the impedance parameter determination method for distributed generation and transformer that connects distributed generation to the distribution system is required.

Since the 3-limb core transformers have a much smaller zero-sequence magnetizing impedance than another core type transformer due to the core structure, it has different zero-sequence impedance parameters from the transformers of the other core type. So, we introduce the methods of determining the zero-sequence impedance of the 3-limb core transformers that link most distributed generations to the distribution system for economical reasons.

First one is the method of determining the typical value of the zero-sequence impedance parameter of the 3-limb core transformer using IEC 60076-8 standard. We propose a process of deriving typical zero-sequence impedance parameters through IEC standards, and several equations have been derived during this process. And second one is the method of determining the actual value of the zero-sequence impedance parameter of the 3-limb core transformer using testing data. If testing data is not provided, the typical value by IEC standard will be valid, but otherwise the test data will provide a more accurate value.

In the future, it is planned to test for various 3-limb core transformers manufactured in Korea to obtain the zero-sequence impedance of the actual transformers. And, based on measured data, the proposed determining method using IEC standards will be verified and be complemented.

VI. References

[1] Hun-Tae Kim, and Seong-Su Jhang, "Key Technologies for Stabilization of Power System for Successful Achievement of 3020 Renewable Energy Policy," *The Transactions of the Korean Institute of Electrical Engineers*, vol. 67, no. 2, pp. 149-157, Feb. 2018.

[2] Patrick Tendayi Manditereza, and Ramesh Bansai, "Renewable distributed generation: The hidden challenges – A review from the protection perspective," *Renewable and Sustainable Energy Reviews,* vol. 58, pp. 1457-1465, May. 2016.

[3] Alberta Electric System Operator (AESO), "Transformer Modeling Guide," Jul. 2014.

[4] Hyunsik Jo, Sungwoo Cho, Changhoon Shin, and Hanju Cha, "Zero-sequence Impedance of Yg-Yg Three Phase Core Type Transformer," *The Transactions of the Korean Institute of Electrical Engineers*, vol. 65, no. 6, pp. 940-945, Jun. 2016.

[5] B. A. Mork, D. Ishchenko, F. Gonzalez, Sung D. Cho, "Parameter Estimation Methods for Five-Limb Magnetic Core Model," *IEEE Transactions on Power Delivery*, vol. 23, no. 4, Oct. 2008.

[6] Jialong Wang, and Raluca Lascu, "Zero-sequence circuit of three-legged core type transformers," *2009 62nd Annual Conference for Protective Relay Engineers*, Apr. 2009.

[7] IEC Standard 60076-8, "Power transformers - Part 8 : Application guide," 1997.

[8] J.Duncan Glover, Thomas J. Overbye, Mulukutla S. Sarma, "Power System Analysis & Design (Sixth Edition)", CENGAGE Learning, 2016.

[9] Wade G. Enright, "Transformer models for electromagnetic transient studies with particular reference to HVdc transmission," Ph.D. thesis, Electrical and Electronic Engineering, Univ. Canterbury, Christchurch, New Zealand, 1996.