Modeling Multi-Winding Transformers

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September 14, 2013

Figure 1 shows the common 3-winding transformer equivalent model used in power system analysis based on positive-sequence equivalent circuits. This is used in nearly all (if not all) of the popular transmission system power flow, short-circuit, and dynamics tools. The popularity of the model likely stems from the fact that it can be constructed entirely from simple two-terminal R-L branch models. This makes the programming somewhat simpler, although it does create some issues because a single device (a transformer) is modeled by three branches. So programs usually contain some "kluge code" to keep track of branches that are associated with transformers. Also, it requires the creation of a fictitious node (M) that doesn't physically exist.

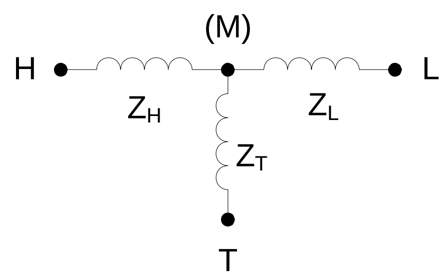

Figure 1. Common Model of 3-Winding Transformers used in Positive-Sequence Analysis

This model is so ingrained in the minds of electric power systems analysts that many, if not most, think the impedances in the model are actually found somewhere in a transformer. It is not until one encounters an unusual transformer such as a 4-winding transformer that one discovers that this modeling approach works only for the special case of a 3-winding transformer.

The leakage impedance network of a 3-winding transformer is defined by (3x2)/2 = 3 short circuit tests that yield Z_{HL}, Z_{HT}, and Z_{LT}. The formula for the number of short circuit tests required is: *N(N-1)/2* where is *N* is the number of windings. A model need 3 degrees of freedom to model a 3-winding transformer.

The model in Figure 1 has 3 degrees of freedom, so it works. A 4-winding transformer is defined by (4x3)/2 = 6 short circuit tests and requires 6 degrees of freedom. Some sort of mesh circuit is required to represent the transformer leakage impedance characteristic. It may be impossible to create a star model that is accurate. The same can be done for the 3-winding case. The model in Figure 2 can be made equivalent to the one in Figure 1 and does not require the creation of a fictitious node. Note: Z_{H-L} is not the same as the short-circuit impedance between H an L, Z_{HL}, above; it can be obtained by a simple star-delta conversion from the circuit in Figure 1. Inside a power flow program, a *Kron* reduction can be performed on the admittance matrix to eliminate the fictitious node. This will accomplish the same thing as the star-delta conversion.

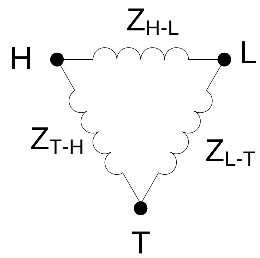

Figure 2. Equivalent Model that Does Not require Fictitious Node

The architects of the Common Information Model (CIM) chose to use the values of Z_H, Z_L, and Z_T to describe a 3-winding transformer. Each winding – H, L, and T – of the transformer is stored in the database separately, each with a single value of resistance, *R*, and reactance, *X*. While it might be argued that it is acceptable to store the resistance with the winding model because each winding does indeed have resistance, there is no such thing as the reactance of a single winding, such as X_H, for example. Short-circuit leakage reactances only exist between *pairs* of windings. If the architects of the CIM had wanted to model transformers more correctly, they would have defined a separate object to contain short circuit tests, of which there would be 3 for a 3-winding transformer. This defect (in my opinion) in the CIM has caused problems trying to adapt it to distribution system analysis, which uses more complicated transformer models. As it is, one can only model 2- and 3-winding transformers.

Reasons for NOT using the model in Figure 1

- The model requires the creation of an additional node.
- Need to model a transformer with more than 3 windings.
- X_L often comes out negative for autotransformers with tertiaries.
- It is incapable of modeling the most common 3-winding transformer in the North American power grid – the ubiquitous split-phase distribution transformer.

Each of these points is addressed further in the following:

Each fictitious node requires an equation in a nodal admittance formulation. In a case with hundreds of transformers, this could add significant time to the solution. So it would be nice to avoid this with a model that does not require an extra node. In the case of a three-phase model, the impact of the extra nodes could be even greater than for a simple positive-sequence model.

While not common in the transmission grid, transformers with more than 3 windings show up in various industrial processes and have also been used to connect inverter-based DG such as fuel cells. They are used to provide isolation between devices with electronic power converters.

A negative X_L is not necessarily a show stopper. If it can be buried in the system Y matrix along with overwhelming positive values of the other parts of the model, it is seldom a problem. It was a problem in the past with models in electromagnetic transient analysis where the integration formulae would yield unstable solutions for a R-L branch defined with negative inductance. It used to be common to ignore the small negative X_L branch to avoid this. It is not known whether this is still an issue, but I suspect most transients program vendors use more sophisticated transformer models now. But this is something to keep in mind if creating software for transients analysis.

While it is common to think of a residential service transformer only as a simple single-phase 2-winding transformer, it is actually a 3-winding transformer. It has one primary-voltage winding and two 120-V secondary windings. While it might seem like it is just like the single-phase model used in a positive-sequence power flow, it is not. In the transmission model, the three windings are connected to the power system model with the same polarity. In the distribution transformer model, the two secondaries are connected in series. The grounded terminals of the secondaries are connected in opposite polarity. The link below describes how the transformer is modeled in OpenDSS

http://sourceforge.net/apps/mediawiki/electricdss/index.php?title=TechNote_Modeling_Single-phase,_Center-tapped_Distribution_Transformers

To make the modeling problem for the distribution transformer more interesting, the mixture of 240 V and 120 V loads makes it impossible to model the transformer with a single per-unit model. (Try it if you don't believe me.) That is one reason why we don't use per-unit models of lines and transformers in the distribution analysis tools such as OpenDSS. A more general transformer model is needed.

A more general way to model transformers

Is there a way to avoid these issues? Let's take a look at a general method that will allow the construction of a leakage impedance model of nearly any transformer for power system analysis.

While I learned the conventional 3-winding model for power flow in college and have worked with several computer programs that use it, I learned a different way of modeling transformers in 1973 and have used it almost exclusively in programs I designed and wrote myself. At the core of most power systems analysis programs whether for power flow, short circuit, harmonics, dynamics, or transients, is a system nodal admittance (Y) matrix. Y may be a plain nodal admittance matrix, an augmented matrix or a component of another set of equations such as a Jacobian for a Newton-based solution. The general approach is to first build Y from so-called "primitive" admittance matrices for each element.

For the simple 3-winding transformer in Figure 1, a primitive Y matrix, Y_{Prim}, is illustrated in Eq. (1).

$$\begin{bmatrix} I_H \\ I_L \\ I_T \end{bmatrix} = \begin{bmatrix} & & \\ & Y_{Prim} & \\ & & \end{bmatrix} \begin{bmatrix} V_H \\ V_L \\ V_T \end{bmatrix} \tag{1}$$

This equation relates the transformer's terminal currents to the node-to-ground voltage at the terminal. This is the voltage of the positive-sequence network model. Thus, every element of Y_{Prim} can be summed directly into the system Y matrix. There is a direct mapping of each element of the Y_{Prim} matrix to the system Y determined by a terminal-to-node incidence list.

The Y_{Prim} matrix can be constructed directly from short-circuit test data. There is no need to generate an intermediate equivalent circuit. This method applies not only to a simple single-phase positive-sequence model but to general n-phase, m-winding transformers. This is the approach used in OpenDSS.

Here is description of the method adapted from my paper with Surya Santoso presented at the 2003 IEEE T&D show: (Note: Equation numbering restarts at 1.)

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The Transformer Model

Some of the methods for modeling transformers use the per unit system and some use actual values. The authors prefer to work in actual values and will demonstrate that method here. The objective of the method described here is to develop a "primitive" nodal admittance matrix, $\boldsymbol{Y}_{prim}$, describing the transformer. Once the transformer impedance model is in this form, it can generally be incorporated quite easily into most system solution algorithms.

The method permits the modeling of the leakage impedance network of any transformer with any number of phases and any number of windings connected in an arbitrary fashion. It works equally well for developing inductance models for time domain analysis, where it is perhaps more commonly employed, or models of complex impedance values for steady state analysis. The latter is more applicable to distribution system analysis. Therefore, the notation will be presented in terms of complex impedance (z) and admittance (y) values. Bold uppercase letters designate matrices or vectors while lowercase letters designate scalar values.

The starting ingredients are:

1. The short circuit impedance between each pair of windings,
2. The turns ratio or voltage ratings of the windings.

One of the reasons we have adopted this approach is that transformer manufacturers can generally provide accurate values for the short circuit impedances between windings by test or empirical formulae for any number of windings.

From these data, the short circuit impedance matrix, $\boldsymbol{Z}_B$, is constructed with one of the windings serving as the reference (assumed shorted). The process is identical to forming the short circuit matrix for a power system with the infinite bus as reference. Thus, the designation, $\boldsymbol{Z}_B$, is borrowed from that area of power system analysis.

The short circuit impedance between windings i and j, which we will designate $z_{SCi,j}$, is generally expressed in percent on some voltampere (VA) base, usually that of the first winding. Let z_{base} be the multiplier to convert to a convenient voltage base. We generally use either a one-turn or a one-volt depending on how the turns ratios are to be expressed (turns or voltages). This is an arbitrary choice that is simply a matter of choosing the appropriate multiplying factors and any base will work.

With the first winding as the reference winding, $\boldsymbol{Z}_B$ is constructed as follows:

<u>Diagonal Elements of $\mathbf{Z}_{\mathrm{B}}$</u>

$$Z_{Bii} = z_{\mathrm{SC}\ 1,\ i+1} \times z_{\mathrm{base}} \quad \text{for } i = 1 \text{ to } m\text{-}1 \tag{1}$$

where m = number of windings.

<u>Off-diagonal Elements of $\mathbf{Z}_{\mathrm{B}}$:</u>

$$Z_{Bij} = 0.5[z_{\mathrm{Bii}} + z_{\mathrm{Bjj}} - z_{\mathrm{Sc}j+1,i+1} \times z_{\mathrm{base}}] \quad i \neq j \tag{2}$$

Note that the order of $\boldsymbol{Z}_B$ is (m-1) – one less than the number of windings. For a simple 2-winding, single-phase transformer, $\boldsymbol{Z}_B$ is trivial, having only one element.

Once this matrix is computed, any arbitrary transformer connection may be modeled by simply applying linear algebra to perform power-invariant reference frame changes and the conversion to actual values. The desired result here is the primitive admittance matrix for the transformer. This is merged with the primitive admittance matrices for other elements in the system to form a system nodal admittance matrix, $\boldsymbol{Y}$, representing the connections to the buses in the system. Therefore, the immediate goal is to transform $\boldsymbol{Z}_B$ into the corresponding primitive admittance matrix, $\boldsymbol{Y}_{prim}$. The transformation can be written in matrix notation as shown in Equation (3).

$\boldsymbol{B}$ is defined as an m x (m-1) incidence matrix whose elements are either 1, -1, or 0. It relates currents in the short circuit reference frame where the first winding is assumed shorted to the currents in the nodal admittance reference frame on a one-turn or one-volt base designated $\boldsymbol{Y}_1$. This network is essentially a per-unit value model with no winding connections represented, similar to what one might use for a positive-sequence power flow.

$$\boldsymbol{Y}_{prim} = \boldsymbol{A}\ \underbrace{\boldsymbol{N}\ \underbrace{\boldsymbol{B}\ \boldsymbol{Z}_B^{-1}\ \boldsymbol{B}^{\mathrm{T}}}_{\boldsymbol{Y}_1}\ \boldsymbol{N}^{\mathrm{T}}}_{\boldsymbol{Y}_w}\ \boldsymbol{A}^{\mathrm{T}} \tag{3}$$

$\boldsymbol{N}$ is either a m x m or a $2m$ x m incidence matrix whose non-zero elements are the inverse of the number of turns in the windings (or the voltage rating of the winding, depending on the base of $\boldsymbol{Z}_B$). The matrix is $2m$ x m if you wish to explicitly represent each terminal of each winding individually at this point. This matrix relates the currents in the $\boldsymbol{Y}_1$ equation to the actual winding currents. The resulting admittance matrix in the *winding* reference frame, $\boldsymbol{Y}_W$, is in actual values (S). The voltages and currents in this reference frame are the voltages across the windings and the currents through the windings.

The $\boldsymbol{A}$ matrix is an incidence matrix, whose non-zero elements are generally either 1 or -1, that relates the *winding* currents to the actual transformer *terminal* currents. A single-phase, two-winding transformer would yield a 4x4 $\boldsymbol{Y}_{prim}$ matrix because there are 4 conductors available for connecting to something (two conductors per winding). A three-phase, wye-delta transformer with the neutral terminal explicitly modeled would yield a 7x7 $\boldsymbol{Y}_{prim}$ matrix. (In OpenDSS it would be a 8x8 because all terminals must have the same number of conductors and there is a neutral conductor for the delta winding that is not connected to anything.)

Note that nowhere in this formulation is a three-phase system assumed. There are not necessarily any values appearing in the incidence matrices as in many formulations found in the literature. When the √3 is used, the model generally applies only to 3-phase transformers. The model described here will work for any number of windings and phases. The phases do not have to be balanced nor must they have the same turns ratios. If you get the short circuit impedances, number of turns, and the winding connections correct, everything will come out correctly in the system model. Whether the transformer is single-phase, three-phase, or n-phase unit, the notation stays the same. Only the contents of the matrices are changed.

Figure 3 illustrates the process defined in Eq. (3) schematically.

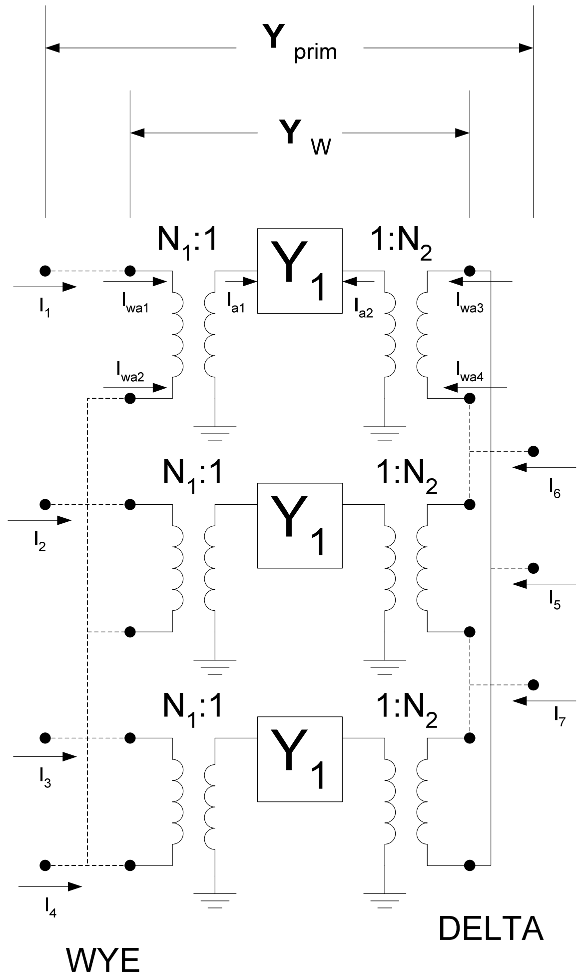

Figure 3.Schematic of transformer model development for a simple wye-delta 3-phase transformer.

$\boldsymbol{Y}_1$ represents a ground-referenced nodal admittance network that will give the proper leakage impedance model on a one-turn or one-volt base. The $\boldsymbol{N}$ matrix represents the effect of the ideal transformers shown to obtain actual winding voltages. Finally, the $\boldsymbol{A}$ matrix represents the connections of the winding conductors to obtain the transformer terminals as depicted by the dashed lines.

A neutral impedance of wye-connected windings can be implicitly included in $\boldsymbol{Y}_{prim}$ by adding the appropriate admittance to the corresponding diagonal element ($\boldsymbol{Y}_{prim\ 44}$ in this case).

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See the Appendix for more detail on modeling transformers adapted from an OpenDSS document. The focus of the Appendix is on how to address core behavior for multiphase transformer models, but the general principles can be gleaned from the material to apply to modeling the short circuit impedance characteristics of any transformer.

Appendix

Adapted from OpenDSS Documentation

Modeling Core Effects in OpenDSS

For distribution system analysis studies that involve only power flow analysis, it is generally sufficient to model 3-phase transformers using the positive-sequence leakage impedance values. You rarely need to represent the magnetizing impedance unless you are doing loss analysis that is sensitive to the magnetizing current. However, there are types of analysis where the zero-sequence response of some types of transformers is important to model. Since the OpenDSS models transformers as they are physically rather than using symmetrical component equivalents, you have to understand a little more about transformer behavior than you might otherwise.

The main issue with core effects is with core structure of 3-phase transformers. The existing OpenDSS Transformer model does not represent the transformer core other than as a linear reactance (if the "%imag" property is greater than zero). The magnetizing branch is embedded within the matrices as the short-circuit impedance matrix is computed. Therefore, it is difficult to separate it explicitly from the model. Most of the time, this is sufficient for distribution system analysis, but there are exceptions. One, in particular, is when the characteristics of the magnetic circuit in 3-legged core transformers results in significant impacts on zero-sequence impedances. The present Transformer model in OpenDSS assumes no magnetic coupling between the phases. Coupling between phases is accomplished by electrical connections of the windings. So when it becomes important to model the core effects on the zero sequence impedances, something special must be done.

Instances Where Modeling 3-Legged Core Effects Might Be Important

- Manufacturers have told me that the vast majority (>90%) of the utility distribution substation transformers are *core-form* transformers (3-legged core designs – sometimes called "E" cores). Thus, the single-phase fault current at the primary distribution bus can be slightly higher than what one might get by assuming the zero sequence leakage impedance of the transformer is the same as the positive-sequence leakage impedance. Whether this is important depends on the purpose of the analysis. If you are most interested in things that happen more than ½ mile or so out on the feeder, it generally doesn't matter much. However, if breaker duties due to DG infeed are being computed at the substation bus, it could be important.
- Many of the distribution substation transformers in areas where the transmission system is strong are two-winding transformers connected Delta-Yg. It is typically most important for these transformers for the zero-sequence model to be correct only when looking into the Yg side. The physical Delta winding dominates the effect while the core model makes a minor contribution to the zero sequence.

However, in many other systems such as where the transmission system needs a lower grounding impedance, the distribution substation transformers are 3-winding transformers connected Yg-Delta-Yg. The delta winding (usually called the "tertiary" winding) is frequently unloaded and buried, but in some cases reactors or capacitors may be connected to it to support transmission functions. For many distribution system analysis cases, it is only necessary for the transformer model to appear accurate from the distribution side of the substation. However, the OpenDSS can represent the transmission system simultaneously and it may be important for the transformer model to be accurate when looking from both transmission and distribution sides of the substation.

- Most utility 3-phase distribution (service) transformers these days are made up of either a bank of single-phase transformers or are 5-legged core padmounted transformers. Nothing special needs to be done for these transformer designs for the typical kinds of studies that OpenDSS can perform. Simply define the transformer using the high-to-low leakage impedance from the test report or nameplate. A special 5-legged core model may be important for time-domain (i.e., EMTP) studies such as ferroresonance, but rarely for OpenDSS studies. On the other hand, I have encountered many 3-legged core dry-type service transformers connected at primary distribution voltage levels. Some are owned by utilities, but the majority were installed by end users. It usually doesn't matter significantly for power flow calculations, but these transformers can have an impact on the single-phase fault current calculations and on any condition where one phase is open or is otherwise grossly unbalanced. The latter is often quite important when considering things that can go wrong with DG installations. The common Yg-Yg transformer connection on a 3-legged core will behave as if it has a 3rd delta-connected winding (called a "phantom" tertiary), which can lead to surprising results.

Symmetrical Components and the OpenDSS Program

Many power engineers are accustomed to have fault current calculation tools that form positive-, negative-, and zero-sequence networks and connect them in various ways to compute fault currents and other quantities resulting from significant unbalances. Unfortunately, in order to meet its analysis and modeling objectives, the OpenDSS cannot use this approach. There are many system conditions such as unbalanced lines that cannot be accurately studied with symmetrical component models – at least not easily. Network unbalances result in coupling between the sequence networks. When the networks end up coupled together, it is usually simpler to solve the system in phase components, which is the OpenDSS approach. Also, the OpenDSS is capable of n-phase models, not just 3-phase models. Symmetrical component transformations technically do not apply to circuits with other than 3 phases (either more or less). For 1- and 2-phase models, there are certain kluges[1] that power engineers have applied that give approximate answers.

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[1] *Kluge = a workaround, a quick-and-dirty solution, a clumsy or inelegant, yet effective, solution to a problem, typically using parts that are cobbled together. (Wikipedia)*

Per unit representations raise another issue. Per unit models were introduced into power system simulation to be able to model multiple voltage levels without having to specifically represent the transformer. The OpenDSS is capable of analyzing problems where impedances span transformers, which are difficult to represent in per unit systems without resorting to kluges. Two common examples are:

1. High-to-low capacitance in transformers for certain harmonics problems, and
2. The 69 kV overbuild falling into the 12.5 kV distribution line.

Also, the common split-phase 120/240V residential service transformer is not amenable to per unit representation when there are both 120V and 240V loads. Which base do you use?

Therefore, the OpenDSS represents everything in admittance matrices in units of actual Siemens. Voltages and currents are likewise in units of actual volts and amperes. While 30 years ago this frequently resulted in a problem with numerical accuracy because of the great differences in the numerical values at different voltage levels, modern numerical methods with at least 64-bit floating-point arithmetic pretty much makes this a non-issue. There are few distribution system circuit modeling conditions in which the equations are sufficiently ill-conditioned to require remedial actions.

Both of the issues in the preceding paragraphs have a bearing on the transformer model in the OpenDSS. As a *Power Delivery* element, a transformer is ultimately modeled by a primitive Y matrix that embodies all impedances and winding connections. No attempt is made to model the nonlinear portion of the magnetizing impedance within the transformer model; it is modeled as a linear reactance, if specified at all - *%imag* defaults to zero. The model is focused on the leakage impedance behavior, which has the most impact on power flow, harmonics, etc.

The OpenDSS transformer model, like other models in OpenDSS, is a physically-based model. Windings are modeled and connected as they would be in the actual transformer. A split-phase service transformer is actually constructed as a 3-winding transformer and must be modeled that way if necessary to capture the true behavior. In some analysis programs, one might represent a phase shifting transformer by specifying the phase angle. In the OpenDSS, you would define and connect the windings as the manufacturer would when the phase shifter is built. With this is mind, let’s go back to the 3-legged core transformer model.

Figure A-4 shows the schematic for a Yg-Delta-Yg transformer. If this transformer is constructed from three single-phase transformers, a shell-type 3-phase transformer, or even a 5-legged core 3-phase transformer, we generally do not worry about interphase coupling of the magnetic circuit for the types of analysis performed with OpenDSS. Of course, the delta winding provides coupling between the phases.

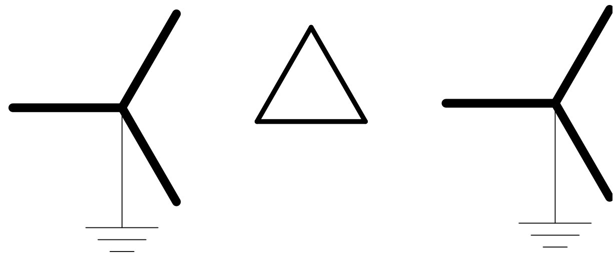

Figure A-4. Yg-Delta-Yg Transformer

There are 3 short circuit measurements between each pair of windings required to construct the short circuit reactance matrix as depicted in Figure A-5. The OpenDSS can take this matrix and construct a full 12x12 primitive Y matrix that represents the transformer windings including the neutral point.[2] (A dummy neutral point is generated for the delta winding to satisfy an OpenDSS requirement that all terminals have the same number of conductors. By default, it gets connected to ground and its current is zero.)

$$X_{SC} = \begin{bmatrix} X_{1-2} & \\ X_{1-3} & X_{2-3} \end{bmatrix}$$

Figure A-5. Short circuit reactance matrix required to represent a 3-winding transformer (percent or per unit values).

The OpenDSS transformer model provides the *XHL*, *XHT*, and *XLT* properties as a means for specifying the reactances of a 3-winding transformer. Alternatively, users may use the *xscarray* property, which accepts the short circuit reactances as an array representing the lower triangle matrix depicted in Figure A-5.

Note that some data sources provide per unit or percent values for X_H, X_L, and X_T to represent a 3-winding transformer (Figure A-6). Keep in mind these values are for a *model* that works for the special case of a 3-winding transformer. In reality, there are no corresponding physical values for these reactances. A clue to this is that X_L frequently comes out negative.

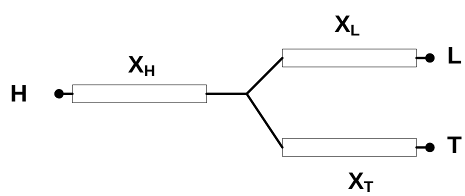

Figure A-6. Three-branch per unit or percent model commonly used in power system analysis programs.

The reactances arise from the leakage flux between *pairs of windings*. OpenDSS is designed to model transformers of nearly arbitrary numbers of windings. All that is

[2] R. Dugan and S. Santoso, "An example of 3-phase transformer modeling for distribution system analysis", IEEE T&D 2003 Conf Proceedings.

required to construct the model are short circuit impedances between each pair of windings. Very complex models can be constructed in this way depending on the ability to compute or measure the short circuit impedances.

Phantom Windings

If the transformer is constructed around a 3-legged core, there is a complication to specifying the short circuit impedances between the windings. As shown in Figure A-7, zero sequence flux is in phase in each leg of the core and has to leave the core to complete the magnetic circuit. The path is mostly "air core" (i.e., not in steel). Thus, the magnetizing reactance to zero-sequence flux is considerably less than for other normal mode fluxes (positive- and negative- sequence, for example). In fact, although it is larger, it is of the same order of magnitude as the leakage (short circuit) reactances and often cannot be neglected.

The net effect for a 3-winding 3-phase transformer is like having separate cores for each phase but having a 4th delta-connected winding. In transformer literature, this is often referred to as a "phantom" delta winding as depicted in Figure A-8. A 4-winding model is required to construct a physically-based model of the Yg-Delta-Yg transformer if we choose not to neglect the error introduced by neglecting, or approximating, the phantom winding effect. Unfortunately, the phantom winding does not physically exist and a measurement of the short circuit impedances cannot be made. Measurements can be made only to the physical windings. However, some transformer design programs can compute these values (I used to work for a transformer manufacturer and could obtain the appropriate values from the Engineering Department on special occasions).

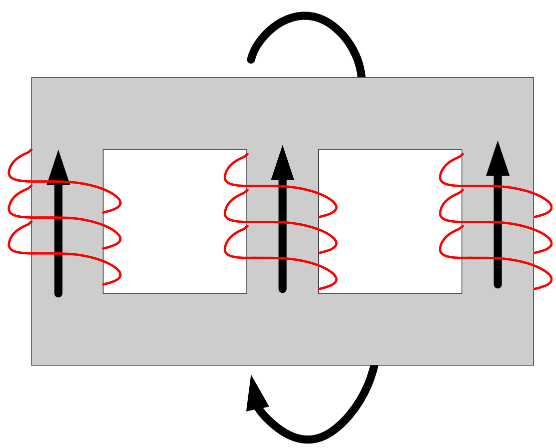

Figure A-7. Three-legged core zero sequence flux paths.

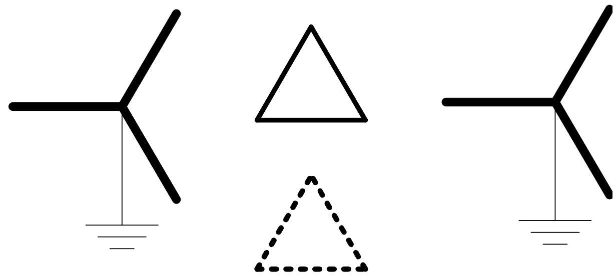

Figure A-8. The effect of the 3-legged core is like having an extra "phantom" delta-connected winding

$$X_{SC} = \begin{bmatrix} X_{1-2} & & \\ X_{1-3} & X_{2-3} & \\ X_{1-4} & X_{2-4} & X_{3-4} \end{bmatrix}$$

Figure A-9. Ideally, one would provide three additional short circuit measurements to the phantom winding.

Modeling Options

Having a physical delta winding on the core will help with zero-sequence modeling. It will naturally get the zero-sequence impedance in the ballpark of where it should be. But the zero-sequence impedance still needs to be a little lower. Options for OpenDSS modelers include:

- Define a 4 winding transformer in OpenDSS and estimate the 3 additional short circuit measurements. Sometimes, these can be reasonably estimated from transformer test reports, but not always. For modeling a 2-winding transformer on a 3-legged core with this approach, you would define a 3-winding transformer and estimate values for the XHT and XLT properties.
- If the physical delta winding is not to be loaded, one option is to define a 3-winding transformer and reduce the values of XHT and XLT to more closely match the zero-sequence short circuit measurements. XHL is specified as the positive sequence value so that the basic power flow solution is correct. This approximation is good enough for many studies.
- The transformer is defined as a 3-winding transformer and the positive-sequence leakage impedance values are used for the XHL, XHT, and XLT properties. Then add a separate Yg-Delta 2-winding transformer on the Low voltage Yg winding with an appropriate impedance to bring the net zero-sequence impedance down closer to the tested value. The additional transformer acts as a *grounding transformer*. You could also define a zig-zag transformer, but a 2-winding transformer is much easier in the OpenDSS. Again, this approximation is satisfactory for many studies involving the distribution feeder. It may not be good enough if impacts on the transmission system are critical.

- The OpenDSS allows another modeling option not available in other programs. You can define the transformer model using the zero-sequence model values and then add a special positive sequence impedance in series with the High winding of the transformer to make up the additional impedance seen by positive- and negative-sequence currents.

Estimating Impedances to the Phantom Winding

For the case where you choose to estimate the impedance to the phantom delta winding, the values of the short circuit reactance from the actual winding to the phantom winding are typically in the range of 75 – 200 % on the main transformer's kVA base. In parallel with the physical Delta, for which the reactances are typically in the 7 – 30% range, this reduces the net zero sequence impedance by 5-10% from the positive-sequence impedance. To better understand what values to choose, it is necessary to understand more about how transformers are constructed.

As shown in Figure A-10, the physical Tertiary winding is generally wound next to the core. Then the Low voltage winding and the High voltage winding are wound on top of the Tertiary in that order. The short circuit reactance is proportional to the physical space between the winding. The greater the space, the higher the reactance is. Proportions vary with designs. The default values in the OpenDSS transformer model are XHL=7%, XHT=35% and XLT = 30%. The Low winding is closer to the Tertiary than the High winding. Thus, XLT is lower than XHT. In another transformer (from the example in this document) in which the Low is physically much closer to the Tertiary the values are XHL = 8.98%, XLT = 7.3%, and XHT=13.32%.

For estimating the short circuit reactance to the phantom winding, we need to come up with three values as indicated in Figure A-9. One might think of the phantom (4^{th}) winding as occupying the space inside the Tertiary winding. The Tertiary (3^{rd}) winding is closest, so $X_{3\text{-}4}$ would be smallest of the three and $X_{1\text{-}4}$ (High to phantom) would be the largest. Knowing these proportions, we can make some educated guesses and can generally match test results after a few quick iterations using OpenDSS scripts.

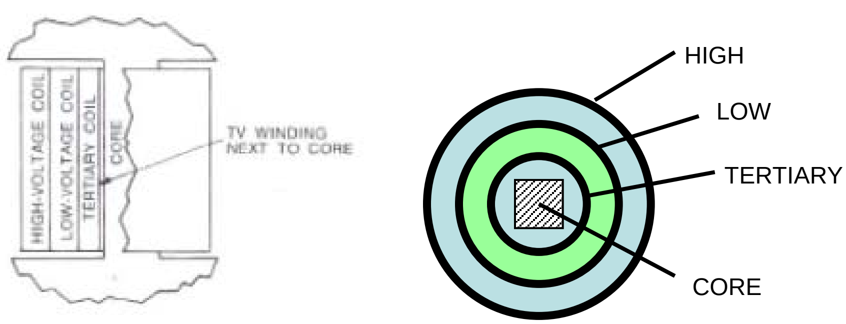

Figure A-10. Typical coil arrangement for a 3-winding transformer.

Examples

Two examples of modeling a 3-winding Y-D-Y 30 MVA transformer to meet the following impedances:

Positive sequence: 10.79%

Zero Sequence:

XHL = 8.98%
XLT = 7.3%
XHT=13.32%

Both models use a bank constructed of 1-phase units for clarity, although a 3-phase model could also be used.

Estimating Impedances to 4th (Phantom) Winding

In this case, the base 4-winding model is built using the positive-sequence short circuit reactances. Then the impedances to the phantom (4th) winding are adjusted until the SLG fault currents match the test results. Knowing the typical values were in the 75% to 200% range, I started by guessing

X_{1-4} = 100%
X_{2-4} = 80%
X_{3-4} = 75%

This was based on my assumption of the construction of the windings (see above). This turned out to be a good guess because I had only to drop the last two values slightly to obtain the desired fault currents.

X_{1-4} = 100%
X_{2-4} = 70%
X_{3-4} = 65%

This took only 4 or 5 iterations using the script on the next page. Note that this script uses the new XfmrCode object to define the transformer. If you get an error when you run this, you will need to update your version of the OpenDSS.

```
Clear

!!!! Modeling Y-Delta-Y 3-legged core as 4-Winding Transformer
!!!! Values to the phantom delta winding are estimated
!!!! Uses a bank of 1-phase transformers

New Circuit.4Winding
~ BasekV=161  isc3=1000000   isc1=100000

New XfmrCode.4winding   phases=1 windings=4
~ Wdg=1 %r=.2  Conn=Wye  kV=(161 3 sqrt /)  kVA=10000
~ Wdg=2 %r=.2  Conn=Wye  kV=(13.8 3 sqrt /) kVA=10000
~ Wdg=3 %r=.2  Conn=Delta kV=7.97  kVA=10000
~ Wdg=4 %r=.2  Conn=Delta kV=7.97  kVA=10000     !!!! Phantom Delta winding
!!!!              [X12   X13   X14  X23  X24  X34]
~ XSCArray=[10.79  15   100   7.3   70    65]


New Transformer.PhaseA   xfmrcode=4winding
~ Wdg=1  Bus=SourceBus.1.0
~ Wdg=2  Bus=LowBus.1.0
~ Wdg=3  Bus=TertBus.1.2
~ Wdg=4  Bus=Phantom.1.2


New Transformer.PhaseB   xfmrcode=4winding
~ Wdg=1  Bus=SourceBus.2.0
~ Wdg=2  Bus=LowBus.2.0
~ Wdg=3  Bus=TertBus.2.3
~ Wdg=4  Bus=Phantom.2.3


New Transformer.PhaseC   xfmrcode=4winding
~ Wdg=1  Bus=SourceBus.3.0
~ Wdg=2  Bus=LowBus.3.0
~ Wdg=3  Bus=TertBus.3.1
~ Wdg=4  Bus=Phantom.3.1


Solve

New Fault.F1   Phases=1  Bus1=LowBus

solve

Show Currents Elements
```

Figure A-11. Model with three 1-phase 4-winding transformers