Modeling of Two-Winding Voltage Regulating Transformers for Positive Sequence Load Flow Analysis in PSS®E

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Introduction
Electrical transformers are important components in transmission and distribution power systems; they make possible the transfer of MWs and Mvars between networks operating at various voltage levels. The modeling of these power system components in the steady-state analysis of electrical networks is critical since incorrect data for their positive sequence winding leakage impedance, magnetizing branch admittance, off-nominal turn ratio, number of tap positions, tap range or voltage control band, may lead to erroneous results in the verification of voltage control schemes, assessment of transmission losses and computation of system var flows.

The main objective of this article is to assist PSS®E users with a guide for entering electrical transformer data for the positive sequence model of the electrical network with a minimum of effort and minimal causes for errors.

Notes/suggestions for entering each of the required model variables follow, along with an example of a two-winding voltage regulating transformer modeled in PSS®E.

Model Data Requirements
The per-phase positive sequence network model used by PSS®E for three-phase two-winding transformers or three-phase banks of three identical single-phase two-winding transformers is shown in Figure 1 below. This model allows the modeling of the transformer magnetizing admittance, \( Y_m = G_{hm} + jB_m \), that is often neglected on the I-side (winding 1) of the transformer and allows the modeling of the between windings 1-2 equivalent leakage impedance \( Z_{eq} = r_{eq} + jx_{eq} \). One of the many features of PSS®E is that the user does not have to calculate the winding equivalent leakage impedance, magnetizing branch admittance, effective off-nominal transformer tap, tap step and tap limits; these calculations are done within PSS®E.

Figure 1. PSS®E Two-Winding Transformer Model
As users create their transformer data records, PSS®E’s flexibility becomes apparent. Each of the required model variables is discussed below.

- **Equivalent winding leakage impedance** $Z_{eq}$:
  
  - in per unit on a system three-phase apparent power MVA base–$SBASE$, usually 100 MVA–and windings 1 and 2 phase-to-phase rated voltages for fixed tap transformers and nominal tap for transformers fitted with either under-load or off-load taps ($t_{10} = t_{20} = 1.0$ per unit or $t_{10} = VB1$ kV and $t_{20} = VB2$ kV) – **Impedance code CZ=1**.
  
  - in per unit on a winding 1-2 three-phase apparent power MVA base–$SB1-2$, usually the ONAN rating–and windings 1 and 2 phase-to-phase rated voltages ($VB1$ and $VB2$) for fixed tap transformers and nominal tap for transformers fitted with either under-load or off-load taps ($t_{10} = t_{20} = 1.0$ per unit or $t_{10} = VB1$ kV and $t_{20} = VB2$ kV) – **Impedance code CZ=2**.
  
  - short-circuit test three-phase full-load winding copper losses ($W_{sc}$) in Watts and the impedance voltage magnitude or equivalent winding leakage impedance magnitude in per unit on a winding 1-2 three-phase apparent power MVA base–$SB1-2$, usually the ONAN rating–and windings 1 and 2 phase-to-phase rated voltages ($VB1$ and $VB2$) for fixed tap transformers and nominal tap for transformers fitted with either under-load or off-load taps ($t_{10} = t_{20} = 1.0$ per unit or $t_{10} = VB1$ kV and $t_{20} = VB2$ kV) – **Impedance code CZ=3**.

- **Transformer magnetizing admittance** $Y_m$:
  
  - in per unit on a system three-phase apparent power MVA base–$SBASE$, usually 100 MVA–and winding 1 phase-to-phase bus voltage base – **Magnetizing Admittance code CM=1**.
  
  - open circuit test three-phase no-load core losses ($W_{nl}$) in Watts and the no-load excitation current magnitude or the magnetizing admittance magnitude in per unit on a winding 1-2 three-phase apparent power MVA base–$SB1-2$, usually the ONAN rating–and windings 1 phase-to-phase rated voltage ($VB1$) for fixed tap transformers and nominal tap for transformers fitted with either under-load or off-load taps ($t_{10} = 1.0$ per unit or $t_{10} = VB1$ kV) – **Magnetizing Admittance code CM=2**.

- **Winding 1-2 three-phase apparent power MVA (SB1-2)**:
  This is the three-phase apparent power MVA used in the normalization (per unit representation) of the winding leakage impedance $Z_{eq}$. Use of the transformer’s three-phase nameplate rating—which is usually the ONAN rating—is strongly recommended; however, any other three-phase apparent power base can be used. (As a matter of fact, all of the two-winding transformer legacy data up to version 26 of PSS®E is expressed on a system three-phase apparent power base—most likely 100 MVA—and a system bus voltage base.) System bus voltage base refers to the bus phase-to-phase voltage in kV when specifying the buses to which the terminals of the two-winding transformer are connected. Note that when specifying base quantities for two-winding transformers you must specify an apparent power base and two voltage base values; one for winding 1 (NOMV1) and another for winding 2 (NOMV2).

- **Winding nominal voltage (NOMV1, NOMV2)**:
  A nominal phase-to-phase voltage—usually the phase-to-phase rated or nominal tap winding voltage—should be entered for winding 1 and winding 2. The nominal voltage for winding 1 is used in the conversion of the no-load test data expressed on a winding three-phase apparent power MVA and winding nominal (rated) phase-to-phase voltage base on a system three-phase apparent power MVA and system bus voltage base. The nominal voltage for winding 2 is used in PSS®E version 31 and newer versions to convert the per unit tap values on a winding voltage base (that is, as they appear on the transformer test report and nameplate data) to per unit tap values on system bus voltage base. The default value for these two data entry points is 0.0 kV, which means that the winding nominal voltage is equal to the voltage base of the bus to which the transformer is connected. For PSS®E
version 30 and earlier versions the nominal voltage for winding 2 is not used in any calculations related to the winding leakage impedance, per unit tap value, or performance of a transformer unit.

- **Number of tap positions in winding 1 (NTP1):**
  PSS®E assumes that the nominal tap position is located midway the tap range: \((NTP1+1)/2\). PSS®E also assumes that the winding 1 tap step is constant: \(\Delta t_1 = TSTEP1 = (R_{max} - R_{min})/(NTP1-1)\).

- **Winding off-nominal taps (WINDV1 and WINDV2):**
  - Automatic adjustable taps (ULTCs) will be associated with winding 1 \(t_1\), and manually or off-load adjustable taps will be associated with winding 2 \(t_2\). These taps may be specified in:
    - per unit on bus “I” and “J” phase-to-phase system voltage – **Winding code CW=1**.
    - kV winding 1 and 2 phase-to-phase voltages – **Winding code CW=2**.
    - per unit on winding 1 and 2 phase-to-phase rated voltages – **Winding code CW=3**.

- **Tap limits \((R_{max}, R_{min})\):**
  These apply only to taps in winding 1 and they define the winding tap range. Two values are used for these limits \(R_{max}\) for the upper limit and \(R_{min}\) for the lower limit. These tap limits may be specified in:
  - per unit on bus “I” and “J” phase-to-phase system voltage – **Winding code CW=1**.
  - kV winding 1 and 2 phase-to-phase voltages – **Winding code CW=2**.
  - per unit on winding 1 and 2 phase-to-phase rated voltages – **Winding code CW=3**.

- **Winding 1-2 voltage phase angle or winding 1 phase shift angle \((\Theta_{12} = \Theta_1 - \Theta_2)\):**
  The relative phase angle between winding 1 and winding 2 may be specified in the transformer data record. This phase shift angle is measured in electrical degrees and is assumed to be positive when winding 1 phase voltage leads winding 2 phase voltage, and to be negative when winding 1 phase voltage lags winding 2 phase voltage. For example, if winding 1 (wye-grounded connected) lags winding 2 (delta connected) by 30° (Ygd11 in the IEC notation), then the angle \(\Theta_{12} = -30°\). In a future newsletter, we will address the modeling in PSS®E of phase-shifter transformers.

- **Transformer control band \((V_{max}, V_{min})\):**
  The upper and lower limits of voltage regulating transformers are specified in the entries \(V_{max}\) and \(V_{min}\), respectively. These limits may be expressed in either kV or per unit when the transformer control mode is 1 (i.e., voltage control) or in Mvar flow into the terminals of winding 1 when the transformer control mode is 2 (i.e., reactive power flow control). When the upper and lower voltage limits are expressed in per unit, the voltage base is the bus voltage base of the bus bar when local or it is the bus voltage at the remote bus where voltage is to be controlled. It is important to keep in mind that the control band width \((V_{max} - V_{min})\) must be equal to or greater than two times the transformer's tap step TSTEP1. This will guarantee that when the tap adjustment option is used in a load flow solution, and the control mode is 1, the tap solution will not oscillate between tap limits. When the control mode is 1, the default values are: for the upper limit, 1.1 per unit (or 1.1*bus voltage base in kV) and, for the lower limit, 0.9 per unit (or 0.9*bus voltage base in kV). There are no default values allowed for control mode 2.

- **Transformer control mode \((COD1)\):**
  Voltage regulating transformers in PSS®E can be modeled in three control modes:
→ mode 0, the default mode, where taps in both windings are set manually and are fixed
→ mode 1, voltage control mode, where winding 1 tap is adjusted when the load flow solution option “tap adjustment” is selected
→ mode 2, Mvar control mode, where winding 1 tap is adjusted when the load flow solution option “tap adjustment” is selected.

An Important Note:

It is important to note that the transformer model in PSS®E automatically adjusts the winding leakage impedance when there is mismatch between the winding base voltage (NOMV1 and NOMV2) and the base voltage of the bus where transformer terminals are connected. Figure 2 shows that when the winding 2 base voltage is not the same as its bus voltage base, PSS®E will automatically multiply the specified winding leakage impedance in per unit on a winding apparent power base and a winding voltage base by the square of the winding 2 off-nominal winding turns ratio \( (t_2)^2 \) as this impedance is referred to the bus “J” side – see Figure 1. If the winding 1 base voltage is also not the same as its bus voltage base, PSS®E will adjust the transformer winding leakage impedance using the winding 1 off-nominal winding turns ratio \( t_1 \). These off-nominal winding turn ratios, \( t_1 \) and \( t_2 \), are specified by the user as:

\[
t_1 = \text{winding 1 voltage/ bus “I” base voltage when given in per unit} = \text{winding 1 voltage when given in kV}
\]

\[
t_2 = \text{winding 2 voltage/ bus “J” base voltage when given in per unit} = \text{winding 2 voltage when given in kV}
\]

When the winding code is 3, taps are specified in per unit on a winding voltage base and PSS®E will automatically take care of the voltage base mismatch by multiplying the winding off-nominal tap by the factor (winding base voltage/bus base voltage).

The winding 1 tap limits \( R_{\text{max}} \) and \( R_{\text{min}} \) must also be adjusted when they are specified in per unit on a bus “I” voltage base.

All computations carried out by PSS®E are performed in per unit on a system apparent power base and bus voltage base.

\[
t_j/t_j : 1
\]

\[
t_i : t_j
\]

\[
|t_j|^2 r_{eq}^\prime + j |t_j|^2 x_{eq}^\prime = r_{eq} + j x_{eq}
\]

Figure 2. Standard PSS®E Two-Winding Transformer Circuit
Numerical Example

A numerical example follows to show how a two-winding voltage regulating transformer is modeled and how the model data is entered in PSS®E.

For our example we will use a two-winding three-phase transformer unit with nominal phase-to-phase winding voltages of 69 kV and 13.2 kV, OA/FA/FA three-phase ratings of 36/48/60 MVA, five off-load taps (±2 + neutral position) on the HV winding with a tap step of 2.5%, a nominal operating frequency of 60 Hz, the high voltage (HV) windings are connected wye-grounded through a 8.29% impedance on a 36 MVA, 69 kV base, and the low voltage (LV) windings are connected delta. The transformer unit has the following test data:

Short-Circuit Test:
Three-phase load losses at 85°C of 122300 W.
Impedance voltage or winding leakage impedance magnitude of 8.24% on a 36 MVA apparent power base, 69/13.2 kV voltage base and 85°C.

No-load or Open Circuit Test:
Three-phase no-load losses at 85°C, 100% (1.0 per unit or nominal) voltage 24900 W.
Excitation current RMS magnitude of 0.17% (0.0017 per unit) at 85°C, 100% voltage (69/√3 kV) and 36 MVA apparent power base.

This three-phase, two-winding transformer unit will be used in a generator step-up (GSU) substation where the generating unit has a rated terminal voltage of 13.8 kV. The bus voltage base for the HV and LV bus bars of the GSU substation chosen by the electric utility are 69 kV and 13.8 kV respectively.

Based on the transformer nameplate data, the short-circuit and no-load test data the following is known:

HV bus voltage base: 69 kV
LV bus voltage base: 13.8 kV
HV winding voltage base: 69 kV
LV winding voltage base: 13.2 kV
Number of taps: 5
Tap range, Rmax = 1.05 pu (72.45 kV) and Rmin = 0.95 pu (65.55 kV) on a 69 kV voltage base
Winding three-phase MVA base (SB1-2): 36 MVA
System three-phase MVA base (SBASE): 100 MVA

Since the short-circuit and the no-load test data are available, the first choice for entering the transformer unit data in PSS®E is recommended to be:
Impedance code CZ=3, load losses and impedance voltage
Magnetization admittance code CM=2, no-load losses and excitation current
Winding code CW=1, taps in per unit on a bus voltage base
Control mode: None if the transformer is fit with off-load taps and Voltage if the transformer is fit with an under-load tap changer.

All four steps listed above are recommended to be selected before entering any electric parameter and tap data in the transformer unit record in PSS®E.

Given that tap values for windings 1 and 2 will be entered in per unit on a bus voltage base (CW=1), and if a user selects the 69 kV as winding 1 in the transformer model, the tap value t1, and upper and lower tap limits, Rmax and Rmin, will be specified as:

\[ t_1 = 1.0 \text{ pu (if the tap is set at its neutral position, i.e., nominal tap)} \]
\[ R_{\text{max}} = 1.05 \text{ per unit on a 69 kV base} \]
\[ R_{\text{min}} = 0.95 \text{ per unit on a 69 kV base} \]
Winding 2 in this case will be assigned to the 13.2 kV winding and since the winding voltage base (13.2 kV) does not match the bus voltage base (13.8 kV) it is necessary to adjust the per unit value of $t_2$ so that the per unit transformer model is correct. Hence,

$$t_2 = \frac{13.2 \text{ kV}}{13.8 \text{ kV}} = 0.9565 \text{ per unit on a 13.8 kV base}$$

Note that 1.0 per unit voltage on a 13.8 kV base (bus system base) is equivalent to 1.04545 per unit on a 13.2 kV base. In general, whenever there is a mismatch between the winding voltage base and the bus voltage base and the winding code is 1, taps expressed in per unit on bus voltage base must be entered using the expression:

$$t_1 \text{ or } t_2 = \frac{\text{winding 1 or winding 2 voltage}}{\text{bus voltage base}} = (t_1 \text{ or } t_2 \text{ in pu on winding voltage base}) \times K$$

Where $K = (\text{winding voltage base/bus voltage base})$

If a user selects the 13.2 kV winding as winding 1 and the 69 kV winding as winding 2, then the values for taps $t_1$ and $t_2$, and tap range $R_{max}$ and $R_{min}$ will be:

$t_1 = 0.9565 \text{ pu (13.2 kV/13.8 kV) on a 13.8 kV base}$
$R_{max} = \text{default (1.1 pu since this winding has no taps)}$
$R_{min} = \text{default (0.9 pu since this winding has no taps)}$
$t_2 = 1.0 \text{ per unit on a 69 kV base}$

Note that off-nominal tap values for $t_2$ will be manually entered if the above arrangement is used.

If a user selects the winding code 2 (CW=2), winding 1 is the 69 kV winding and winding 2 is the 13.2 kV winding, the values for taps $t_1$ and $t_2$, and tap range $R_{max}$ and $R_{min}$ will be:

$t_1 = 69 \text{ kV (nominal tap position)}$
$R_{max} = 72.45 \text{ kV}$
$R_{min} = 65.55 \text{ kV}$
$t_2 = 13.2 \text{ kV}$

and if the 13.2 kV windings was selected as winding 1 and the 69 kV winding as winding 2, the values for taps $t_1$ and $t_2$, and tap range $R_{max}$ and $R_{min}$ will be:

$t_1 = 13.2 \text{ kV}$
$R_{max} = 15.18 \text{ kV default value (1.1 pu on a 13.8 bus voltage base)}$
$R_{min} = 12.42 \text{ kV default value (0.9 pu on a 13.8 bus voltage base)}$
$t_2 = 69 \text{ kV nominal tap position}$

In PSS®E version 31 the new winding code 3 (CW=3) was introduced. If a user selects the winding code 3 (CW=3), and winding 1 is the 69 kV winding and winding 2 is the 13.2 kV winding, the values for taps $t_1$, $t_2$ and tap range $R_{max}$ and $R_{min}$ will be:

$t_1 = 1.0 \text{ pu (if the tap is set at its neutral position, i.e., nominal tap)}$
$R_{max} = 1.05 \text{ per unit on a 69 kV base}$
$R_{min} = 0.95 \text{ per unit on a 69 kV base}$
$t_2 = 1.0 \text{ pu (on a 13.2 kV winding voltage base)}$

and if the 13.2 kV windings was selected as winding 1 and the 69 kV winding as winding 2, the values for taps $t_1$, $t_2$ and tap range $R_{max}$ and $R_{min}$ will be:

$t_1 = 1.0 \text{ pu (on a 13.2 kV winding voltage base)}$
$R_{max} = 1.1 \text{ per unit on a 13.2 kV base}$
$R_{min} = 0.95 \text{ per unit on a 13.2 kV base}$
$t_2 = 1.0 \text{ pu (if the tap is set at its neutral position, i.e., nominal tap)}$

The data record for the transformer unit and codes CW=1, CZ=3 and CM=2 is then
The benefit for entering the transformer model data in this format is that the user will store in the PSS®E database the short-circuit test data, no-load tests and nameplate winding MVA and voltage ratings. The user will no longer have to keep separate records for this important data and all the calculations to convert the test data to winding leakage impedance and magnetization admittance branch in per unit will be carried out by PSS®E. The only action required is to change the impedance and admittance codes to CZ=1 or 2 and CM=1 and PSS®E will show in the data record for this transformer unit the values in per unit for the winding leakage impedance and magnetization admittance branch.

For example if the codes used are CW=1, CZ=2 and CM=1, the data record shown by PSS®E will be:

Note that the equivalent winding resistance and equivalent winding leakage reactance in per unit on a winding apparent power base and winding voltage base are:

\[ R_{12} = r'_{eq} = \frac{W_{Cu \text{ losses}}}{S_{B1-2}} = \frac{0.1223}{36} = 0.003397 \text{ pu} \]

\[ X_{12} = x'_{eq} = \sqrt{(0.0824^2 - 0.0034^2)} = 0.08233 \text{ pu} \]

and the complex equivalent winding impedance \( Z_{eq, \text{ nominal}} \) in per unit on a winding apparent power base and winding voltage base is:

\[ Z_{eq, \text{ nominal}} = R_{12} + j X_{12} = 0.003397 + j 0.08233 \text{ pu} \]

and the magnetizing admittance conductance and susceptance in per unit on a system apparent power base (100 MVA) and winding 1 bus voltage base (69 kV) are:

\[ G_{h+e} = \frac{W_{NL \text{ losses}}}{S_{BASE}} = \frac{0.0249}{100} = 0.000249 \text{ pu} \]

and since

\[ |I_p| \text{ pu} = |Y_m| \text{ pu} * 1.0 \text{ pu voltage} = |Y_m| \text{ pu} = 0.0017^* (36/100) = 0.000612 \text{ pu} \]

then,

\[ B_m = \sqrt{(0.000612^2 - 0.000249^2)} = 0.00559 \text{ pu} \]

The user must keep in mind that the complex magnetizing admittance in pu on a system apparent power base (100 MVA) and winding 1 bus voltage base (69 kV) is:

\[ Y_m = G_{h+e} - j B_m = 0.000249 - j 0.00559 \text{ pu} \]

If the user is interested in finding out the values stored by PSS®E for the equivalent winding leakage impedance and equivalent magnetizing branch admittance as per the IEEE Standard Model shown in Figure 2, they can be found by displaying them in the Report Window by showing the network data with the IEEE Format Power Flow Data activity. The result of this procedure is shown below:

Note that the bus data displays the equivalent magnetizing branch admittance.
\[ Y_m = 0.0002 - j0.0006 \text{ pu on a 100 MVA and 69 kV base} \]

the branch data displays the equivalent winding leakage impedance \( Z_{eq} \)

\[
Z_{eq} = (t_2)^2 r'_{eq} + j (t_2)^2 x'_{eq}
\]

\[ = 0.008634 + j0.209231 \text{ pu on 100 MVA and 69 kV/13.8 kV base} \]

and the transformer turns ratio

\[ t = t_1 / t_2 = 1.0 / 0.9565 = 1.0455 \text{ pu on 69 kV / 13.8 kV bus voltage base} \]

The winding connection for this transformer unit is wye-grounded for HV (69 kV) winding and delta for the LV (13.2 kV) winding. Since no phase shift angle between the wye and delta connected windings has been provided, it is safe to assume the ANSI standard phase shift angle for the wye/delta connection: the HV winding leads the LV winding by 30°. Thus, the winding 1 angle entry in PSS®E (relative phase angle between winding 1 and winding 2 with winding 1 leading winding 2) will be:

- +30° if the HV (69 kV) winding is assigned to winding 1 and the LV (13.2 kV) winding is assigned to winding 2
- -30° if the HV (69 kV) winding is assigned to winding 2 and the LV (13.2 kV) winding is assigned to winding 1.

With this numerical example we have shown the various ways available in PSS®E to create an electric network model for a two-winding voltage regulating transformer. The author strongly recommends the use of the short-circuit and open-circuit test data whenever possible, since use of this data allows PSS®E users to keep track of not only the transformer’s winding leakage impedance and magnetizing admittance data but also of the transformer test data, all in one single data record.