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

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Introduction

Multi-winding power transformers and autotransformers are important components in transmission and distribution power systems. They make possible the transfer of energy between networks operating at various voltage levels, the interconnection of multiple shaft combined cycle generating units to a power grid and the connection of reactive compensation resources to EHV transmission networks, just to name a few applications. 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 admittance, off-nominal turn ratios, number of tap positions, tap range or voltage control band may lead to erroneous results in the verification of voltage and reactive power control schemes, and in the assessment of transmission losses and system reliability.

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 minimizing the potential for errors.

Notes and suggestions for entering each of the required model variables are given below, along with an example demonstrating the entry of the data for a three-winding voltage regulating transformer.

Model Data Requirements

The positive sequence network model used by PSS®E for three-phase three-winding transformers or autotransformers or three-phase banks of three identical single-phase three-winding transformers is shown in Figure 1 below. The model includes the three equivalent leakage impedances of the windings, Z1= r_1 +j x_1, Z2 = r_2 +j x_2 and Z3 = r_3 +j x_3, and allows off-nominal taps to be represented on each of the windings. This model also allows the modeling of the transformer magnetizing admittance, $Y_m = G_{h+e} - j B_m$, that is often neglected on the I-side (winding 1) of the transformer. One of the many features found in PSS®E is that the user does not have to calculate the between-windings leakage impedances, magnetizing admittance, effective off-nominal transformer taps, tap steps or tap limits; these calculations are performed within PSS®E.

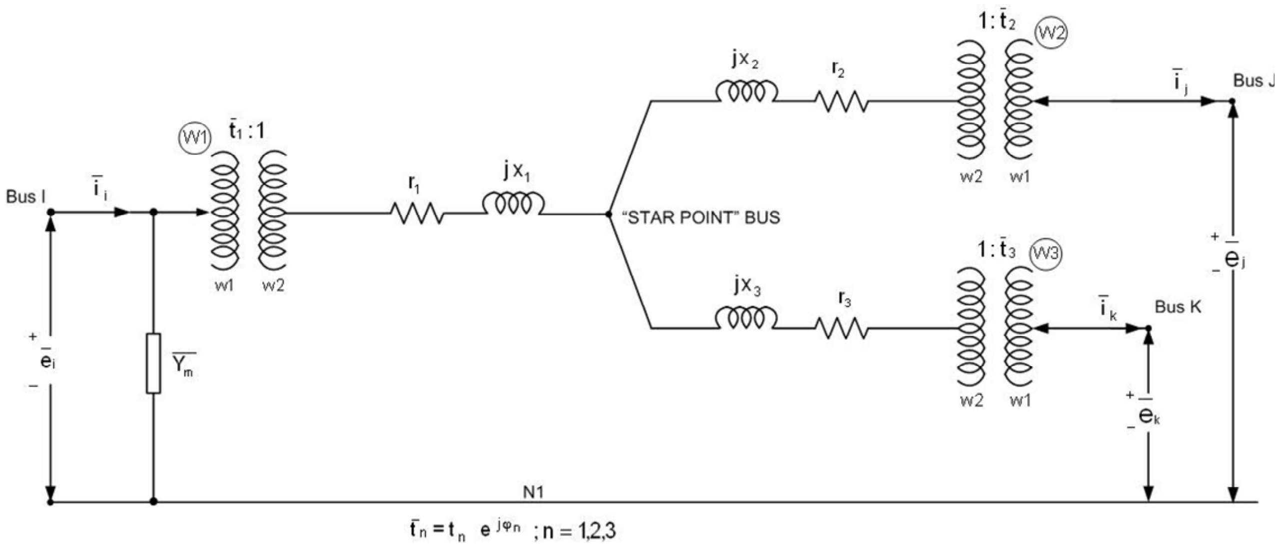

Figure 1 - PSS®E Three-Winding Transformer Model

The "star" or "T" network equivalent model shown in Figure 1 for three-winding transformers and three-winding autotransformers includes the equivalent leakage impedances Z1, Z2 and Z3 in per unit on a common three-phase apparent power base and phase-to-phase winding base voltages VWB1, VWB2 and VWB3. Simple linear relationships exist between the equivalent leakage impedances Z1, Z2 and Z3 and the between-windings leakage impedances Z1-2, Z2-3 and Z3-1 that are generally supplied on a transformer data sheet or test report. These are:

Z1-2 = Z1 + Z2 (Ohm or pu)

Z2-3 = Z2 + Z3 (Ohm or pu) (Eqs. 1)

Z3-1 = Z3 + Z1 (Ohm or pu)

and

Z1 = (1/2)*[Z1-2 + Z3-1 – Z2-3] (Ohm or pu)

Z2 = (1/2)*[Z1-2 + Z2-3 – Z3-1] (Ohm or pu) (Eqs. 2)

Z3 = (1/2)*[Z2-3 + Z3-1 – Z1-2] (Ohm or pu)

Note that the between-windings leakage impedances Z1-2, Z2-3 and Z3-1 are complex number quantities (resistance and reactance) obtained from the following short circuit tests:

1. Z1-2 = $r_{1\text{-}2}$ +j $x_{1\text{-}2}$, obtained from a test where winding 2 is shorted, winding 1 is excited with a voltage such that rated current flows through the short circuit in winding 2 and winding 3 is left with its terminals open.
2. Z2-3 = $r_{2\text{-}3}$ +j $x_{2\text{-}3}$, obtained from a test where winding 3 is shorted, winding 2 is excited with a voltage such that rated current flows through the short circuit in winding 3 and winding 1 is left with its terminals open.
3. Z3-1 = $r_{3\text{-}1}$ +j $x_{3\text{-}1}$, obtained from a test where winding 1 is shorted, winding 3 is excited with a voltage such that rated current flows through the short circuit in winding 1 and winding 2 is left with its terminals open.

PSS®E models three-winding transformers internally as three two-winding transformers connected together at a common “star point” bus. This star point bus is handled internally to PSS®E and is not visible to the user. The windings selected as winding 1 in each of these three two-winding transformers are connected to buses “I,” “J” and “K,” respectively, as shown in Figure 1. The model has the capability of under-load tap adjustment in all three windings. The ideal transformers used in the “star” network equivalent model have the off-nominal taps t_1, t_2 and t_3 associated with their winding 1. Winding 2 always has a nominal tap (i.e., 1.0 per unit) in these transformers.

As users create their transformer data records, PSS®E’s flexibility becomes apparent. Each of the required model variables is discussed below:

- *Between-windings leakage impedances (Z1-2, Z2-3 and Z3-1) can be specified in three ways:*
  - → in per unit on a system three-phase apparent power base (SBASE, usually 100 MVA) and windings 1, 2 and 3 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} = t_{30}= 1.0 per unit on winding voltage base or t_{10} =VWB1 kV, t_{20} = VWB2 kV and t_{30}= VWB3 kV) – **Impedance code CZ=1.**
  - → in per unit on winding base (usually the ONAN rating), using winding 1-2 three-phase apparent power base (SB1-2),winding 2-3 three-phase apparent power base (SB2-3), and winding 3-1 three-phase apparent power base (SB3-1), and windings 1, 2 and 3 phase-to-phase rated voltages (VWB1, VWB2 and VWB3) for fixed tap transformers and nominal tap for transformers fitted with either under-load or off-load taps (t_{10} = t_{20} = t_{30} = 1.0 per unit on winding voltage base or t_{10} = VWB1 kV, t_{20} = VWB2 kV and t_{30} = VWB3 kV) – **Impedance code CZ=2.**
  - → entering the short circuit test three-phase full-load winding copper losses between windings 1-2, 2-3 and 3-1 (W_{sc}1-2, W_{sc}2-3, and W_{sc}3-1) in Watts and the winding impedance voltage magnitude or between windings leakage impedance magnitude |Z1-2|, |Z2-3| and |Z3-1|. These impedances are expressed in per unit on windings 1-2 (SB1-2), windings 2-3 (SB2-3), and windings 3-1 (SB3-1) three-phase apparent power base, (usually the ONAN rating), and phase-to-phase winding rated voltages (VWB1, VWB2 and VWB3) for fixed tap transformers, and nominal tap for transformers fitted with either under-load or off-load taps (t_{10} = t_{20} = t_{30} = 1.0 per unit on winding voltage base or t_{10} = VWB1 kV, t_{20} = VWB2 kV and t_{30} = VWB3 kV) – **Impedance code CZ=3.**
- *Transformer magnetizing admittance (Y_m) can be specified in two ways:*
  - → in per unit on a system three-phase apparent power base (SBASE, usually 100 MVA), and winding 1 phase-to-phase bus voltage base – **Magnetizing Admittance code CM=1.**
  - → entering the 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 the winding 1-2 three-phase apparent power base (SB1-2) and winding 1 phase-to-phase rated voltage (VWB1) for fixed tap transformers and nominal tap for transformers fitted with either under-load or off-load taps (t_{10} = 1.0 per unit on winding voltage base or t_{10} = VWB1 kV) – **Magnetizing Admittance code CM=2.**
- *Windings 1-2, 2-3 and 3-1 three-phase apparent power MVA (SB1-2, SB2-3 and SB3-1):*

  This is the three-phase apparent power MVA used in the normalization (per unit representation) of the between-windings leakage impedances Z1-2, Z2-3 and Z3-1. Use of the transformer’s three-phase winding nameplate rating, which is usually the ONAN rating, is strongly recommended. However, any other three-phase apparent power base can be used. System bus voltage base refers to the bus phase-to-phase voltage base kV of the buses to which the terminals of the three-winding transformer are connected. Note that when specifying base quantities for three-winding transformers, you must specify three apparent power base quantities

and three winding voltage base values, one for winding 1 (NOMV1), one for winding 2 (NOMV2) and another for winding 3 (NOMV3).

- *Winding nominal voltage (NOMV1, NOMV2, NOMV3):*

A nominal phase-to-phase voltage, usually the phase-to-phase rated winding voltage or nominal tap winding voltage, should be entered for winding 1, winding 2 and winding 3. The nominal voltage for winding 1 is used in the computation of the per unit transformer magnetizing admittance on a system three-phase apparent power MVA and system bus voltage base. The nominal voltage for windings 2 and 3 are used to convert the per unit tap values on a winding voltage base to per unit tap values on system bus voltage base (PSS®E version 31 and 32). The default value for these three data entry points is 0.0 kV, which is interpreted by PSS®E to mean that the winding nominal voltage is equal to the voltage base of the bus to which the transformer is connected. For PSS®E versions 30 and earlier, the nominal voltages for windings 2 and 3 are not used in any calculations related to the between-windings leakage impedances, per unit tap values, or performance of a transformer unit.

- *Number of tap positions in windings 1, 2 and 3 (NTP1, NTP2 and NTP3):*

PSS®E assumes that the nominal tap position is midway in the tap range - (NTP1+1)/2, (NTP2+1)/2 and (NTP3+1)/2. PSS®E also assumes that the winding tap step is constant: Δt_1= TSTEP1= (Rmax1 – Rmin1)/(NTP1-1), Δt_2= TSTEP2= (Rmax2 – Rmin2)/(NTP2-1), and Δt_3= TSTEP3= (Rmax3 – Rmin3)/(NTP3-1).

- *Winding off-nominal taps (WINDV1, WINDV2, WINDV3):*

Automatic adjustable taps (ULTC or OLTC) can be associated with winding 1 (t_1), winding 2 (t_2) and/or winding 3 (t_3). These taps may be specified in three ways:

→ in per unit on bus “I”, “J” and “K” phase-to-phase bus voltages – **Winding code CW=1.**

→ in kV on winding 1, 2 and 3 phase-to-phase voltages (NOMV1, NOMV2, NOMV3) – **Winding code CW=2.**

→ in per unit on winding 1, 2 and 3 phase-to-phase rated or nominal voltages – **Winding code CW=3.**

- *Tap limits (Rmax1, Rmax2, Rmax3, Rmin1, Rmin2, Rmin3):*

These parameters apply to the taps in windings 1, 2 and 3 and they define the winding tap range. Maximum and minimum tap values are used for these limits: Rmax1, Rmax2, and Rmax3 for the upper limits and Rmin1, Rmin2, and Rmin3 for the lower limits. These tap limits may be specified in three ways:

→ in per unit on bus “I,” “J” and “K” phase-to-phase bus base voltages – **Winding code CW=1.**

→ in kV on winding 1, 2 and 3 phase-to-phase voltages – **Winding code CW=2.**

→ in per unit on winding 1, 2 and 3 phase-to-phase nominal voltages (NOMV1, NOMV2, NOMV3) – **Winding code CW=3.**

- *Winding 1, winding 2 and winding 3 voltage phase shift angle (Θ1, Θ2 and Θ3):*

The relative phase angle between winding 1 and winding 2 for each of the three two-winding transformers used in the modeling of three-winding transformers may be specified in the transformer data record. This phase shift angle is measured in electrical degrees and is assumed to be positive when the phase voltage at each of the three W1 windings leads the phase voltage

at the “star point” bus. For example, for the transformer connection YNynd5 (using IEC notation), the angle Θ_1= 0°, Θ_2= 0° and Θ_3= -150°.

- *Transformer control band (Vmax, Vmin):*

  The upper and lower limits of voltage control band for regulating transformers, one for each winding, are specified in the entries Vmax and Vmin, respectively. The value for these limits may be expressed in either kV or per unit on bus voltage base when the transformer control mode is 1 (i.e., voltage control) or in Mvar flow into the terminals of windings 1, 2 or 3 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 base voltage of the controlled bus, that is the bus where local or remote voltage control is desired. It is important to keep in mind that the control band width (Vmax – Vmin) must be large enough to ensure that there is a tap position that will result in operation within that voltage band. For example, if the control band width is equal to or greater than two times the transformer’s tap step TSTEP, this will guarantee that when the tap adjustment option is used in a load flow solution (and the transformer control mode is 1), the load flow solution will not oscillate between tap limits and, assuming that a limit is not reached, that the solution will find a tap position that results in operation within that voltage band. When the control mode is 1, the default values are: 1.1 per unit for the control band upper limit (or 1.1*bus voltage base in kV) and 0.9 per unit for the control band lower limit (or 0.9*bus voltage base in kV). There are no default values allowed for control mode 2. Each winding can exert control on voltage, active power or reactive power on a selected local or remote bus.

- *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 (not adjusted by the load flow solution)

  → mode 1, voltage control mode, where windings 1, 2 and 3 taps are adjusted when the load flow solution option “tap adjustment” is selected

  → mode 2, Mvar control mode, where windings 1, 2 and 3 taps are adjusted when the load flow solution option “tap adjustment” is selected

  Each winding has an independent control mode function in PSS®E.

Important Notes:

It is important to note that the transformer model in PSS®E automatically adjusts the between-windings leakage impedance when there is a mismatch between the winding voltage base (NOMV1, NOMV2 and NOMV3) and the bus base voltage where these terminals are connected. For example, if the winding 1 voltage base (NOMV1) is not the same as its bus base voltage, PSS®E will adjust the transformer winding leakage impedance using the winding 1 turns ratio t_1. Similar adjustment will be made to the other winding turns ratios, t_2 and t_3, if the other two windings’ base voltages do not match their respective bus base voltages.

When specifying data in per unit (winding code CW=1), these off-nominal winding turn ratios, t_1, t_2 and t_3, are specified by the user as:

t_1 = (winding 1 voltage base NOMV1 / bus “I” base voltage), when specifying data in per unit (winding code CW=1)

= winding 1 voltage base NOMV1when given in kV (winding code CW=2)

t_2 = (winding 2 voltage base NOMV2 / bus “J” base voltage), when specifying data in per unit (winding code CW=1)

= winding 2 voltage base NOMV2 when given in kV (winding code CW=2)

t_3 = (winding 3 voltage base NOMV3 / bus “K” base voltage), when specifying data in per unit (winding code CW=1)

= winding 3 voltage base NOMV3 when given in kV (winding code CW=2)

When the winding code CW 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 tap limits Rmax1, Rmax2, Rmax3, Rmin1, Rmin2, and Rmin3 must also be adjusted when they are specified in per unit on bus base voltage (winding code CW=1).

Note that all computations carried out by PSS®E are performed in per unit on a system three-phase apparent power base and phase-to-phase bus voltage base. Also, it is important to note that the selection as to which winding will be called winding 1, winding 2 or winding 3 is arbitrary. But once the selection is made, the user must be consistent in applying the appropriate index to all parameters associated with each winding.

Legacy data for three-winding transformers (entered using the data formats available in all versions of PSS®E up to and including version 26) was limited to (1) using three two-winding transformers, (2) an explicit “star point” node modeled as a bus and (3) equivalent leakage impedances Z1, Z2 and Z3 specified in per unit on a three-phase apparent power system base and bus base voltage. These legacy three-winding transformers can continue to be used, or they can be removed and re-entered using the formats described above. Care should be taken in converting to the new format that the proper bases are used.

Numerical Example

A numerical example follows to show how a three-winding transformer is modeled and how the model data is entered into PSS®E.

For our example we will use a three-winding, three-phase autotransformer unit with the following characteristics:

- → nominal phase-to-phase winding voltages of 135.4 kV, 69.5 kV and 47.3 kV
- → OA/FA/FA three-phase apparent power ratings of 30/40/50 MVA for the HV and MV windings
- → 24/32/40 MVA for the LV (tertiary) winding
- → 33 under-load taps (±16 steps + neutral position) on the HV winding with a tap step of 0.625%
- → a nominal operating frequency of 60 Hz
- → high and medium voltage (HV, MV) circuits connected wye solidly grounded
- → low voltage (LV) windings connected delta

The transformer unit has the following transformer test report data:

Short Circuit Test

1. Three-phase load losses at 75°C between HV and MV circuits of 64,360 W.
2. Three-phase load losses at 75°C between HV and LV circuits of 90,960 W.
3. Three-phase load losses at 75°C between MV and LV circuits of 107,060 W.

4. Impedance voltage or winding leakage impedance magnitude between HV and MV circuits of 3.74% on a 30 MVA three-phase apparent power base, 135.4 kV/69.5 kV voltage base and 75°C.
5. Impedance voltage or winding leakage impedance magnitude between HV and LV circuits of 11.66% on a 24 MVA three-phase apparent power base, 135.4 kV/47.3 kV voltage base and 75°C.
6. Impedance voltage or winding leakage impedance magnitude between MV and LV circuits of 8.18% on a 24 MVA three-phase apparent power base, 69.5 kV/47.3 kV voltage base and 75°C.

No-load or Open Circuit Test:

1. Three-phase no-load (core) losses at 100% voltage (1.0 per unit or nominal) of 34,380 W.
2. Excitation current RMS magnitude of 0.29% (0.0029 per unit) at 100% voltage (135.4/√3 kV) and 30 MVA three-phase apparent power base.

This three-phase, three-winding autotransformer unit will be used in a sub-transmission substation to deliver energy from a 138 kV HV bus bar to circuits operating at nominal voltages of 69 kV and 46 kV.

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

1. HV bus base voltage: 138.0 kV
2. MV bus base voltage: 69.0 kV
3. LV bus base voltage: 46.0 kV
4. HV winding voltage base (model's winding 1): 135.4 kV
5. MV winding voltage base (model's winding 2): 69.5 kV
6. LV winding voltage base (model's winding 3): 47.3 kV
7. Number of taps: 33
8. Tap range, Rmax1 = 1.10 per unit (148.94 kV) and Rmin1 = 0.90 per unit (121.86 kV) on a 135.4 kV voltage base
9. Between Circuits (windings for conventional three-winding transformers) 1 and 2 three-phase MVA base (SB1-2): 30 MVA
10. Between Circuits (windings for conventional three-winding transformers) 3 and 1 winding three-phase MVA base (SB3-1): 24 MVA
11. Between Circuits (windings for conventional three-winding transformers) 2 and 3 winding three-phase MVA base (SB2-3): 24 MVA
12. System three-phase MVA base (SBASE): 100 MVA

Since the short-circuit and the no-load test data are available, the recommended approach for entering the transformer data in PSS®E is:

1. Impedance code CZ=3, load losses and per unit impedance voltage (per unit leakage impedance magnitude)
2. Magnetization admittance code CM=2, no-load losses and per unit excitation current
3. Winding code CW=1, taps in per unit on a bus voltage base
4. Control mode: None if the transformer is equipped with off-load taps or Voltage if the transformer is equipped with an under-load tap changer.

The four data entry codes above define the data entry format and thus must be selected before the correct values to enter can be determined. Using the codes recommended above, the process described below is used.

Given that tap values for circuits 1, 2 and 3 will be entered in per unit on a bus voltage base (CW=1), the tap value t_1 and upper and lower tap limit, Rmax1 and Rmin1, will be specified as:

t_1 = 135.4/138 = 0.98116 per unit (assuming that the transformer tap is set at its neutral position, i.e., at nominal tap)

Rmax1 = (1.10*135.4)/138 = 1.07928 per unit on a 138 kV base

Rmin1 = (0.90*135.4)/138 = 0.88304 per unit on a 138 kV base

Winding 2 and winding 3 will have the following tap data because their winding rated voltages do not match their bus base voltages:

t_2 = 69.5 kV/69.0 kV = 1.00725 per unit on a 69.0 kV base

t_3 = 47.3 kV/46.0 kV = 1.02826 per unit on a 46.0 kV base

Note that 1.0 per unit voltage on a 69.5 kV base (winding voltage base) is equivalent to 1.00725 per unit on a 69.0 kV system voltage base. In general, whenever there is a mismatch between the winding voltage base and the bus base voltage and the winding code is CW=1, taps expressed in per unit on bus voltage base must be entered using the expression:

t_1, t_2 or t_3 = (winding 1, winding 2 or winding 3 nominal voltage)/ bus base voltage

The parameters Rmax2, Rmax3, Rmin2 and Rmin3 are left undisturbed at their default values since these windings do not have taps; if they did have taps, the user must also modify these parameters using the following expressions:

Rmaxi = ($kV_{i,max}$ / Vbus,i base)

Rmini = ($kV_{i,min}$ / Vbus,i base) i = 2, 3

If a user selects the winding code CW=2, the values for taps t_1, t_2, t_3 and tap range Rmax1 and Rmin1 would be:

t_1 = 135.4 kV (nominal tap position)

t_2 = 69.5 kV

t_3 = 47.3 kV

Rmax1 = 148.94 kV

Rmin1 = 121.86 kV

In PSS®E version 31, the new winding code 3 (CW=3) was introduced. If a user selects the winding code to be (CW=3), and winding 1 is the 134.5 kV winding, winding 2 is the 69.5 kV winding and winding 3 is the 47.3 kV winding, then the values for taps t_1, t_2, and t_3, and tap range Rmax1 and Rmin1 would be:

t_1 = 1.0 per unit (assuming the tap is set at its neutral position, i.e., nominal tap)

t_2 = 1.0 per unit (on a 69.5 kV winding voltage base)

t_3 = 1.0 per unit (on a 47.3 kV winding voltage base)

Rmax1 = 1.10 per unit on a 135.4 kV base

Rmin1 = 0.90 per unit on a 135.4 kV base

The data record for the transformer unit for CW=1, CZ=3 and CM=2 is:

```
CASE 1

                                                           GENERAL DATA
 X- XFRMER -X X---- WINDING 1 BUS ----X X---- WINDING 2 BUS ----X X---- WINDING 3 BUS ----X     S C C C
 X-- NAME --X   BUS# X-- NAME --X BASKV   BUS# X-- NAME --X BASKV   BUS# X-- NAME --X BASKV CKT T W Z M OWN1 FRAC1 OWN2 FRAC2 OWN3 FRAC3 OWN4 FRAC4
                  1 HV         138.00      2 MV          69.000      3 LV          46.000  1  1 1 3 2    1 1.000


                                                           IMPEDANCE DATA
 X- XFRMER -X S C X--------- SPECIFIED NOMINAL MEASURED IMPEDANCES AND MVA BASES ----------X X-ACTUAL IMPEDANCES FROM IMPEDANCE CORRECTION TABLE-X
 X-- NAME --X T Z   R 1-2    X 1-2 SBAS1-2   R 2-3    X 2-3 SBAS2-3   R 3-1    X 3-1 SBAS3-1   R 1-2    X 1-2    R 2-3    X 2-3    R 3-1    X 3-1
             1 3    64360  0.03740   30.0   107060  0.08180   24.0    90960  0.11660   24.0

                                                          WINDING DATA
 X- XFRMER -X X----- WINDING BUS -----X  S C    MAGNETIZING Y   SYSTEM BASE NOM.                           TBL CORRECTED   STAR POINT BUS
 X-- NAME --X   BUS# X-- NAME --X BASKV  T M    MAG1     MAG2   R WNDNG  X WNDNG  RATEA  RATEB  RATEC TBL R WNDNG  X WNDNG VOLTAGE  ANGLE
                  1 HV         138.00* 1 2    34380  0.00290  0.00218  0.13486    0.0    0.0    0.0  0                  1.00000    0.0
                  2 MV         69.000  1                      0.00497 -0.01039    0.0    0.0    0.0  0
                  3 LV         46.000* 1                      0.01361  0.35072    0.0    0.0    0.0  0

                                                          TAP/CONTROL DATA
 X- XFRMER -X X----- WINDING BUS -----X C                                                      X---- CONTROLLED BUS ----X
 X-- NAME --X   BUS# X-- NAME --X BASKV W CN  WIND V  NOM V  ANGLE   RMAX    RMIN    VMAX    VMIN  NTPS    BUS# X-- NAME --X BASKV    CR      CX
                  1 HV         138.00 1  0 0.98116 135.40    0.0 0.98116 0.88304 1.10000 0.90000   33
                  2 MV         69.000    0 1.00725 69.500    0.0 1.10000 0.90000 1.10000 0.90000   33
                  3 LV         46.000    0 1.02826 47.300 -150.0 1.10000 0.90000 1.10000 0.90000   33
```

The benefit of entering the transformer model data in this format is that the user will store in the PSS®E database the transformer's test report short circuit test, no-load test, nameplate winding MVA and winding voltage ratings. Thus the user will not have to keep separate records for this important data and all the calculations to convert the test report data to equivalent leakage impedances, Z1, Z2 and Z3, and magnetization admittance Y_m, in per unit, will be automatically carried out by PSS®E. The user is required to simply select the impedance and admittance codes CZ=1 or 2 and CM=1, and PSS®E will display the between-windings leakage impedances and the magnetization admittance of the three-winding autotransformer.

When specified differently using CW=1, CZ=2 and CM=1 the data record shown by PSS®E will be:

```
CASE 2
                                                         GENERAL DATA
 X- XFRMER -X X---- WINDING 1 BUS ----X X---- WINDING 2 BUS ----X X---- WINDING 3 BUS ----X     S C C C
 X-- NAME --X   BUS# X-- NAME --X BASKV   BUS# X-- NAME --X BASKV   BUS# X-- NAME --X BASKV CKT T W Z M OWN1 FRAC1 OWN2 FRAC2 OWN3 FRAC3 OWN4 FRAC4
                  1 HV         138.00      2 MV          69.000      3 LV          46.000  1  1 1 3 2    1 1.000

                                                           IMPEDANCE DATA
 X- XFRMER -X S C X--------- SPECIFIED NOMINAL MEASURED IMPEDANCES AND MVA BASES ----------X X-ACTUAL IMPEDANCES FROM IMPEDANCE CORRECTION TABLE-X
 X-- NAME --X T Z   R 1-2    X 1-2 SBAS1-2   R 2-3    X 2-3 SBAS2-3   R 3-1    X 3-1 SBAS3-1   R 1-2    X 1-2    R 2-3    X 2-3    R 3-1    X 3-1
             1 2  0.00215  0.03734   30.0  0.00446  0.08168   24.0  0.00379  0.11654   24.0


                                                            WINDING DATA
 X- XFRMER -X X----- WINDING BUS -----X  S C    MAGNETIZING Y   SYSTEM BASE NOM.                           TBL CORRECTED   STAR POINT BUS
 X-- NAME --X   BUS# X-- NAME --X BASKV  T M    MAG1     MAG2   R WNDNG  X WNDNG  RATEA  RATEB  RATEC TBL R WNDNG  X WNDNG VOLTAGE  ANGLE
                  1 HV         138.00* 1 2    34380  0.00290  0.00218  0.13486    0.0    0.0    0.0  0                  1.00000    0.0
                  2 MV         69.000  1                      0.00497 -0.01039    0.0    0.0    0.0  0
                  3 LV         46.000* 1                      0.01361  0.35072    0.0    0.0    0.0  0

                                                          TAP/CONTROL DATA
 X- XFRMER -X X----- WINDING BUS -----X C                                                      X---- CONTROLLED BUS ----X
 X-- NAME --X   BUS# X-- NAME --X BASKV W CN  WIND V  NOM V  ANGLE   RMAX    RMIN    VMAX    VMIN  NTPS    BUS# X-- NAME --X BASKV    CR      CX
                  1 HV         138.00 1  0 0.98116 135.40    0.0 0.98116 0.88304 1.10000 0.90000   33
                  2 MV         69.000    0 1.00725 69.500    0.0 1.10000 0.90000 1.10000 0.90000   33
                  3 LV         46.000    0 1.02826 47.300 -150.0 1.10000 0.90000 1.10000 0.90000   33
```

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

$R_{12} = W1\text{-}2_{Cu\ losses}/SB1\text{-}2 = 0.06436/30 = 0.00215$ pu

$X_{12} = \sqrt{(0.0374^2 - 0.00215^2)} = 0.03734$ pu

$R_{31} = W3\text{-}1_{Cu\ losses} / SB3\text{-}1 = 0.09096/24 = 0.00379$ pu

$X_{31} = \sqrt{(0.1166^2 - 0.00379^2)} = 0.11654$ pu

$R_{23} = W2\text{-}3_{Cu\ losses} / SB2\text{-}3 = 0.10706/24 = 0.00446$ pu

$X_{23} = \sqrt{(0.0818^2 - 0.00446^2)} = 0.08168$ pu

The complex between-windings leakage impedances Z1-2, Z2-3 and Z3-1 in per unit on a three-phase winding apparent power base and winding voltage base are:

$Z1\text{-}2 = R_{12} + j\,X_{12} = 0.00215 + j\,0.03734$ pu

$Z2\text{-}3 = R_{23} + j\,X_{23} = 0.00446 + j\,0.08168$ pu

$Z3\text{-}1 = R_{31} + j\,X_{31} = 0.00379 + j\,0.11654$ pu

The magnetizing admittance conductance and susceptance in per unit on a system three-phase apparent power base (100 MVA) and winding 1 bus voltage base (138 kV) are:

$G_{h+e} = [W_{NL\ losses}/SBASE]*(Vnew/Vold)^2 = [0.03438/100]*(138/135.4)^2 = 0.00035$ pu

and since

$|I_\Phi|$ pu $= |Y_m|$ pu * 1.0 pu voltage $= |Y_m|$ pu $= 0.0029*(30/100)*(138/135.4)^2 = 0.00090$ pu

then,

$B_m = \sqrt{(0.00090^2 - 0.00035^2)} = 0.00083$ 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 (138 kV) is expressed as:

$Y_m = G_{h+e} - j\,B_m = 0.00035 - j\,0.00083$ pu

If the user is interested in finding out the values stored by PSS®E for the equivalent leakage impedances Z1, Z2 and Z3 and the equivalent magnetizing admittance Y_m as per the IEEE Standard Model shown in Figure 1, this can be done by displaying the values in the PSS®E Report Window using the IEEE Format Power Flow Data activity. The result of this procedure is shown below:

```
CASE 3
BUS DATA FOLLOWS                      4 ITEMS
   1 HV           1  1  0 1.0000   0.00     0.00     0.00     0.00    0.00  138.00 0.0000    0.00    0.00  0.0004 -0.0008    0    1
   2 MV           1  1  0 1.0000   0.00     0.00     0.00     0.00    0.00   69.00 0.0000    0.00    0.00  0.0000  0.0000    0    2
   3 LV           1  1  0 1.0000   0.00     0.00     0.00     0.00    0.00   46.00 0.0000    0.00    0.00  0.0000  0.0000    0    3
9999              1  1  0 1.0000   0.00     0.00     0.00     0.00    0.00    0.00 0.0000    0.00    0.00  0.0000  0.0000    0    4
-999
BRANCH DATA FOLLOWS                   3 ITEMS
   1 9999  0  0 1 1  0.002178  0.134856   0.00000    0     0     0    0 0  0.9812    0.00 0.0000 0.00000.00000  0.0000 0.0000     1
   2 9999  0  0 1 1  0.004973 -0.010394   0.00000    0     0     0    0 0  1.0072    0.00 0.0000 0.00000.00000  0.0000 0.0000     2
   3 9999  0  0 1 1  0.013614  0.350721   0.00000    0     0     0    0 0  1.0283 -150.00 0.0000 0.00000.00000  0.0000 0.0000     3
```

Note that the bus data displays the equivalent magnetizing admittance:

$Y_m = 0.0004 - j\,0.0008$ pu on a 100 MVA and 138 kV base

The branch data displays the equivalent leakage impedances Z1, Z2 and Z3:

$Z1 = r1_{eq} + j\,x1_{eq}$

$= 0.002178 + j\,0.134856$ pu on a 100 MVA and 135.4/69.5/47.3 kV base

$Z2 = r2_{eq} + j\,x2_{eq}$

$= 0.004973 - j\,0.010394$ pu on a 100 MVA and 135.4/69.5/47.3 kV base

$Z3 = r3_{eq} + j\, x3_{eq}$

$= 0.013614 + j\, 0.350721$ pu on a 100 MVA and 135.4/69.5/47.3 kV base

These equivalent leakage impedances are connected between buses “I,” “J” and “K” and the “star point” bus 9999, which is an internal bus and not explicitly available to the user.

Note that the windings turns ratios are displayed as well:

$t_1 = 0.9812$ pu on a 138 kV bus voltage base

$t_2 = 1.0072$ pu on a 69 kV bus voltage base

$t_3 = 1.0283$ pu on a 46 kV bus voltage base

The circuit connection for this autotransformer unit is YNynd5 with the HV (135.4 kV) circuit connected wye-grounded, the MV (69.5 kV) circuit connected wye-grounded and the LV (47.3 kV) circuit connected delta. The phase shift angle between the HV wye connected circuit and the MV wye connected circuit, as well as between the HV wye connected circuit and the delta connected windings have been provided. These phase shift angles are 0º between the HV circuit and MV circuit and 150º between the HV circuit and the LV circuit. Thus, the phase shift angles in PSS®E for circuits 1, 2 and 3, measured with respect to the “star point” voltage, i.e. the reference point used by PSS®E, are:

1. 0º for winding 1 of the three-winding autotransformer
2. 0º for winding 2 of the three-winding autotransformer
3. -150º for winding 3 of the three-winding autotransformer