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Memorandum

Date: May 2, 2019

To: Bruce Fardanesh, NYPA

CC:

From: Daniel Feltes, Carlos Grande-Moran, Dinemayer Silva and James Feltes

RE: **Modeling of the Sen Transformer in PSS®E**

The Sen single-core three-phase transformer is a power flow regulating transformer that performs independent active and reactive power flow control. The Sen transformer includes wye-grounded shunt primary windings (exciter unit) electrically connected to secondary windings in series with the transmission circuit where active and reactive flows will be controlled (by the compensating voltage unit.) Active and reactive flow control is carried out by changes in taps available on the Sen transformer's series windings. This change in tap position results in changes in both voltage magnitude and phase angle across the compensating voltage unit.

Currently there is no mathematical model for representing the Sen transformer for steady state analysis in commercial grade software such as PSS®E. A series connection of a phase angle regulator (PAR) transformer and a voltage regulating transformer (LTC) is proposed for the modeling of the Sen transformer. This model was tested in the Chilean transmission grid to evaluate if it emulates the expected performance of a Sen transformer.

1.1 Sen Transformer

The Sen transformer can be represented by the asymmetrical PAR transformer model shown in Figure 1. This transformer model has a complex voltage ratio $te^{j\Psi}$ where t is associated to the magnitudes of the voltage ratio and the angle Ψ is associated with the voltage phase angle difference between phasors V_s and $V_{s'}$. An important component of the transformer is the series compensating voltage $V_{ss'}\angle\beta$ introduced by the compensating voltage unit. The Q-component (i.e., quadrature) of the compensating voltage is used to control the throughput reactive power flow. Whereas the P-component (i.e., in-phase) is used to adjust the phase shift angle, Ψ, so that the throughput active flow can be controlled. These parameters are mutually dependent as shown in the phasor diagram in Figure 2.

The phasor equation to represent the sending end voltage to the receiving end voltage is shown below.

$$\overrightarrow{V_{S'}} = \frac{1}{t}\,\overrightarrow{V_s}e^{-j\Psi} \tag{1}$$

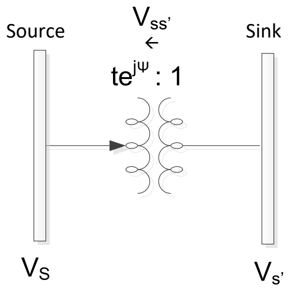

Figure 1. Sen Transformer Representation

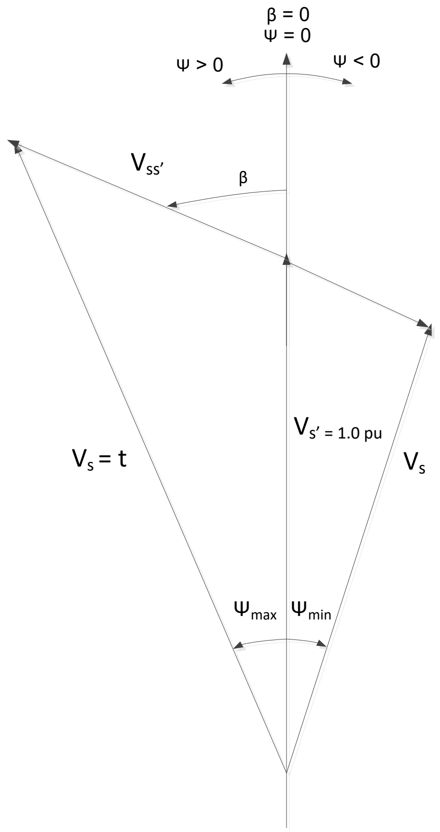

Figure 2. Phasor Diagram of the Sen Transformer

1.2 Modeling with Two Transformers in Series

Using the no-load complex voltage ratio shown in eqn. 1, a suggested representation for the Sen transformer in load flow analysis is one in which a symmetrical phase angle regulator (PAR) on MW control mode is connected in series with a load tap changer transformer (LTC) on voltage control mode, as shown in Figure 3.

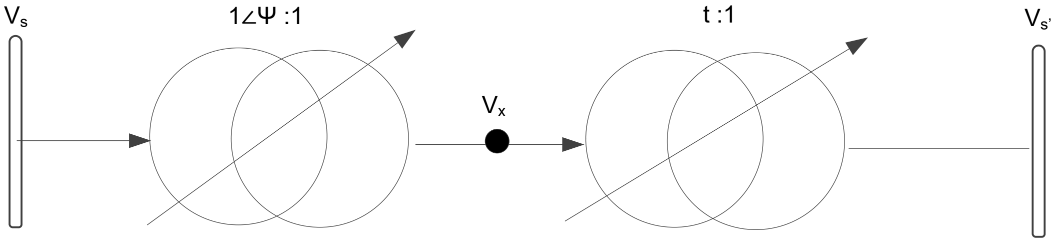

Figure 3. Proposed Sen transformer representation in PSS®E load flow

The PAR controls the MW flow and the LTC regulates the phasor $\boldsymbol{V_s}$ voltage, although it may also regulate the receiving end phasor voltage $\boldsymbol{V_{s'}}$ or a remote bus voltage. The winding one of the symmetrical PAR transformer model is connected to the sending end bus and the winding one of the LTC transformer model is connected to the midpoint bus.

The active power regulating transformer uses the continuous phase angle adjustment control mode in PSS®E and the voltage regulating transformer uses the discrete tap adjustment control mode. It is also suggested that the PAR leakage impedance be set to a small value, for example, 5 to 10 times the default value for zero impedance in PSS®E (default value is 0+j0.0001 pu). The LTC leakage impedance will be equal to the difference between the Sen transformer leakage impedance and the PAR leakage impedance.

The per-unit positive sequence leakage impedance values can be specified on either winding MVA base or system MVA base, and winding voltage base.

The following quantities need to be specified for the PAR and the LTC transformers:

PAR transformer :

- Phase angle range (**ψ**max, **ψ**min)
- Desired MW control band (**MW**max, **MW**min)
- Control mode "**3**" (symmetrical PAR transformer)
- MVA ratings (same as LTC transformer model)

LTC transformer :

- Tap range (**t**max, **t**min)
- Desired voltage control band (**V**max, **V**min) at the controlled bus voltage.
- Control mode "**1**" (LTC Voltage regulating transformer).
- MVA ratings (same as PAR transformer model)

The desired MW flow would be adjusted by the PAR phase angle and MW control band settings and the desired voltage would be adjusted by the LTC tap range and voltage control band settings. Note that when solving the load flow in PSS®E, the options "Tap Adjustment" and "Adjust phase shift" should be activated.

The phasor equation to solve is shown below. This is the same phasor equation that is used for the Sen transformer above.

$$\overrightarrow{V_{S'}} = \frac{1}{t}\,\overrightarrow{V_s} e^{-j\Psi} \tag{2}$$

1.3 Relating the Sen Transformer with the PSS®E Model

Because the Sen transformer model in PSS®E is not a one-to-one match to the original model of the Sen transformer, a set of equations were derived to relate the two models. The equations below can be used to compute the PSS®E quantities of off-nominal tap ***t*** and phase angle ***Ψ*** from the given magnitude voltage change ***ΔV($V_{ss'}$)*** and phase angle ***β*** from the Sen transformer.

$$\mathrm{t} = \sqrt{\Delta\mathrm{V}^2 + 2\Delta\mathrm{V}\cos\beta + 1} \tag{3}$$

$$\Psi = \sin^{-1}\left(\frac{\Delta\mathrm{V}}{\mathrm{t}} * \sin\beta\right) \tag{4}$$

The inverse equations are given below. These equations would be used to compute ***ΔV (|$V_{ss'}$|)*** and ***β*** from the PSS®E quantities ***t*** and ***Ψ***.

$$\Delta\mathrm{V} = \sqrt{\mathrm{t}^2 - 2\mathrm{t}\cos\Psi + 1} \tag{5}$$

$$\beta = \sin^{-1}\left(\frac{\mathrm{t}}{\Delta\mathrm{V}} * \sin\Psi\right) \tag{6}$$

These equations are important for exchanging parameters between the two models and checking the validity of the results.

1.4 Chilean Case Study

To test the performance of the two series transformer representation, a three-phase 300 MVA, 154/154 kV Sen transformer was added to a PSS®E load flow base case of the Chilean grid, supplied by for use in these investigations by Transelec of Chile. This transformer was placed in one of the parallel paths between the Southern and Central control areas of the system. The proposed PSS®E model was added between the Punta de Cortes and the Tilcoco 154 kV substations. These buses and the surrounding area are shown in Figure 4.

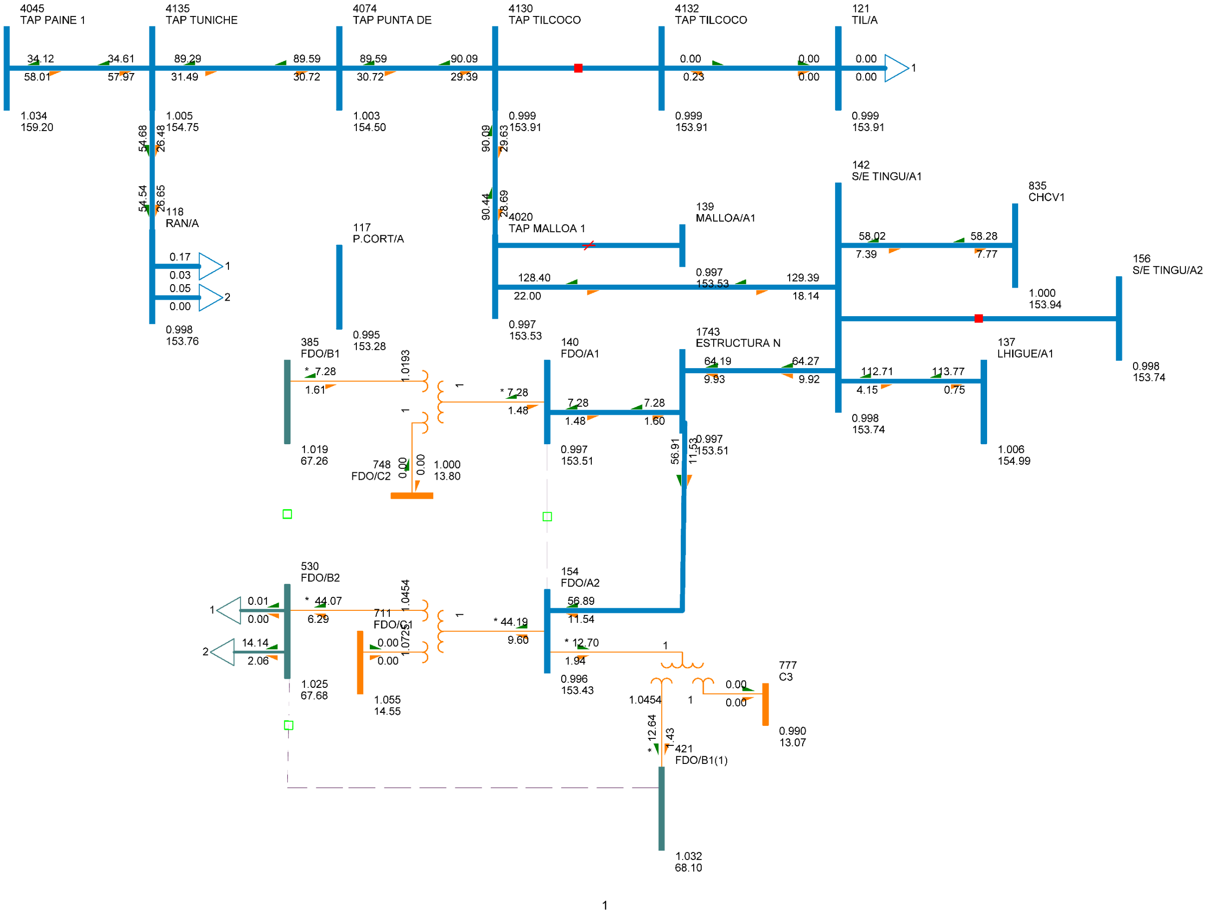

Figure 4. Chilean Power System – Study Area

The study area after adding the Sen transformer is shown in Figure 5. The PAR component of the two-transformer model is placed between buses 4074 TAP PUNTA DE and 10000 SEN. This transformer has a small of impedance of 0.1% on a 300 MVA base. This transformer is also in control mode 3 or MW flow control. The LTC portion of the two-transformer model is placed between bus 10000 SEN and 4130 TAP TILCOCO. This transformer has a leakage impedance of 6% on a 300 MVA and 154 kV base. The control mode for the LTC transformer is control mode 1 or voltage control and is controlling the voltage at bus 4074 TAP PUNTA DE. The base settings for the model are to control 90 MW (within range of +/- 1 MW)from TAP PUNTA DE to TAP TILCOCO and to control the voltage at TAP PUNTA DE to a desired magnitude of 1.0 pu (within range of +/- 0.005 pu).

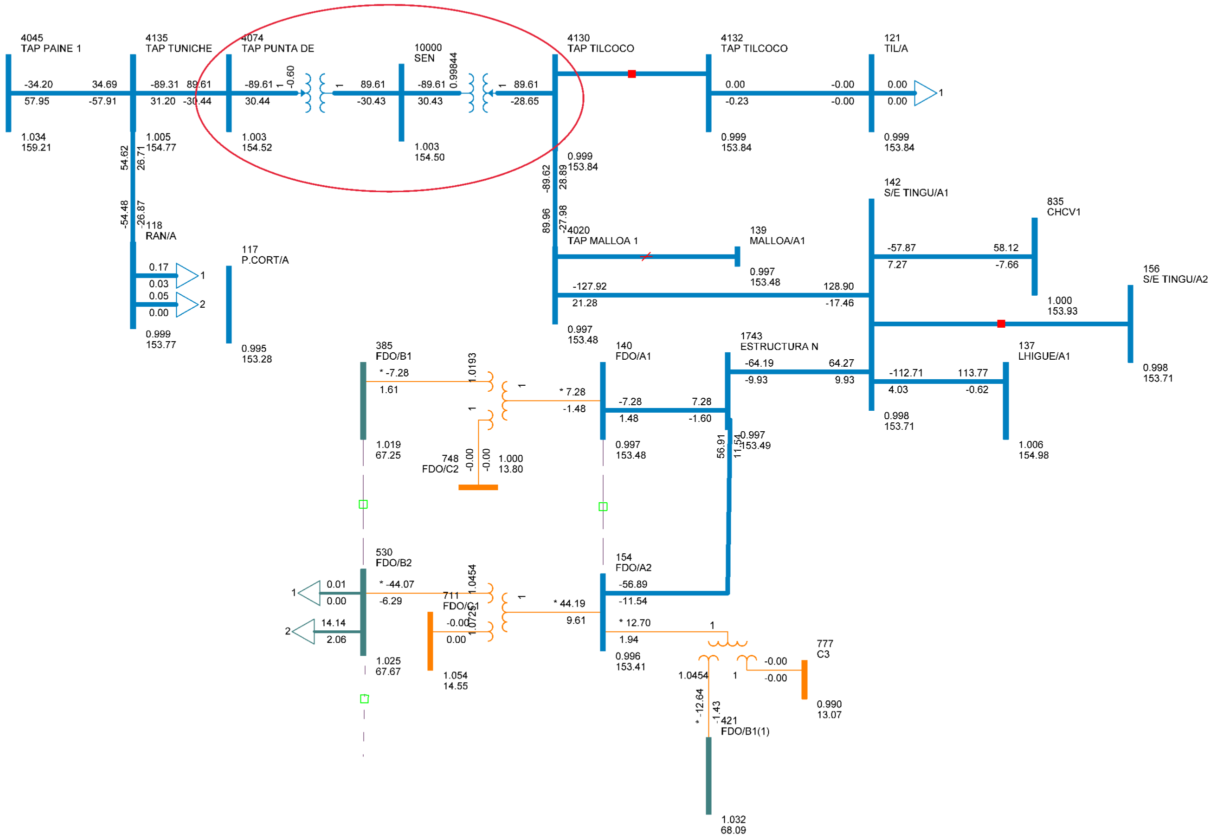

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Figure 5. Chilean System Post Sen Transformer

Several steady state simulations were performed with the model controlling different MW and voltage setpoints. In these simulations the MW flow was varied between 70 MW and 120 MW and three different voltage setpoints of 0.95 pu, 1.0 pu and 1.05 pu were tested. For all simulations tested the model was able to control to its desired control point. The equivalent voltage magnitude ***ΔV*** and phase angle ***β*** were also calculated for easy comparison to actual Sen transformer values. These results are shown in Table 1.

Table 1. Chilean Grid Simulation Results

Voltage Controlled to 0.95 pu

Pr (MW)	Measured Vs	Tap(t=t1/t2)	PSA ψ(deg)	ΔV_{ssp}	WindingAng β(deg)
70	0.954	0.9000	-1.800	0.10	195.719
80	0.954	0.9000	-0.790	0.10	187.068
90	0.953	0.9000	0.220	0.10	178.021
100	0.953	0.9000	1.240	0.10	169.001
110	0.952	0.9000	2.260	0.11	160.585
120	0.952	0.9000	3.270	0.11	153.163

Voltage Controlled to 1.0 pu

Pr (MW)	Measured Vs	Tap(t=t1/t2)	PSA ψ(deg)	ΔV_{ssp}	WindingAng β(deg)
70	1.004	1.0000	-2.600	0.05	268.700
80	1.004	1.0000	-1.590	0.03	269.205
90	1.004	1.0000	-0.550	0.01	269.725
100	1.004	1.0000	0.450	0.01	90.225
110	1.003	1.0000	1.470	0.03	90.735
120	1.003	1.0000	2.500	0.04	91.250

Voltage Controlled to 1.05 pu

Pr (MW)	Measured Vs	Tap(t=t1/t2)	PSA ψ(deg)	ΔV_{ssp}	WindingAng β(deg)
70	1.048	1.1156	-3.330	0.13	209.677
80	1.048	1.1156	-2.290	0.12	201.236
90	1.048	1.1156	-1.250	0.12	191.915
100	1.048	1.1156	-0.210	0.12	182.026
110	1.047	1.1156	0.840	0.12	171.939
120	1.047	1.1156	1.890	0.12	162.257

Simulations were also performed to test the model under contingency conditions. For these tests the model was set to control the flow of 90 MW from TAP PUNTA DE to TAP TILCOCO and to control voltage at TAP PUNTA DE at 1.0 pu. This was the base case pre-contingency conditions. N-1 and N-2 outages of transmission lines in the study area were simulated with both PAR adjustment and LTC adjustment solution options enabled. Table 2 below shows the results of this analysis with the first two columns showing the results of the case without the Sen transformer model and the other columns showing the results with the Sen transformer included in study area. This comparison shows that without the Sen transformer model the controlled voltage and power flow are below the desired control points, but the desired control points are satisfied when the Sen transformer is included.

The most constraining case of the tested contingencies was the loss of the154 kV lines S/E TINGU/A to LHIGUE/A1 154 kV and the TAP PAINE1 to TAP TUNICHE. Without the Sen transformer model in the power flow case the MW flow from TAP PUNTA DE to TAP TILCOCO dropped to 77 MW and the voltage at TAP PUNTA DE dropped to 0.973 pu. With the Sen transformer model added the power flow case the MW flow from TAP PUNTA DE to TAP TILCOCO was controlled to 90 MW and the voltage at TAP PUNTA DE was also controlled to 1.0 pu. Thus, the Sen transformer was able to control the MW flow and bus voltage to their pre-contingency values under this contingent scenario.

Table 2. Chilean Contingency Scenario Results

Base Case with no Sen Transformer		**PAR set to control 90 MW and Voltage to 1.0 pu**					
Power Flow (MW)	Voltage at 4074 TAP PUNTA DE	Pr (MW)	Measured Vs	Tap(t=t1/t2)	PSA ψ(deg)	ΔV_{ssp}	WindingAng β(deg)
N-0		N-0					
89	1.003	90	1.003	0.99844	-0.6	0.01	261.221
Loss of 4045 TAP PAINE 1 to 4135 TAP TUNICHE		Loss of 4045 TAP PAINE 1 to 4135 TAP TUNICHE					
78	0.981	90	0.997	1.0297	0.68	0.03	157.585
Loss of 4135 TAP TUNICHE to 118 RAN/A		Loss of 4135 TAP TUNICHE to 118 RAN/A					
66	1.017	90	1.001	0.97969	3.4	0.06	110.769
Loss of 142 S/E TINGU/A to 137 LHIGUE/A1		Loss of 142 S/E TINGU/A to 137 LHIGUE/A1					
89	0.998	90	0.998	0.99844	-0.46	0.01	258.766
Loss of 142 S/E TINGU/A to 137 LHIGUE/A1 and Loss of 4045 TAP PAINE 1 to 4135 TAP TUNICHE		Loss of 142 S/E TINGU/A to 137 LHIGUE/A1 Loss of 4045 TAP PAINE 1 to 4135 TAP TUNICHE					
77	0.973	90	0.997	1.0484	0.65	0.05	166.176

1.5 Limitations – PSS®E Two-Transformer Model

In PSS®E the phase angle limits of a PAR transformer are defined by Ψ_{max} and Ψ_{min} and similarly for an LTC voltage regulating transformer its limits are defined by R_{max} and R_{min}. PSS®E then controls the phase angle Ψ continuously between the limits to maintain the desired MW flow and adjusts the taps of the LTC discretely between the limits to control voltage. The Sen transformer, on the other hand, is controlled by adjusting it taps and thus the parameters: voltage magnitude $V_{ss'}$ and phase angle β. This control method is constrained by a hexagon that represents the allowable operating area.

The limits used in the PSS®E model and the Sen transformer are shown in Figure 6. The Ψ_{max} and Ψ_{min} and R_{max} and R_{min} limits used in PSS®E result in a control area having a trapezoidal shape, rather than the hexagonal shape of the control area of the Sen transformer. It is important to note that if the PSS®E limits (the blue trapezoidal area) are set to the bottom edges of the hexagonal operating range of the Sen transformer (shown in yellow), then the model in PSS®E may reach an operating point where the Sen transformer cannot operate as shown by the blue region of Figure 6. A solution to this problem is to limit the PSS®E model to only operate within the region bound by the hexagon. This operating range is shown by the green trapezoidal region in Figure 6. With this solution, the model is conservative and always operates within the equipment capabilities, although the model will not use the full capability available of the Sen transformer.

Another solution to this problem is to develop a python script that would adjust the PSS®E model to perform additional checks. The script would solve the load flow using the above limits of the Sen transformer. If we are using the recommended conservative approach (the green area in Figure 6), then the script would check to see if the Sen transformer was on limits. If the Sen transformer was on limits, the script could then adjust the phase angle of the PAR and the tap of the LTC to implement the full range of the Sen transformer. This would be an iterative approach, likely requiring several load flow solutions to converge into either a solution that meets the flow and voltage settings or alternately is on the actual Sen transformer limits. But we again note that if the conservative green area limits are used and the script is not run, the Sen transformer is operating within its limits in the load flow solution, although not necessarily optimally as some of its limits are modeled as too limiting in the load flow model. The importance of this “lost area” in modeling of the available control range is hard to quantify without analyzing an actual application of the Sen transformer.

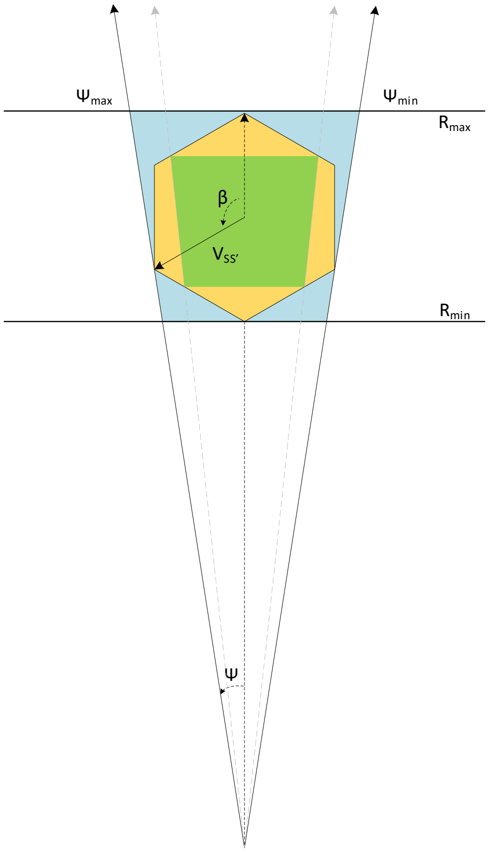

Figure 6. Operating Limits of the Two-Transformer Model and the Sen Transformer

1.6 Conclusion

The two-transformer representation using standard PSS®E transformer models is a reasonable way to represent the Sen transformer. Use of this representation in the steady state simulations with the Chilean transmission system showed that it was able to control to the desired MW and voltage control points. Also, under selected N-1 and N-2 contingency conditions the proposed Sen transformer model was able to control MW flow and bus voltage magnitude to the desired set points and provide some voltage support in the study area.

When using the proposed PSS®E two-transformer representation, the phase angle and tap range limits must be carefully considered as to not overestimate the operating range of the Sen transformer. This can be done either by setting the PSS®E model limits within the hexagonal operating zone of the Sen transformer limits or by the use of a python script to perform more detailed calculations incorporating the Sen transformer’s full control range was also discussed.