ISSUE: March 2018

Modeling Of The Sen Transformer Using An Electromagnetic Transients Program

by Kalyan K. Sen and Mey Ling Sen, Sen Engineering Solutions, Pittsburgh, Penn.

The Sen Transformer (ST) is an impedance regulator (IR) that emulates an impedance in series with an electric power transmission line. The ST connects a compensating voltage in series with the transmission line to modify the magnitude and phase angle of the line voltage so that independent active and reactive power flows can be achieved. While increasing the active power flow with maintenance of the voltage stability, if the reactive power flow is reduced, the losses in the power grid components (generator, transformer, transmission line and so on) may be reduced. This results in a more efficient grid and less global warming. An additional benefit of reducing reactive power flow is the increase in the active power transfer capacity of the line.

Modeling is essential for a successful implementation of a concept; it is also true that a model is just an approximation of the actual equipment. A model can be of a first-order approximation to provide rough-order-magnitude data of interest. Increasing the level of detail in a model, a design query can be answered.

Before the realization of a utility project, a load flow[1] and voltage stability study is usually performed. In this study, the power system network may consist of tens of thousands of voltage busses. A transient study typically involves the simulation of a power system network that consists of a few to tens of voltage busses. The transients study can be performed using a mathematical model of a particular controller, such as an impedance regulator. This model is also suitable for a transients study during a fault to formulate a protection scheme. Many such examples are presented.[2, 3, 4] The real-time digital simulator may also be used for this purpose, which usually requires the use of a commercially available simulator platform.[5, 6]

In this article, an ST model is developed using an electromagnetic transient program (EMTP) and executed in the Alternative Transients Program software package. The emphasis of this model is to preserve the details of an ST configuration that cannot be obtained from a load flow model, since a load flow model produces steady-state results using a positive-sequence single-phase equivalent circuit. The operation of the EMTP model is verified with the model connected to a simple power system network that can easily be upgraded to a particular utility's more representative power system network. The model is run for a sufficiently long time until steady state results are obtained.

The results presented in this article give the transmission planners important information before proceeding further in realization of an actual installation. As with previous discussions of the ST in this publication, the ST model has relevance to power electronics engineers as the ST competes with power electronics-based impedance regulators.

Also presented in this article are some new topologies of the ST using two-transformer designs. These may be considered when a final topology is selected, based on functional requirements and the need for the most cost-effective solution.

Background

In the 1990s, Westinghouse developed an impedance regulator (IR) in the form of a Unified Power Flow Controller (UPFC)[7] that consists of two voltage-sourced converters (VSCs), coupled with two transformers—one connected in shunt and one connected in series with the line. Even today, the UPFC offers the most comprehensive power flow control features (voltage regulation, phase angle regulation and impedance regulation) when compared with other power flow controllers developed to date.

The development of high-power VSC-based power flow controllers in the early 1990s was made feasible by the availability of high power semiconductor devices, such as 4500-V, 4000-A GTOs. However, from their inception, two major drawbacks (high installation and operating costs) plagued all VSC-based power flow controllers. Over the years, the list of drawbacks has expanded to include component obsolescence, lack of portability and interoperability. In order to address these issues, the ST was proposed as a part of a broader SMART Power Flow Controller (SPFC) concept that enhances the controllability in an electric power transmission system by using functional requirements and cost-effective solutions.[8, 9]

An SPFC utilizes the best features of all the technical concepts that have been developed in the power flow control area until now. It does not discriminate among any solutions based on whether an SPFC uses power electronics or not; or whether it is stationary or rotating. As long as it fulfils the utilities' needs, it is acceptable in its form. The Sen Transformer (ST), a member of an SPFC family, adopts the best features of a UPFC (its capability of providing various control techniques) and a phase angle regulator (PAR)[10] with its proven low-cost hardware, creating a viable power flow controller that can be affordable to utilities worldwide.

An IR connects a compensating voltage, $\mathbf{V}_{s's}$ (i.e., $V_{s's}\ \angle\delta_s+\beta$), in series with the transmission line as shown in Fig. 1. When the compensating voltage is added to the sending-end voltage, $\mathbf{V}_s$ (i.e., $V_s\ \angle\delta_s$), the modified sending-end voltage becomes $\mathbf{V}_{s'}$ (i.e., $V_{s'}\ \angle\delta_{s'}$). The difference between the modified sending-end voltage ($\mathbf{V}_{s'}$) and receiving-end voltage, $\mathbf{V}_r$ (i.e., $V_r\ \angle\delta_r$), determines the voltage ($\mathbf{V}_X$) across the line reactance (X), the line current ($\mathbf{I}$) and, in turn, the active and reactive (P, Q) power flows in the line. The related phasor diagram is shown in Fig. 2. The circle defines the controllable area of an IR.

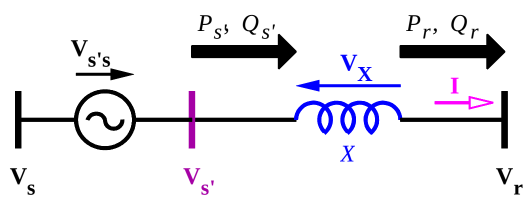


Fig. 1. A simple power transmission system with a series-connected compensating voltage, $\mathbf{V}_{s's}$.

The natural active and reactive (P_{sn}, Q_{sn}) power flows at the sending end and active and reactive (P_{rn}, Q_{rn}) power flows at the receiving end are defined as

$$P_{sn} = P_{rn} = \frac{V_s V_r}{X}\sin\delta \qquad (1)$$

$$Q_{sn} = \frac{V_s V_r}{X}\left\{\frac{V_s}{V_r} - \cos\delta\right\} \qquad (2)$$

$$Q_{rn} = \frac{V_s V_r}{X}\left\{\cos\delta - \frac{V_r}{V_s}\right\} \qquad (3)$$

where $\delta = \delta_s - \delta_r$.

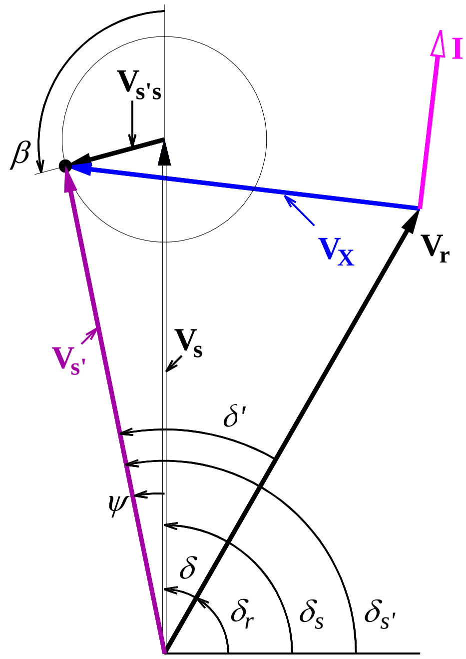


Fig. 2. Phasor diagram of an IR.

The active and reactive ($P_{s'}$, $Q_{s'}$) power flows at the modified sending end for a new phase angle ($\delta'=\delta+\psi$) and active and reactive (P_r, Q_r) power flows at the receiving end are defined as

$$P_{s'} = P_r = \frac{V_{s'}V_r}{X}\sin\delta' \qquad (4)$$

$$Q_{s'} = \frac{V_{s'}V_r}{X}\left\{\frac{V_{s'}}{V_r} - \cos\delta'\right\} \qquad (5)$$

$$Q_r = \frac{V_{s'}V_r}{X}\left\{\cos\delta' - \frac{V_r}{V_{s'}}\right\} \qquad (6)$$

where $\delta' = \delta_{s'} - \delta_r$.

From equations (4) and (6), it can be found that for given active and reactive (P_r, Q_r) power flows at the receiving end, a power flow controller with a shunt-shunt topology[9] applies a voltage $\mathbf{V_{s'}}$ (i.e., $V_{s'}\angle\delta_{s'}$), such that

$$V_{s'} = \frac{X}{V_r}\sqrt{P_r^{\,2} + \left(Q_r + \frac{V_r^{\,2}}{X}\right)^2} \qquad (7)$$

$$\delta' = \tan^{-1}\frac{P_r}{Q_r + \frac{V_r^{\,2}}{X}} \qquad (8)$$

In an alternate approach, the same active and reactive (P_r, Q_r) power flows can be obtained using a power flow controller with a shunt-series topology[8] that applies a series-compensating voltage $\mathbf{V_{s's}}$ (i.e., $V_{s's}\angle\delta_s+\beta$), such that $\mathbf{V_{s'}} = \mathbf{V_s} + \mathbf{V_{s's}}$ or

$$V_{s'}\angle\psi = V_s + V_{s's}\angle\beta \tag{9}$$

where the phase shift angle, $\psi = \delta' - \delta = \delta_{s'} - \delta_s$.

The magnitude ($V_{s's}$) and injection angle (β) of the series-connected compensating voltage are

$$V_{s's} = \sqrt{V_{s'}^2 + V_s^2 - 2V_{s'}V_s\cos\psi} \tag{10}$$

$$\beta = \tan^{-1}\frac{V_{s'}\sin\psi}{V_{s'}\cos\psi - V_s} \tag{11}$$

Various features of all shunt-shunt and shunt-series configurations are summarized in Table 1. The VSC-based solutions provide more features than electrical machine (EM)-based solutions, which provide more features than transformer/LTC-based solutions. However, most of the power flow control needs are in synchronous networks and the use of the shunt-series topology of the ST that uses transformer/LTC-based solutions is sufficient to meet the utilities' power flow control needs in the most cost-effective way.[8]

Table 1. Various features of all shunt-shunt and shunt-series configurations.

Features	VSC	EM	Transformer/LTCs
	Shunt-shunt configuration		
Independent P-Q flow control	Yes	Yes	Yes
Different frequency system	Yes	Yes	No
Different phase angle system	Yes	Yes	Yes
Intermediate dc transmission	Yes	No	No
	Shunt-series configuration		
Independent P-Q flow control	Yes	Yes	Yes
One frequency system	Yes	Yes	Yes
Cost	High	Medium	Low

Sen Transformer With Shunt-Series Topology

Fig. 3 shows the ST circuit[2], which is a three-phase transformer with Y-connected primary windings (A, B, and C), called the exciter unit, and nine secondary windings (a_1, a_2, and a_3 on the core of the A phase; b_1, b_2, and b_3 on the core of the B phase; and c_1, c_2, and c_3 on the core of the C phase), called the compensating voltage unit.

This unit can be used to form a series-connected compensating voltage that is at any phase angle with respect to the transmission line voltage. By choosing the number of turns from each of the three windings and, therefore, the magnitudes of the components of the three 120º phase-shifted induced voltages, the compensating voltage ($\mathbf{V_{s's}}$) in any phase is derived from the phasor sum of the voltages induced in a three-phase winding set (a_1, b_1, and c_1 for compensation in the A phase; a_2, b_2, and c_2 for compensation in the B phase; and a_3, b_3, and c_3 for compensation in the C phase). Fig. 4 shows the related operating points.

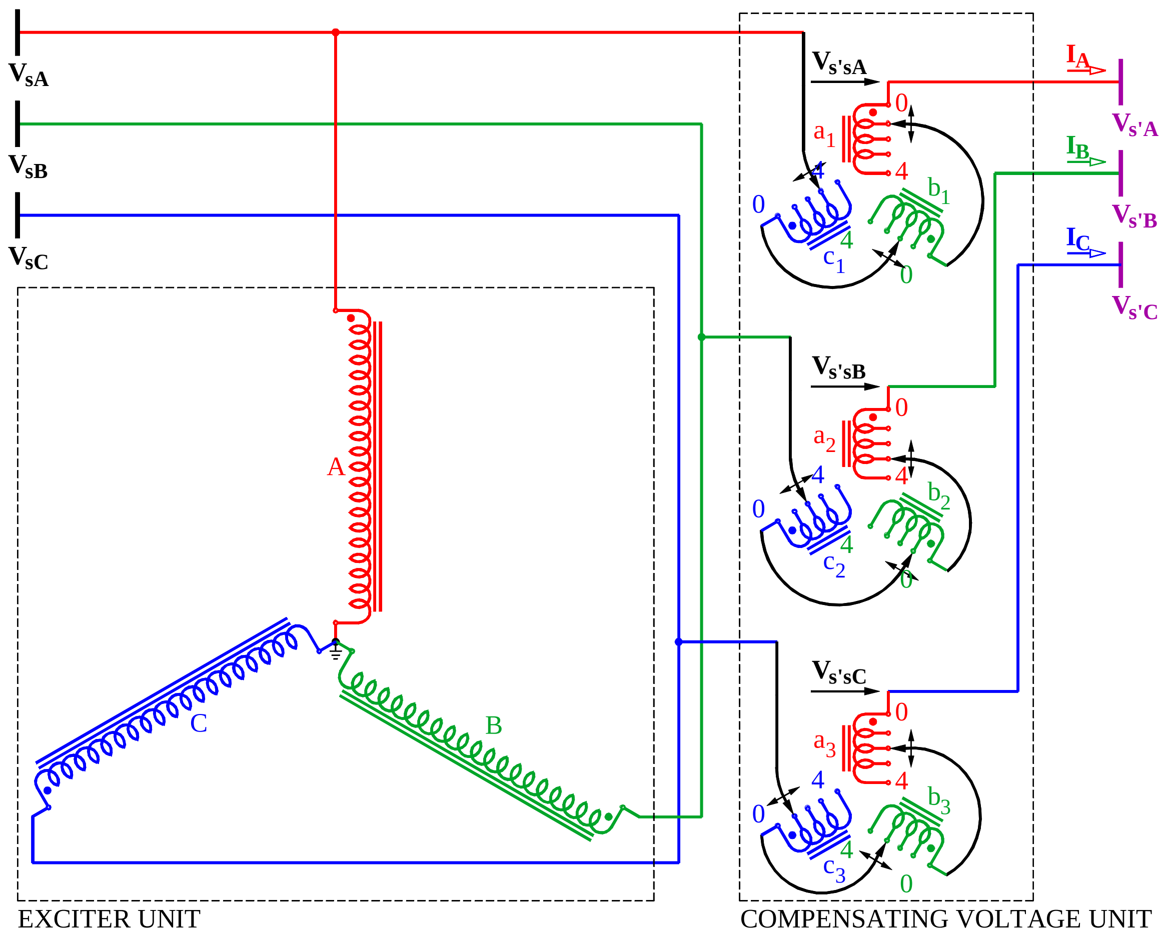


Fig. 3. Sen Transformer schematic.

The LTCs, used in an ST, change their positions in steps; therefore, the compensating points of an ST are discrete in the allowable control range. Shorter steps in the LTCs make the compensating points closer to each other and vice versa.

Note that typical LTCs offer 0.5% steps, which are sufficient for most utility applications. For legibility in this paper, the magnitude ($V_{s's}$) of the compensating voltage ($\mathbf{V_{s's}}$) is assumed to be 0.2 per unit (pu) and the change of voltage in each step of an LTC is 0.05 pu; therefore, there are N = 4 steps associated with each secondary winding. The total number of possible compensating points (cp) in this example is defined by

$$cp = 3N(N+1) \tag{12}$$

and it is 60. A comprehensive study of the power system network integrated with the power flow controller can show how many steps is the right number of steps. Fig. 4 shows that the theoretical circular control area is actually a hexagon.[2]

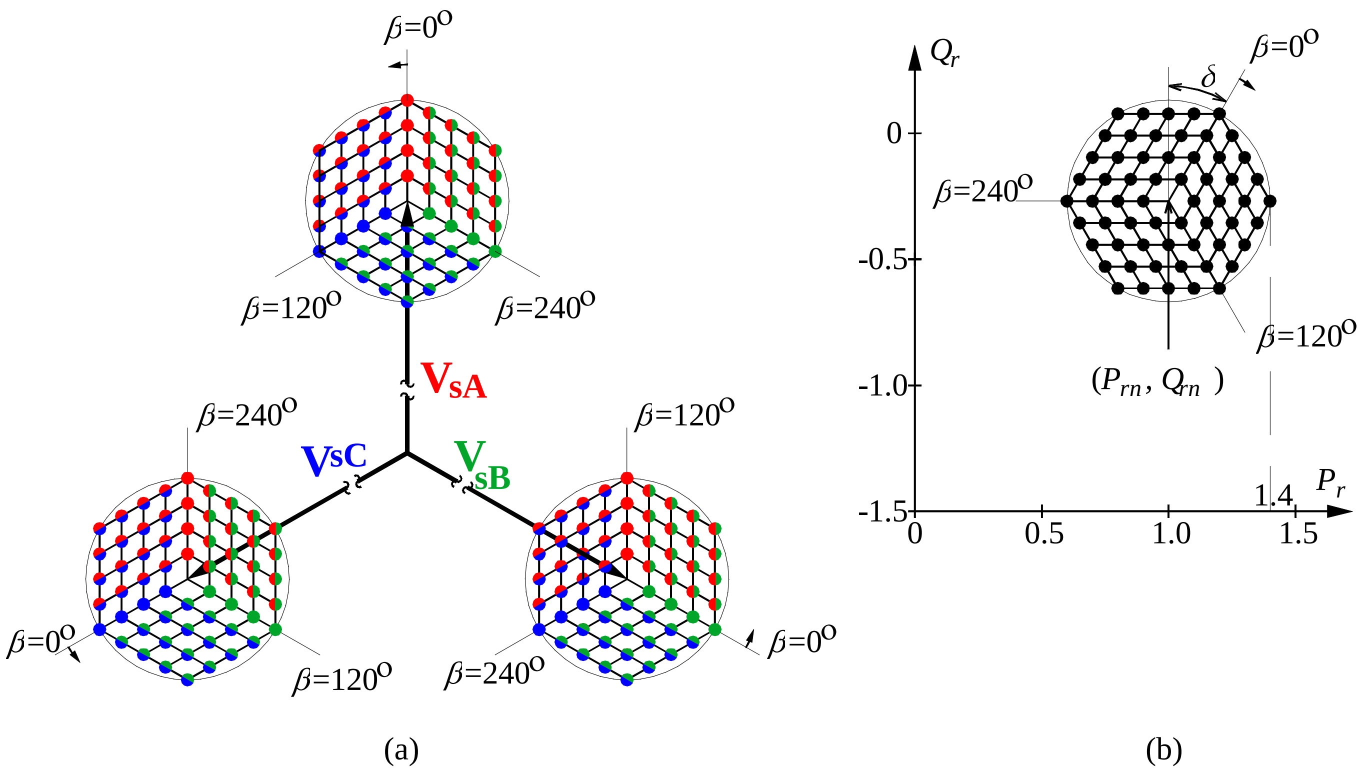


Fig. 4. Operating points of a Sen Transformer: modified sending-end voltage (a) and active and reactive power flows at the receiving end (b).

The magnitude ($V_{s's}$) of the compensating voltage and its injection angle (β) can be calculated in terms of taps associated with a particular phase as shown in Fig. 4. Note that windings a_1, b_1 and c_1 are associated with the compensating voltage for phase A. Similarly, windings a_2, b_2 and c_2 are associated with the compensating voltage for phase B; windings a_3, b_3 and c_3 are associated with the compensating voltage for phase C.

It should also be noted that each of a_1, b_2, and c_3 is tapped at the same number of turns; each of b_1, c_2, and a_3 is tapped at the same number of turns; and each of c_1, a_2, and b_3 is tapped at the same number of turns. However, the number of turns in the a_1-b_2-c_3 set, b_1-c_2-a_3 set, and c_1-a_2-b_3 set can be different from each other.

The compensating voltage for the A phase for the injection angle in the range of β = 0 to 2π is derived as

$$
\begin{aligned}
&V_{s's}\angle\beta = \mathrm{a}_1 V_s + \mathrm{b}_1 e^{-j2\pi/3} V_s + \mathrm{c}_1 e^{j2\pi/3} V_s \\
&= \mathrm{a}_1 V_s + \mathrm{b}_1 V_s\left(-1/2 - j\sqrt{3}/2\right) + \mathrm{c}_1 V_s\left(-1/2 + j\sqrt{3}/2\right) = \left(\mathrm{a}_1 - \mathrm{b}_1/2 - \mathrm{c}_1/2\right)V_s + j\left(\sqrt{3}/2\right)\left(\mathrm{c}_1 - \mathrm{b}_1\right)V_s \\
&= V_{s's}\cos\beta + jV_{s's}\sin\beta \\
&= V_s\sqrt{\mathrm{a}_1^{\,2} + \mathrm{b}_1^{\,2} + \mathrm{c}_1^{\,2} - \mathrm{a}_1\mathrm{b}_1 - \mathrm{b}_1\mathrm{c}_1 - \mathrm{c}_1\mathrm{a}_1}\angle\tan^{-1}\frac{\sqrt{3}\left(\mathrm{c}_1 - \mathrm{b}_1\right)}{2\mathrm{a}_1 - \mathrm{b}_1 - \mathrm{c}_1}
\end{aligned}
\tag{13}
$$

The theoretical magnitude of the compensating voltage ($V_{s's}$) in pu, considering the primary voltage (V_s) of one pu, during the entire range of the injection angle (β) from 0º to 360º is shown in Fig. 5.

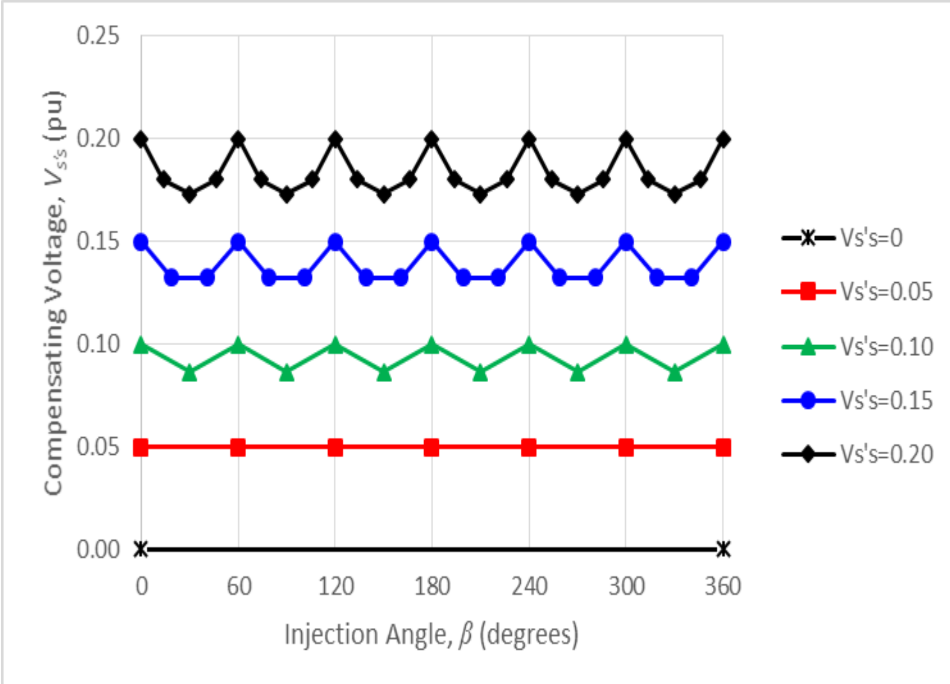


Fig. 5. Theoretical magnitude of the series-connected compensating voltage ($V_{s's}$) in pu during the entire range of the injection angle (β) from 0° to 360°.

To generate the compensating voltage for phase B, Eq. (13) may be used replacing a_1, b_1, c_1 with b_2, c_2, a_2, respectively. To generate the compensating voltage for phase C, Eq. (13) may be used replacing a_1, b_1, c_1 with c_3, a_3, b_3, respectively.

Using Eq. 13, the magnitude and the phase shift angle of the modified sending end voltage can be derived as

$$V_{s'}\angle\psi = V_s + V_{s's}\angle\beta = V_s + V_{s's}\cos\beta + jV_{s's}\sin\beta = V_s + (a_1 - b_1/2 - c_1/2)V_s + j(\sqrt{3}/2)(c_1 - b_1)V_s$$
$$= V_s\sqrt{1 + a_1^2 + b_1^2 + c_1^2 - a_1b_1 - b_1c_1 - c_1a_1 + 2a_1 - b_1 - c_1}\angle\tan^{-1}\frac{\sqrt{3}(c_1 - b_1)}{2 + 2a_1 - b_1 - c_1} \qquad (14)$$

The theoretical magnitude of the modified sending-end voltage ($V_{s'}$) in pu, considering the primary voltage (V_s) of one pu, during the entire range of injection angle (β) from 0º to 360º is shown in Fig. 6. The variation of the phase shift angle (ψ) in degrees during the entire range of the injection angle (β) from 0º to 360º is shown in Fig. 7.

Table 2 shows the LTC settings for the windings for the entire range of the injection angle (β) from 0° to 360º.

Table 2. Various contributions from each of the three windings in the A phase for operation in each hexagon (related to operation of 1, 2, 3, and 4 taps on each winding), the corresponding magnitude ($V_{s's}$) and injection angle (β) of the compensating voltage ($\mathbf{V_{s's}}$), and the corresponding magnitude ($V_{s'}$) and phase shift angle (ψ) of the modified sending end voltage ($\mathbf{V_{s'}}$).

a_1	b_1	c_1	Theoretical $V_{s's}$ (pu)	β (deg)	Theoretical $V_{s'}$ (pu)	ψ (deg)
0.00	0.00	0.00	0.00	0.00	1.00	0.00
0.00	0.00	0.00	0.00	360.00	1.00	0.00

a_1	b_1	c_1	$V_{s's}$ (pu)	β (deg)	$V_{s'}$ (pu)	ψ (deg)
0.05	0.00	0.00	0.05	0.00	1.05	0.00
0.05	0.00	0.05	0.05	60.00	1.03	2.42
0.00	0.00	0.05	0.05	120.00	0.98	2.54
0.00	0.05	0.05	0.05	180.00	0.95	0.00
0.00	0.05	0.00	0.05	240.00	0.98	-2.54
0.05	0.05	0.00	0.05	300.00	1.03	-2.42
0.05	0.00	0.00	0.05	360.00	1.05	0.00

a_1	b_1	c_1	$V_{s's}$ (pu)	β (deg)	$V_{s'}$ (pu)	ψ (deg)
0.20	0.00	0.00	0.20	0.00	1.20	0.00
0.20	0.00	0.05	0.18	13.90	1.18	2.11
0.20	0.00	0.10	0.17	30.00	1.15	4.31
0.20	0.00	0.15	0.18	46.10	1.13	6.59
0.20	0.00	0.20	0.20	60.00	1.11	8.95
0.15	0.00	0.20	0.18	73.90	1.06	9.37
0.10	0.00	0.20	0.17	90.00	1.01	9.83
0.05	0.00	0.20	0.18	106.10	0.97	10.33
0.00	0.00	0.20	0.20	120.00	0.92	10.89
0.00	0.05	0.20	0.18	133.90	0.88	8.44
0.00	0.10	0.20	0.17	150.00	0.85	5.82
0.00	0.15	0.20	0.18	166.10	0.83	3.00
0.00	0.20	0.20	0.20	180.00	0.80	0.00
0.00	0.20	0.15	0.18	193.90	0.83	-3.00
0.00	0.20	0.10	0.17	210.00	0.85	-5.82
0.00	0.20	0.05	0.18	226.10	0.88	-8.44
0.00	0.20	0.00	0.20	240.00	0.92	-10.89
0.05	0.20	0.00	0.18	253.90	0.97	-10.33
0.10	0.20	0.00	0.17	270.00	1.01	-9.83
0.15	0.20	0.00	0.18	286.10	1.06	-9.37
0.20	0.20	0.00	0.20	300.00	1.11	-8.95
0.20	0.15	0.00	0.18	313.90	1.13	-6.59
0.20	0.10	0.00	0.17	330.00	1.15	-4.31
0.20	0.05	0.00	0.18	346.10	1.18	-2.11
0.20	0.00	0.00	0.20	360.00	1.20	0.00

a_1	b_1	c_1	$V_{s's}$ (pu)	β (deg)	$V_{s'}$ (pu)	ψ (deg)
0.10	0.00	0.00	0.10	0.00	1.10	0.00
0.10	0.00	0.05	0.09	30.00	1.08	2.31
0.10	0.00	0.10	0.10	60.00	1.05	4.72
0.05	0.00	0.10	0.09	90.00	1.00	4.95
0.00	0.00	0.10	0.10	120.00	0.95	5.21
0.00	0.05	0.10	0.09	150.00	0.93	2.68
0.00	0.10	0.10	0.10	180.00	0.90	0.00
0.00	0.10	0.05	0.09	210.00	0.93	-2.68
0.00	0.10	0.00	0.10	240.00	0.95	-5.21
0.05	0.10	0.00	0.09	270.00	1.00	-4.95
0.10	0.10	0.00	0.10	300.00	1.05	-4.72
0.10	0.05	0.00	0.09	330.00	1.08	-2.31
0.10	0.00	0.00	0.10	360.00	1.10	0.00

a_1	b_1	c_1	$V_{s's}$ (pu)	β (deg)	$V_{s'}$ (pu)	ψ (deg)
0.15	0.00	0.00	0.15	0.00	1.15	0.00
0.15	0.00	0.05	0.13	19.11	1.13	2.20
0.15	0.00	0.10	0.13	40.89	1.10	4.50
0.15	0.00	0.15	0.15	60.00	1.08	6.89
0.10	0.00	0.15	0.13	79.11	1.03	7.22
0.05	0.00	0.15	0.13	100.89	0.98	7.59
0.00	0.00	0.15	0.15	120.00	0.93	7.99
0.00	0.05	0.15	0.13	139.11	0.90	5.50
0.00	0.10	0.15	0.13	160.89	0.88	2.83
0.00	0.15	0.15	0.15	180.00	0.85	0.00
0.00	0.15	0.10	0.13	199.11	0.88	-2.83
0.00	0.15	0.05	0.13	220.89	0.90	-5.50
0.00	0.15	0.00	0.15	240.00	0.93	-7.99
0.05	0.15	0.00	0.13	259.11	0.98	-7.59
0.10	0.15	0.00	0.13	280.89	1.03	-7.22
0.15	0.15	0.00	0.15	300.00	1.08	-6.89
0.15	0.10	0.00	0.13	319.11	1.10	-4.50
0.15	0.05	0.00	0.13	340.89	1.13	-2.20
0.15	0.00	0.00	0.15	360.00	1.15	0.00

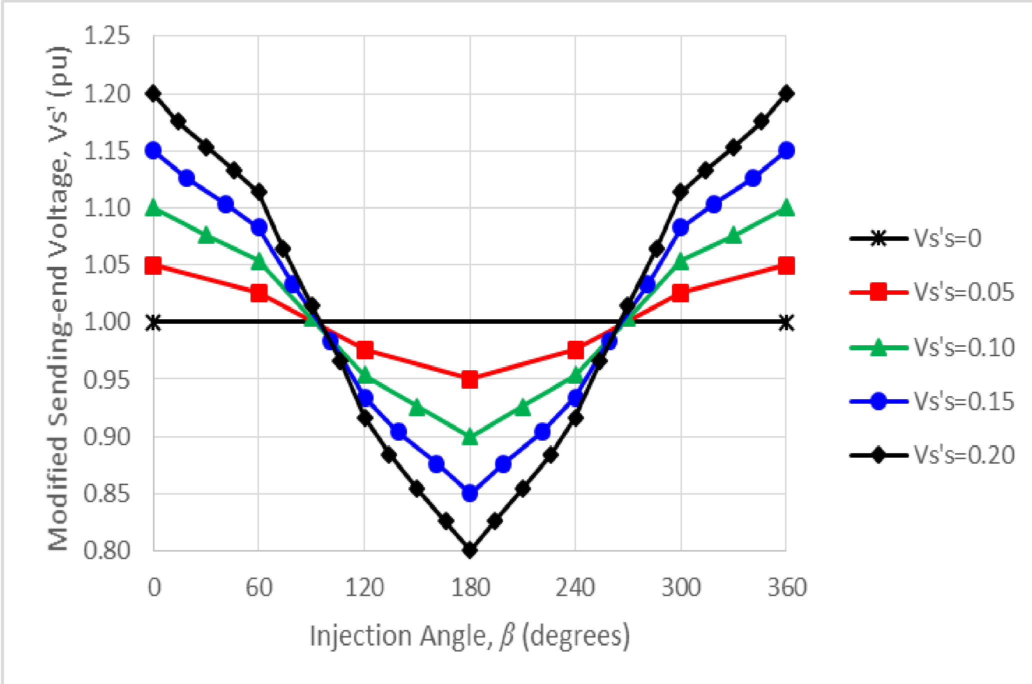


Fig. 6. Theoretical magnitude of the modified sending-end voltage ($V_{s'}$) in pu during the entire range of the injection angle (β) from 0° to 360°.

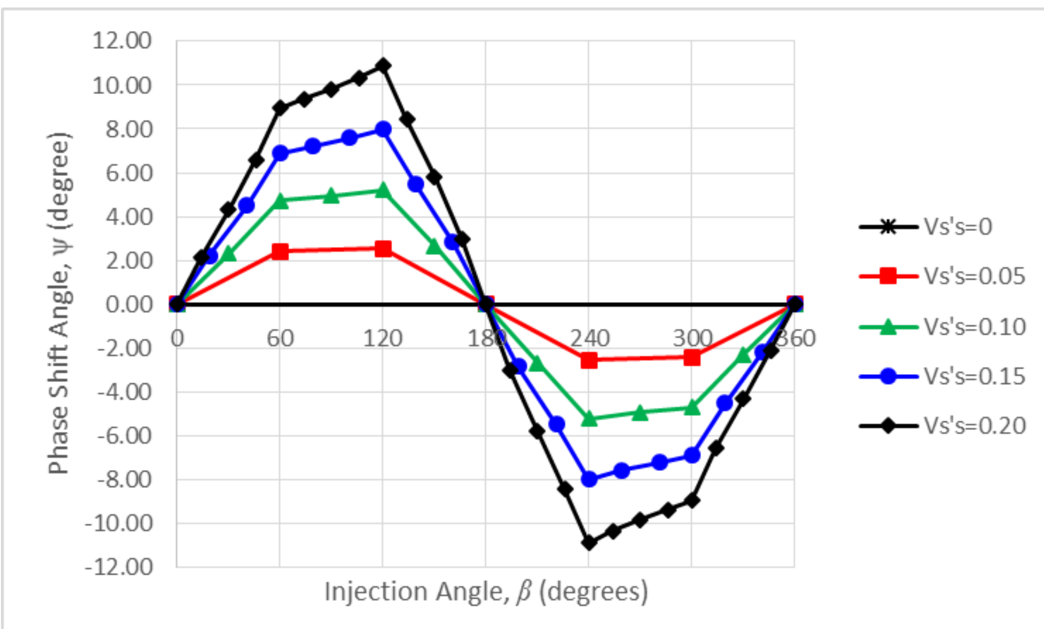


Fig. 7. Variation of phase shift angle (ψ) in degrees during the entire range of the injection angle (β) from 0° to 360°.

Modeling In EMTP

Fig. 8 shows the block diagram of the modeling structure in EMTP. First, some general constants are defined. Next, the control or the transient analysis of control systems (TACS) section receives its input signals from the sensors or measuring switches. The control operations and calculations are performed in this section.

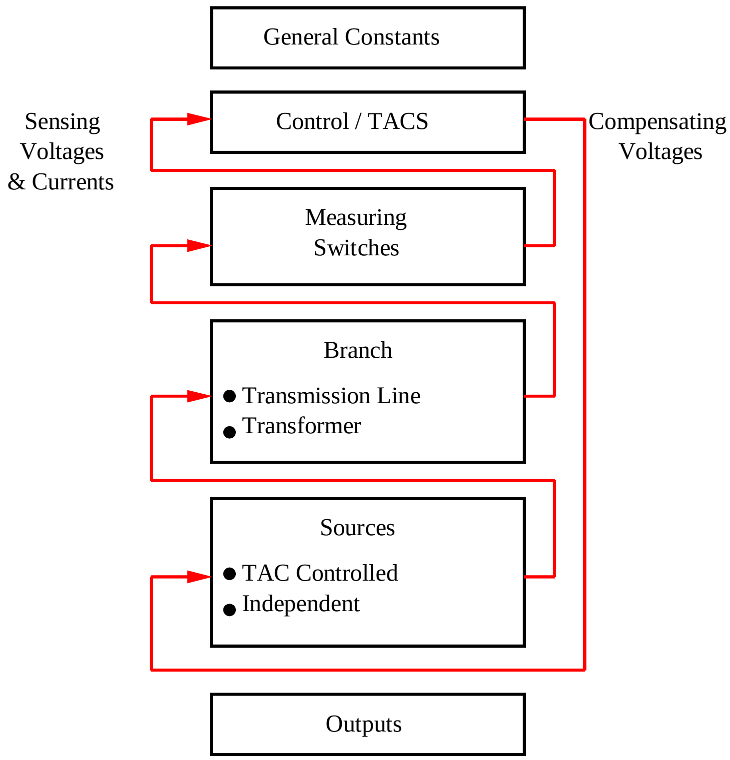


Fig. 8. EMTP modeling structure.

The sources section contains TAC-controlled and independent voltage sources, which establish the power flow in a transmission line. The branch section contains the transmission line and ST. The line voltage and the line current are measured by the measuring switches. Finally, the output section is defined.

The three-phase nominal power of 160 MVA and phase-to-phase nominal rms voltage of 138 kV are used. The base voltage (V_{base}) is chosen to be the phase-to-neutral peak voltage (V_p) and calculated as

$$V_{base} = V_p = \frac{138*10^3}{\sqrt{3}}\sqrt{2} = 112{,}677\text{V} \qquad (15)$$

The base current (I_{base}) is chosen to be the peak current (I_p) and calculated as

$$P_{base} = 3*V_{rms(L-N)}*I_{rms} = 3\frac{V_p}{\sqrt{2}}\frac{I_p}{\sqrt{2}} = 1.5V_pI_p = 1.5V_{base}I_{base} \qquad (16)$$

or

$$I_{base} = \frac{P_{base}}{1.5V_{base}} = \frac{160*10^6}{1.5*112{,}677} = 946.66\text{A} \qquad (17)$$

The base impedance (Z_{base}) is calculated as

$$Z_{base} = \frac{V_{base}}{I_{base}} = \frac{112{,}677}{946.66}\,\Omega = 119.02\,\Omega \qquad (18)$$

A sample EMTP code is shown below. The code in red lines simulates a three-phase source voltage ($\mathbf{V_{src}}$) of 138 kV-rms (√3 pu) and a source reactance (X_{src}) of 7.438 Ω (0.0625 pu) with a quality factor (Q = X_{src}/R_{src}) of 7.4 as shown in Fig. 9 and outputs the A-phase voltage as shown in Fig. 10.

```
BEGIN NEW DATA CASE
C File Name: TEST.DAT
C A SINGLE-GENERATOR, SINGLE-LINE POWER SYSTEM NETWORK
C 000000011111111112222222222333333333344444444445555555555666666666677777777778
C 345678901234567890123456789012345678901234567890123456789012345678901234567890
C ----dt<---tmax<---Xopt<---Copt<--Toler<      ><      >
16.666-6150.00-3
C 000000011111111112222222222333333333344444444445555555555666666666677777777778
C 345678901234567890123456789012345678901234567890123456789012345678901234567890
C -Iprnt<--Iplot<-Idoubl<-KssOut<-MaxOut<      ><      ><---Icat<-Nenerg
      20      10                                               1
TACS HYBRID
C BASE VOLTAGE
99Vbase   = 112676.528
90BUS01A
90BUS01B
90BUS01C
C 000000011111111112222222222333333333344444444445555555555666666666677777777778
C 345678901234567890123456789012345678901234567890123456789012345678901234567890
C BUS01 VOLTAGE COMPUTATION
99v1apu   = BUS01A / Vbase
C TACS OUTPUT
33BUS01A
BLANK RECORD ENDING TACS
C 000000011111111112222222222333333333344444444445555555555666666666677777777778
C 345678901234567890123456789012345678901234567890123456789012345678901234567890
C <-Bus1<-Bus2<-Bus3<-Bus4<----R<----L<----C                                   V
  VSRCA BUS01A            1.0053 19.73
  VSRCB BUS01BVSRCA BUS01A
  VSRCC BUS01CVSRCA BUS01A
BLANK RECORD ENDING BRANCHES
BLANK RECORD ENDING SWITCHES
C 000000011111111112222222222333333333344444444445555555555666666666677777777778
C 345678901234567890123456789012345678901234567890123456789012345678901234567890
C <--Bus<I<-----Ampl<-----Freq<----Phase<-------A1<------T1><---Tstart<----Tstop
14VSRCA   112676.528     60.00      0.00                          -1.0
14VSRCB   112676.528     60.00   -120.00                          -1.0
14VSRCC   112676.528     60.00    120.00                          -1.0
BLANK RECORD ENDING SOURCES
BLANK RECORD ENDING NODE VOLTAGE OUTPUT
BLANK RECORD ENDING PLOT
```

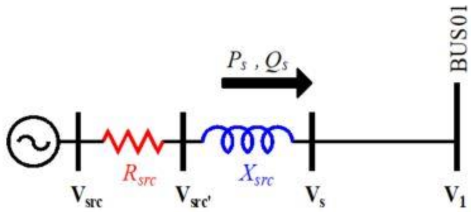


Fig. 9. Three-phase voltage source with source impedance.

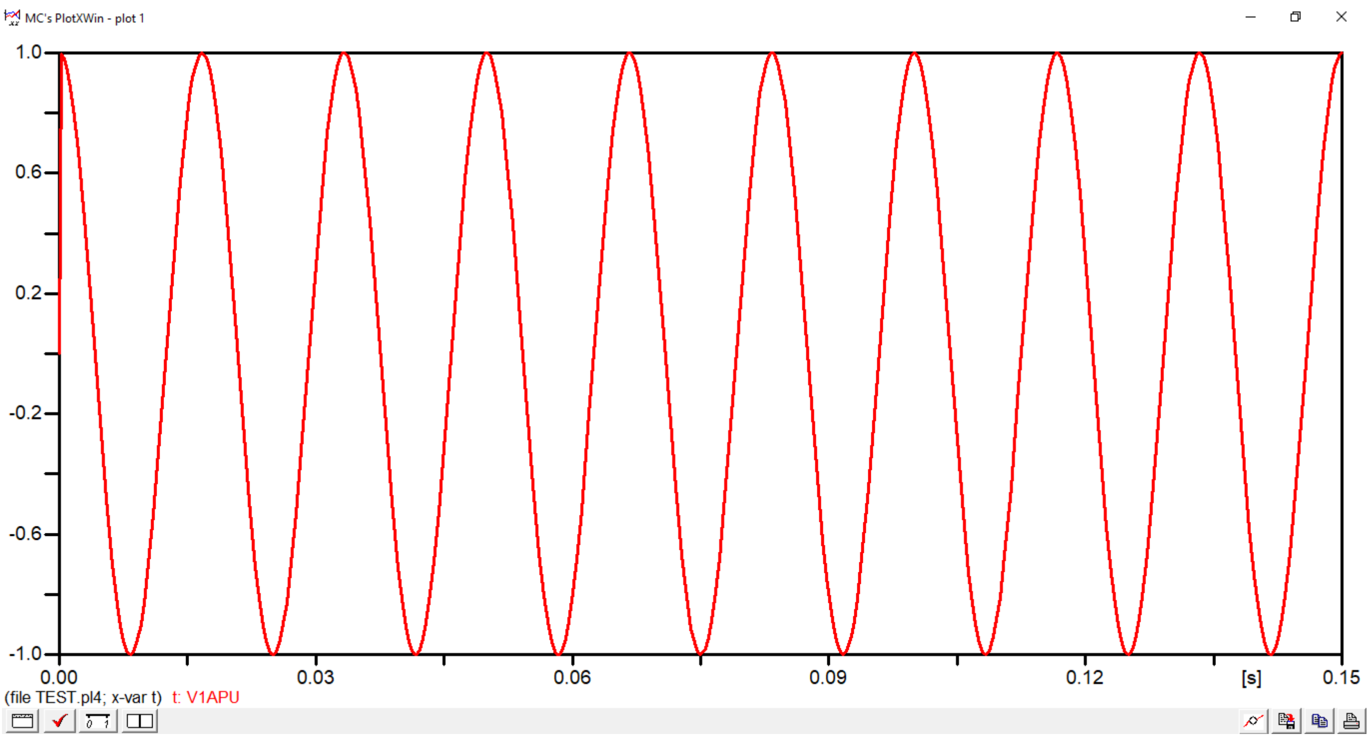


Fig. 10. The A-phase voltage.

The EMTP program is "column-specific." Certain parameters should be placed within certain columns (for example, the resistor values between columns 27 and 32) and there are 80 columns in each line. Special attention to right or left justification inside the specified columns is needed. To indicate a comment statement, a C in column 1 and a blank column 2 must appear. A reading of the EMTP program manual is recommended for further details.

The following statement indicates the start of the program:

```
BEGIN NEW DATA CASE
```

In the next statement, the time step, Δt = 16.666 μs, is entered in columns 1-8 and the simulation time, T_{max} = 150.00 ms is entered in columns 9-16:

```
C File Name: TEST.DAT
C A SIMPLE GENERATOR, SINGLE LINE POWER SYSTEM NETWORK
C 000000011111111112222222222333333333344444444445555555555666666666677777777778
C 345678901234567890123456789012345678901234567890123456789012345678901234567890
C ----dt<---tmax<---Xopt<---Copt<--Toler<       ><       >
16.666-6150.00-3
```

The next statement indicates the miscellaneous data card:

```
C 000000011111111112222222222333333333344444444445555555555666666666677777777778
C 345678901234567890123456789012345678901234567890123456789012345678901234567890
C -Iprnt<--Iplot<-Idoubl<-KssOut<-MaxOut<      ><      ><---Icat<-Nenerg
      20      10                                                 1
```

Iprnt 20 in columns 7-8 denotes "printout every 20th point." Iplot 10 in columns 15-16 denotes "plot every 10th point." Icat 1 in column 64 denotes a plot file that is to be generated and saved.

In the next section are the data cards for TACS. An Itype of 99 is used in columns 1-2 preceding a variable name or constant in columns 3-8:

```
TACS HYBRID
C BASE VOLTAGE
99Vbase   = 112676.528
```

The next statement measures the voltages:

```
90BUS01A
90BUS01B
90BUS01C
```

An Itype of 90 is used in columns 1-2 preceding a variable name in columns 3-8 for voltage measurement. Note that an Itype of 91 is used in columns 1-2 preceding a variable name in columns 3-8 for current measurement.

```
C 000000011111111112222222222333333333344444444445555555555666666666677777777778
C 345678901234567890123456789012345678901234567890123456789012345678901234567890
C BUS01 VOLTAGE COMPUTATION
99v1apu   = BUS01A / Vbase

C TACS OUTPUT
33BUS01A
```

An Itype of 33 is used in columns 1-2 that is followed by a variable name in columns 3-8 for the values to be sent to the output. Other variable names, each of maximum 6 characters long can be listed in the designated columns, such as 9 through 14, 15 through 20, 21 through 26, and so on.

The next statement indicates the end of the TACS section:

```
BLANK RECORD ENDING TACS
```

The branch data cards are located in the following section where columns 1-2 are left blank for the Itype. Columns 3-8 are for the first node name. Columns 9-14 are for the second node name. The resistor values in ohms (Ω) are entered in columns 27-32. The inductor values in millihenries (mH) are entered in columns 33-38. The capacitor values in microfarads (μF) are entered in columns 39-44.

```
C 000000011111111112222222222333333333344444444445555555555666666666677777777778
C 345678901234567890123456789012345678901234567890123456789012345678901234567890
C <-Bus1<-Bus2<-Bus3<-Bus4<----R<----L<----C                                     V
  VSRCA BUS01A            1.0053 19.73
  VSRCB BUS01BVSRCA BUS01A
  VSRCC BUS01CVSRCA BUS01A
```

The source impedance for the A phase is entered in one line. The source impedances for the B and C phases are the same as that in the A phase. The impedances with proper node names and resistor and inductor values are entered into the appropriate columns.

The impedance at the sending end (from the infinity bus to the point of compensation) is represented by an inductive impedance of 6.25% of the base impedance that translates to an inductor, L_{src} = 19.73 mH ($0.0625*Z_{base}/\omega$) where $\omega = 2*\pi*f$ (system frequency, f = 60 Hz) and a resistor, R_{src} = 1.0053 Ω where $R_{src} = \omega L_{src}/Q = 2*\pi*60*0.01973/7.4$. The impedance is assumed to have a quality factor (Q) of 7.4. The next statement indicates the end of the BRANCH section:

```
BLANK RECORD ENDING BRANCHES
```

The next statement indicates the end of the SWITCH section:

```
BLANK RECORD ENDING SWITCHES
```

The following section contains the source data cards.

```
C 00000001111111111222222222233333333334444444444555555555566666666667777777778
C 345678901234567890123456789012345678901234567890123456789012345678901234567890
C <--Bus<I<-----Ampl<-----Freq<----Phase<-------A1<------T1><---Tstart<----Tstop
14VSRCA   112676.528     60.00      0.00                              -1.0
14VSRCB   112676.528     60.00   -120.00                              -1.0
14VSRCC   112676.528     60.00    120.00                              -1.0
```

An Itype of 14 in columns 1-2 is used for a sinusoidal voltage source. A node name is entered in columns 3-8. The peak value of the voltage source (112,676.528 V in the present case) is entered in columns 11-20. The value of the frequency (60 Hz in the present case) is entered in columns 21-30, and the phase angles of 0°, -120°, and 120° for the three phases of the sending-end voltage sources are entered in columns 31-40. A –1.0 in columns 67-70 is needed if an initial phasor solution is desired at the start of the simulation.

The next statement indicates the end of the SOURCE section:

```
BLANK RECORD ENDING SOURCES
```

The following two statements are required for a successful run of the simulation:

```
BLANK RECORD ENDING NODE VOLTAGE OUTPUT
BLANK RECORD ENDING PLOT
```

Modeling Of Sen Transformer

A basic simulation of the ST was carried out and the results are shown in this section. Consider a power system network as shown in Fig. 11. In the natural or uncompensated network, no ST is connected. Later, the network is studied with an ST connected to it. A series-connected compensating voltage ($\mathbf{V_{s's}}$) modifies the sending-end voltage ($\mathbf{V_s}$) to be the modified sending-end voltage ($\mathbf{V_{s'}}$). The transmission line consists of a reactance (X) of 22.316 Ω (0.1875 pu) with a quality factor (Q = X/R) of 7.4. The receiving-end voltage is to be 138 kV, lagging the source voltage by 20°.

The EMTP code (SENTRAN1.DAT) is given in the appendix. The EMTP code is set up corresponding to the operating point when no compensating voltage is used. Therefore, all nine secondary windings of the ST have a turns-ratio of 1.0×10^{-6}. The uncompensated or natural active and reactive (P_{rn}, Q_{rn}) power flows at the receiving end of the line are 209.87 MW (1.3117 pu) and –66.97 Mvar (–0.4185 pu), respectively.

To study the effects of other operating points of an ST, the turns-ratios are set according to Table 2. As shown in the code, the leakage reactance of the ST was set to 1.0×10^{-6} Ω and 1.0×10^{-6} mH to eliminate its secondary effects. The EMTP code is green in the appendix for what has already been discussed. The EMTP code in red is the additional code to simulate the following network with an ST.

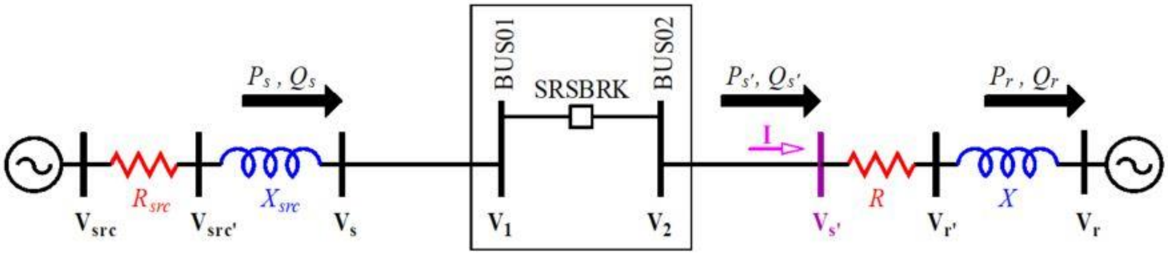


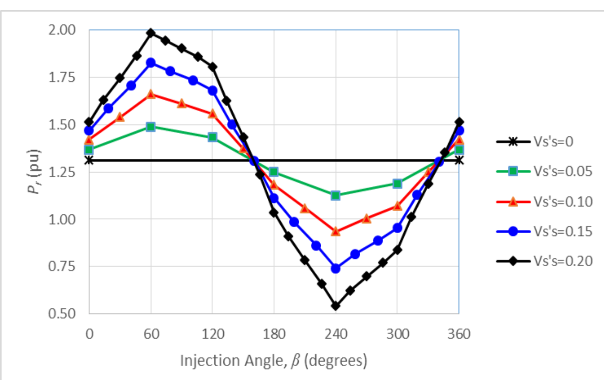
Fig. 11. Network model.

The parameters of the network are given in Table 3.

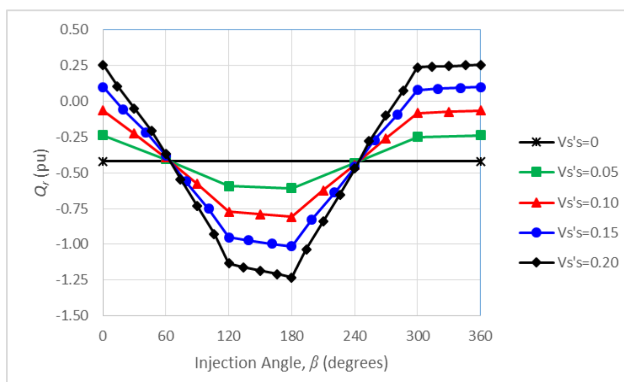
Table 3. Electrical system data.

Parameters	Values
Base values	160 MVA, 138 kV
Sending-end line-to-line voltage	$1\angle 0°$ pu
Receiving-end line-to-line voltage	$1\angle\text{-}20°$ pu
Series impedance for sending-end source	6.25% = 1.0053 Ω, 19.73 mH
Series impedance for receiving-end source	0 Ω, 0 mH
Transmission line impedance	18.75% = 3.0159 Ω, 59.19 mH

The control was implemented in an open-loop voltage injection mode, traveling from one operating point to the next in one particular hexagon in the entire range of the injection angle (β) from 0º to 360º. Fig. 12 shows the active and reactive power flows (P_r and Q_r) at the receiving end during the entire range of the injected angle (β) from 0º to 360º. Fig. 13 shows the active power flow (P_r) versus reactive power (Q_r) flow at the receiving end during the entire range of the injection angle (β) from 0º to 360º.



(a)



(b)

Fig. 12. (a) Active power (P_r) and (b) reactive power (Q_r) flows at the receiving end during the entire range of the injection angle (β) from 0º to 360º.

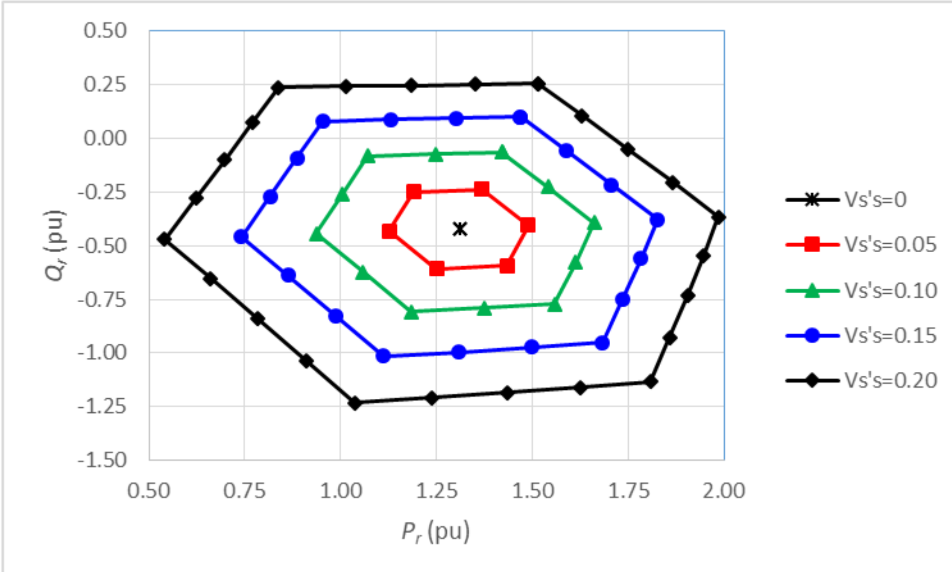


Fig. 13. Active power (P_r) flow versus reactive power (Q_r) flow at the receiving end during the entire range of the injection angle (β) from 0^o to 360^o.

The *P-Q* plot is somewhat different from an ideal hexagon (shown in Fig. 4) due to the fact that the primary voltage ($\mathbf{V_s}$) keeps moving from its original (uncompensated) location because of the change in load current and the resulting voltage drop in the line between the point of compensation and the infinite bus. The variation of voltage magnitude (V_s) is shown in Fig. 14.

A more ideal hexagon-like characteristic results if the point of compensation is closer to an infinite bus. The measured magnitude ($V_{s's}$) of the compensating voltage and the calculated magnitude ($V_{s's}$) (from Eq. 13) are identical. The measured magnitude ($V_{s's}$) of the compensating voltage in pu over the entire range of the injection angle (β) from 0º to 360º is shown in Fig. 15. The measured magnitude ($V_{s'}$) of the modified sending-end voltage and the calculated magnitude ($V_{s'}$) (from Eq. 14) are also identical. The measured magnitude ($V_{s'}$) of the modified sending-end voltage in pu during the entire range of the injection angle (β) from 0º to 360º is shown in Fig. 16.

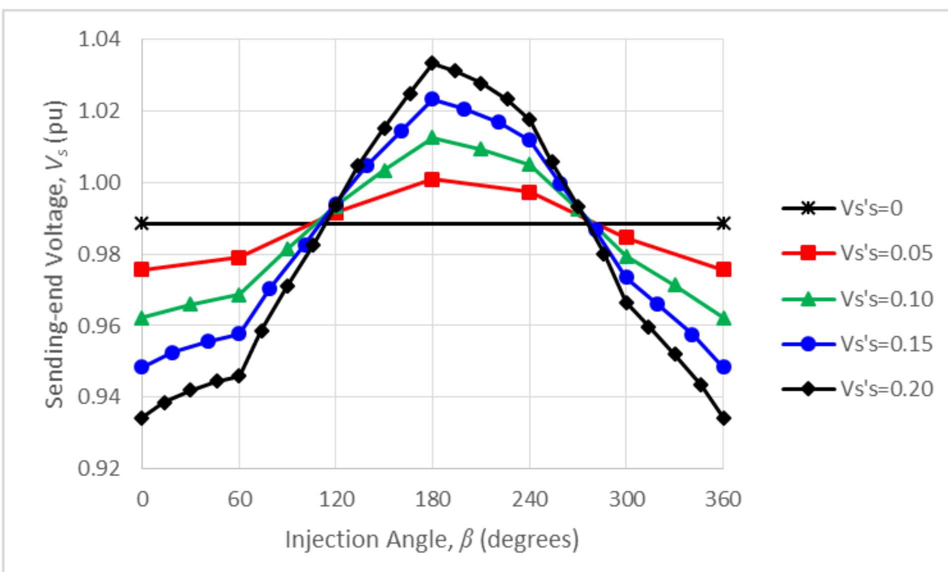


Fig. 14. Magnitude of the measured sending-end voltage (V_s) in pu over the entire range of the injection angle (β) from 0^o to 360^o.

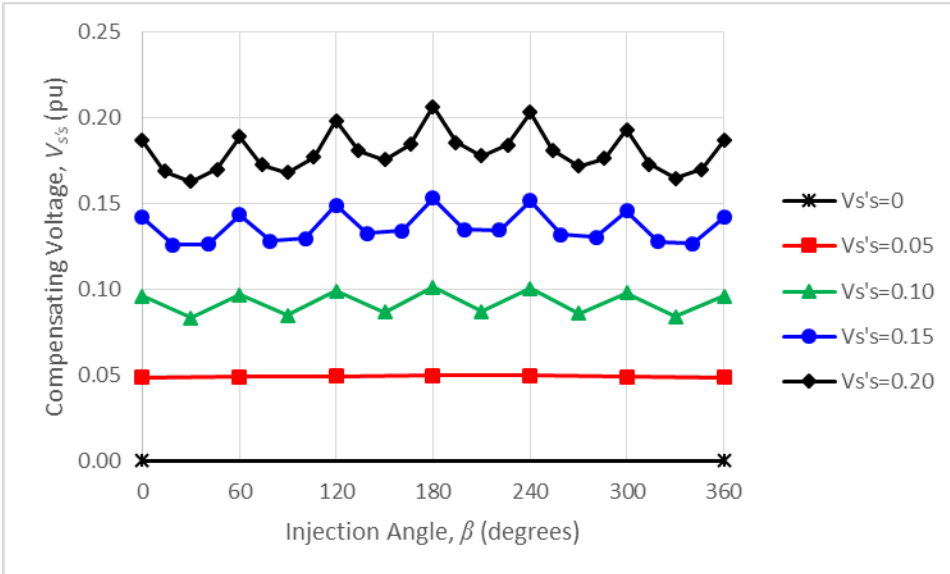


Fig. 15. Magnitude of the measured compensating voltage ($V_{s's}$) in pu during the entire range of its injection angle (β) from 0^o to 360^o.

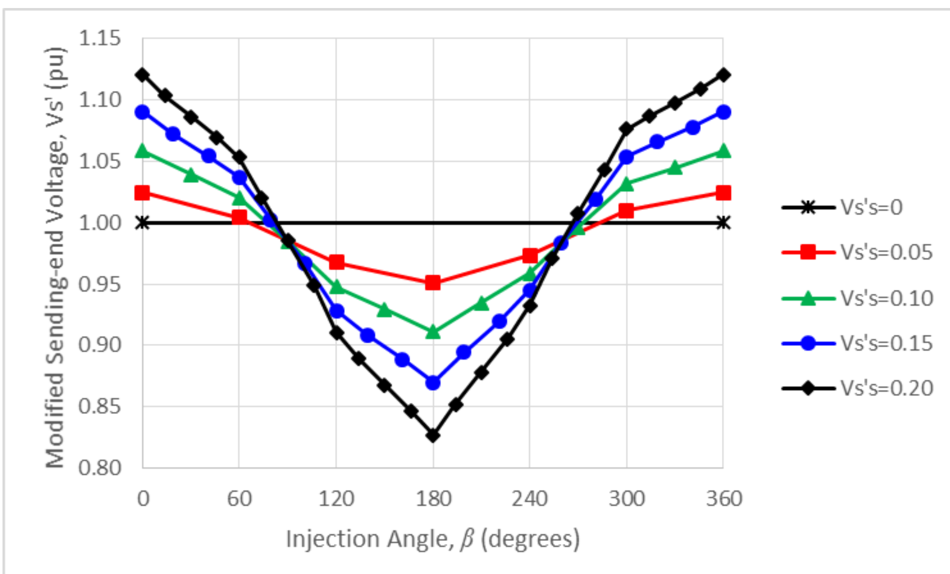


Fig. 16. Magnitude of the measured modified sending-end voltage ($V_{s'}$) in pu during the entire range of the injection angle (β) from 0^o to 360^o.

Alternate Configurations Of Sen Transformer

The Sen Transformer, in its basic design, is a single transformer, consisting of 12 windings—three primary and nine secondary as shown in Fig. 3. The primary windings are Y-connected. A dedicated three-winding set creates a compensating voltage that is connected in series in each of the three phases. Each of the windings in the three-winding set is excited from a different phase voltage. Therefore, by selecting the number of turns in each of these three windings, a composite voltage that is variable in magnitude ($V_{s's}$) and variable in injection angle (β) can be created, which in turn, makes the modified line voltage of desired magnitude ($V_{s'}$) and desired phase shift angle (ψ).

However, applications with more than a 230-kV voltage level require a two-transformer design where the taps are not exposed to high voltage[11] as shown in Fig. 17. The exciter unit excites the primary windings A, B and C. The compensating voltage unit creates the compensating voltage and the series unit connects the compensting voltage in series with the line.

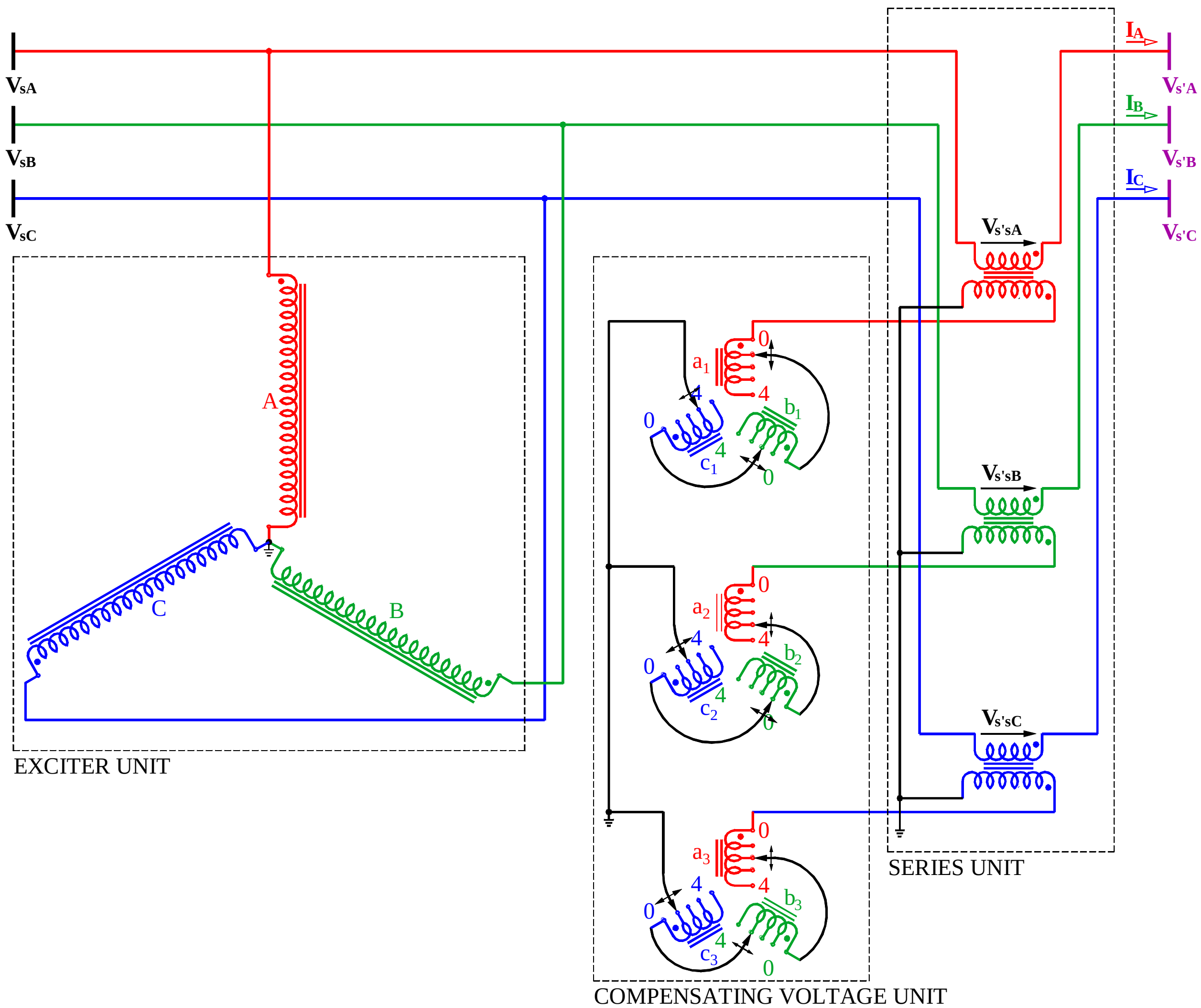


Fig. 17. ST configuration using taps with lower voltage and current ratings in a two-transformer design.

When a two-transformer design is used, the configuration of the compensating voltage unit can be simplified, requiring six secondary windings, as shown in Fig. 18 to provide the same hexagonal operating area as shown in Fig. 4. In this case, the primary windings in the exciter unit also induce the in-phase secondary voltages as is done in an autotransformer. This configuration can be further simplified, requiring only three secondary windings and two tap changers (one less than the usual three tap changers). In this simplest configuration of ST, out of the two parts of the compensating voltage, the first part is induced in the exciter unit as an in-phase or an out-of-phase voltage in all three phases.

There are three options in the arrangement of the secondary windings in the compensating voltage unit to induce the second part of the compensating voltage and achieve the 360º range of the injection angle. Each compensating voltage is designated as (+) if it is an in-phase component or (–) if it is an out-of-phase component. The compensating voltages in Option 1 for all the phases are given in Table 4. The required compensating points for the A phase are shown in Fig. 19 for 360º injection angle. The required winding configuration and the operating area are shown in Figs. 20 and 21, respectively.

Table 4. Components of Option 1 compensating voltages in A, B and C phases for the entire range of the injection angle (β) from 0° to 360°.

Ranges of injection angle of the compensating voltages	Components of A-phase compensating voltage	Components of B-phase compensating voltage	Components of C-phase compensating voltage
0° to 120°	+A phase and +C phase	+B phase and +A phase	+C phase and +B phase
120° to 180°	+C phase and −A phase	+A phase and −B phase	+B phase and −C phase
180° to 300°	−A phase and −C phase	−B phase and −A phase	−C phase and −B phase
300° to 360°	−C phase and +A phase	−A phase and +B phase	−B phase and +C phase

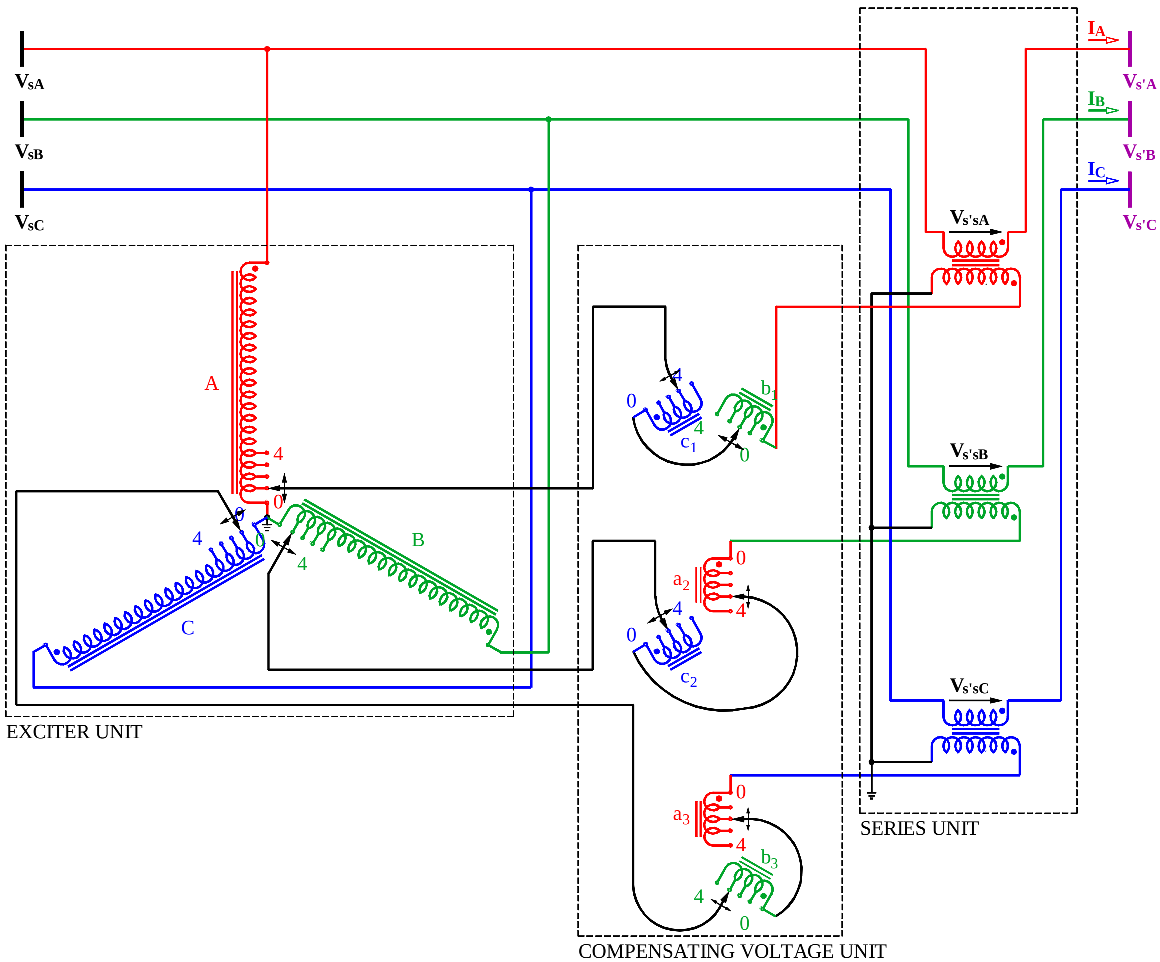


Fig. 18. ST configuration with six secondary windings in a two-transformer design.

The operating area, which is a rhombus consists of a total number of possible compensating points (cp) that is defined by

$$cp = 4N(N+1) \tag{19}$$

and it is 80. Therefore, from equations (12) and (19), the additional number of compensating points are defined by

$$cp_{additional} = N(N+1) \quad (20)$$

which is one-third more than the number of the compensating points in a hexagon.

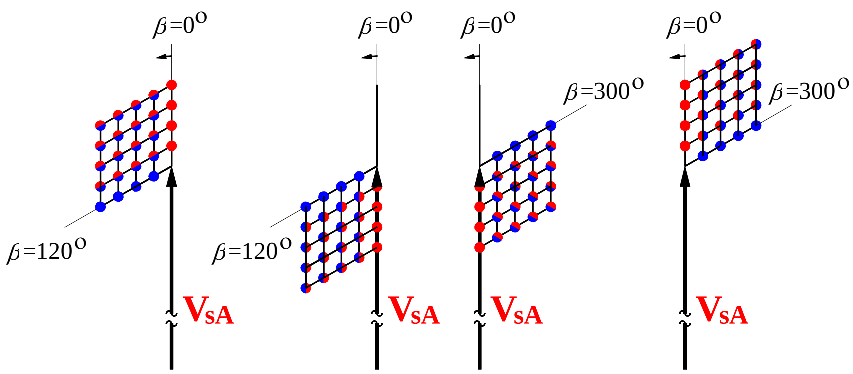


Fig. 19. The voltage compensating points for A phase in Option 1 configuration using ±A and ±C secondary windings.

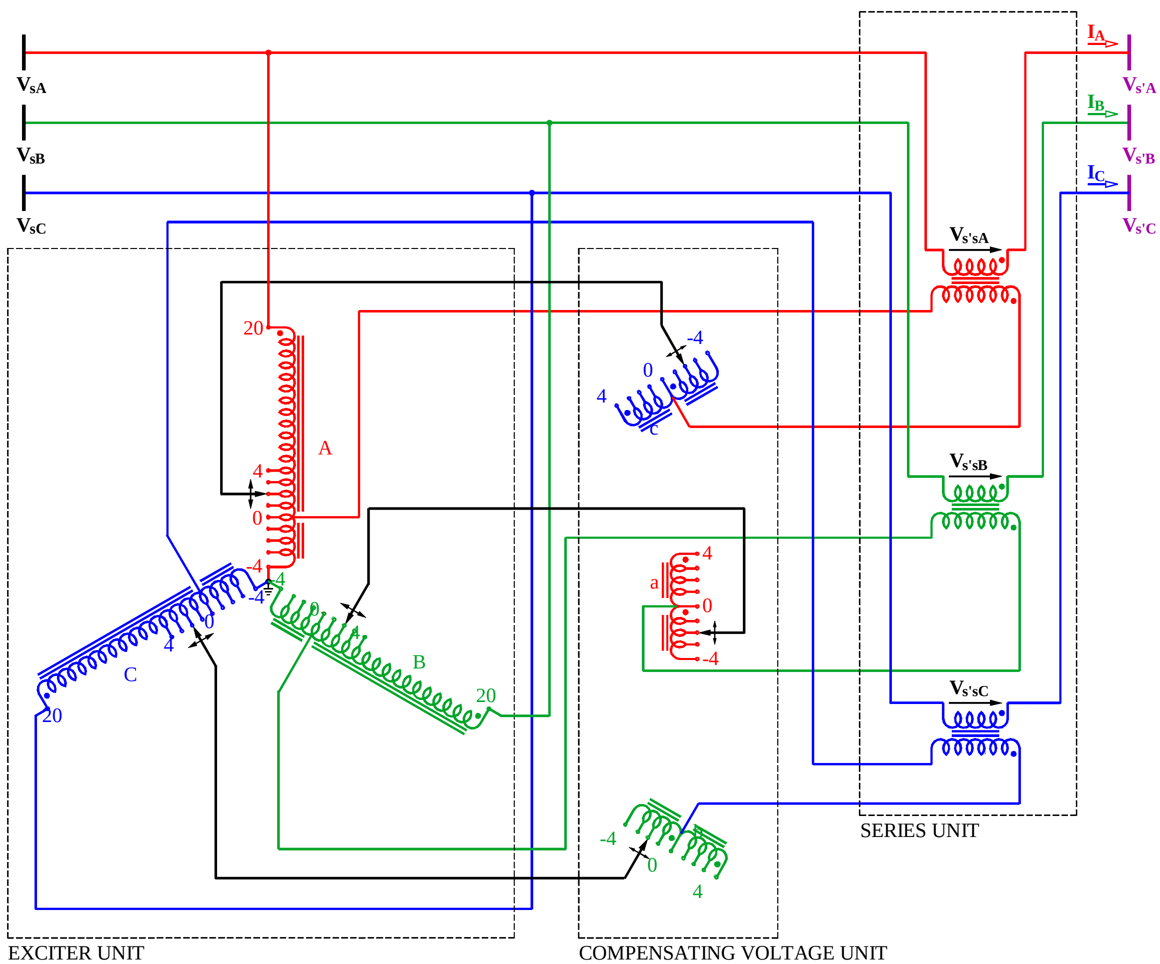
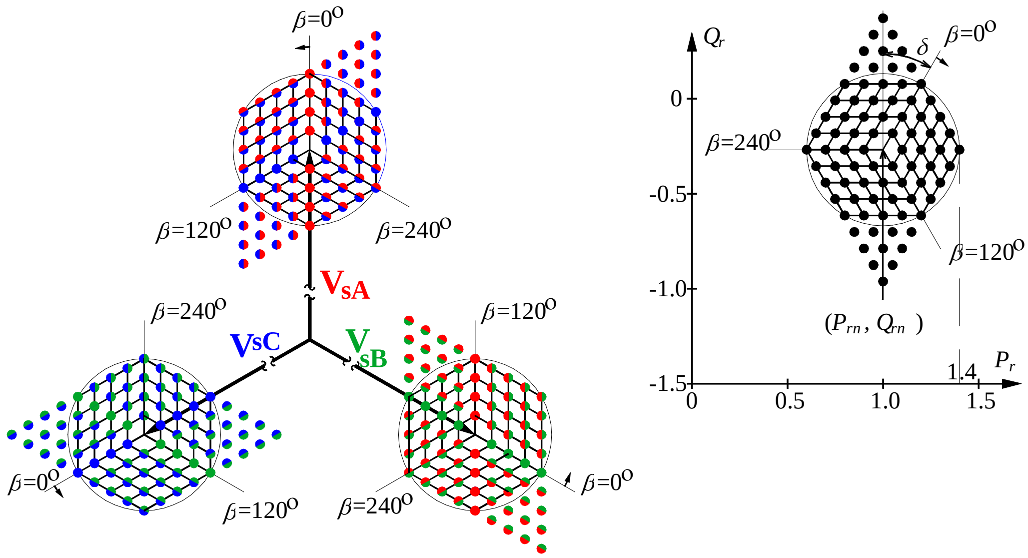


Fig. 20. ST configuration with three secondary windings in a two-transformer design: ±A and ±C secondary voltages for injection in A phase, ±B and ±A secondary voltages for injection in B phase and ±C and ±B secondary voltages for injection in C phase.



(a) (b)

Fig. 21. Operating points of a Sen Transformer in Option 1: modified sending-end voltage (a) and active and reactive power flows at the receiving end (b).

The compensating voltages in Option 2 for all the phases are given in Table 5. The required compensating points for the A phase are shown in Fig. 22 for 360º injection angle. The required winding configuration and the operating area are shown in Figs. 23 and 24, respectively.

Table 5. Components of Option 2 compensating voltages in A, B and C phases for the entire range of the injection angle (β) from 0° to 360°.

Ranges of injection angle of the compensating voltages	Components of A-phase compensating voltage	Components of B-phase compensating voltage	Components of C-phase compensating voltage
0º to 60º	+A phase and −B phase	+B phase and −C phase	+C phase and −A phase
60º to 180º	−B phase and −A phase	−C phase and −B phase	−A phase and −C phase
180º to 240º	−A phase and +B phase	−B phase and +C phase	−C phase and +A phase
240º to 360º	+B phase and +A phase	+C phase and +B phase	+A phase and +C phase

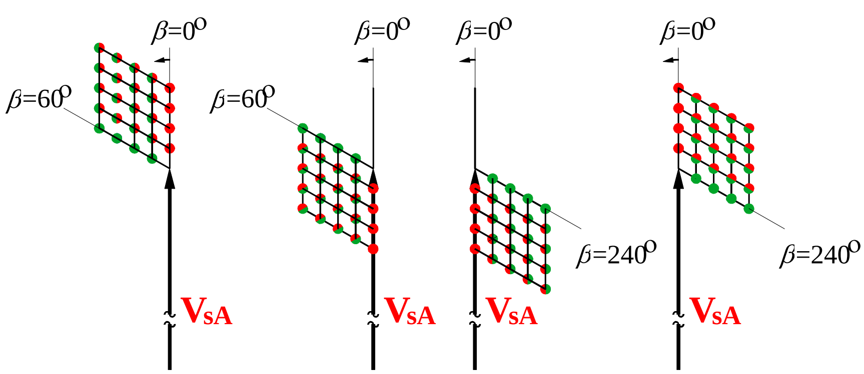


Fig. 22. The voltage compensating points for A phase in Option 2 configuration using ±A and ±B secondary windings.

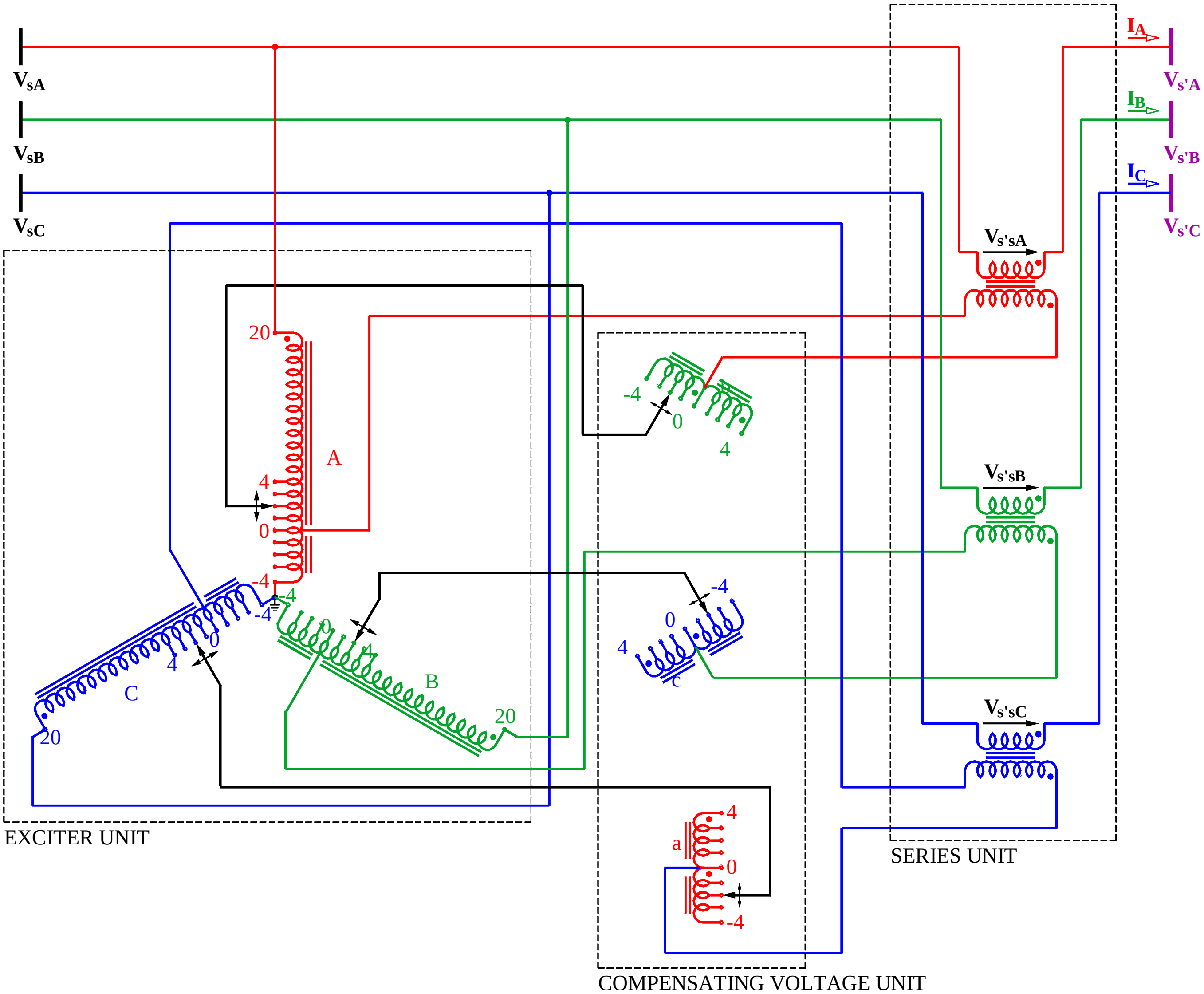


Fig. 23. ST configuration with three secondary windings in a two-transformer design: ±A and ±B secondary voltages for injection in A phase, ±B and ±C secondary voltages for injection in B phase and ±C and ±A secondary voltages for injection in C phase.

The compensating voltages in Option 3 for all the phases are given in Table 6. The required compensating points for the A phase are shown in Fig. 25 for 360º injection angle. The required winding configuration and the operating area are shown in Figs. 26 and 27, respectively.

Table 6. The compensating voltages in Option 3 for all phases.

Ranges of injection angle of the compensating voltages	Components of A-phase compensating voltage	Components of B-phase compensating voltage	Components of C-phase compensating voltage
−60º (300º) to 60º	−C phase and −B phase	−A phase and −C phase	−B phase and −A phase
60º to 120º	−B phase and +C phase	−C phase and +A phase	−A phase and +B phase
120º to 240º	+C phase and +B phase	+A phase and +C phase	+B phase and +A phase
240º to 300º	+B phase and −C phase	+C phase and −A phase	+A phase and −B phase

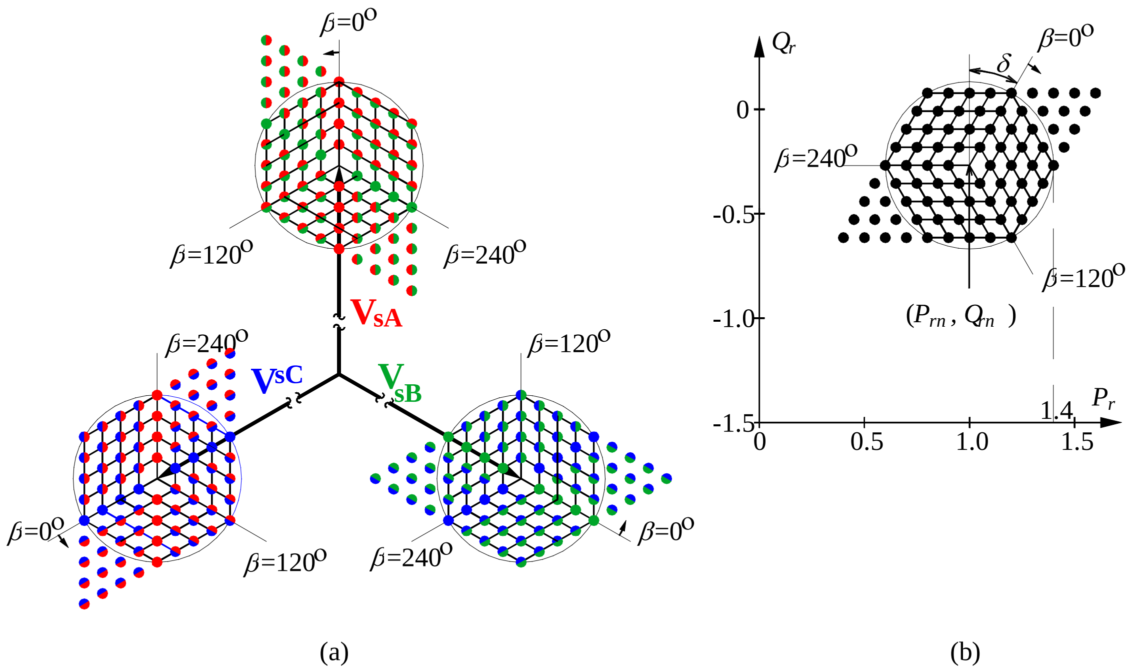


Fig. 24. Operating points of a Sen Transformer in Option 2: modified sending-end voltage (a) and active and reactive power flows at the receiving end (b).

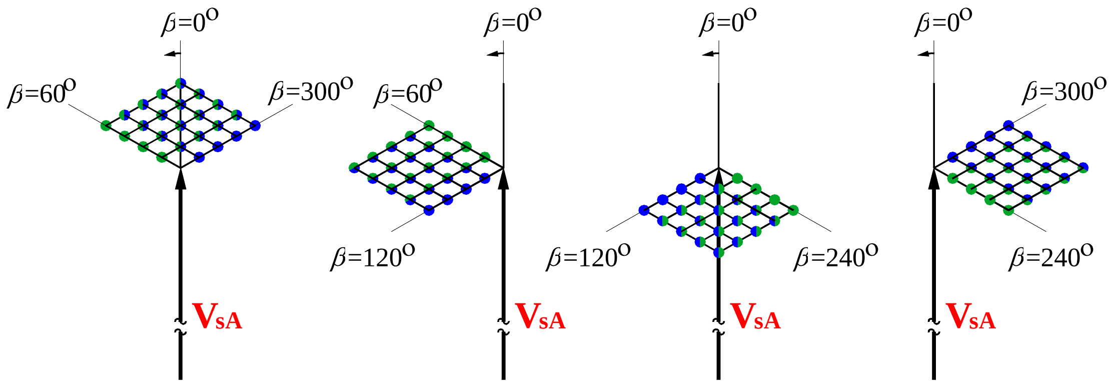


Fig. 25. The voltage compensating points for A phase in Option 3 configuration using ±B and ±C secondary windings.

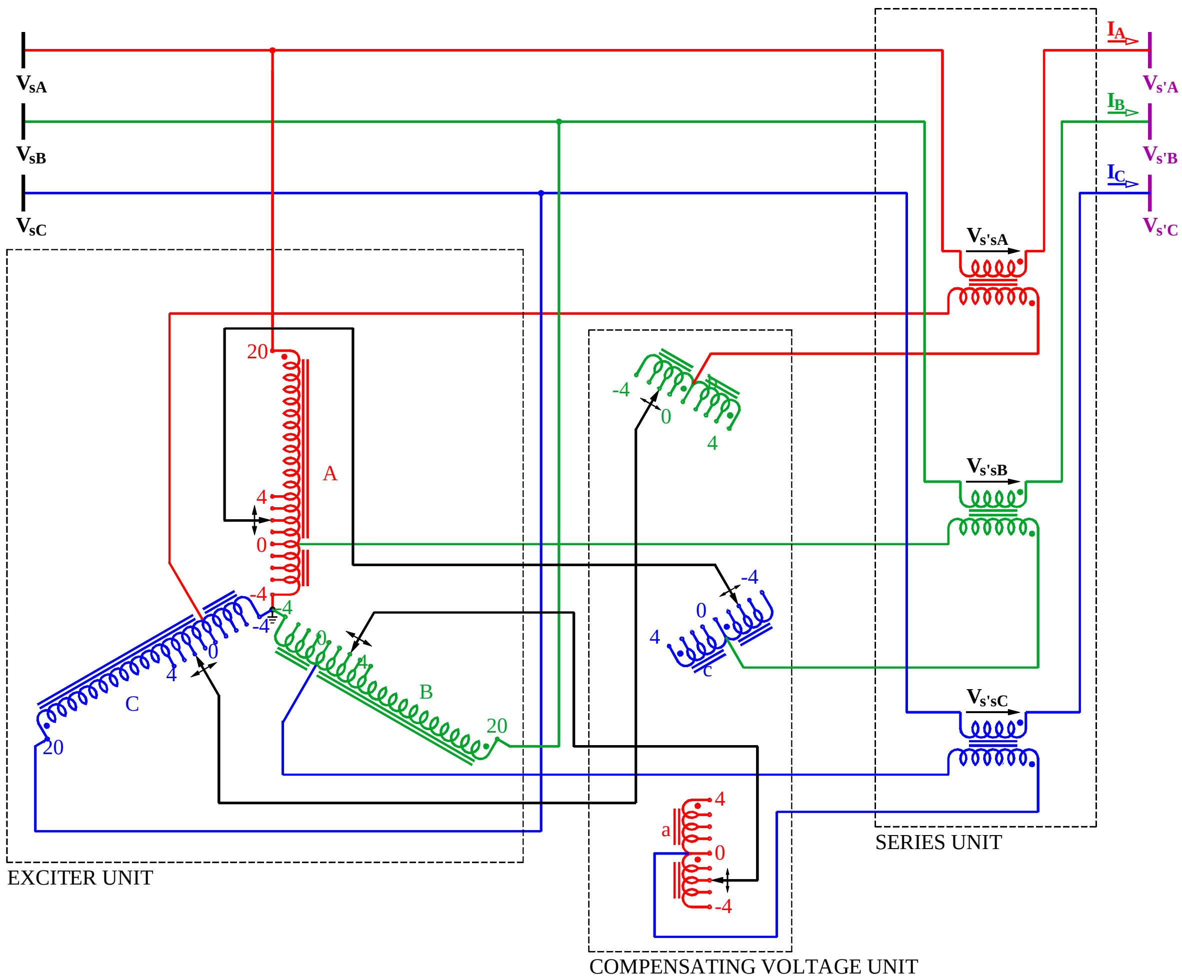
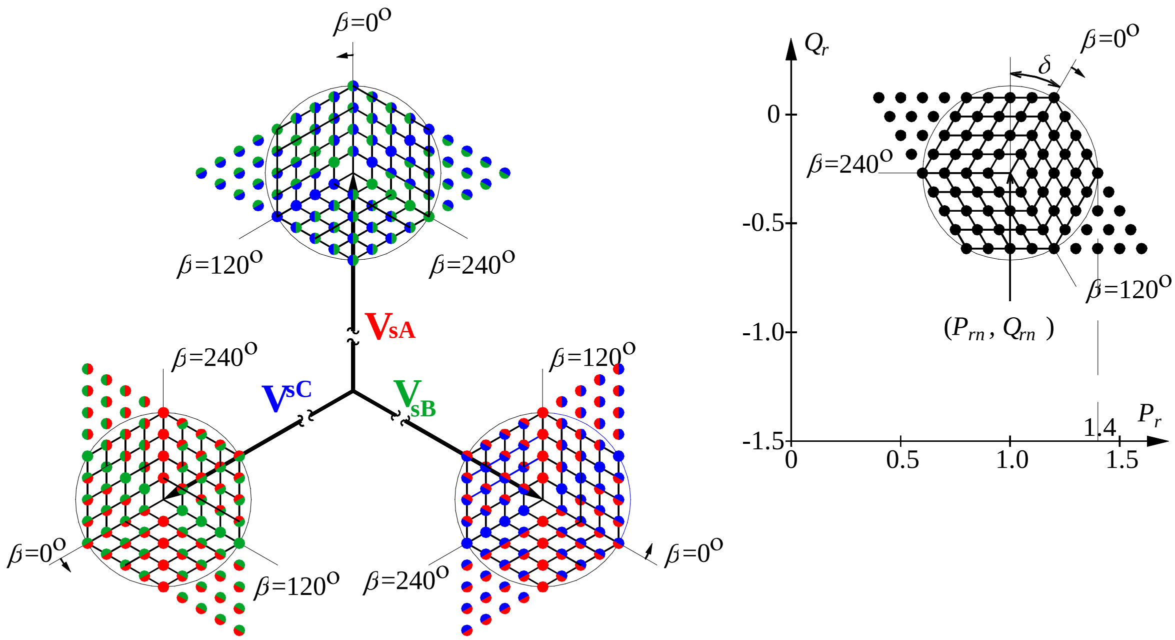


Fig. 26. An ST configuration with three secondary windings in a two-transformer design: ±B and ±C secondary voltages for injection in A phase, ±C and ±A secondary voltages for injection in B phase and ±A and ±B secondary voltages for injection in C phase.



(a) (b)

Fig. 27. Operating points of Sen Transformer in Option 3: modified sending-end voltage (a) and active and reactive power flows at the receiving end (b).

Each of these alternate configurations must be studied further for its merits and demerits to select the best power flow controller that meets the needs of the utilities worldwide.

Summary

A Sen Transformer has been modeled using an ATP version of the EMTP simulation package. The ST connects a compensating voltage in series with a transmission line to modify the magnitude and phase angle of the line voltage so that an independent active and reactive power flow can be achieved. The ST model has been operated by selecting the load tap changer (LTC) positions in an open loop manner. The operation of the model is verified while the model is connected to a simple power system network that can easily be upgraded to a particular utility's more representative power system network.

Also presented in this article are some new topologies of ST using two-transformer designs, which may be considered when a final topology is selected, based on functional requirements and the need for the most cost-effective solution

Appendix

```
BEGIN NEW DATA CASE
C File Name: SENTRAN1.DAT
C A TWO-GENERATOR, SINGLE-LINE POWER SYSTEM NETWORK WITH A SEN TRANSFORMER
C 00000001111111111222222222233333333334444444444555555555566666666667777777778
C 34567890123456789012345678901234567890123456789012345678901234567890123456789 0
C ----dt<---tmax<---Xopt<---Copt<--Toler<        ><        >
16.666-6150.00-3
C 00000001111111111222222222233333333334444444444555555555566666666667777777778
C 34567890123456789012345678901234567890123456789012345678901234567890123456789 0
C -Iprnt<--Iplot<-Idoubl<-KssOut<-MaxOut<        ><        ><---Icat<-Nenerg
      20      10                                                      1
TACS HYBRID
99TWOPI    = 2.0 * PI
```

```
C BASE VOLTAGE, CURRENT, AND POWER
99Vbase   = 112676.528
99Ibase   = 946.662704
99Zbase   = Vbase / Ibase
99Pbase   = Vbase * Ibase
90BUS01A
90BUS01B
90BUS01C
90BUS02A
90BUS02B
90BUS02C
90VRA
90VRB
90VRC
91VSPA
91VSPB
91VSPC
C 00000001111111111222222222233333333334444444444555555555566666666667777777778
C 34567890123456789012345678901234567890123456789012345678901234567890123456789O
C BUS01 VOLTAGE COMPUTATION
99v1apu   = BUS01A / Vbase
99v1bpu   = BUS01B / Vbase
99v1cpu   = BUS01C / Vbase
99v1pu    = SQRT((v1apu * v1apu + v1bpu * v1bpu + v1cpu * v1cpu) * 2 / 3)
C BUS02 VOLTAGE COMPUTATION
99v2apu   = BUS02A / Vbase
99v2bpu   = BUS02B / Vbase
99v2cpu   = BUS02C / Vbase
99v2pu    = SQRT((v2apu * v2apu + v2bpu * v2bpu + v2cpu * v2cpu) * 2 / 3)
C RECEIVING-END VOLTAGE COMPUTATION
99vrapu   = VRA / Vbase
99vrbpu   = VRB / Vbase
99vrcpu   = VRC / Vbase
99vrpu    = SQRT((vrapu * vrapu + vrbpu * vrbpu + vrcpu * vrcpu) * 2 / 3)
C LINE CURRENT COMPUTATION AT Vs' BUS
99iapu    = VSPA / Ibase
99ibpu    = VSPB / Ibase
99icpu    = VSPC / Ibase
99ipu     = SQRT((iapu * iapu + ibpu * ibpu + icpu * icpu) * 2/3)
C SERIES-CONNECTED VOLTAGE COMPUTATION
99v12apu  = v1apu - v2apu
99v12bpu  = v1bpu - v2bpu
99v12cpu  = v1cpu - v2cpu
99v12pu   = SQRT((v12apu * v12apu + v12bpu * v12bpu + v12cpu * v12cpu) * 2 / 3)
C TACS OUTPUT
33v1pu  v12pu
C 00000001111111111222222222233333333334444444444555555555566666666667777777778
C 34567890123456789012345678901234567890123456789012345678901234567890123456789O
C RECEIVING-END POWER COMPUTATION
99Prpu    = (vrapu*iapu + vrbpu*ibpu + vrcpu*icpu) / 1.5
99Qrpu    = (vrapu*icpu - vrcpu*iapu) * SQRT(3) / 1.5
C TACS OUTPUT
33Prpu  Qrpu
BLANK RECORD ENDING TACS
C 00000001111111111222222222233333333334444444444555555555566666666667777777778
C 34567890123456789012345678901234567890123456789012345678901234567890123456789O
```

```
C ------SERIES COMPENSATING TRANSFORMER FOR PHASE A------
C TRANSFORMER <--Refxxxxxx<--Iss<--Phi<-Name<-Rmag<----------------------------O
  TRANSFORMER                         SRSTRA
C NEXT LINE (9999 IN COLUMNS 13-16) INDICATES A LINEAR TRANSFORMER
            9999
C <---Nodes--><----------><-Ohms<---mH<---kV
C <-Bus1<-Bus2<----------><---Rk<---Lk<Volt|---------------------------------->O
 1BUS01A                  1.0E-61.0E-6   1.0
 2A1HEADA1TAIL            1.0E-61.0E-61.0E-6
 3A2HEADA2TAIL            1.0E-61.0E-61.0E-6
 4A3HEADA3TAIL            1.0E-61.0E-61.0E-6
C 00000001111111111222222222233333333334444444444555555555566666666667777777778
C 34567890123456789012345678901234567890123456789012345678901234567890123456789 0
C <-Bus1<-Bus2<-Bus3<-Bus4<----R<----L<----C                                   V
  A1HEADBUS02A            1.0E-6
  A2HEADBUS02B            1.0E-6
  A3HEADBUS02C            1.0E-6
C ------SERIES COMPENSATING TRANSFORMER FOR PHASE B------
  TRANSFORMER                         SRSTRB
            9999
 1BUS01B                  1.0E-61.0E-6   1.0
 2B1HEADB1TAIL            1.0E-61.0E-61.0E-6
 3B2HEADB2TAIL            1.0E-61.0E-61.0E-6
 4B3HEADB3TAIL            1.0E-61.0E-61.0E-6
C 00000001111111111222222222233333333334444444444555555555566666666667777777778
C 345678901234567890123456789012345678901234567890123456789012345678901234567890
C <-Bus1<-Bus2<-Bus3<-Bus4<----R<----L<----C                                   V
  B1HEADA1TAIL            1.0E-6
  B2HEADA2TAIL            1.0E-6
  B3HEADA3TAIL            1.0E-6
C ------SERIES COMPENSATING TRANSFORMER FOR PHASE C------
  TRANSFORMER                         SRSTRC
            9999
 1BUS01C                  1.0E-61.0E-6   1.0
 2C1HEADC1TAIL            1.0E-61.0E-61.0E-6
 3C2HEADC2TAIL            1.0E-61.0E-61.0E-6
 4C3HEADC3TAIL            1.0E-61.0E-61.0E-6
C 00000001111111111222222222233333333334444444444555555555566666666667777777778
C 345678901234567890123456789012345678901234567890123456789012345678901234567890
C <-Bus1<-Bus2<-Bus3<-Bus4<----R<----L<----C                                   V
  C1HEADB1TAIL            1.0E-6
  C2HEADB2TAIL            1.0E-6
  C3HEADB3TAIL            1.0E-6
C 00000001111111111222222222233333333334444444444555555555566666666667777777778
C 345678901234567890123456789012345678901234567890123456789012345678901234567890
C <-Bus1<-Bus2<-Bus3<-Bus4<----R<----L<----C                                   V
  C1TAILBUS01A            1.0E-6
  C2TAILBUS01B            1.0E-6
  C3TAILBUS01C            1.0E-6
C 00000001111111111222222222233333333334444444444555555555566666666667777777778
C 345678901234567890123456789012345678901234567890123456789012345678901234567890
C <-Bus1<-Bus2<-Bus3<-Bus4<----R<----L<----C                                   V
  VSRCA BUS01A            1.0053 19.73
  VSRCB BUS01BVSRCA BUS01A
  VSRCC BUS01CVSRCA BUS01A
  VSPA  VRA               3.0159 59.19
```

```
  VSPB  VRB   VSPA  VRA
  VSPC  VRC   VSPA  VRA
BLANK RECORD ENDING BRANCHES
C 00000001111111111222222222233333333334444444444555555555566666666667777777778
C 34567890123456789012345678901234567890123456789012345678901234567890123456789 0
C <-Bus1<-Bus2<---Tclose<----Topen<-------Ie<----Flash<--Request<-----Target<--O
  BUS02AVSPA                                                  MEASURING
  BUS02BVSPB                                                  MEASURING
  BUS02CVSPC                                                  MEASURING
BLANK RECORD ENDING SWITCHES
C 00000001111111111222222222233333333334444444444555555555566666666667777777778
C 34567890123456789012345678901234567890123456789012345678901234567890123456789 0
C <--Bus<I<-----Ampl<-----Freq<----Phase<-------A1<------T1><---Tstart<----Tstop
14VSRCA    112676.528     60.00      0.00                          -1.0
14VSRCB    112676.528     60.00   -120.00                          -1.0
14VSRCC    112676.528     60.00    120.00                          -1.0
14VRA      112676.528     60.00    -20.00                          -1.0
14VRB      112676.528     60.00   -140.00                          -1.0
14VRC      112676.528     60.00    100.00                          -1.0
BLANK RECORD ENDING SOURCES
BLANK RECORD ENDING NODE VOLTAGE OUTPUT
BLANK RECORD ENDING PLOT
```

References

1. "Power Flow Model of Sen Transformer for Loadability Enhancement and Comparison with UPFC in Hybrid Electricity Markets" by K. Ashwani and W. Gao, Electric Power Components and Systems, vol.37, no. 2, pp. 189-209, Feb. 2012.
2. "Introduction to FACTS Controllers: Theory, Modeling, and Applications" by K. K. Sen and M. L. Sen, IEEE Press and John Wiley & Sons, 2009.
3. "Transient Modeling and Protection of Sen Transformer" by D. Fentie, M.S. Thesis, University of Saskatchewan, 2010.
4. "EMT Model of the 'Sen Transformer' for Fault Analysis Studies" by D. Fentie, J. C. Garcia, R. Gokaraju and S. O. Faried, International Conference on Power Systems Transients (IPST 2015), Cavtat, Croatia, Jun. 2015.
5. "A tap-changing algorithm for the implementation of Sen transformer" by M. O. Faruque and V. Dinavahi, IEEE Trans. on Power Delivery, vol. 22, no. 3, pp. 1750-1757, July 2007.
6. "Detailed real-time transient model of Sen transformer" by B. Asghari, M. O. Faruque and V. Dinavahi, IEEE Trans. on Power Delivery, vol. 23, no. 3, pp. 1513-1521, July 2008.
7. "AEP unified power flow controller performance" by B. A. Renz, A. Keri, A. S. Mehraban, C. Schauder, E. Stacey, L. Kovalsky, L. Gyugyi, and A-A. Edris, IEEE Trans. on Power Delivery, vol. 14, no. 4, pp. 1374-1381, Oct. 1999.
8. "Introducing the SMART Power Flow Controllers - an Integral Part of Smart Grid" by M. L. Sen and K. K. Sen, paper #103, 2012 Electrical Power and Energy Conference, London, Canada.
9. "SMART Power Flow Controller for Smarter Grid Applications" by K. K. Sen and M. L. Sen, paper no. 15PESGM1910, IEEE PES General Meeting, July 2015, Denver, USA.
10. "Phase Angle Regulation Versus Impedance Regulation: Which Offers Greater Control Of Power Flow On the Grid?" by K. K. Sen and M. L. Sen, How2Power Today, February 2017 issue, [Online]. Accessed on September 2, 2017.
11. "Unique Capabilities of Sen Transformer: a Power Flow Regulating Transformer" by K. K. Sen & M. L. Sen, IEEE Power & Energy Society General Meeting, paper no. 16PESGM0961, July 2016, Boston, USA.

About The Authors

Currently the chief technology officer of Sen Engineering Solutions, Kalyan K. Sen has spent 31 years in academia and industry. Sen who was selected to be a Westinghouse Fellow Engineer, was a key member of the FACTS development team at the Westinghouse Science & Technology Center in Pittsburgh. He contributed in all aspects (conception, simulation, design, and commissioning) of FACTS projects at Westinghouse. Sen conceived some of the basic concepts in FACTS technology. He has authored over 25 publications, eight issued patents, one book and four book chapters in the areas of FACTS and power electronics. He is a licensed Professional Engineer in the Commonwealth of Pennsylvania.

Sen received BEE, MSEE, and PhD degrees in electrical engineering, from Jadavpur University, Tuskegee University, and Worcester Polytechnic Institute, respectively. In addition, he received an MBA from Robert Morris University. A senior member of IEEE, Sen has served the organization in many positions. Under his leadership, IEEE Pittsburgh Section and its three chapters (PES, IAS and PELS) received Best Section and Chapter Awards. His other past positions include Editor of the IEEE Transactions on Power Delivery *(2002 – 2007), the Technical Program Chair of the 2008 PES General Meeting in Pittsburgh, Chapters/Sections Activities Track Chair for the 2008 IEEE Section Congress, Quebec City, Power & Energy Society Region 2 Representative (2010, 2011) and Member of IEEE Center for Leadership Excellence (CLE) Committee (2013, 2014). He has been serving as an IEEE Distinguished Lecturer since 2002. In that capacity, he has given presentations on power flow control technology more than 100 times in 15 countries. He is an inaugural class (2013) graduate of the IEEE CLE Volunteer Leadership Training (VOLT) program. Sen is the recepient of the IEEE Pittsburgh Section PES Outstanding Engineer Award (2004) and Outstanding Volunteer Service Award for reviving the local chapters of PES and IAS from inactivity to world-class performance (2004). He has been serving as the Special Events Coordinator of the IEEE Pittsburgh Section for the last decade. He is the Regions 1-3 & 7 Coordinator of Power Electronics Society. He is also serving as the Chair of Society on Social Implications of Technology in IEEE Pittsburgh Section. He has served as a Fulbright Scholar (sponsored by U.S. Government) and a GIAN Scholar (sponsored by Government of India). He is a Distinguished Toastmaster who led District 13 of Toastmasters International as its Governor to be the 10th-ranking District in the world in 2007-8.*

Currently the President of Sen Engineering Solutions, Mey Ling Sen has spent over 15 years in industry. She worked as an Engineering Consultant at Westinghouse and ABB. She is the co-inventor of the Sen Transformer—a SMART Power Flow Controller that is based on functional requirements and the most cost-effective power flow control solution. She is the coauthor of the book titled, Introduction to FACTS Controllers: Theory, Modeling, and Applications*, IEEE Press and John Wiley & Sons, Inc. 2009, which is also published in Chinese and English paperback editions in China and India, respectively.*

Sen received BSEE and MEE degrees in electrical engineering, from Worcester Polytechnic Institute and Rice University, respectively. A member of IEEE, Sen has served the organization in many positions. Under her leadership, IEEE Pittsburgh Section PES and IAS Chapters received Best Chapter Awards. She also served as the Section Treasurer and Co-Chair of Women In Engineering affinity group and Vice Chair of Pittsburgh Power Electronics Chapter. She led her Club and Area to win the President's Distinguished Awards from Toastmasters International in 2006-8. Currently, she is serving as the Chair of Women In Engineering affinity group in IEEE Pittsburgh Section.