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Installation of a Sen Transformer in a Loop Distribution System for Line Loss Minimization by Loop Current Elimination

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ABSTRACT

A loop distribution system is mostly preferred in the distribution network rather than the radial one for reliable power and satisfaction of the customers with comparably less power loss. This paper proposes a method to achieve line loss minimization by installing a "Sen" Transformer (ST) in a loop distribution system. An ST works as a series voltage regulator or impedance regulator in the loop distribution system to address power quality issues with better economic impact by inserting the compensating voltage or virtual impedance in the line. In the present work, the use of an ST is proposed in the loop distribution system with two different control schemes for balanced power flow with a reduction in line loss. The total minimization in line loss can be obtained if the summation of the all voltage drop across the line inductor in the loop distribution system tends to be zero. The total reduction in line loss can be realized by installing the ST in the line that eliminates the circulating current by injecting the compensating voltage. Validation of the present work has been done by the simulating loop distribution system with an ST and the loop current is eliminated to address the line loss minimization problem with two different control schemes, line voltage compensation scheme (LVCS) and line inductance compensation scheme (LICS).
Keywords: Compensating voltage, distribution system, loop current flow, power loss, sen transformer

Introduction

Distribution losses are one of the important aspects of any power system. Saving energy saving is a major concern for power engineers, and effective measures need to be taken to reduce distribution losses in the existing system with cost-effective modifications [1, 2].

Two typical types of distribution systems—radial and loop—are in use. A radial system is a simpler protective system with avoidable complications compared to a loop distribution system. However, the main disadvantage of a radial system is that when a fault occurs at the top end, the whole line is affected and it gets isolated from the power system. To avoid this problem, a loop distribution system is preferred in the distribution grid for effective operation. In [3], Ryuta Saino proposed power flow estimation and the control scheme of a unified power flow controller (UPFC) for line loss minimization. A voltage-source-converter-based UPFC can provide a fast, dynamic response to regulate the line voltage and the power flow in the line. The realization of line loss reduction was done by eliminating circulating current in loop distribution lines with the help of UPFC; here UPFC has been used as a series voltage regulator. For line loss minimization, the voltage drop across the line must be compensated. Hence, line current estimation is required to eliminate the circulating current in the loop distribution line. In [4], line loss minimization and voltage regulation have been achieved by M. A. Sayed with the UPFC in loop distribution line. Zhang Zhi-Hua has presented an optimal power flow control method with minimum capacity of the UPFC. Power limitation and node voltage deviation are considered for both sides of feeders. The simulation results validate the proposed method by solving the optimization target function with the help of the global optimization method [5]. In [6], the UPFC is put in a loop distribution system where it works as a series compensator to control power flow in the loop lines to get power loss reduction. The elimination of loop current is possible only if the total reactance voltage drop of the loop system becomes equal to zero. The high penetration of renewable energy sources in the distribution network

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leads to many challenges. The UPFC is used by P. Song [7] for line loss minimization with high constrained insecurity in the distribution system. The voltage fluctuation and overload in the distribution feeder is raised with varying renewable energy generation. Along with reduced line loss, optimal security enhancement is proposed. An IEEE 33 bus test distribution feeder is considered to verify application of the UPFC to reduce line loss with security enhancement strategies.

A Sen transformer (ST) was introduced by K. K. Sen as a set of power flow controlling transformer, in which the traditional technology of a transformer and on-load tap changers is used with the voltage regulation capability with less cost than UPFC. The response time in ST is comparatively slow than in the power electronics-based controller, but it is not adequate in normal utility. In an ac transmission line, independent power flow of real power and reactive power can be realized through the ST by connecting in series with the line. The Sen Transformer has the capability to inject a compensating voltage that can emulate positive and negative resistance as well as an inductance in the line [8-10]. In this paper, loss minimization was achieved by Sen Transformer by eliminating the loop current. The ST can change the power flow in the loop distribution system by varying impedance of that line. The loop current elimination has been realized by ST to minimize total line loss by following two conditions; (i) To make the R/L ratio of all lines in the loop system the same. (ii) The reactance voltage drop in all lines in the loop system is zero.

The formulation of the above conditions has been described in the presented work. Validation of work has been done by simulating a loop distribution system with ST, and elimination of loop current is achieved to address line loss minimization problem.

In Section 2, the loop distribution model and the loop system with ST installation are explained. The formulation of line current equations, line loss equations, and loop current equations are mentioned. In Section 3, the basics of ST with its phasor diagram are described. In Section 4, the two different control scheme of compensation is presented, (i) line inductance compensation scheme and (ii) line voltage compensation scheme with the mathematical formulation. Section 5 presents the simulation results of the radial and loop distribution system with and without the installation of ST for both control schemes.

Loop Distribution System with ST

The simple model of a single-phase loop distribution system is shown in Figure 1. The reactance diagram of the simplified loop distribution system is presented here. It consists of four distribution lines, which are having an impedance of Z_1, Z_2, Z_3, and Z_4 respectively. Here consider that impedances of four lines are $Z_1 = R_1 + j\omega L_1$, $Z_2 = R_2 + j\omega L_2$, $Z_3 = R_3 + j\omega L_3$, and $Z_4 = R_4 + j\omega L_4$ respectively. The illustrated loop distribution system is fed from one side through a substation, i.e., by substation voltage V_s and three different loads Z_{L1}, Z_{L2}, and Z_{L3} are taken out at
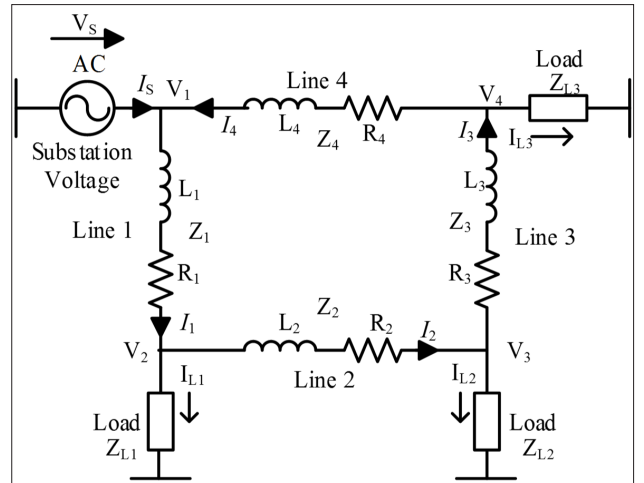
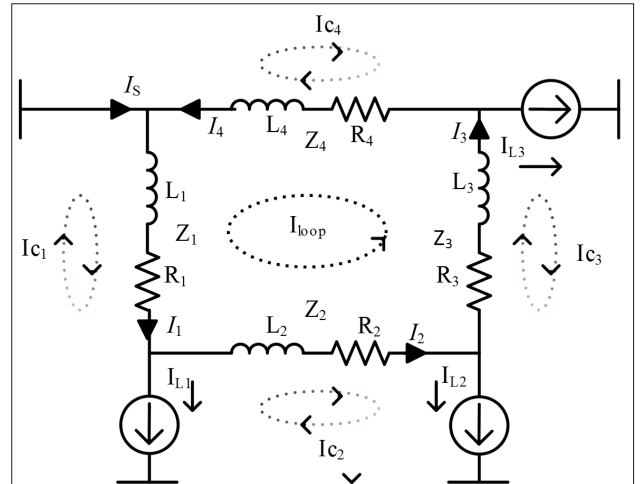

Figure 1. Loop distribution system model

Figure 2. Equivalent circuit of the loop distribution model for line loss minimization

three different points, as shown in Figure 1. Figure 2 shows the equivalent circuit of the loop distribution model for Figure 1. In that, the load currents I_{L1}, I_{L2}, and I_{L3} are considered as constant current sources.

Line Current Equations

In general, the flow of current in each line can be observed from the Figure 1. Using the superposition theorem, the line currents I_i (where i = 1, 2, 3, 4) is given by,

$$I_1 = \frac{(Z_2 + Z_3 + Z_4)I_{L1} + (Z_3 + Z_4)I_{L2} + Z_4 I_{L3}}{Z_{loop}}$$

$$I_2 = \frac{-Z_1 I_{L1} + (Z_3 + Z_4)I_{L2} + Z_4 I_{L3}}{Z_{loop}}$$

$$I_3 = \frac{-Z_1 I_{L1} - (Z_1 + Z_2)I_{L2} + Z_4 I_{L3}}{Z_{loop}}$$

$$I_4 = \frac{-Z_1 I_{L1} - (Z_1 + Z_2)I_{L2} - (Z_1 + Z_2 + Z_3)I_{L3}}{Z_{loop}}$$

(1)

Here,

$$Z_{loop} = \sum_{i=1}^{4} Z_i \qquad (2)$$

Based on current I_1, the other line current can also be formulated as follows:

$$I_2 = I_1 - I_{L1}$$
$$I_3 = I_1 - (I_{L1} + I_{L2}) \qquad (3)$$
$$I_4 = I_1 - (I_{L1} + I_{L2} + I_{L3})$$

Power Loss Equations
The total line loss P_l is given by,

$$P_l = \sum_{i=1}^{4} |I_i|^2 R_i \qquad (4)$$

$$P_l = \sum_{i=1}^{4} |I_{Ci}|^2 R_i + 2 \left\{ \sum_{i=1}^{4} |I_{Ci}|^2 R_i \right\} I_{loop} + |I_{loop}|^2 R_{loop} \qquad (5)$$

Here,

$$R_{loop} = \sum_{i=1}^{4} R_i \qquad (5\text{-}a)$$

The line current is the summation of closing current I_{Ci} and circulating loop current I_{loop}, as explained in the next section. In equation (5), the first term shows load currents I_{L1}, I_{L2}, and I_{L3} and line resistances R_1, R_2, R_3, and R_4; the first term can be considered as a constant term for the load, as given in equation (7). The second term is derived as a zero by the circuit analysis, as shown in Figure 3. Therefore, total line loss P_l can be minimized by the circulating current I_{loop} equating to zero.

$$P_{l\min} = \sum_{i=1}^{4} |I_{Ci}|^2 R_i \qquad (6)$$

Here, I_{Ci} = closing current

Under the loss minimization condition, with the help of an analytical model of loop distribution system expressed with
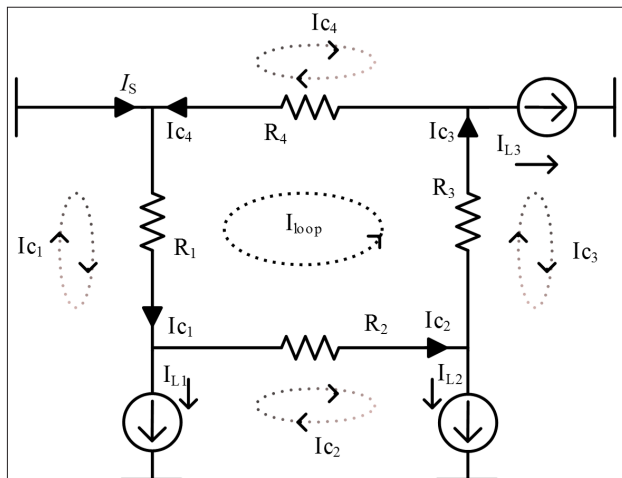

Figure 3. Analytical model of the loop distribution system expressed resistances and load currents

resistances and load currents as shown in Figure 3, the line currents can be formulated as follows which is known as a closing current:

$$I_{C1} = \frac{(R_2 + R_3 + R_4)I_{L1} + (R_3 + R_4)I_{L2} + R_4 I_{L3}}{R_{loop}}$$
$$I_{C2} = \frac{-R_1 I_{L1} + (R_3 + R_4)I_{L2} + R_4 I_{L3}}{R_{loop}}$$
$$I_{C3} = \frac{-R_1 I_{L1} - (R_1 + R_2)I_{L2} + R_4 I_{L3}}{R_{loop}} \qquad (7)$$
$$I_{C4} = \frac{-R_1 I_{L1} - (R_1 + R_2)I_{L2} - (R_1 + R_2 + R_3)I_{L3}}{R_{loop}}$$

The closing current I_{Ci} are expressed by line resistances R_i and load currents I_{L1}, I_{L2}, and I_{L3} as shown in Figure 3.

Hence, closing currents I_{Ci} can be calculated by the circuit without sending the end voltage and line reactance. Here, I_{Ci} is also known as the line current that passes in the loop distribution system, while achieving total line loss minimization.

Loop Current Equations
In the loop distribution line, based on the line loss minimization theory, the line current I_i is the summation of closing current I_{Ci} and loop current I_{loop} as illustrated in Figure 2. Hence, the equation of line current can be given by,

$$I_i = I_{Ci} + I_{loop} \qquad (8)$$

The circulating current I_{loop} is derived from equations (1) and (8) as,

$$I_{loop} = -\frac{1}{Z_{loop}} \sum_{i=1}^{4} Z_i I_{Ci} \qquad (9)$$

The circulating current I_{loop} is obtained from equations (7), (8), and (9),

$$I_{loop} = -\frac{1}{R_{loop}} \sum_{i=1}^{4} j\omega L_i I_i \qquad (10)$$

In that, the summation of the voltage across line inductors is in the numerator and total line resistances R_{loop} in the denominator, it can be concluded that the circulating current flows in the system are due to self-inductance effect of the feeder or distribution line inductors.

Sen Transformer

A Sen Transformer is an impedance-regulating transformer that can emulate positive and negative resistances and inductance in a line. An ST consists of one unit that contents shunt connected primary and series-connected secondary. As shown in Figure 4 (only one phase is shown), three primary windings and nine secondary windings are known as an exciting winding and compensating windings respectively [11-13]. The series-connected compensating winding acts as a controlled voltage source, which can inject voltage in line with variable magnitude and angle by changing tappings of secondary windings. Generally compensating winding can exchange active and reactive power while in use. The main function of ex-
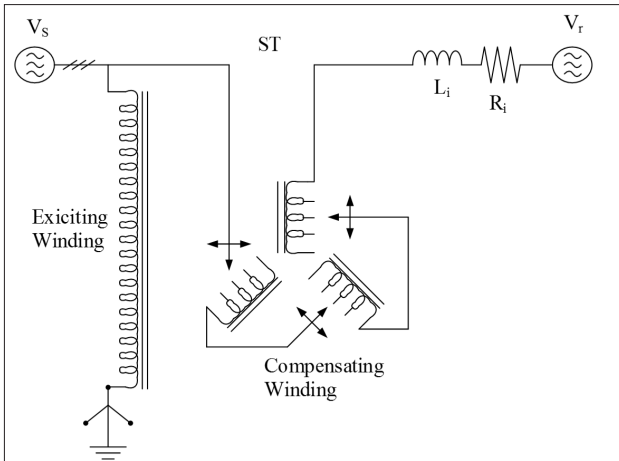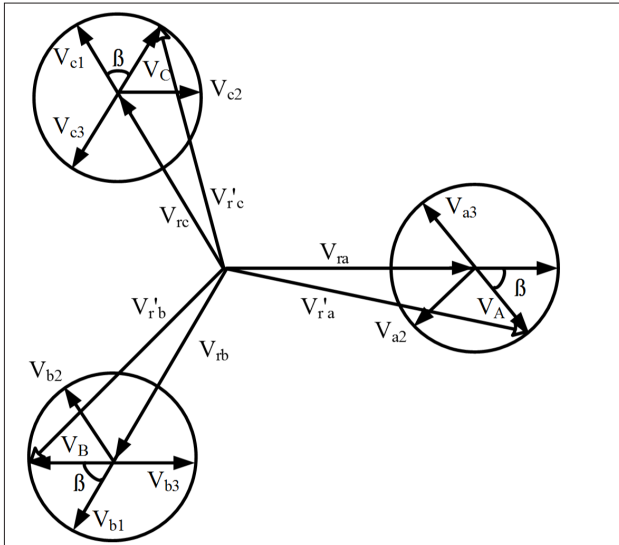
Figure 4. Configuration of ST

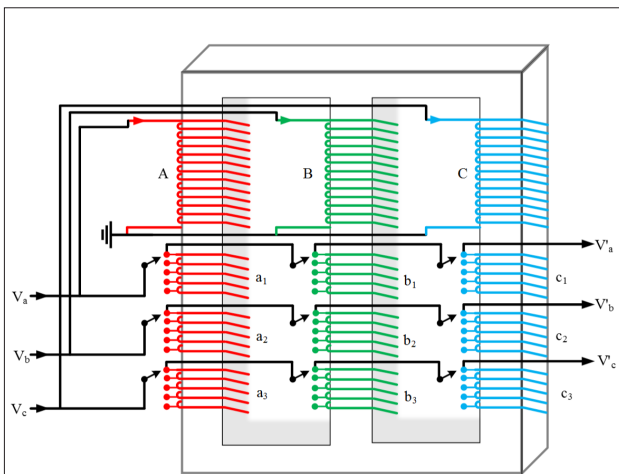**Figure 5.** Phasor diagram of ST

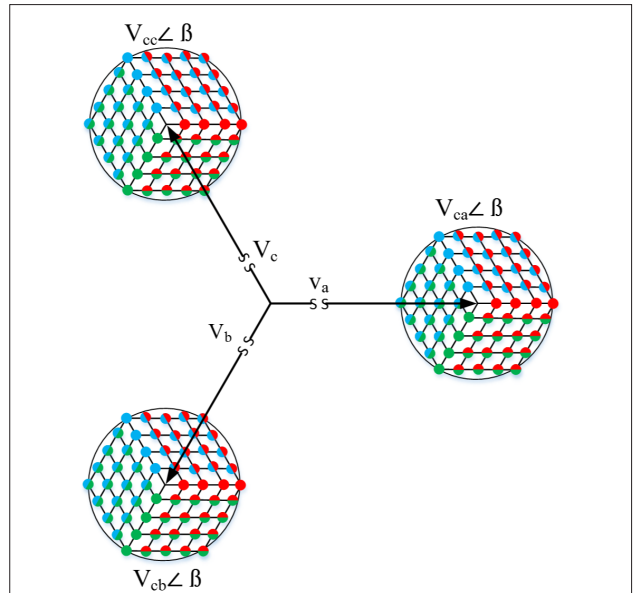**Figure 6.** Structure diagram of ST

Figure 7. Operating point of ST

citing winding is to provide the required excitation to the compensating winding from the source to meet real power needed to compensating winding and to control the reactive power in the system. The performance of ST is compared with UPFC in detail [14-17]. The hybrid of UPFC and ST gives better results with salient features of least cost and fast response, as small scale UPFC and large-scale ST combination works as a hybrid unified power flow controller in transmission line. [18-20]. Here, the ST is introduced for loss minimization in the loop distribution system and becomes a cost-effective solution in comparison with the power electronics-based controller.

The phasor diagram of ST is illustrated in Figure 5, in that V_{ra}, V_{rb}, and V_{rc} are the reference voltages; V_{ca}, V_{cb}, and V_{cc} are the compensating voltages of all three phases a, b, and c respectively. Here, V_{a1} to V_{a3}, V_{b1} to V_{b3}, and V_{c1} to V_{c3} are ST compensating winding voltages [11]. The structure of ST is shown in Figure 6; three primary windings named A, B, and C; with nine secondary windings a_1, a_2, a_3; b_1, b_2, b_3; and c_1, c_2, c_3 wound on three different limbs. Each secondary winding has four tappings on it and combinations of these make compensating voltage having magnitude V_c and angle ß. The operating points of ST are illustrated in Figure 7 for each phase. A total of 60 compensating points is there for the mentioned structure of ST, which depends upon the number of tappings. In this work, the main function of ST is to control power flow in the line to minimize the total line loss in the loop distribution system. The power loss reduction is small in the mentioned system; however, it may vary based on line impedances. It is also verified that with different ratings of the loop distribution system the losses are accountable. The ST is having low installation and operating costs with minimum maintenance and losses. The losses occur in ST <1% in the mentioned system and the cost of it is 15–20$/KVA [9]. In addition, voltage

regulating transformer (VRT) and phase angle regulator (PAR) can change only one parameter of the distribution line. However, ST provides the combined effect of VRT and PAR in a single unit to regulate voltage as well as it can independently change active and reactive power.

Control Scheme

In the loop distribution system, to achieve the conditions of line loss minimization as shown in equation (11), two control schemes are proposed here; one is the line inductance compensation scheme and another is the line voltage compensation scheme.

$$\frac{R_1}{L_1} = \frac{R_2}{L_2} = \frac{R_3}{L_3} = \frac{R_4}{L_4} \qquad (11)$$

According to system line parameters, the control scheme should be applied. The detailed explanation of the control schemes is as follows.

Line Inductance Compensation Scheme

In the loop distribution system, if only one line has a different resistance-to-inductance ratio, the line inductance compensation scheme can be applied. The following condition as per equation (12) must be fulfilled for the present compensation scheme.

$$\frac{R_2}{L_2} \neq \frac{R_1}{L_1} = \frac{R_3}{L_3} = \frac{R_4}{L_4} \qquad (12)$$

The ST can insert compensating inductance L_c in the line, which is having a different R/L ratio (i.e., line 2 in the present case) to make all R/L ratio of loop line equal. The formulation of L_c is as follows:

$$\frac{R_1}{L_1} = \frac{R_2}{L_2 + L_c} = \frac{R_3}{L_3} = \frac{R_4}{L_4} \qquad (13)$$

$$L_c = \frac{R_2 L_1}{R_1} - L_2 \qquad (14)$$

The inserted compensating inductance value can be positive or negative, which is based on loop distribution line parameters. To insert a particular value of inductance in the line, the reference voltage of ST can be formulated in form of compensating voltage V_c in a steady-state condition. As line 2 has a different R/L ratio, the expression can be formulated as follows:

$$V_C = -j\omega L_c I_2 \qquad (15)$$

To get a quick response, the equation of compensating voltage V_c can be formulated in the form of differential voltage in the transient state as follows:

$$V_C = -L_C \frac{di_2}{dt} \qquad (16)$$

Line Voltage Compensation Scheme

In the loop distribution system, if more than one line has a different resistance-to-inductance ratio, the line voltage compensation scheme can be applied. The following condition must be fulfilled for the compensation scheme.

$$\frac{R_1}{L_1} \neq \frac{R_2}{L_2} \neq \frac{R_3}{L_3} \neq \frac{R_4}{L_4} \qquad (17)$$

The ST can insert the compensating voltage, V_c, in the opposite direction; it is the summation of the reactance voltage drop of all the lines having unequal R/L ratio. Compensating voltage can be calculated as follows:

$$-\sum_{i=1}^{4} j\omega L_i I_i + V_c = 0 \qquad (18)$$

$$V_c = \sum_{i=1}^{4} j\omega L_i I_i \qquad (19)$$

To get a quick response, the equation of the compensating voltage, V_c, can be formulated in the form of differential voltage in the transient state,

$$V_c = \sum_{i=1}^{4} L_i \frac{di_i}{dt} \qquad (20)$$

The calculated compensating voltage, V_c, will be provided by ST. Hence, based on the value of V_c, tap has been selected by a predefined program in the controller, and accordingly, switching of the ST secondary winding has to be performed. In general, in both schemes, the value of V_c is calculated by equations
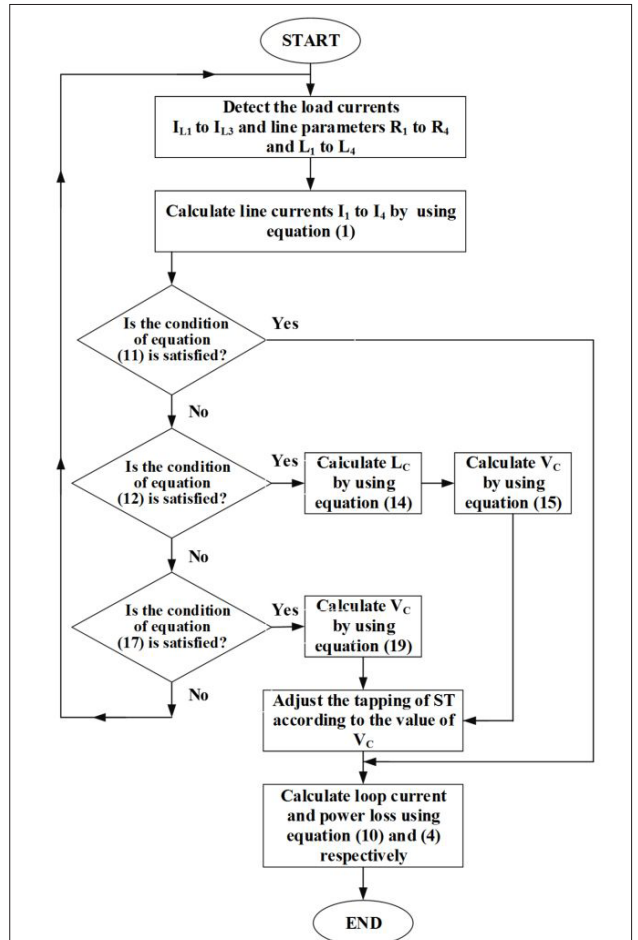

Figure 8. Flow chart for control algorithm

(18), (19), and (20). Hence, total line loss minimization can be realized by installing an ST in the loop distribution line as a series voltage regulator.

Control Algorithm

Here, the control algorithm of the ST is described for both the schemes, line voltage compensation scheme and line voltage compensation scheme. The line current can be calculated from line parameters and load currents. If the R/L ratio of all lines is the same (equation 11) it means that the loop current is zero and power loss is minimum, so there is no need to inject voltage. If the R/L ratio is not the same, either LICS or LVCS is required to calculate V_c and accordingly, ST tapping is to be selected. When the R/L ratio of only one line is different from others (equation 12), the LICS is applied. Injected L_c and V_c are to be calculated using equations 14 and 15, and ST tapping is to be selected accordingly. When the R/L ratio of all the lines are different (equation 17), the LVCS is applied. Injected V_c is to be calculated using equation 19, ST tapping can be selected accordingly.
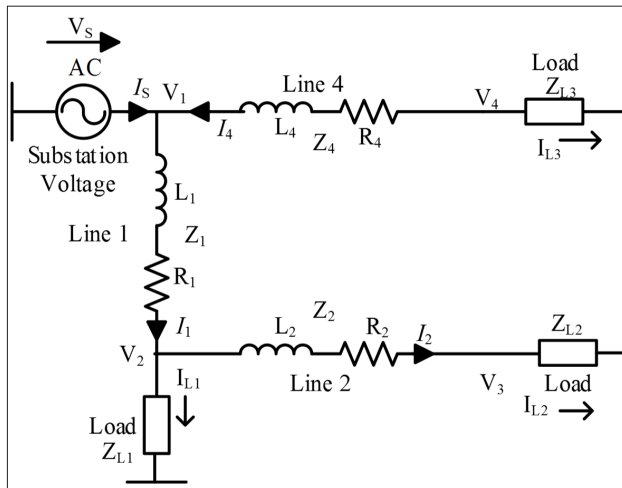

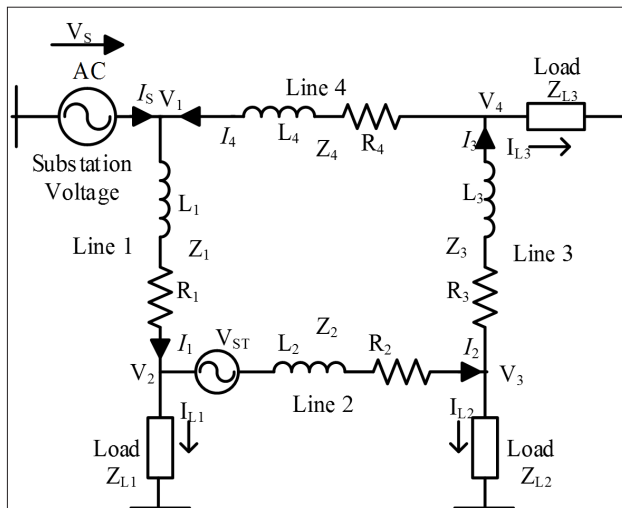**Figure 9.** Radial distribution system model

Figure 10. Loop distribution system model with an ST

Results and Discussion

To validate the proposed work, a 4-bus system has been considered for MATLAB simulation, the parameters are given in Table 1. Radial system and loop systems are simulated for comparative analysis. The line loss minimization has been achieved with the use of ST in line 2 as shown in Figure 9. Here, both the schemes of compensation are described in details with results. A comparison of power loss in the radial distribution system and the loop distribution system is represented without ST and with ST. The operation of ST is realized with both the schemes; line inductance compensation scheme and line voltage compensation scheme.

Radial System

The radial system is simulated, using the system parameter listed in Table (1), as shown in Figure 9. There are only three lines that are simulated to form a radial system. Table (2) presents the readings of line currents, node voltages, and power loss. The power loss is calculated using equation (4), which shows that 54.59 W power loss occurred in the radial system with major variation in node voltage 2 and 3.

Loop System Without an ST

The loop distribution system is simulated using the system parameter tabulated in Table 1. In Figure 10, a loop system is simulated by four distribution lines. Table (2) presents the readings of line currents, node voltages, and power loss. The power loss is calculated by equation (4), which shows that the value of loop current is 0.553 A and 52.7 W power loss occurred in the loop system with allowable variation in all node voltage.

Table 1. Loop system parameters

Parameters	Value
Source voltage	203V,60Hz
Line 1 R1	0.6Ω
Line 1 L1	6mH
Line 2 R2	0.8Ω
Line 2 L2	6mH
Line 3 R3	1.2Ω
Line 3 L3	6mH
Line 4 R4	0.6Ω
Line 4 L4	6mH
Load 1	40 ohm
Load 2	60 ohm
Load 3	80 ohm
ST rating	6 KVA
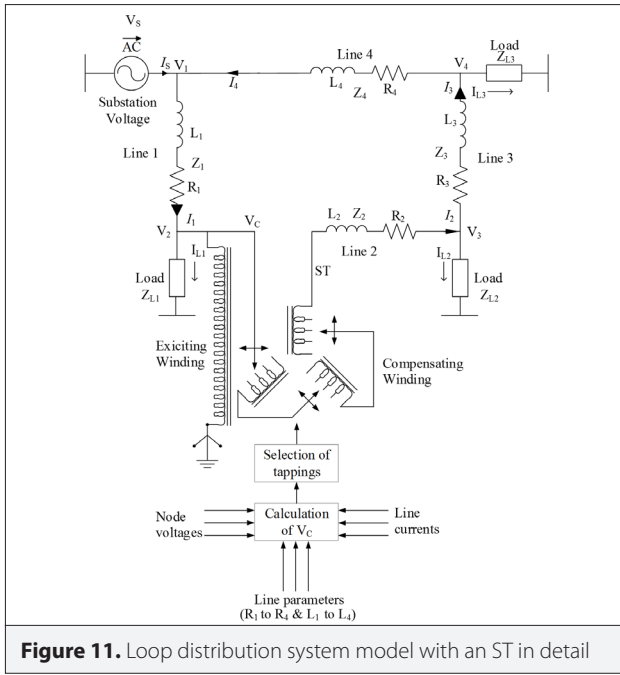
Figure 11. Loop distribution system model with an ST in detail

Figure 12. Results of the LICS without and with installation of ST

Loop System with ST for Line Inductance Compensation Scheme

To achieve total line loss minimization, ST is installed in the loop system as shown in Figure 11. To get loss minimization, the line inductance compensation scheme is applied in the loop system, when only one line has a different R/L ratio as per equation (12). The value of compensating inductance L_c is 2 mH calculated from equations (13) & (14).

Based on the value of L_c, the value of compensating voltage V_c is calculated using equation (15), a 90° phase shift between compensated voltage and current is considered. To insert V_c in series with the line, the tapping of ST secondary winding is to be selected. The waveforms of line currents, loop current, and compensated voltage with and without ST using line inductance compensation scheme are shown in Figure 12. The magnitude of line currents I_1 and I_2 increased, whereas the magnitude of I_3 and I_4 decreased; it proves that the power flow control is possible in the loop system using an ST. By inserting an ST in line 2, the impedance of the lines changes as a result circulating current (loop current) is reduced up to 0.046 A and power loss is minimized up to 49.34 W with 13 V as the compensating voltage. As the impedance of the line changes, the value of loop current decreases as given in equation (10). Hence, the line currents also change. The values of line currents, loop current, node voltages, compensated voltage, and total power loss reductions with line voltage compensation scheme are given in Table 3.

Loop System with an ST for the Line Voltage Compensation Scheme

To achieve total line loss minimization, ST is installed in the loop system as shown in Figure 11. To get loss minimization, the line voltage compensation scheme is applied in a loop sys-
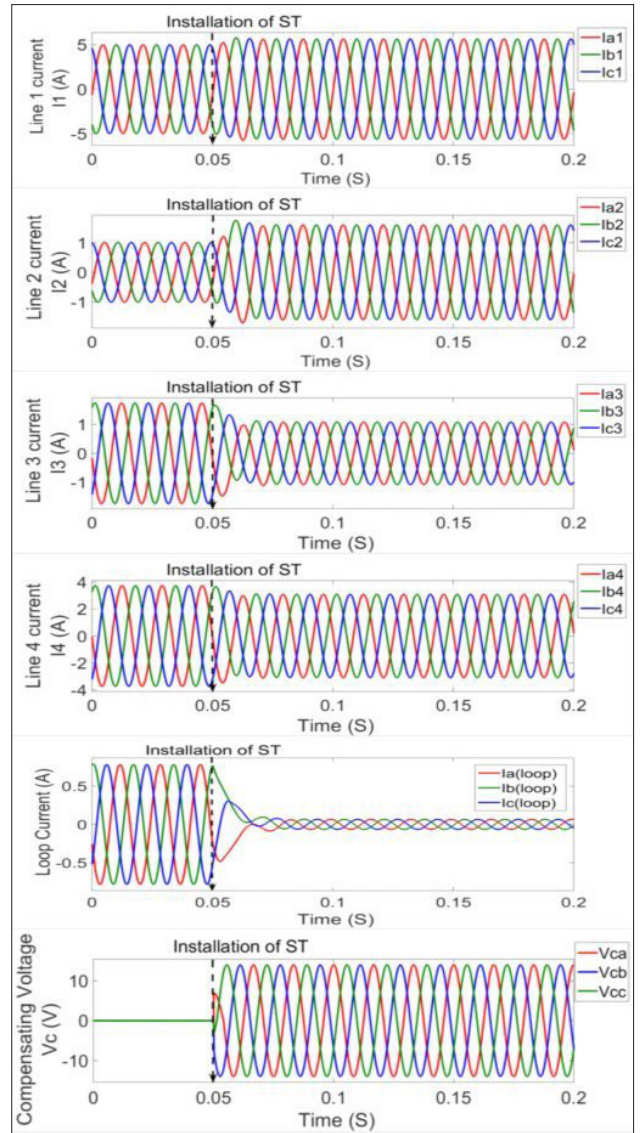
tem, when all lines have a different R/L ratio as per equation (17). The value of compensating voltage V_c is calculated by equations (18) and (19). In Figure 11, the value of V_c has been calculated as follows;

$$V_c = L_1 \frac{di_1}{dt} + L_2 \frac{di_2}{dt} + L_3 \frac{di_3}{dt} + L_4 \frac{di_4}{dt} \qquad (21)$$

In equation (21), all line currents and inductance values are required to calculate compensating voltage V_c. To inject V_c in series with the line, the tapping of ST secondary winding is to be selected. The waveforms of line currents, loop current, and compensated voltage with and without ST using line inductance compensation scheme are shown in Figure 13. The magnitude of line currents I_1 and I_2 have increased whereas the magnitude of I_3 and I_4 have decreased, which proves that power flow control is possible in the loop system using ST. By inserting ST in line 2, the impedance of the lines changes as a
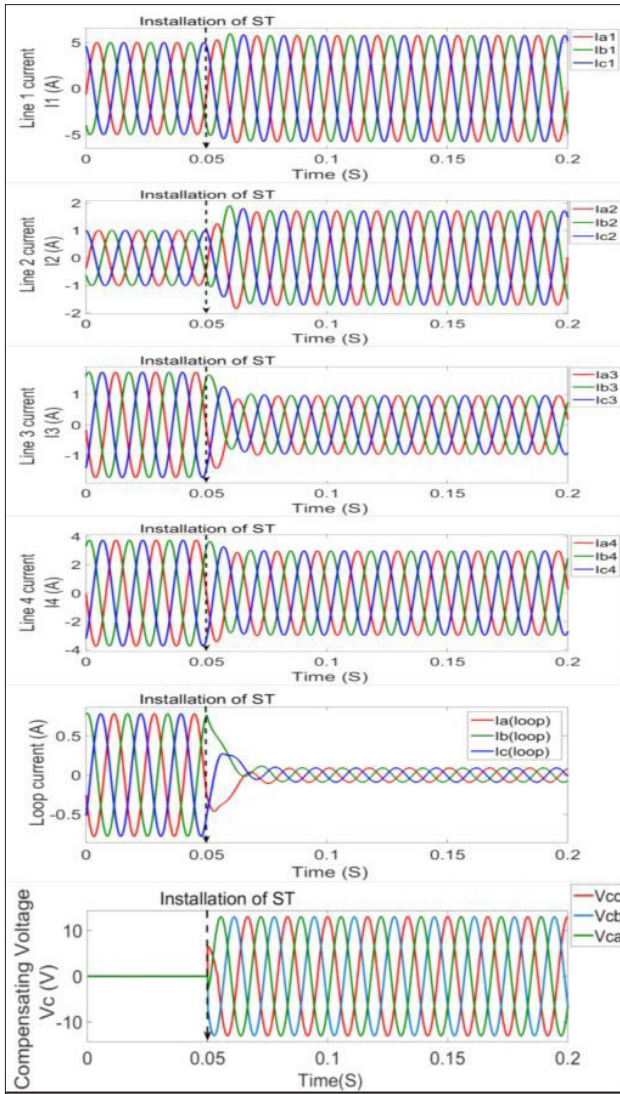
Figure 13. Results of the LVCS without and with installation of ST

Table 2. Results of simulation of the radial and loop system without ST

Parameters	Radial system	Loop system without ST
I1 (A)	4.703	3.54
I2 (A)	1.865	0.712
I3 (A)	-	1.222
I4 (A)	1.442	2.642
Iloop (A)	-	0.553
V1 (V)	202.8	202.8
V2 (V)	196.4	197.5
V3 (V)	193.6	195.7
V4 (V)	199.6	197.5
Vc (V)	-	0
Ploss (W)	54.59	52.7

Table 3. Results of simulation of the loop system with two different control schemes

Parameters	Line inductance compensation scheme	Line voltage compensation scheme
I1 (A)	3.989	4.034
I2 (A)	1.176	1.129
I3 (A)	0.716	0.759
I4 (A)	2.142	2.187
Iloop (A)	0.046	0.066
V1 (V)	202.8	202.8
V2 (V)	198	198
V3 (V)	195.9	195.9
V4 (V)	197.7	197.7
Vc (V)	13	14
Ploss (W)	49.34	50.9

result circulating current (loop current) is reduced up to 0.066 A and power loss is minimized up to 50.9 W with 14 V compensating voltage. As the impedance of the line changes, the value of loop current decreases as given in equation (10). Hence, the line currents also change. The values of line currents, loop current, node voltages, compensated voltage, total power loss reductions with line voltage compensation scheme are given in Table 3.

Competitive Analysis of Results
From the tabulated results in Table 2, it is observed that the loop distribution system is a reliable and economical approach in the distribution system than the radial system. In the radial system, if a fault occurs in any line, the whole line is cut off from the source. Not only that but, power loss occurs in the radial system is higher than the loop system. In contrast, the loop system is more reliable and economical if power loss is considered.

In the radial system, power loss is 54.59 W, whereas in the loop system, power loss is reduced up to 52.59 W. Therefore, power loss is reduced by around 4% in the loop system. If an ST is installed in the loop system in line 2, the power loss in the line inductance compensation scheme is 49.34 W, whereas the power loss in the line voltage compensation scheme is 50.99 W. Figure 14, 15, and 16 show power loss, node voltages, and loop current for (I) radial system, (II) loop system, (III) Line In-
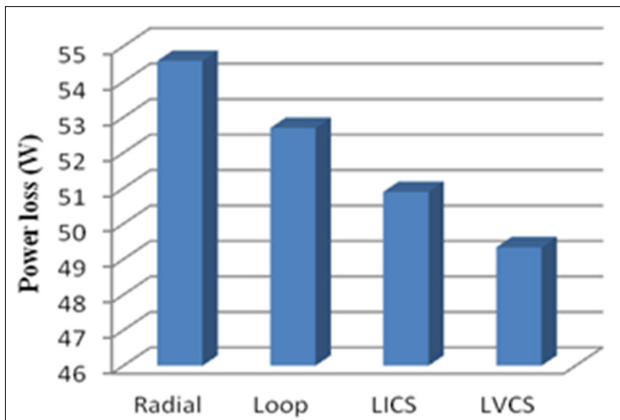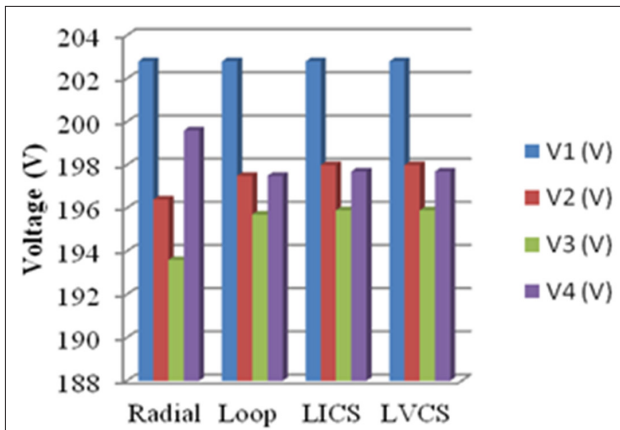
Figure 14. Total power loss
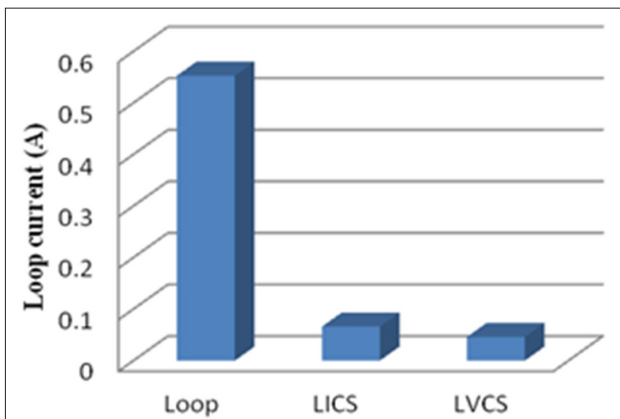

Figure 15. Node voltage RMS value

Figure 16. Loop current value

ductance Compensation Scheme (LICS), and (IV) Line Voltage Compensation Scheme (LVCS) respectively. In the loop system, the variation in node voltages is within the permissible limit.

In the loop system, power loss is reduced by up to 6.37%. Note that both the control schemes provide approximately the same power loss reduction by eliminating the loop current from the

loop distribution system. Hence, an ST is proposed as a power flow controller in the loop distribution system to achieve power loss minimization by eliminating the loop current from the system.

Conclusions

In this work, an ST is installed in the loop distribution system to achieve total line loss minimization. Two control schemes of ST are proposed to validate the results for loss minimization. Both the control schemes—line inductance compensation and line voltage compensation—have been used successfully for line loss minimization in the loop distribution system.

The line inductance compensation scheme is applied when only one line R/L ratio is different than others, whereas the line voltage compensation scheme is applied when all lines have different R/L ratios. Here, the results of both control schemes are almost equal. Therefore, the ability of an ST is proved as a series voltage and impedance regulator to achieve total line loss minimization in the loop distribution system by eliminating the loop current. The results show that total line loss is reduced by up to 9.6%, by installing an ST in the loop distribution system, thereby reducing the loop current.

Although the power loss reduction is small in the mentioned system, it may vary based on the line impedances. It is also verified that with different ratings of loop distribution systems, the losses are accountable. It can be implemented in a large-rated distribution system also and get more loss reduction with an improved voltage profile. In the results, a 4-bus system of a small rating is used, as mentioned in [3], to show that an ST can be used in loop distribution line for loss minimization.

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