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Realization of Power Loss Reduction by Installation of Sen Transformer in Multi-Loop Distribution System

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ABSTRACT

The demand for electrical energy increases day by day. Hence, energy conservation is an important occurrence nowadays, which is why mitigation of distribution system losses is considered one of them. For an efficient distribution system, restructuring of the existing system is happening consequently. In this study, the restructuring of radial feeders is integrated into a multi-loop distribution system, and power loss reduction is achieved in the system by using a cost-effective and reliable power flow controller, that is, the Sen transformer. The objective of Sen transformer is to eliminate circulating loop currents from the multi-loop distribution system by injecting compensating voltage into the feeders. The realization of the power loss reduction through Sen transformer is achieved by compensating the voltage reactance drop of the feeders and eliminating loop current from the system. The prototype laboratory setup is established to validate the proposed method and the results are presented in this study. The experimental setup is established first for radial distribution feeders, secondly for multi-loop distribution feeders, and lastly for multi-loop distribution feeders with the installation of Sen transformer. When compared to the radial system and multi-loop system, the installation of Sen transformer results in around 40% and 30% reduction in power loss, respectively.
***Index Terms*—**Loop current, multi-loop distribution system, Power loss, Sen transformer, voltage compensator

I. INTRODUCTION

One of the most important and significant attributes of any power system network is distribution system losses. Energy conservation is the main consideration for power system operators, and steps are being taken to achieve this goal. Effectual measures will be implemented to mitigate distribution system losses in the present structure of the power system through cost-effective improvements [1]. Basically, there are two types of distribution systems. The first is the radial distribution system and the second is the loop distribution system. The radial distribution system is the preferable one because of its simple structure and easy protection system. While the loop distribution system is relatively complicated, its protection system is also a complex one. However, for reliability, a loop system will have to be adopted.

A. Literature Review

Many problems have emerged as a consequence of the highly distributed energy resources inside the distribution systems. The versatile flexible AC transmission system (FACTS) controller, that is, unified power flow controller (UPFC), is used for power loss reduction in the distribution network in [2–5]. The power flow estimation and a UPFC control strategy for power loss reduction are presented in [2]. The voltage–source–converter (VSC)-based UPFC can provide a quick system behavior to control the power flow in the line. The reduction of power loss was accomplished by removing the circulating loop current in the loop distribution network using UPFC, which was used as a voltage controller. The potential drop throughout the power line must be adjusted in order to minimize line loss. As a result, the estimation of the line current is expected to remove the circulating loop current with loop distribution system. The power loss reduction and voltage control with the FACTS controllers in the loop distribution system is achieved in [3]. An optimized power flow control technique with the smallest FACTS controllers capacity is presented. On both sides of the feeders, voltage regulation and power loss constraints are taken into account. The proposed method, that is the global optimization method, is used to solve the optimization target function, and its validation is proven by the simulation results in [4]. The power loss reduction in the loop distribution system is proposed by the versatile facts controller, that is the UPFC,

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by installing it. The FACTS controller acts as a series compensating device in the loop distribution system in order to behave as a power flow controller. For the power loss reduction, eliminating the loop current from the isolated substations distribution system has to be accomplished in [5], which can be possible only with the compensation of the total reactance drop of the loop distribution system.

Many problems have emerged as a consequence of the highly distributed energy resources inside the distribution systems. The versatile FACTS controller, that is UPFC, is used for power loss reduction in the distribution network in [3-5]. The voltage variations will increase because of excessive renewable energy production in the distribution grid. It is proposed in [6] that optimized security advancement be implemented in terms of reduced line loss. The IEEE 33 bus test distribution feeder is being considered to prove the use of UPFC in conjunction with enhanced security designed to mitigate line loss.

K.K. Sen introduced the "Sen Transformer" (ST) as an array of power flow governing transformers wherein conventional transformers and on-load tap changer techniques are used for the voltage control abilities at a cheaper cost than UPFC. Although the system's response through ST is slower than that through the VSC-based controller, it is insufficient for normal use [7,8]. By connecting the ST in series with the transmission line, independent energy flow of real and reactive power can be eventually realized. The ST can be able to compensate for voltage in the line that really can simulate positive and negative resistance as well as inductance [9,10]. The detailed comparative performance of ST and UPFC is described in [11-13]. The non-linear model of ST is described in [14]. As small-rated UPFC and large-rated ST fusion appear to work as a hybrid unified power flow controller (HUPFC) in transmission network, the fusion of UPFC and ST produces better performance with key characteristics of least expense and rapid response [15,16]. In [17], power transistor-assisted Sen transformer (TAST) is introduced which fulfills the gap between the most versatile power flow controller following the FACTS categories. In [18], analysis of various ST topologies, taps control systems, and a better tap selection method with tap reversal arrangement are shown for improved ST functioning for power flow management. A multi-winding transformer-based power flow controller [19] is proposed with limited number of switches and great resolution by providing reduced amount of iron and copper used.

B. Research Gap and Motivation

After an extensive literature survey, it is observed that in certain domain research, efforts are applied to a lesser extent as given below. As mentioned in the literature survey, there are significant numbers of studies available to improve the reliability of the distribution system which include the enhancement of primary distribution feeders, utilization of different FACTS devices to address issues in distribution system, mitigation of voltage fluctuations, effective use of distribution network with the easy establishment of distribution generations (DG), a mesh or loop structure for distribution network by using voltage source converter (VSC)-based loop power flow controller, and many more. To the best of the authors' knowledge and evaluation, ST has never been presented in the distribution system to address various issues faced by the recent distribution systems.

The ST works as a series voltage regulator or impedance regulator in the multi-loop distribution system to address the objectives of line loss reduction.

C. Contribution and Paper Organization

In the presented work, the ST is used to reduce loss in the multi-loop distribution system and proves to be a more cost-effective solution than the VSC-based controller.

In this study, the power loss reduction has been achieved in the multi-loop distribution system through the ST by eliminating the loop currents. By modifying the impedance of a specific feeder, the ST can improve the power flow in the loop distribution network. The ST has achieved elimination of the loop current to reduce total power loss by meeting two criteria: 1) all feeders must have the same R/L ratio of the multi-loop distribution system and 2) all the feeders must have zero voltage drop due to reactance in the multi-loop distribution system.

In the proposed methodology, a detailed description of the above-mentioned concept is presented. To address the power loss reduction problem, the work was validated by experimental results of the multi-loop distribution system by installing ST to eliminate the loop currents.

The multi-loop distribution system model is described in detail in section II Power loss reduction conditions with the ST in multi-loop distribution systems are presented in section III Section IV depicts three different experiment setups: 1) radial distribution feeders, 2) multi-loop distribution feeders, and 3) installation of ST in the multi-loop distribution system and also discussed the results of all three configurations and their comparative analysis.

II. MULTI-LOOP DISTRIBUTION SYSTEM MODEL

The multi-loop distribution system configuration is presented in Fig. 1, where many radial feeders are fed from the single substation and, after connecting the dotted lines, it is integrated into the multi-loop system. Figure 2 shows the schematic diagram of the multi-loop distribution system, which consists of three radial feeders; feeder-1, feeder-2, and feeder-3, which are connected to the three parallel-connected loads, load-A, load-B, and load-C, fed from a single sub-station. Here, E_S is the single substation voltage, which feeds all three feeders connected in parallel, one of which (feeder-1) has a voltage regulator for compensating the load voltage through the distribution feeders. The ST is installed in series with feeder-1 to reduce power loss by eliminating the loop currents in the multi-loop distribution system.

Figure 3 shows the simplified circuit of a multi-loop distribution system, in which the three loads are formed together to make a lumped load for calculation. Because the voltage regulator is connected in the middle of feeder-1, the feeder parameters are referred to its secondary side.

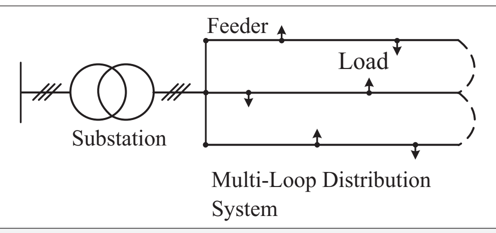

Fig. 1. Configuration of multi-loop distribution system.

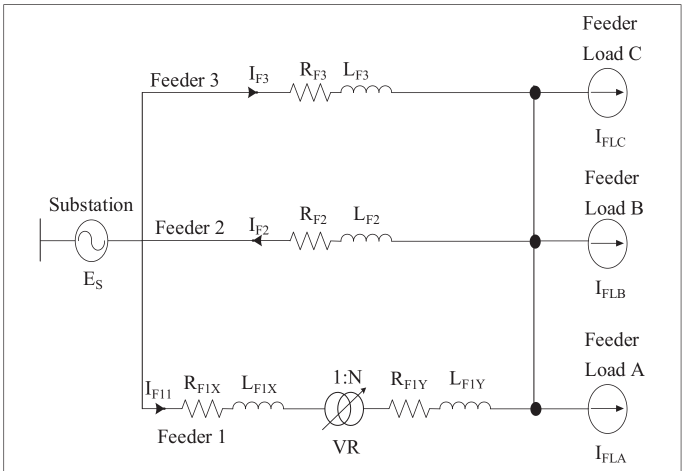

Fig. 2. Multi-loop distribution system model.

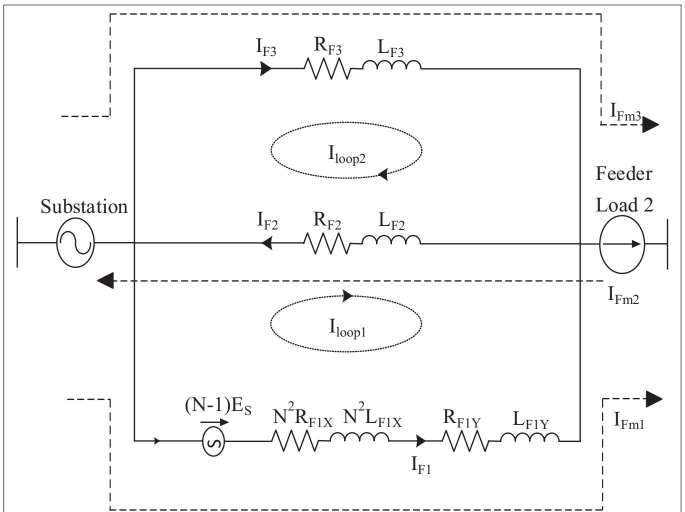

Fig. 3. Simplified circuit of multi-loop distribution system.

Each feeder current can be calculated as follows:

$$\left.\begin{aligned} I_{F1} &= \frac{1}{Z_{F1}+\dfrac{Z_{F2}Z_{F3}}{Z_{F2}+Z_{F3}}}\left[\frac{Z_{F2}Z_{F3}}{Z_{F2}+Z_{F3}}I_{FL}+(N-1)E_s\right] \\ I_{F2} &= \frac{-1}{Z_{F2}+\dfrac{Z_{F1}Z_{F3}}{Z_{F1}+Z_{F3}}}\left[\frac{Z_{F1}Z_{F3}}{Z_{F1}+Z_{F3}}I_{FL}-\frac{Z_{F3}}{Z_{F1}+Z_{F3}}(N-1)E_s\right] \\ I_{F3} &= \frac{1}{Z_{F3}+\dfrac{Z_{F1}Z_{F2}}{Z_{F1}+Z_{F2}}}\left[\frac{Z_{F1}Z_{F2}}{Z_{F1}+Z_{F2}}I_{FL}-\frac{Z_{F2}}{Z_{F1}+Z_{F2}}(N-1)E_s\right] \end{aligned}\right\} \quad (1)$$

where the impedance of the feeders is defined as

$$\left.\begin{aligned} Z_{F1} &= R_{F1}+j\omega L_{F1} \\ R_{F1} &= N^2R_{F1x}+R_{F1y} \\ L_{F1} &= N^2L_{F1x}+L_{F1y} \end{aligned}\right\} \quad (2)$$

$$Z_{F2} = R_{F2}+j\omega L_{F2} \quad (3)$$

$$Z_{F3} = R_{F3}+j\omega L_{F3} \quad (4)$$

The feeder loads of the multi-loop distribution system are considered lumped together as

$$I_{FL} = I_{FLA}+I_{FLB}+I_{FLC} \quad (5)$$

The feeder currents in each feeder can be separated further into circulating loop currents, adding to the currents at the condition of the power loss reduction because the distribution network is integrated to execute neighboring loop systems.

Hence, the feeder currents can be further calculated as

$$\left.\begin{aligned} I_{F1} &= I_{Fm1}+I_{loop1} \\ I_{F2} &= I_{Fm2}+I_{loop1}+I_{loop2} \\ I_{F3} &= I_{Fm3}+I_{loop2} \end{aligned}\right\} \quad (6)$$

In each loop system, the loop circulating currents can be described as

$$\left.\begin{aligned} I_{loop1} &= \frac{-(E_{Fm1}+E_{Fm2}-(N-1)E_S+\dfrac{Z_{F2}}{Z_{F2}+Z_{F3}}(E_{Fm2}+E_{Fm3})}{Z_{F1}+\dfrac{Z_{F2}Z_{F3}}{Z_{F2}+Z_{F3}}} \\ I_{loop2} &= \frac{\dfrac{Z_{F2}}{Z_{F1}+Z_{F2}}(E_{Fm1}+E_{Fm2}-(N-1)E_S-(E_{Fm2}+E_{Fm3})}{Z_{F3}+\dfrac{Z_{F1}Z_{F2}}{Z_{F1}+Z_{F2}}} \end{aligned}\right\} \quad (7)$$

Here,

$$V_{Fmk} = Z_{Fk}I_{Fmk} \quad (8)$$

where $k = 1, 2, 3$.

If the loop circulating currents (I_{loop1} as well as I_{loop2}) are removed from the multi-loop distribution system, it is feasible to realize power loss reduction in the multi-loop distribution system. It could be accomplished by utilizing a series compensation to compensate for the inductance voltage drop within every feeder in the multi-loop distribution system. As a result, in the condition of power loss reduction, the identical circuit of the multi-loop distribution system, illustrated in Fig. 2, can be represented just by the resistance of the feeder, which can be seen in Fig. 4.

For the power loss reduction condition, Fig. 4 depicts the feeder current of each feeder as follows:

$$\left.\begin{aligned} I_{Fm1} &= \frac{1}{R_{F1}+\dfrac{R_{F2}R_{F3}}{R_{F2}+R_{F3}}}\left[\frac{R_{F2}R_{F3}}{R_{F2}+R_{F3}}I_{FL}\right] \\ I_{Fm2} &= \frac{-1}{R_{F2}+\dfrac{R_{F1}R_{F3}}{R_{F1}+R_{F3}}}\left[\frac{R_{F1}R_{F3}}{R_{F1}+R_{F3}}I_{FL}\right] \\ I_{Fm3} &= \frac{1}{R_{F3}+\dfrac{R_{F1}R_{F2}}{R_{F1}+R_{F2}}}\left[\frac{R_{F1}R_{F2}}{R_{F1}+R_{F2}}I_{FL}\right] \end{aligned}\right\} \quad (9)$$

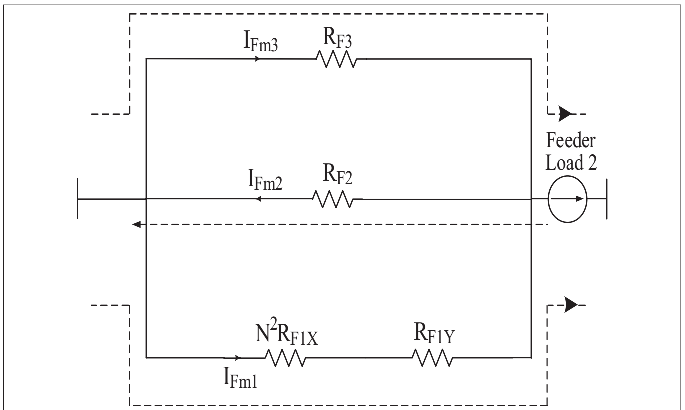

Fig. 4. Simplified circuit of multi-loop distribution system at line loss reduction condition.

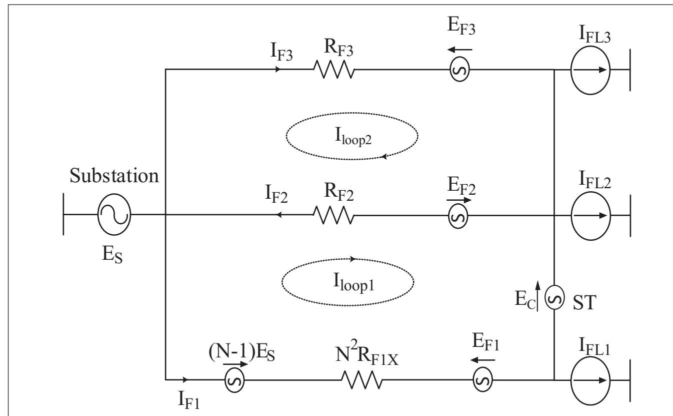

Fig. 5. Power Loss Reduction with ST in Multi-loop Distribution System.

According to (6), (7), and (9), the loop circulating currents of both the loop can be described as

$$\left.\begin{aligned} I_{loop1} &= \frac{-(E_{F1}+E_{F2}-(N-1)E_S+\dfrac{R_{F2}}{R_{F2}+R_{F3}}(E_{F2}+E_{F3})}{R_{F1}+\dfrac{R_{F2}R_{F3}}{R_{F2}+R_{F3}}} \\ I_{loop2} &= \frac{\dfrac{R_{F2}}{R_{F1}+R_{F2}}(E_{F1}+E_{F2}-(N-1)E_S-(E_{F2}+E_{F3})}{R_{F3}+\dfrac{R_{F1}R_{F2}}{R_{F1}+R_{F2}}} \end{aligned}\right] \tag{10}$$

Here,

$$V_{Fk}=j\omega L_k I_{Fk} \tag{11}$$

where k = 1, 2, 3.

As a function of feeder currents and loop circulating currents, the total power loss of all feeders can be expressed as follows:

$$\begin{aligned} P_{Fl} &= \sum_{k=1}^{3}\left|I_{Fk}\right|^2 R_k \\ P_{Fl} &= \sum_{k=1}^{3}\left|I_{Fmk}\right|^2 R_k + 2\left\{R_{F1}I_{Fm1}+R_{F2}I_{Fm2}\right\}J_{loop1} \\ &+2\left\{R_{F2}I_{Fm2}+R_{F3}I_{Fm3}\right\}J_{loop2}+R_{F1}\left|I_{loop1}\right|^2 \\ &+R_{F2}\left|I_{loop1}+I_{loop2}\right|^2+\left|I_{loop2}\right|^2 R_{F3} \end{aligned} \tag{12}$$

The elimination of both loop currents results in the power loss reduction condition [5].

The reduced power loss can be expressed as

$$P_{Flred}=\sum_{k=1}^{3}\left|I_{Fmk}\right|^2 R_k \tag{13}$$

According to (10), the two conditions give the power loss reduction realization if the elimination of the loop circulating current happens. The realization of the two simultaneous conditions is given as follows:

$$\left.\begin{aligned} &(E_{F1}+E_{F2}-(N-1)E_S=0 \\ &E_{F2}+E_{F3}=0 \end{aligned}\right] \tag{14}$$

III. POWER LOSS REDUCTION WITH SEN TRANSFORMER IN MULTI-LOOP DISTRIBUTION SYSTEM

In a multi-loop distribution system, the power loss reduction can be achieved by installing ST in it. The main objective of the ST is to control the power flow in a multi-loop distribution system. Series compensating voltage provided by ST can realize the line loss reduction conditions. The multi-loop distribution system with the ST in the case of power loss reduction is depicted in Fig. 5. The inductive drop can be represented as E_{F1}, E_{F2}, and E_{F3} for feeders 1, 2, and 3. The Thevenin equivalent circuit is obtained, as shown in Fig. 6a to calculate the required compensating voltage for the ST. A feeder resistor

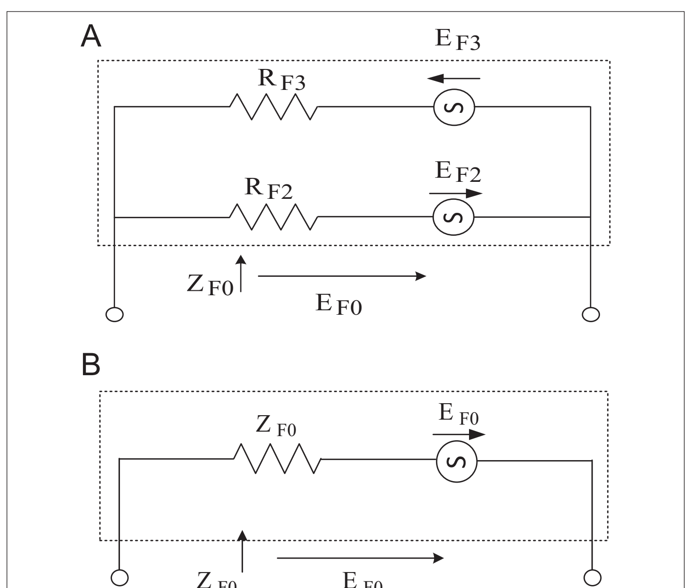

Fig. 6. (A) Thevenin's circuit with feeder-2 and feeder-3. (B) Thevenin's equivalent circuit.

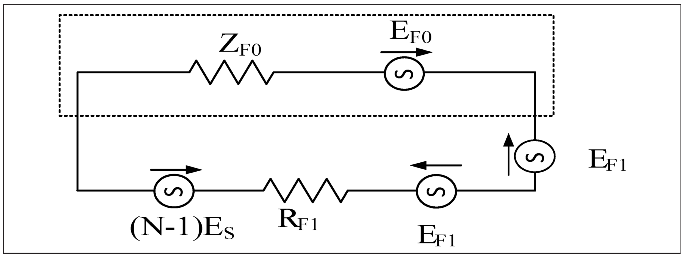

Fig. 7. Equivalent circuit of feeders with the ST.

Z_{F0} is shown in series with a voltage source E_{F0} approximates the parallel feeders 2 and 3, as shown in Fig. 6b, which could be represented in the following way:

$$Z_{F0} = \frac{R_{F2}R_{F3}}{R_{F2}+R_{F3}} \tag{15}$$

$$E_{F0} = \frac{R_{F3}}{R_{F2}+R_{F3}}E_{F2} - \frac{R_{F2}}{R_{F2}+R_{F3}}E_{F3} \tag{16}$$

The compensating voltage, E_C of ST, can be formulated from Fig. 7 as follows:

$$E_C = E_{F1} + E_{F0} - (N-1)E_S \tag{17}$$

Hence, a regulated series voltage introduced using the ST as stated in (29) results in loop currents I_{loop1} and I_{loop2} to be as follows:

$$I_{loop1} = 0 \tag{18}$$

$$I_{loop2} = -\frac{E'_{F2}+E'_{F3}}{R_2+R_3} \tag{19}$$

where $E'_{Fk} = j\omega L_k I'_{Fk}$ (20)

$$I'_{F1} = I_{Fm1} \tag{21}$$

$$I'_{F2} = I_{Fm2} + I'_{loop2} \tag{22}$$

$$I'_{F3} = I_{Fm3} + I'_{loop3} \tag{23}$$

The considered loop distribution system is adjacent; as a result, the effects of loop-1 and loop-2 currents are reversed. The loop-1 current can be eliminated by inserting a series compensating voltage that can also decrease the loop-2 current. If the loop lines (feeders) have the same R/L ratio, then the loop-2 current can also be reduced with the loop-1 current. The series compensating voltage of ST can be formulated as follows:

$$E_C = L_{F1}\frac{di_{F1}}{dt} + \frac{R_{F3}}{R_{E2}+R_{E3}}L_{F2}\frac{di_{F2}}{dt} - \frac{R_{F2}}{R_{E2}+R_{E3}}L_{F3}\frac{di_{F3}}{dt} - (N-1)E_S \tag{24}$$

The compensated series voltage E_C, as per (24), is clearly dependent on the feeder currents or feeder parameters. Hence, by detecting all feeder currents of the multi-loop distribution system and feeder parameters, one can get the compensating voltage value.

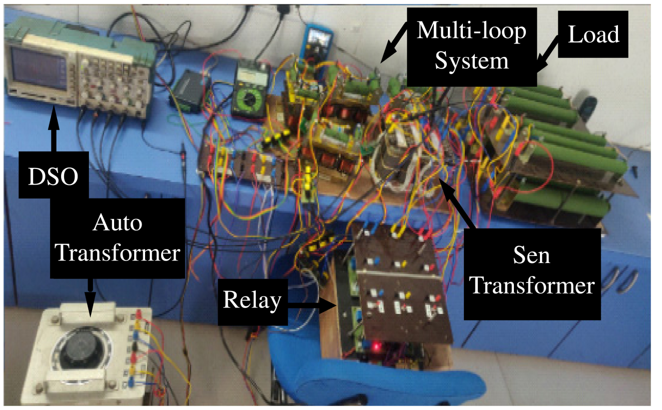

Fig. 8. Experimental setup.

IV. EXPERIMENTAL CONFIGURATIONS

The laboratory prototype experiment setup establishes a multi-loop distribution system and ST, as shown in Fig. 8, to validate the proposed work. All the parameters are described in Table I. Here, three lines of the same R and L values are considered as feeders, which are connected in parallel to fed with the common voltage source as a substation. Three-different resistive loads are connected through feeders. The ST is installed to eliminate loop currents and to achieve power loss reduction conditions; compensating voltage is injected to nullify the reactive voltage drop of the multi-loop distribution system. Firstly, all feeders are worked as radial distribution feeders; secondly, all the feeders are connected in parallel to form multi-loop distribution feeders; lastly, ST is installed in multi-loop distribution feeders to achieve power loss reduction conditions. The comparison of all the configurations is represented in the bar chart. Experimental results waveform of all the feeders current and the two-loop currents

TABLE I. EXPERIMENTAL PARAMETERS OF THE SYSTEM

Parameters	Value
ST rating	0.6 kVA
Substation voltage	100 V
Frequency	50 Hz
Feeder-1a resistance R_{F1a}	1 Ω
Feeder-1a inductance L_{F1a}	15 mH
Feeder-1b resistance R_{F1b}	1 Ω
Feeder-1b inductance L_{F1b}	15 mH
Feeder-2 resistance R_{F2}	3 Ω
Feeder-2 inductance L_{F2}	5 mH
Feeder-3 resistance R_{F3}	3 Ω
Feeder-3 inductance L_{F13}	5 mH
Load A, Load B, Load C	20 Ω, 60 Ω, 60 Ω
Voltage regulator	1:1.07 pu

ST, Sen transformer.

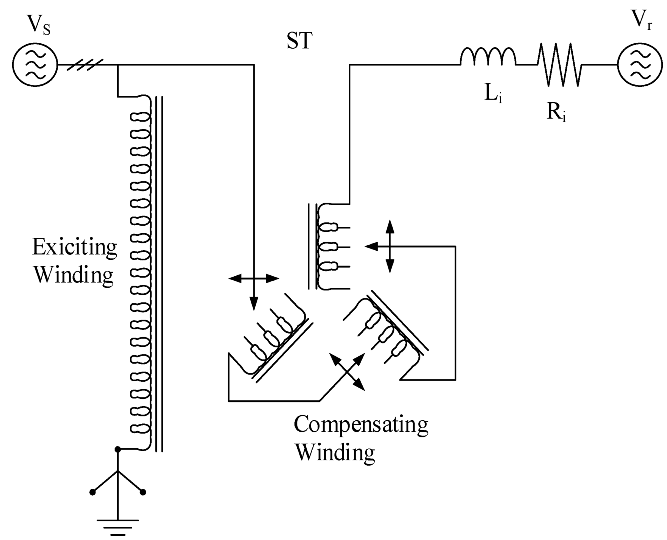

Fig. 9. Configuration of ST.

are captured. The power loss of the system is calculated as a sending and receiving end power difference.

A. Sen Transformer Configuration

The ST is capable of emulating variable impedance in the distribution feeders. It is considered a single unit with an exciting winding and a compensating winding with a shunt and series connection, respectively [10,20-22]. By changing the taps of the series-connected compensating winding, the injected voltage in a feeder can vary in magnitude and angle. While in use, the active and reactive power can be exchanged through the compensating winding. The main purpose of the exciting winding is to provide required excitation to the compensating winding from the source in an attempt to reach the compensating winding's real power requirements and to control the system's reactive power, as shown in Fig. 9.

The phasor diagram of ST is illustrated in Fig. 10, in which 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 [8]. In Fig. 11, ST structure diagram is illustrated, A, B and C are the three-phase primary winding and a_1, a_2, a_3; b_1, b_2, b_3; and c_1, c_2, c_3

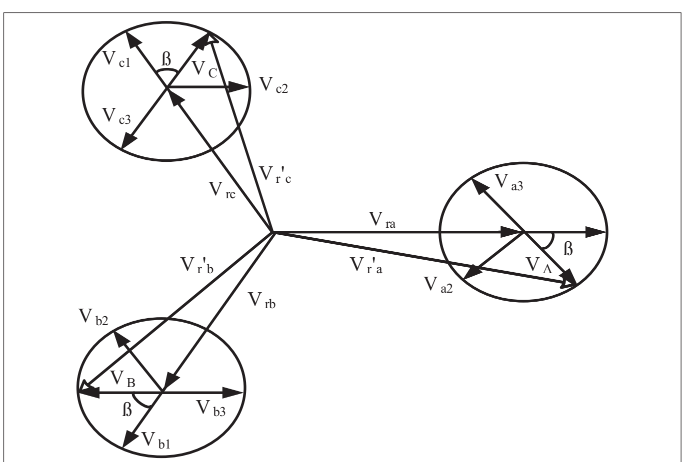

Fig. 10. Phasor diagram of ST.

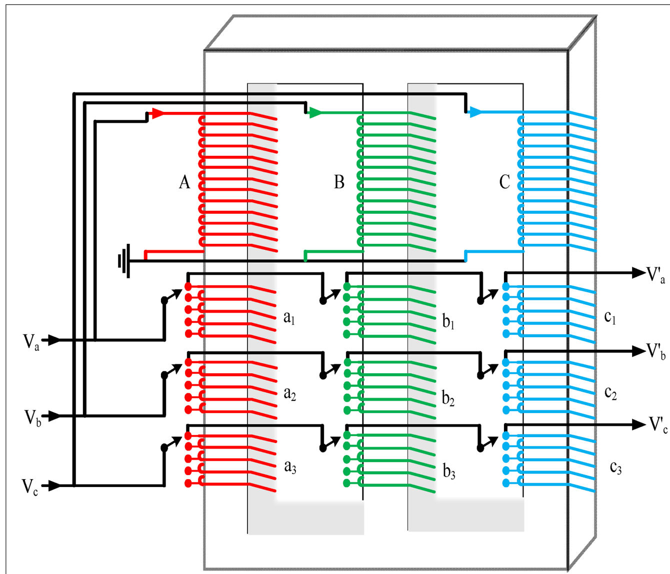

Fig. 11. Structure diagram of ST [14].

are the nine secondary windings, which are wrapped on three different limb. There are four taps on each compensating winding, and the sum of them produces a compensating voltage with magnitude E_C and angle *ß*.

B. Radial Distribution System Configuration

Fig. 12 shows the experimental prototype of the 0.6 kVA, 100 V-rated radial distribution system configuration. It is made up of three radial feeders that are fed by a common voltage source and three loads that are connected in parallel. A voltage regulator is connected in series with the feeder-1. The system parameters are described in Table I. The readings of all the feeder currents and power loss are listed in Table II.

In the radial feeder configuration, as all three feeders are connected in parallel, 2.1 A and 1.9 A currents flow through feeder-1 before and after the voltage regulator. The feeders-2 and -3 carry currents of 1.12 A and 1.35 A, respectively. The power loss measured in this configuration is 51.75 W.

C. Multi-Loop Distribution System Configuration

Fig. 13 shows the experimental prototype of the 0.6 kVA, 100 V rated multi-loop distribution system configuration. It is made up of three

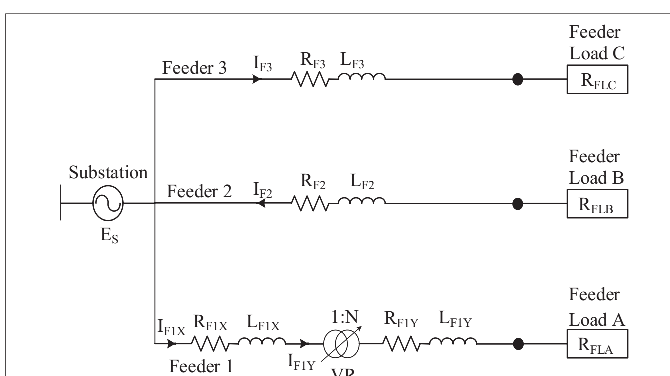

Fig. 12. Radial distribution system configuration.

TABLE II. EXPERIMENTAL RESULTS OF MULTI-LOOP DISTRIBUTION SYSTEM

Parameters	Radial Distribution System	Multi-loop Distribution System Without ST	Multi-loop Distribution System With ST
I_{F1a} (A)	2.1	1.82	0.71
I_{F1b} (A)	1.9	1.69	0.65
I_{F2} (A)	1.12	0.85	1.52
I_{F3} (A)	1.35	0.85	1.52
I_{loop1} (A)	-	1.83	0.23
I_{loop2} (A)	-	1.21	0.14
E_S (V)	100	100	100
E_C (V)	-	0	18.46
P_{loss} (W)	51.75	44.32	31.44

ST, Sen transformer.

radial feeders that are fed by a common voltage source and three loads that are connected in parallel. A voltage regulator is connected in series with the feeder-1. The loop system is formed from the radial feeder by reconfiguring the system by connecting all the feeders in a parallel connection.

In the multi-loop feeder configuration, all three feeders are connected in parallel through the loop wire. 1.82 A and 1.69 A currents flow through feeder-1 before and after the voltage regulator. The current 0.85 A flows through feeder-2 and feeder-3. The power loss measured in this configuration is 44.32 W, which shows the loop system has less power loss than the radial one.

The system parameters are described in Table I. The readings of all the feeder currents, loop currents, and power loss are listed in Table II. The waveforms of the feeder currents and loop currents of the prototype laboratory setup are shown in Fig. 15.

D. ST in Multi-Loop Distribution System Configuration

Fig. 14 shows the experimental prototype of the 0.6 kVA, 100 V-rated multi-loop distribution system configuration with the ST. It is made

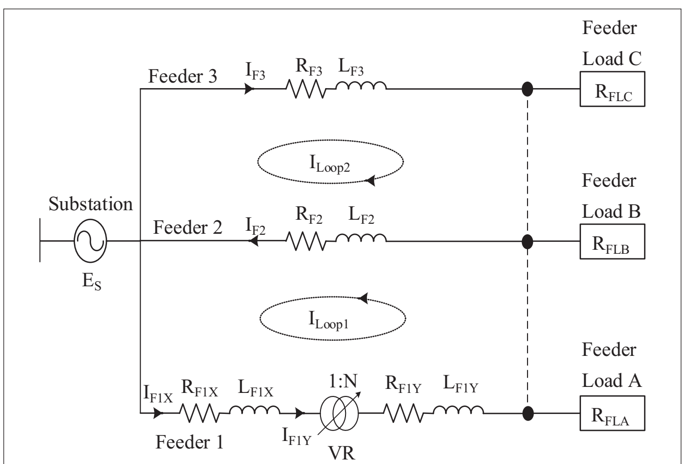

Fig. 13. Multi-loop distribution system configuration.

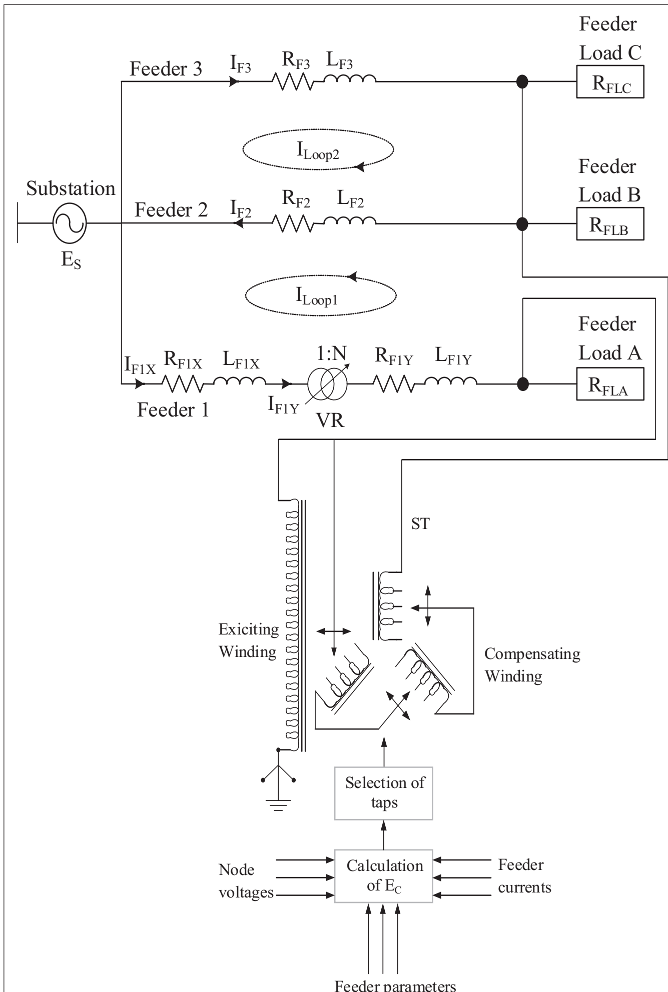

Fig. 14. Multi-loop distribution system configuration with the ST.

up of three radial feeders that are fed by a common voltage source and three loads that are connected in parallel. A voltage regulator is connected in series with the feeder-1. The loop system is formed from the radial feeder by reconfiguring two feeders in a parallel connection. The ST is installed between feeder-1 and feeder-2 to achieve power loss reduction. The required compensating voltage is injected into the multi-loop distribution feeder to realize the objective. The readings of all the feeder currents, loop currents, and power loss are listed in Table II. The waveforms of the feeder currents, loop currents, and compensating voltage of the prototype laboratory setup are shown in Fig. 15. Figure 16 shows the injected compensating voltage by ST and the line current. The line injected voltage is at 90° to the line current.

In the multi-loop feeder configuration with ST, all three feeders are connected in parallel through the loop wire and ST. Feeder-1 and feeder-2 are connected through ST, while feeder-2 and feeder-3 are connected through loop wire. The current 0.71 A and 0.65 A flow through feeder-1 before and after the voltage regulator. The current 1.52 A flows through feeder-2 and feeder-3. The power loss measured in this configuration is 31.44 W, which shows the multi-loop system with ST has less power loss than both configurations.

The corresponding analysis is demonstrated in Fig. 17 in the form of a bar chart, which shows that 38.64% and 29.06% power loss

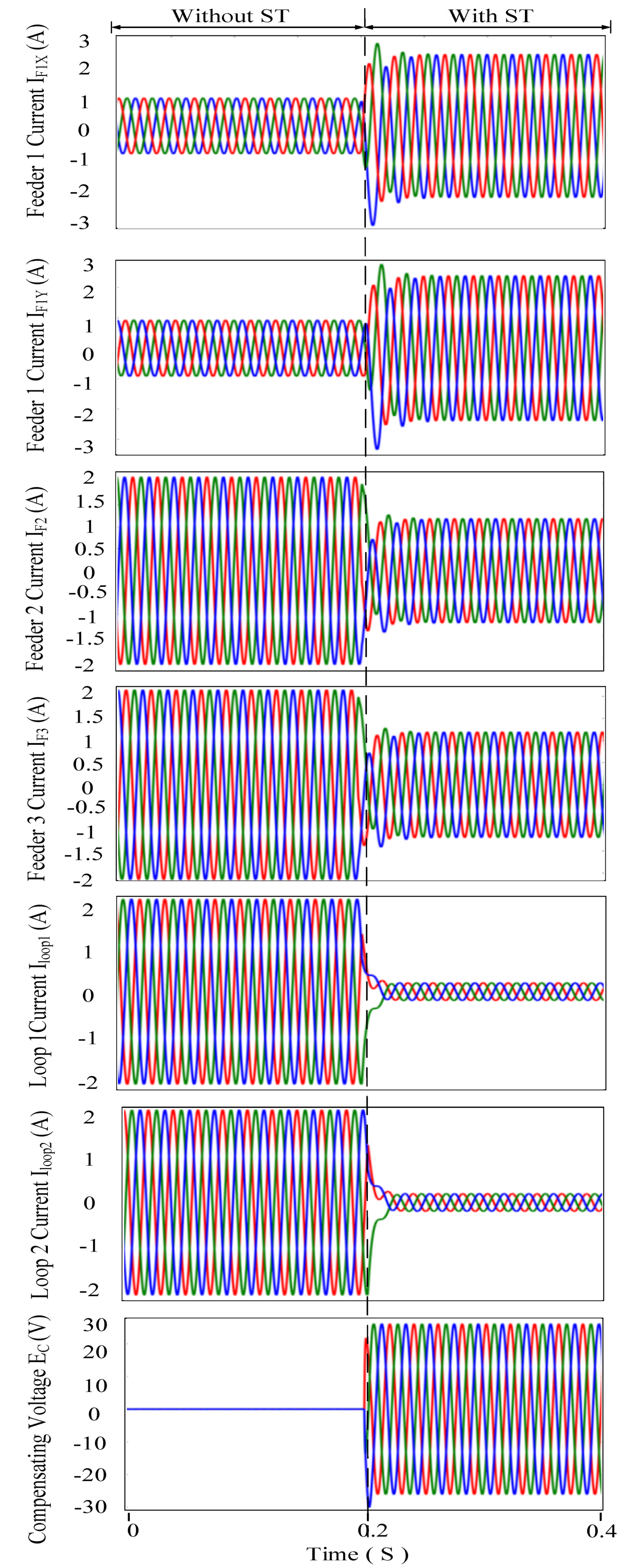

Fig. 15. Experimental results of multi-loop distribution system with and without ST.

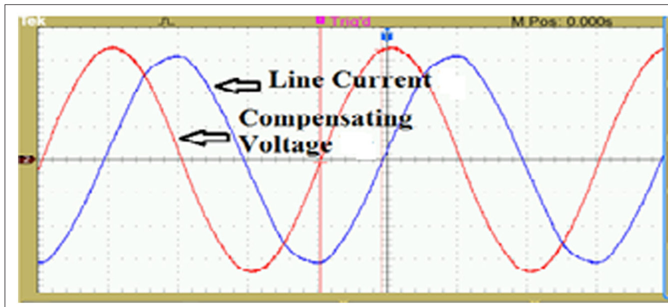

Fig. 16. Experiment results of injected compensating voltage and line current of ST.

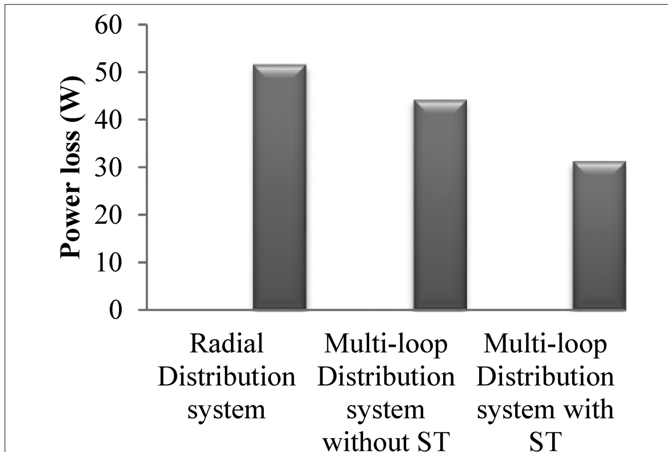

Fig. 17. Comparison of all three configuration.

reductions are achieved with the ST compared to the radial distribution system and multi-loop distribution system, respectively.

This work has presented line loss reduction by using ST in the multi-loop distribution system. Line loss reduction has been realized with ST by controlling the phase angle and magnitude of compensating voltage. Experimental results prove that the ST has a great capability to achieve the objectives with a cost-effective solution than other VSC-based power electronics devices. Using a traditional transformer/LTCs-based technology with proven reliability, the ST is a viable cost-effective solution for distribution line loss reduction. The ST is an alternative option for power electronics inverter-based FATCS devices for the distribution system.

V. CONCLUSION

- For reliable power and customer satisfaction with comparable power loss, the distribution network's loop distribution system should be preferred over the radial one.
- The whole work has proposed a power loss reduction method using the ST in the multi-loop distribution network.
- The ST functions as a voltage controller or impedance regulator to address power loss problems in the multi-loop distribution system.
- If the sum of the reactance drops in the feeders were to be injected in the form of compensating voltage through ST, the total power loss reduction could be obtained.

- The experimental setup is created first for radial distribution feeders, then for multi-loop distribution feeders, and finally with the installation of ST for multi-loop distribution feeders.
- When compared to the radial system and the multi-loop system, the installation of ST results in a power loss reduction of roughly 40% and 30%, respectively.
- To address the power loss reduction conditions, the realization of loop current elimination is economically achieved by ST.

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REFERENCES

1. A. A. Sallam, and O. P. Malik, "Distribution system planning," in *Electric Distribution Systems*. IEEE Publications, 2019, pp. 23–39. Available: https://www.wiley.com/en-us/Electric+Distribution+Systems%2C+2nd+Edition-p-9781119509325
2. R. Saino, T. Takeshita, N. Izuhara, and F. Ueda, "Power flow estimation and line-loss-minimization control using UPFC in loop distribution system," 6th International Power Electronics and Motion Control. Conference, Wuhan: IEEE Publications, 2009, pp. 2426–2431.
3. M. A. Sayed, and T. Takeshita, "All nodes voltage regulation and line loss minimization in loop distribution systems using UPFC," in *IEEE Trans. Power Electron.*, vol. 26, no. 6, pp. 1694–1703, 2011. [CrossRef]
4. Z. Zhi-hua, X. Bing-yin, and C. Qing, "Research on the optimal Power Flow Control method of the closed-loop distribution network with UPFC," *IEEE PES Innovative*. Tianjin: Smart Grid Technologies, 2012, pp. 1–3.
5. M. A. Sayed, and T. Takeshita, "Line loss minimization in isolated substations and multiple loop distribution systems using the UPFC," in *IEEE Trans. Power Electron.*, vol. 29, no. 11, pp. 5813–5822, 2014. [CrossRef]
6. P. Song, Z. Xu, H. Dong, H. Cai, and Z. Xie, "Security-constrained line loss minimization in distribution systems with high penetration of renewable energy using UPFC," in *J. Mod. Power Syst. Clean Energy*, vol. 5, no. 6, pp. 876–886, 2017. [CrossRef]
7. K. K. Sen, and M. L. Sen, "'Introducing the family of "Sen" transformers: A set of power flow controlling transformers," IEEE Power Engineering Society Summer Meeting, Chicago, IL, USA: IEEE Publications, vol. 1, p. 486, 2002.
8. K. K. Sen, and M. L. Sen, "Comparison of the 'Sen' transformer with the unified power flow controller," 2003 IEEE Power Engineering Society General Meeting (Cat. No.03CH37491), Toronto, Ontario: IEEE Publications, pp. 2577–2577, 2003.
9. O. Faruque, and V. Dinavahi, "A tap-chaging algorithm for the implementation of 'Sen' transformer," 2008 IEEE Power and Energy Society General Meeting - Conversion and Delivery of Electrical Energy in the 21st Century. Pittsburgh, PA, 2008, pp. 1–1.
10. K. K. Sen, and M. L. Sen, "SMART Power Flow Controller for smarter grid applications," IEEE Power Energy Soc. Gen. Meet. Denver, CO, vol. 2015, pp. 1–5, 2015.
11. A. Kumar, and C. Sekhar, "Comparison of Sen Transformer and UPFC for congestion management in hybrid electricity markets," *Electr. Power Energy Syst.*, vol. 47, pp. 295–304, 2013. [CrossRef]
12. S. Chanana, and K. Ashwani, "Comparison of Sen Transformer and UPFC for real and reactive power marginal price under maximum loadability condition," *Electr. Power Compon. Syst.*, vol. 36, pp. 1369–1387, 2008.
13. K. Ashwani, and W. Gao, "Power flow model of 'Sen' transformer for loadability enhancement and comparison with UPFC in hybrid electricity markets," *Electr. Power Compon. Syst.*, vol. 37, p. 189, 2009.
14. J. Liu, and V. Dinavahi, "Nonlinear magnetic equivalent circuit-based real-time sen transformer electromagnetic transient model on FPGA for HIL emulation," IEEE Power Energy Soc. Gen. Meet. Chicago, IL, vol. 2017, pp. 1–1, 2017.
15. J. Yuan, L. Liu, W. Fei, L. Chen, B. Chen, and B. Chen, "Hybrid electromagnetic unified power flow controller: A novel flexible and effective approach to control power flow," *IEEE Trans. Power Deliv.*, vol. 33, no. 5, pp. 2061–2069, 2018. [CrossRef]
16. B. Chen, W. Fei, C. Tian, and J. Yuan, "Research on an improved hybrid unified power flow controller," in *IEEE Trans. Ind. Appl.*, vol. 54, no. 6, pp. 5649–5660, Nov.–Dec. 2018. [CrossRef]
17. S. E. Gasim Mohamed, J. Jasni, M. A. M. Radzi, and H. Hizam, "Implementation of the power transistor-assisted Sen transformer in steady-state load flow analysis," in *IET Gener. Transm. Distrib.*, vol. 12, no. 18, pp. 4182–4193, 2018. [CrossRef]
18. T. Behera, and D. De, "Enhanced operation of 'Sen' transformer with improved operating point density/area for power flow control," *IET Gener. Transm. Distrib.*, vol. 13, no. 14, pp. 3158–3168, 2019. [CrossRef]
19. D. Kumari, S. K. Chattopadhyay, and A. Verma, "Multi-Winding Transformer based High Resolution Power Flow Controller," 28th International Symposium on Industrial Electronics (ISIE). IEEE Publications, pp. 2377–2382, 2019. [CrossRef]
20. K. K. Sen, and M. L. Sen, "Comparison of operational characteristics between a Sen Transformer and a phase angle regulator," IEEE Power Energy Soc. Gen. Meet. (PESGM). Boston, MA, vol. 2016, pp. 1–5, 2016.
21. K. K. Sen, and M. L. Sen, "Unique capabilities of Sen Transformer: A power flow regulating transformer," IEEE Power Energy Soc. Gen. Meet. (PESGM), Boston, MA, vol. 2016, pp. 1–5, 2016.
22. A. Kumar, and J. Kumar, "Comparison of UPFC and SEN Transformer for ATC enhancement in restructured electricity markets," *Electr. Power Energy Syst.*, vol. 41, no. 1, pp. 96–104, 2012. [CrossRef]

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