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# Smart Transformer Based Loop Power Controller in Radial Power Distribution Grid

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**Abstract**—In electric distribution grid, increased penetration of renewable energy sources (RES) and electric vehicles (EV) will create several challenging issues such as voltage limits violation in the feeder, line congestion, transformer overloading, etc. These issues could be mitigated using a loop power controller (LPC), by looping the radial distribution system. The LPC is realized either using a back-to-back power converter or with a combination of tap changer and phase shifter transformers. This paper introduces smart transformer (ST), an alternative of line frequency transformer (LFT), to additionally achieve the features of conventional LPC. The ST can achieve operational features of the conventional LPC with effective control and communication functionalities. The ST controls the active and reactive power flow in the radial distribution feeders to achieve voltage regulation in the feeder, loading balancing in the feeders, prevents LFT overloading, etc. Moreover, DC links of the ST also provide an opportunity to integrate energy storage and it allows the ST in the proposed configuration to support the grid during the peak load demand. These advantages of ST in a two feeder radial grid are validated through PSCAD based simulation studies.

**Index Terms**—Loop power control, smart transformer, radial distribution grid.

## I. INTRODUCTION

Power generation through renewable energy sources such as photovoltaic (PV) and wind are highly unpredictable in nature, and it is difficult to maintain feeder voltage within the allowable range [1]. A radial power distribution system consisting of two feeders is shown in Fig. 1. Feeder 1 has many distribution generators (DG) installed, whereas feeder 2 consists of only loads. In this scenario, it is possible that line frequency transformer (LFT) of feeder 2 may be overloaded during the peak load demand with significant voltage reduction at the end of the feeder. Moreover, the feeder 1 LFT may get overloaded during the peak DG power generation with increase in feeder voltage. With this type of voltage unbalance, it is difficult for power utility to set the voltage at the medium voltage grid for satisfactory operation of the distribution grid [2]. Moreover, it is important to achieve load balancing between the feeders so that the load demand can be distributed equally between the feeder and the LFTs, and the LFTs are not overloaded.

Grid reconfiguration schemes are used to eliminate the effects of load unbalancing and line congestion [3]. How-

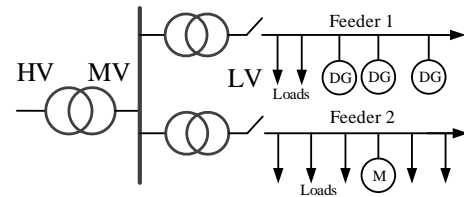


Fig. 1. Schematic of two-feeder radial distribution grid.

ever, these are not suitable for highly variable DG power sources. Power electronics solutions such as distribution static compensator (DSTATCOM), static var compensation (SVC), etc. are proposed and found to be suitable for realizing the load balancing and voltage regulation [4], [5]. But, these are not effective in multifeeder system. Loop power controller (LPC) is one of the most potential solutions for power control between the feeders while ensuring allowable voltage in the feeders [6]–[8]. The LPC, where two radial feeders are looped together, is realized either by using a back-to-back (BTB) power converter or with a combination of tap changer and phase shifter transformers. The LPC can provide reactive power compensation in the feeders independently to reduce the voltage variation, and also controls the power flow between the feeders such that the feeder LFTs are not overloaded.

Recently, power electronic based transformer called smart transformer (ST) is demonstrated for its application in power distribution grid as an alternative of LFT [9], [10]. Control, communication, and power management are essential features of an ST, which sets it apart from the LFT. The most suitable configuration of ST in electric grid is three stage power conversion with two intermediate DC links. Besides the basic operation of voltage transformation and isolation between medium voltage (MV) and low voltage (LV) grid, the ST has more functionalities for improving the performance of electric grid. [9] introduces the additional capability of ST, such as resonance damping, voltage improvement and load compensation features in MV grid, load voltage control in LV grid, etc. These applications of ST in distribution grid show that the ST can control the waveforms of currents in MV side and voltages in LV side independently depending upon the

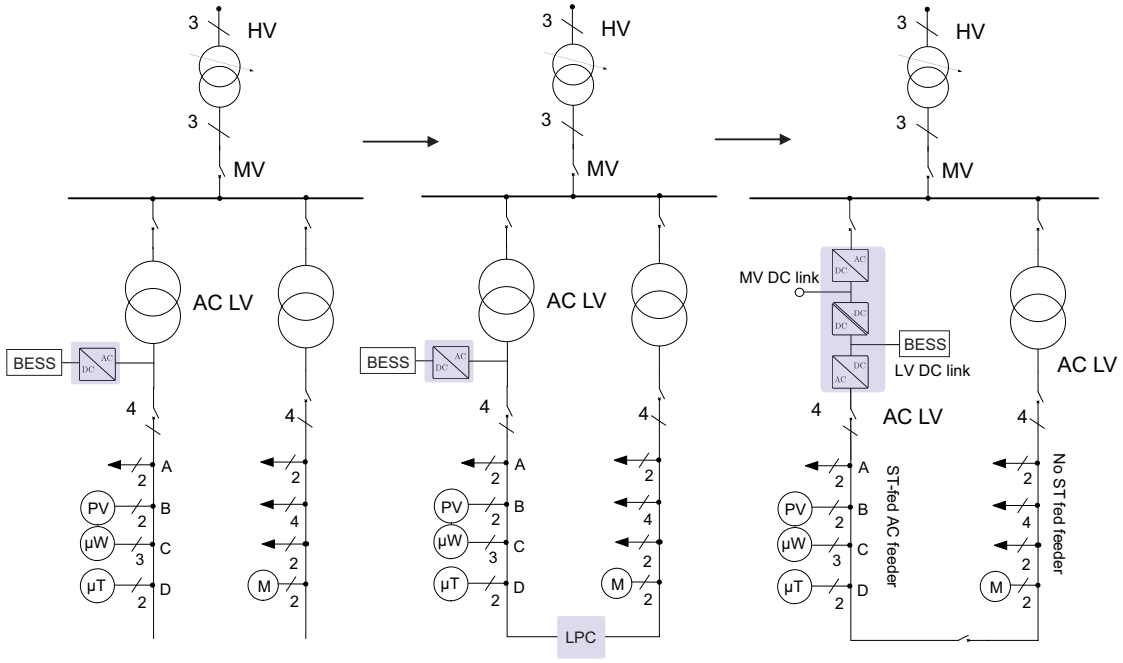


Fig. 2. Schematic of two-feeder radial distribution grid. (a) Feeders without any control. (b) LPC connected between the feeders. (c) ST based system where one of the LFT and LPC is replaced by an ST.

required services.

Considering the potentials of ST in the distribution grid, this paper proposes its application not only to realize features of LFT but also to achieve the advantages of conventional LPC. In the proposed configuration, the ST replaces one of the LFT and the LPC.

This paper is organized as follows: descriptions of conventional LPC integrated radial feeder and proposed ST based radial feeder configuration are explained in Section II; in Section III the control mechanism of power converters of ST is provided. Different operating modes of ST in proposed configuration are explained in Section IV. Simulation results are given in Section V. Conclusions are drawn in Section VI.

## II. DESCRIPTION OF DISTRIBUTION GRID CONFIGURATION

### A. Conventional LPC Integrated Distribution Grid

The conventional radial electric grid is shown in Fig. 2(a). In this configuration, each of the feeder uses an LFT. The primary of LFT is connected to 11 kV MV side grid, whereas secondary is connected to LV side of 400 V. One feeder has significantly large installed DG whereas other feeder has more loads including electrical vehicles charging station. These create voltage variations throughout the feeder at peak DG generation or peak load demand and additionally overload the feeders/LFTs. For power balancing and maintaining voltage throughout the feeders, loop power flow control is realized using LPC. The schematic is shown in Fig. 2(b) where the LPC is connected at the furthest end of the line. The LPC is realized either using back-to-back power converters or through the phase shift and tap changer transformers [7]. Depending upon

the distance between the feeders, the LPC can be connected with or without the step up LFTs [8]. The back-to-back power converters control active and reactive powers in both the feeders to maintain allowable voltage magnitude throughout the feeders. Moreover, power balancing between the feeders is also achieved which avoids overloading of the two LFTs. The LPC is installed at the point where generally open switch is provided. During high penetration of DG in one feeder, the LPC transfers the active from to the feeder with loads. Moreover, during peak load conditions, the LPC uses the lightly loaded feeder to support the loads.

### B. Proposed ST based Radial Distribution Grid Configuration

The proposed radial grid configuration is shown in Fig. 2(c). In this configuration, the ST replaces one of the feeder LFT and the two feeders are connected through the conventional open switch scheme. Moreover, the LPC is completely removed from the electric grid. The ST, used in this work, is a three stage transformer and can control the power flow from MV to LV grid and vice versa. The both MV ac-dc converter and LV dc-ac converter of ST can control active and reactive powers in the MV and LV grid. Moreover, the ST can modify the voltage magnitude of the LV ac grid so that the voltage level does not violate the operating limits. The only constraints that the ST must respect is the active power demand from the LV grid, while voltage amplitude and frequency in LV side and reactive power injection in MV side represent degrees of freedom for the grid management. Unlike other power electronics devices such as inverter of DG, where the maximum capability of reactive power supply is restricted by a certain power factor, e.g. 0.95 (inductive/capacitive), the

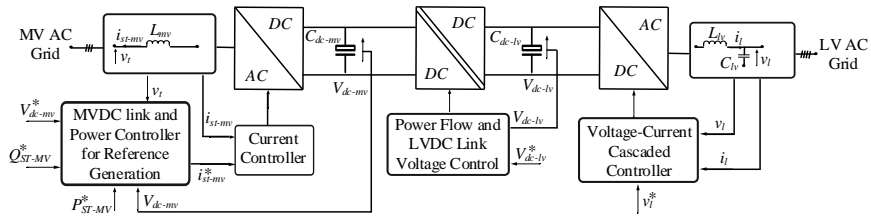


Fig. 3. Smart transformer control scheme in the proposed configuration.

capability of reactive power supply by ST is only limited by the maximum current and active power demand.

The dc-dc converter of ST has two main tasks: adapting the voltage from MV to LV and controlling the voltage level of the LV DC link. This is regulated by means of a power flow controller and it regulates the power flow between the two DC stages to keep the LV DC link voltage at its nominal value. The power constraints are set between  $P_{max}$ , determined by the ST sizing, and  $P_{min}$ , that can be set or equal to  $-P_{max}$ . The ST LV side converter controls the voltage waveform in the LV grid. The ST provides a symmetrical voltage waveform with fixed amplitude and frequency independently from the load power request. The current waveform is instead decided solely by the load.

The LV converter of ST, having flexibility of providing voltage magnitude at LVAC grid, can regulate its terminal voltages at a suitable magnitude which will provide an allowable voltage throughout both the feeders. Another important feature is that the MV converter of ST will compensate for the remaining reactive power requirement of the feeders resulting in exchange of only active power from the MV grid. During the high DG penetration, the ST can store the surplus power in the battery energy storage system (BESS) installed at the LVDC link of the ST. In case of peak load demand, the ST control action can again limit the power flow from the LFT by extracting appropriate active power from the BESS.

### III. CONTROL MECHANISM OF ST IN PROPOSED CONFIGURATION

Fig. 3 shows the control block diagram for ST in the proposed configuration. The MV side converter regulates the voltage of the MVDC link capacitor and controls the active as well as reactive powers exchanged with the MV grid. Moreover, the reactive power is a degree of freedom for the ST MV converter: the ST can work at unity power factor, provide reactive power compensation, or support the voltage by providing reactive power. In this paper, voltage at the MV grid is assumed to be fixed by utility. The reactive power control in MV grid is limited to support the reactive power requirement of feeder with LFT [11].

The dc-dc converter steps down the MVDC link voltage to a regulated lower voltage at LVDC link. The power flow balance in the converter circuit is maintained by controlling the phase shift angle of the pulsed voltages of the two converters linked through the high frequency transformer [9].

The ST LV converter maintains appropriate voltages at the LVAC terminals. The control of the LV stage is cascaded voltage-current control [11].

### IV. DIFFERENT OPERATING MODES OF ST IN PROPOSED CONFIGURATION

In the proposed configuration, the ST provides several operational features by operating in different modes. Generation of reference active and reactive powers are important for ST MV converter operation, whereas appropriate load voltage magnitude and angle is important for maintaining allowable voltage throughout the feeders. The flow chart for control scheme implementation is shown in Fig. 4. The control scheme gives first priority to maintain feeder voltages within the allowable limits. In this paper, a variation of 5% from the rated value is taken as allowable limits. Using Newton Raphson load flow method [12], voltages at the different buses are computed. If the feeder voltages violates the predefined limit, minimization of voltage variations scheme is implemented using the voltage sensitivity analysis as reported in [13]. Based on the analysis, appropriate active and reactive powers is supplied by the ST LV converter. However, in case the voltage variations are within the limits with the active power balancing method, the same is implemented.

#### A. Power Balancing Control Scheme

Conventionally, the power balancing control algorithm ensures that the active and reactive powers in both the feeders are balanced. In the proposed scheme, not only the advantages of conventional LPC is preserved, but additionally, the reactive power demand of the feeder 2 is compensated by the MV converter of ST. Therefore, MV grid only exchanges active power. Let the active power demands of feeder 1 and 2 are  $P_{L1}$  and  $P_{L2}$ , respectively. Also, DG power generation by feeder 1 and 2 are  $P_{DG1}$  and  $P_{DG2}$ , respectively. For the power balancing in the feeders, the power flow through the each feeder (same through ST and LFT) is computed as follows:

$$P_{ST} = \frac{P_{DG1} + P_{DG2}}{2} - \frac{P_{L1} + P_{L2}}{2} - \frac{P_{loss}}{2} \quad (1)$$

where  $P_{loss}$  is losses in MV converter. If this power ( $P_{ST}$ ) is limited by the ST, the LFT will also exchange same power with the MV grid.

Let the reactive power demands of feeders 1 and 2 are  $Q_{L1}$  and  $Q_{L2}$ , respectively. Moreover, a fraction of the reactive power demand will be met by the ST LV converter. The remaining reactive power demand of loads will be supplied by

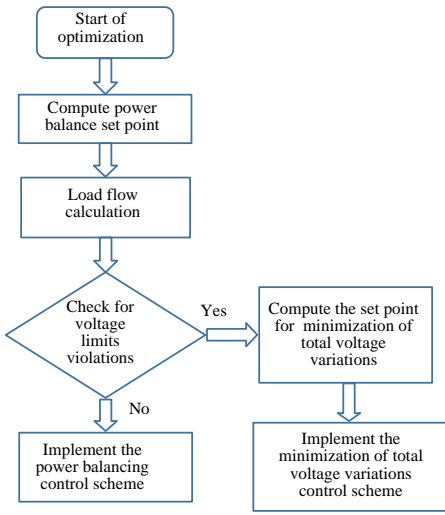


Fig. 4. Flow chart for control scheme implementation.

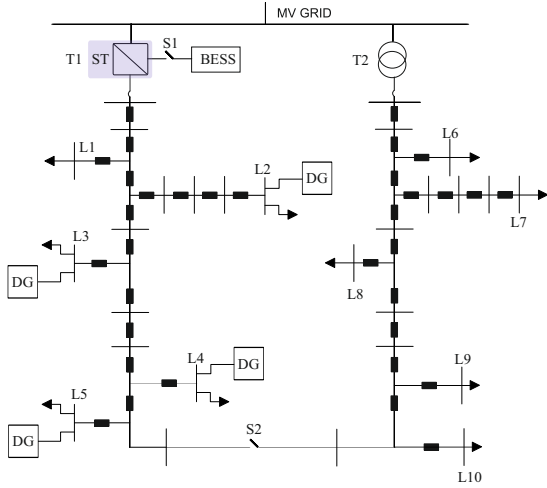


Fig. 5. Radial distribution system under consideration.

the ST MV converter. Let  $Q_{ST-LV}$  is reactive power supplied by the LV converter then MV convertor reactive power is computed as follows:

$$Q_{ST-MV} = (Q_{L1} + Q_{L2}) - Q_{ST-LV}. \quad (2)$$

### B. Minimization of Voltage Variations Control

For the three-phase system, let the total buses in the system are  $M$ . In the LVAC grid with three-phase four-wire configuration, each phase can be considered separately and therefore, an unbalanced network be analyzed with single phase computations. Node equation relating voltage at each bus and current injected to each bus, for three phases  $a$ ,  $b$ , and  $c$ , is given as

$$[\bar{\mathbf{I}}_j^{abc}] = [\bar{\mathbf{Y}}^{abc}] [\bar{\mathbf{V}}_j^{abc}] \quad (3)$$

where  $[\bar{\mathbf{Y}}^{abc}]$  is bus admittance matrix. Conventional load flow analysis using Newton Raphson method is implemented

to compute the voltages at the different buses of the feeder. If the power balancing control scheme can not maintain feeder voltages within limits, then minimization of voltage variations algorithm is implemented. The voltage at the ST LV converter terminal is maintained such that the voltage throughout the feeders 1 and 2 remains within the allowable limits, by supplying appropriate active and reactive powers.

Based on the sensitivity analysis outlined in [13], [14], voltage sensitivity coefficients for the different buses are computed.

$$k_{P,m} = \frac{\partial V_m}{\partial P_{ST}}, \quad m = 1, \dots, M. \quad (4)$$

$$k_{Q,m} = \frac{\partial V_m}{\partial Q_{ST}}, \quad m = 1, \dots, M. \quad (5)$$

These coefficients are computed with respect to the pre-defined voltage at the LVAC terminal, which is maintained by the ST LV converter. Based on the iteration process, a suitable voltage is computed which helps to minimize the total voltage variations along the feeder within the allowable range.

$$\min_{\Delta Q_{MV-ST}} \left\{ \sum_{m=1}^M (V_{MV,m} + K_{Q,m} \Delta Q_{MV-ST} - V^*)^2 \right\} \quad (6)$$

Moreover, this voltage is maintained through appropriate injection of active and reactive powers into the LV distribution grid with the restriction of the size of ST.

$$P_{ST}^2 + Q_{ST}^2 \leq S_{ST}^2. \quad (7)$$

### C. ST based BESS Grid Supporting Control

The BESS connected at the LVDC of ST can support the active power demand of loads during the peak load demand. In that case, both the LV and MV converters of ST can be utilized to inject active power to the loads. The amount of support depends upon the capacity of the battery bank. In general if the MV and LV converters support active power of  $P_{ST-MV}$  and  $P_{LV-ST}$ , respectively then the power supplied by the MV grid is as follows:

$$P_{MV} = (P_{L1} + P_{L2}) - (P_{DG1} + P_{DG2}) - (P_{ST-MV} + P_{ST-LV}). \quad (8)$$

When BESS is activated for supporting the loads during peak demand, it is necessary to maintain feeder voltages within the allowable limits. Therefore, the ST LV converter active power is computed based on the minimization of voltage variations control action. After injecting active power through LV power converter, the additional available BESS power is supplied into the MV grid through the ST MV converter. Therefore, the ST MV converter power injection is

$$P_{ST-MV} = P_{BESS-rated} - P_{ST-LV}. \quad (9)$$

In addition to supporting the electric grid during peak load demand, active power support from both MV and LV converters also improves utilization of ST in this proposed configuration.

TABLE I  
LOAD OF FEEDER I

Bus No.	Peak penetraion		Low penetration	
	DG generation (kVA)	Load (kVA)	DG generation (kVA)	Load (kVA)
L1	0	10+j2	0	20+j4
L2	30	20+j4	10	30+j6
L3	10	20+j4	0	20+j4
L4	50	10+j2	25	20+j4
L5	100	20+j4	50	20+j4

TABLE II  
LOAD OF FEEDER II

Bus No.	Peak load (kVA)	Low load (kVA)
L6	30+j6	15+j3
L7	80+j16	40+j8
L8	50+j10	25+j5
L9	25+j5	12.5+j2.5
L10	60+j12	30+j6

## V. CASE STUDY

The configuration of radial distribution system considered in this paper is shown in Fig. 5. Both feeders are derived from [15]. Both the LFTs and ST are rated for 220 kVA. Feeder 1 consists of significant DG whereas feeder 2 has mainly loads. Loads and DG penetration information for both the feeders are given in Tables I and II. The system is implemented using power system computer aided design (PSCAD) software. Four cases are considered and explained as follows.

### Case I: High DG Penetration and High Load Demand

The first case considers the high DG penetration and high load demand case simultaneously. The voltage magnitude at different buses are in Fig. 6(a). Firstly, both the feeders use LFT without loop and it can be seen that the voltages at bus L4, L5, L7, L8, L9, and L10 are outside the allowable limits. For buses L4 and L5, the voltage is higher than the limit. Moreover, the voltages are lower than the minimum threshold for other buses. When the LFT is replaced by ST in feeder 1 and power balancing control is activated, the voltage at all the buses are within the limits. In the power balancing control, the active power in the ST is set as given by (1). It ensures that the feeder with LFT also exchanges same amount of power. The power balancing is able to bring bus voltages within the limits. The minimization of voltage variations scheme is implemented to see the effects of this control action. It can be observed that the voltages are more close to the nominal value when the minimization of voltage variations scheme is activated.

### Case II: Low DG Penetration and High Load Demand

In this case, low DG penetration and high load demand is assumed. The voltages are shown in Fig. 6(b). The voltages at buses L7, L8, L9, L10 are below the minimum value required. With the power balancing control action, the voltages at all the buses are improved and brought within the limits, except, the voltage at bus L7 is still below 0.95 p.u. Therefore, the power balance control scheme is not sufficient to maintain an

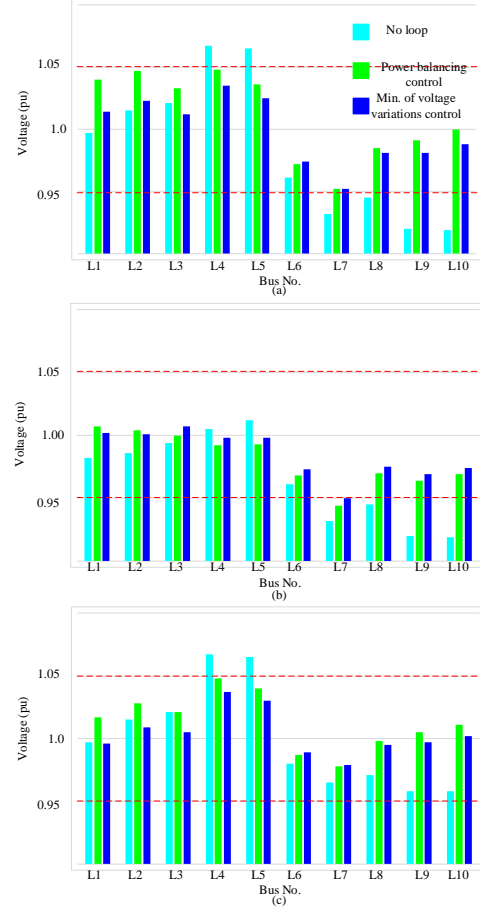


Fig. 6. Voltage profile at different buses for different control schemes. (a) High DG penetration and high load demand. (b) Low DG penetration and high load demand. (c) High DG penetration and low load demand.

allowable voltage in the feeders. However, once the minimization of voltage variations control action is realized, all the bus voltages are improved, brought within the limits and are more close to the nominal value.

### Case III: High DG Penetration and Low Load Demand

This case investigates high DG penetration and low load demand scenario. Without any control with open lines, the voltages at bus L4 and L5 are more than 1.05 p.u as shown in Fig. 6(c). Activating the loop power control strategy, the voltages are within the limits. If the minimization of voltage variations control is considered, the bus voltages are more



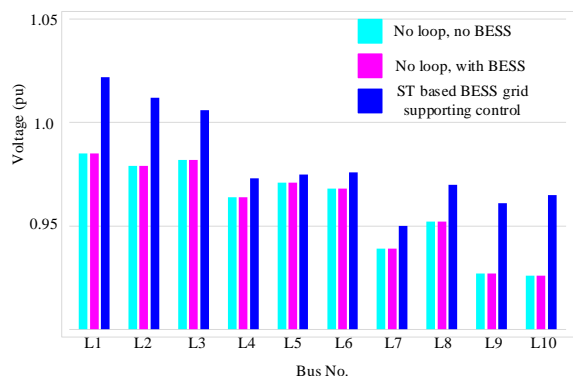


Fig. 7. Voltage profile at different buses for different control schemes with high load demand with BESS (without DG penetration.)

closer to the nominal voltage.

From the above results, it can be concluded that the loop power control with the ST can improve the voltage profile in the feeders. In case this method is not sufficient, minimization of voltage variations control action brings the bus voltages within the allowable limits.

#### Case IV: High Load Demand with BESS (No DG Available)

The voltages at different buses in the feeders are shown in Fig. 7. Both the feeders are heavily loaded and the DG penetration is negligible. As a first scenario when two feeders are operating independently without loop, the feeders are supplied through the LFTs and the BESS was not activated. All the power was supplied by grid. In this case, the voltages at buses L7, L8, L9, L10 are below 0.95 p.u.

In the second scenario, the BESS is pressed into the service having a rating of 200 kW. However, the feeders are still not looped. In this scenario, the power extraction from the electric grid reduces. However, as can be seen from Fig. 7, the voltages of buses are not improved. Since the MV grid voltage is assumed constant, supplying power from BESS has same effect as extracting power from electric grid and does not affect the voltage variations.

The BESS connected at the LVDC of ST in proposed scheme is activated as a third scenario. The minimization of voltage variations scheme is implemented to find out amount of active and reactive power injections from the ST LV converter. This can be seen that the voltage in the feeder is improved and brought within the allowable limits. Moreover, this configuration also allows MV power converter of the ST to utilize the remaining BESS power capacity to support the active power demand in MV grid.

## VI. CONCLUSIONS

In this paper, the ST has been proposed to achieve the advantages of loop power flow controller in the radial distribution grid. The proposed configuration replaces one of the LFT from the grid as well as BTB converter based LPC. With estimation of ST LV converter active and reactive powers injection for total voltage improvement, the ST maintains the

voltage throughout the feeders within the allowable limits even during the extreme loading scenarios. Moreover, the power balancing control action allows the ST to balance the load power of the feeders which avoids the overloading of the LFT. The integration of BESS at the DC link of ST in the proposed configuration allows injection of active power from both MV and LV converters of ST, enhancing the ST utilization.

## VII. ACKNOWLEDGMENT

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