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A Novel Strategy for Reduction of Distribution System Losses using UPFC

SK. Vinod Babu and B. Loveswara Rao

Department of EEE, K L University, Green Fields, Vaddeswaram, Guntur - 522502, Andhra Pradesh, India; Vinodbabu.sk@gmail.com, loveswararao@kluniversity.in

Abstract

Objective: Reduction of distribution system losses is of great significance in the present times. FACTS controller is discussed as the chosen system for this. **Method**: The isolated salutation loop and multiple loop with the same structures are taken range for comparison analysis. By nullified line voltage rotation, many schemes have been evaluated to achieves minimize of loss. Current flowing through the loop algorithm sustainable compression is made over label. **Finding:** It's formed that UPFC injection is necessary distribution loss to minimum for many loss minimization. Radial analysis are found to be single. Finally loss minimization using UPFC is implemented in simulation node. **Application**: Many areas of applications is in impression phenomenon.

Keywords: Compensation Scheme, Distribution System, FACTS Controller, Isolated Distribution System, Loop Distribution System, (UPFC)

1. Introduction

FACTS controllers show innumerable advantages including increase of power transfer capability, damping out power oscillations, stability improvement, etc. UPFC[1] is one such device which effectively accomplishes the above mentioned tasks. It is found out to be instrumental in reducing the voltage losses in case of the different configuration of distribution system. The transmission[2] and distribution system together are called bulk power system. Now days, the current trend in research is witnessing a gradual shift from transmission to distribution side and is mainly focused on distribution system owing to the fact that the losses in the distribution side are more. In Indian scenario, the distribution system losses are found be very high compared to other countries. These losses are generally unaccountable and incorporated in AT&C losses (Aggregate Technical & Commercial losses)[3]. In some of the North-Eastern states, the AT&C losses across 50%, which means the power loss is half of the consumed power. For the purpose of conservation of energy, the system losses have to minimized.

The distribution systems are classified as loop and radial type. Radial systems[4] are simple and easy to implement but they happen to be weak for large loads. Loop type distribution systems are gaining prominence due to ever growing increase in power. Two different types of loop distribution systems are considered in this paper, namely isolated substation loop and multiple loop fed from same substation. However, minimization of the

*Author for correspondence

system loss happens to be a common issue which needs to be addressed in the distribution system side.

Distribution system engineers came out some wise solutions to tackle the problem existing in the system, among them being reconfiguration strategy. Reconfiguration[5] of the existing radial system to loop system is done especially at medium voltage level resulting in isolated substation loop system and multiple loop system as depicted in Figure 1. Reconfiguration of radial feeders are connected to individual substations results in isolation substation loop distribution system. Here, current flowing through the loop is due to the result of line parameters and also voltage difference between the substations. Reconfiguration of radial feeders (two or more) are fed from one substation resulting in the formation of two or more adjacent loops results in multiple loop system. The current flowing through the loop maybe due to asymmetrical components[6] of the line parameters as they are fed from the same substation.

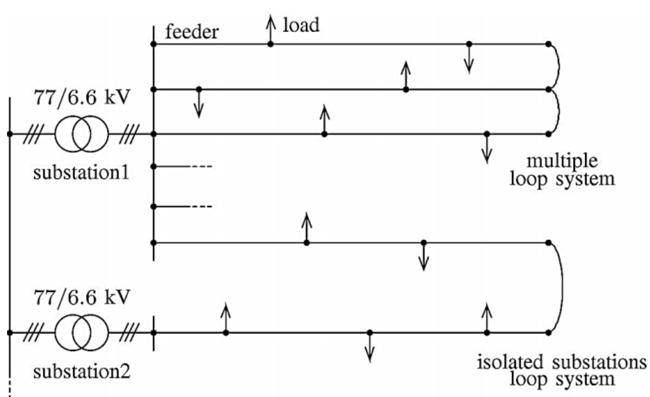


Figure 1. Typical distribution system setup.

Various schemes are proposed for loss reduction such as active filters based power electronic circuits and usage of FACTS controllers[7]. FACTS devices have emerged as a lucrative solution for achieving the task of distribution loss minimization. In order to enhance the voltage profile and loss reduction and achieve feeder power balancing, back to back cascaded[8] converter is used. Mitigation of overloading in addition to loss reduction by using power controller inserted in the loop for the purpose of feeder reconfiguration is introduced in. Voltage regulation scheme is proposed but it fails to ensure that voltages of other lines will be within permissible range during system loss reduction. The voltage magnitude along with the angle is controlled to maintain all the voltage levels be within the permissible values. The reference voltage is obtained based on load drop in the system. The reference angle is calculated from the loss reduction condition.

The loss reduction is achieved by nullifying the effect of the current flowing across the loop if R/X ratio is equal across all the lines. This is feasible in case of same substation loop whereas in case multiple substation feeding, we cannot achieve same R/X ratio due to the voltage difference between them which might result in the flow of circulating currents in the system.

The detailed mathematical model of the proposed system with different configurations of the distribution system is discussed in this paper. Distribution loss minimization strategies for these configurations are elaborated in detail in this paper. UPFC is used to achieve the loss reduction effectively compared to other existing conventional methods. The series converter compensates the necessary voltage difference to ensure that the loop currents remain zero at any point of time. Therefore, the control schemes have also been proposed to mitigate the problem of power loss in the distribution system. The proposed schemes are validated via extensive simulation based case studies.

2. Isolated Substations Loop Distribution System

Figure 2 shows the circuit configuration of isolated type system. From the diagram it is clearly evident that UPFC is installed in line1 of the loop. It can be seen that UPFC acts a compensator connected in series in the loop to alter the flow of electric power. The UPFC shunt current[9,10] is very small and can be easily neglected as it controls the voltage of the dc-link. Ideally, the UPFC is equivalent to voltage source in series with the loop. Three lines constitute the loop system with each having line reactance and resistance. Therefore, the equivalent impedance of the line is given by Zi, which is the summation of the reactance and resistance of the line. The unique feature of isolated substation loop system is that it is fed from two different substations. The loads connected to the loop are Il1 and Il2. The UPFC is diagrammatically represented as Vc.

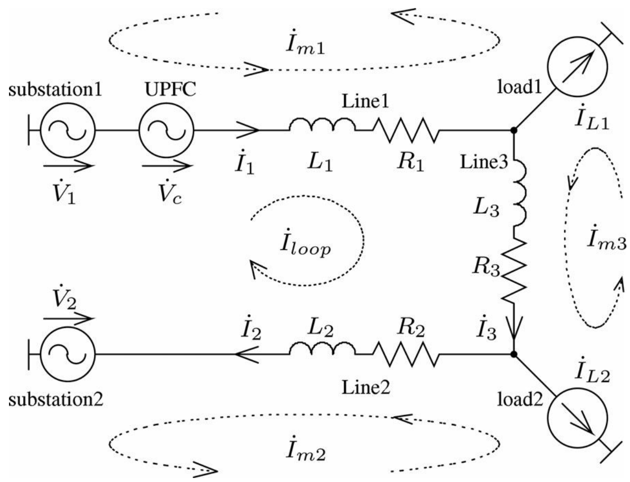


Figure 2. Isolated substations loop system.

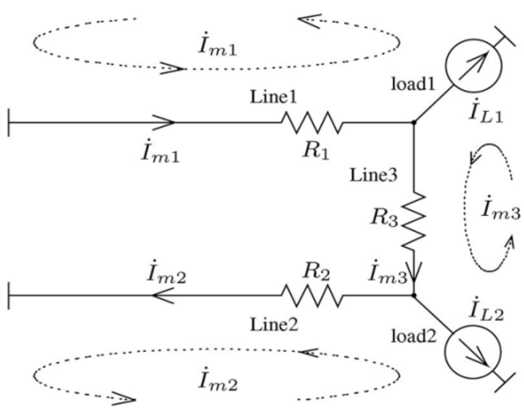


Figure 3. Transformed loss reduction circuit.

From figure 2, we have the line currents obtained using superposition theorm,

$$\dot{I}_1 = \frac{(\dot{Z}_2 + \dot{Z}_3)\dot{I}_{L1} + \dot{Z}_2\dot{I}_{L2} + (\dot{V}_1 - \dot{V}_2)}{\dot{Z}_{loop}}$$

$$\dot{I}_2 = \frac{-\dot{Z}_1\dot{I}_{L1} - (\dot{Z}_1 + \dot{Z}_3)\dot{I}_{L2} + (\dot{V}_1 - \dot{V}_2)}{\dot{Z}_{loop}}$$

$$\dot{I}_3 = \frac{-\dot{Z}_1\dot{I}_{L1} + \dot{Z}_2\dot{I}_{L2} + (\dot{V}_1 - \dot{V}_2)}{\dot{Z}_{loop}} \tag{1}$$

Where $\dot{Z}_{loop} = \sum_{i=1}^{3}\dot{Z}_i, R_{loop} = \sum_{i=1}^{3} R_i, L_{loop} = \sum_{i=1}^{3} L_i$ (2)

According to the electrical energy laws, the line currents can be divided into two currents, namely current during loss minimization and current flowing through the loop[11] or can also called as circulating current.

$$\dot{I}_i = \dot{I}_{im} + \dot{I}_{loop} \tag{3}$$

Where Ii is the line current, Imi is current during loss minimization, Iloop is the current flowing through the loop.

$$\dot{I}_{m1} = \left\{(R_2 + R_3)\dot{I}_{L1} + R_2\dot{I}_{L2}\right\} / R_{loop}$$

$$\dot{I}_{m2} = \left\{-R_1\dot{I}_{L1} - (R_1 + R_3)\dot{I}_{L2}\right\} / R_{loop}$$

$$\dot{I}_{m3} = \left\{-R_1\dot{I}_{L1} + R_2\dot{I}_{L2}\right\} / R_{loop} \tag{4}$$

$$\dot{I}_{loop} = -\frac{1}{R_{loop}}\left\{\sum_{i=1}^{3} jwL_i\dot{I}_i + (\dot{V}_2 - \dot{V}_1)\right\} \tag{5}$$

The total electric power loss is given by

$$P_l = \sum_{i=1}^{3} R_i\left|\dot{I}_i\right|^2$$
$$= \sum_{i=1}^{3} R_i\left|\dot{I}_{im}\right|^2 + 2\left\{\sum_{i=1}^{3} R_i\left|\dot{I}_{im}\right|\right\}.\dot{I}_{loop} + R_{loop}\left|\dot{I}_{loop}\right|^2 \tag{6}$$

$$P_{l\min} = \sum_{i=1}^{3} R_i\left|\dot{I}_{im}\right|^2 \tag{7}$$

In general, the loss are said to be reduced, if the effect of the loop current is nullified. The minimized total electric power loss is given by

Loss reduction is possible only when,

$$\sum_{i=1}^{3} jwL_i\dot{I}_i + (\dot{V}_2 - \dot{V}_1) = 0 \tag{8}$$

$$R_1/L_1 = R_2/L_2 = R_3/L_3$$
$$\dot{V}_2 - \dot{V}_1 = 0 \tag{9}$$

Post installation of UPFC[12] which ideally acts like a voltage regulator or something like more of a tap changing transformer, which compensates for the voltage fluctuations occurring in the system. The main aim of inserting this device is to achieve the task of distribution system loss reduction by nullifying the effect of the loop current.

In order to achieve this task, two compensation control schemes are presented.

- Line voltage compensation scheme
- Line inductance compensation scheme

Two schemes work for the common objective i.e., loss reduction in the system.

In case voltage scheme, UPFC voltage is given by

$$\dot{V}_c = \sum_{i=1}^{3} jwL_i\dot{I}_i + \left(\dot{V}_2 - \dot{V}_1\right) \tag{10}$$

$$v_c = \sum_{i=1}^{3} L_i \frac{di_1}{dt} + \left(v_2 - v_1\right) \tag{11}$$

This scheme is used if and only if R/X ratio is not same in any two lines across the loop.

In case of inductance scheme, UPFC inserts virtual inductance (Lc) which bears same ratio of R/X across the loop. The virtual inductance is given by

$$R_1/(L_1 + L_c) = R_2/L_2 = R_3/L_3 \tag{12}$$

$$L_c = \left(R_1/R_2\right)L_2 - L_1 \tag{13}$$

The UPFC voltage is given by

$$\dot{V}_c = -jwL_c\dot{I}_1 + \left(\dot{V}_2 - \dot{V}_1\right) \tag{14}$$

$$v_c = -L_c \frac{di_1}{dt} + \left(v_2 - v_1\right) \tag{15}$$

This scheme is applicable if any single line in the loop has different R/X ratio. The UPFC reference voltage is obtained using the line currents in addition to substation voltages. Bo the schemes rely on loop current in order to achieve loss minimization.

$$\dot{Z}_1 = R_1 + jwL_1$$
$$R_1 = n^2 R_{1a} + R_{1b}$$
$$L_1 = n^2 L_{1a} + L_{1b}$$

3. Multiple Loop Distribution System

Figure 4 depicts the multiple loop distribution system[13,14]. The radial feeders are running parallel are fed from the same substation to form two loops and connected to the adjacent loads. It is also seen form the figure, the Line 1 has step voltage regulator (SVR) for load voltage compensation. The electrical equivalent circuit diagram of the multiple loop system is enacted in Figure 5.

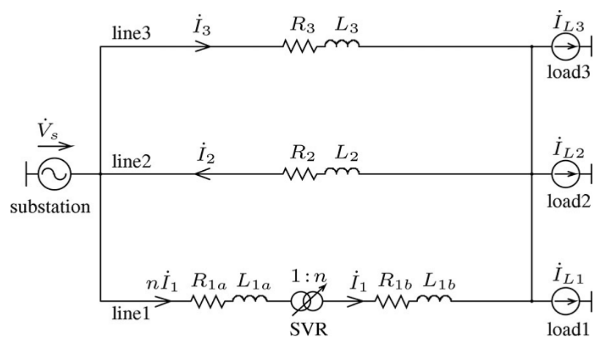


Figure 4. Multiple loop system.

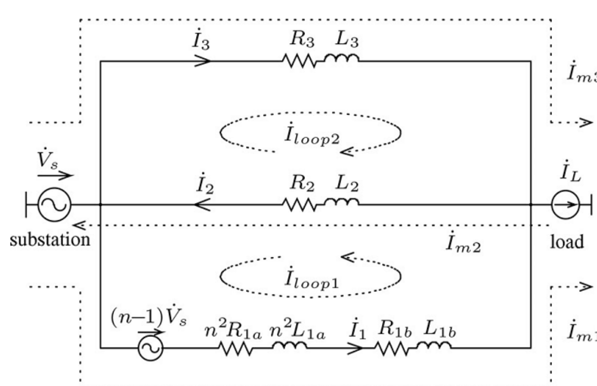


Figure 5. Electrical circuit of multiple loop configurations.

The line currents are given by the summation of the currents during loss reduction and circulating currents flowing in the loop.

Mathematically,

$$\dot{I}_1=\frac{1}{\dot{Z}_1+\frac{\dot{Z}_2\dot{Z}_3}{\dot{Z}_2+\dot{Z}_3}}\left\{\frac{\dot{Z}_2\dot{Z}_3}{\dot{Z}_2+\dot{Z}_3}\dot{I}_L+(n-1)\dot{V}_s\right\}$$

$$\dot{I}_2=\frac{-1}{\dot{Z}_2+\frac{\dot{Z}_1\dot{Z}_3}{\dot{Z}_1+\dot{Z}_3}}\left\{\frac{\dot{Z}_1\dot{Z}_3}{\dot{Z}_1+\dot{Z}_3}\dot{I}_L-\frac{\dot{Z}_3}{\dot{Z}_1+\dot{Z}_3}(n-1)\dot{V}_s\right\}$$

$$\dot{I}_3=\frac{1}{\dot{Z}_3+\frac{\dot{Z}_1\dot{Z}_2}{\dot{Z}_1+\dot{Z}_2}}\left\{\frac{\dot{Z}_1\dot{Z}_2}{\dot{Z}_1+\dot{Z}_2}\dot{I}_L-\frac{\dot{Z}_2}{\dot{Z}_1+\dot{Z}_2}(n-1)\dot{V}_s\right\} \quad (16)$$

Where

$$\dot{I}_L=\dot{I}_{L1}+\dot{I}_{L2}+\dot{I}_{L3} \quad (17)$$

The line currents are obtained from the loop currents as follows

$$\dot{I}_1=\dot{I}_{m1}+\dot{I}_{loop1}$$

$$\dot{I}_2=\dot{I}_{m2}+\dot{I}_{loop1}+\dot{I}_{loop2}$$

$$\dot{I}_3=\dot{I}_{m3}+\dot{I}_{loop2} \quad (18)$$

$$\dot{I}_{loop1}=\frac{-\left(\dot{V}_{m1}+\dot{V}_{m2}-(n-1)\dot{V}_s\right)+\frac{\dot{Z}_2}{\dot{Z}_2+\dot{Z}_3}\left(\dot{V}_{m2}+\dot{V}_{m3}\right)}{\dot{Z}_1+\frac{\dot{Z}_2\dot{Z}_3}{\dot{Z}_2+\dot{Z}_3}} \quad (19)$$

$$\dot{I}_{loop2}=\frac{\frac{\dot{Z}_2}{\dot{Z}_1+\dot{Z}_2}\left(\dot{V}_{m1}+\dot{V}_{m2}-(n-1)\dot{V}_s\right)+\left(\dot{V}_{m2}+\dot{V}_{m3}\right)}{\dot{Z}_3+\frac{\dot{Z}_1\dot{Z}_2}{\dot{Z}_1+\dot{Z}_2}} \quad (20)$$

$$\dot{V}_{im}=\dot{Z}_i\dot{I}_{im} \quad \text{(i=1,2,3)} \quad (21)$$

During the Loss reduction, the circuit is modified as shown in Figure 6

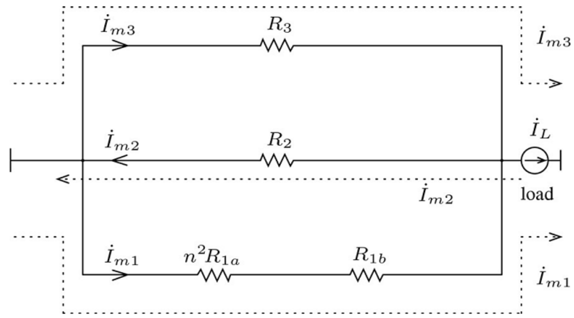


Figure 6. Transformed loss reduction circuit.

The losses are minimized if the loop current is nullified in the same substation fed multiple loop system. This is achieved by using series compensator for providing necessary voltage supplement due to voltage drop across inductance in the system.

Here the line currents during loss reduction condition are given by

$$\dot{I}_{m1}=\frac{1}{R_1+\frac{R_2R_3}{R_2+R_3}}\left(\frac{R_2R_3}{R_2+R_3}\dot{I}_L\right)$$

$$\dot{I}_{m2}=\frac{-1}{R_2+\frac{R_1R_3}{R_1+R_3}}\left(\frac{R_1R_3}{R_1+R_3}\dot{I}_L\right)$$

$$\dot{I}_{m3}=\frac{1}{R_3+\frac{R_1R_2}{R_1+R_2}}\left(\frac{R_1R_2}{R_1+R_2}\dot{I}_L\right) \quad (22)$$

$$\dot{I}_{loop1}=\frac{-\left(\dot{V}_1+\dot{V}_2-(n-1)\dot{V}_s\right)+\frac{R_2}{R_2+R_3}\left(\dot{V}_2+\dot{V}_3\right)}{R_1+\frac{R_2R_3}{R_2+R_3}}$$

$$\dot{I}_{loop2}=\frac{\frac{R_2}{R_1+R_2}\left(\dot{V}_1+\dot{V}_2-(n-1)\dot{V}_s\right)+\left(\dot{V}_2+\dot{V}_3\right)}{R_3+\frac{R_1R_2}{R_1+R_2}} \quad (23)$$

$$\dot{V}_i=jwL_i\dot{I}_i \quad \text{(i=1,2,3)} \quad (24)$$

The primary objective of distribution system study is said to be fulfilled if the loop currents are nullified from the system satisfactorily. The rate of total electric energy loss in case multiple loop system is given by

$$\begin{aligned} P_l &= \sum_{i=1}^{3} R_i \left|\dot{I}_i\right|^2 \\ &= \sum_{i=1}^{3} R_i \left|\dot{I}_{in}\right|^2 + 2\left(R_1\dot{I}_{m1} + R_2\dot{I}_{m2}\right).\dot{I}_{loop1} \\ &+ 2\left(R_2\dot{I}_{m2} + R_3\dot{I}_{m3}\right).\dot{I}_{loop2} + R_1\left|\dot{I}_{loop1}\right|^2 \\ &+ R_2\left|\dot{I}_{loop1} + \dot{I}_{loop2}\right|^2 + R_3\left|\dot{I}_{loop2}\right|^2 \end{aligned} \tag{25}$$

Therefore, the power loss after loss reduction is given by

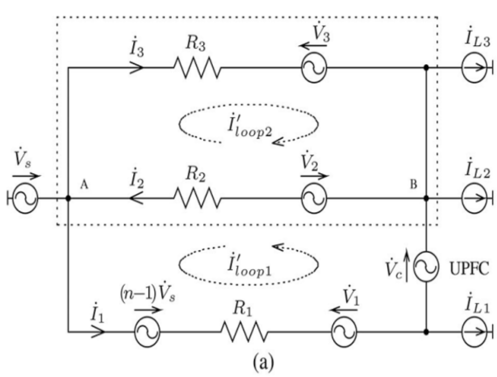
$$P_{l\min} = \sum_{i=1}^{3} R_i \left|\dot{I}_{in}\right|^2 \tag{26}$$

For loss reduction, the following conditions are to be met

$$\begin{aligned} &\dot{V}_1 + \dot{V}_2 - (n-1)\dot{V}_s = 0 \\ &\dot{V}_2 + \dot{V}_3 = 0 \end{aligned} \tag{27}$$

Post installation of UPFC in multiple loop system results in significant minimization of losses in the system through altering the flow of electric power across the loop. The dynamics of the loop is considerably modified to suit the requirement of loss minimization and thereby enhancing the capability and efficiency in terms of power flow in distribution system.

The modified circuit of multiple loop system is shown in Figure 7(a). For simplification of the circuit, the Thevenin's theorem[15,16] is applied the system and resulting circuit versions are available in Figure7(b) & Figrue7(C).



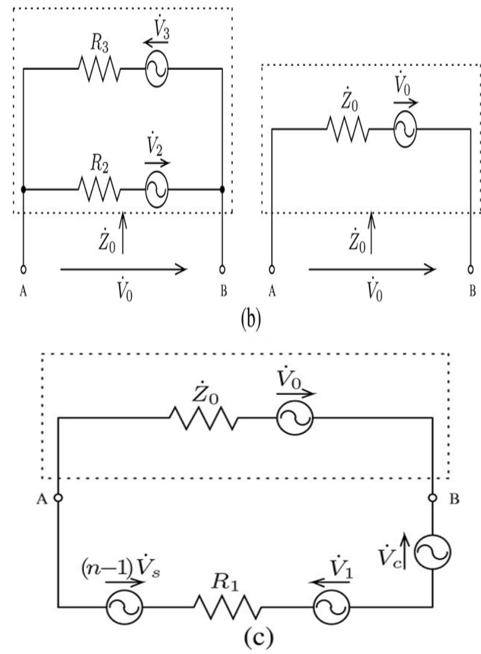


Figure 7(a). Circuit after installation of UPFC. **(b)** The venin's equivalent circuit of line 2 and line 3. **(c)** Equivalent circuit as per The venin's theorem.

The impedance of the feeders running in parallel (Line 2 and Line 3) are approximately represented Zo in series with the voltage source.

$$\begin{aligned} \dot{Z}_0 &= \frac{R_2R_3}{R_2+R_3} \\ \dot{V}_0 &= \frac{R_3}{R_2+R_3}\dot{V}_2 - \frac{R_2}{R_2+R_3}\dot{V}_3 \end{aligned} \tag{28}$$

$$\dot{V}_c = \dot{V}_1 + \dot{V}_0 - (n-1)\dot{V}_s \tag{29}$$

$$\begin{aligned} \dot{I}'_{loop1} &= 0 \\ \dot{I}'_{loop2} &= -\frac{\dot{V}'_2 + \dot{V}'_3}{R_2+R_3} \end{aligned} \tag{30}$$

Where

$$\begin{aligned} \dot{V}'_i &= jwL_i\dot{I}'_i \\ \dot{I}'_i &= \dot{I}_{m1} \\ \dot{I}'_2 &= \dot{I}_{m2} + \dot{I}'_{loop2} \\ \dot{I}'_3 &= \dot{I}_{m3} + \dot{I}'_{loop2} \end{aligned} \tag{31}$$

The UPFC voltage is given by

$$v_c = L_1 \frac{di_1}{dt} + \frac{R_3}{R_2 + R_3} L_2 \frac{di_2}{dt} - \frac{R_2}{R_2 + R_3} L_3 \frac{di_3}{dt} - (n-1)v_s \tag{32}$$

The series voltage is controlled by the parameters of the lien and current flowing across the line. The changes in the parameters due to changes in the temperature are minimum and hence negligible. The power loss in each line is the difference between sending and receiving powers of end points[17-20].

4. Simulation Study

The extensive simulation study of the proposed control schemes is elaborated in this section. The parameters of the isolated and multiple loop type distribution system are depicted in Table 1 and Table 2 respectively.

Table 1. Parameters of the isolated substations Loop system

Transmission Capacity	6 kVA
Substation voltages,v1,v2	200 V, 60 Hz
Substation voltages phase difference	10 deg
Load R_{L1}, R_{L2}	10 Ω, 30 Ω
Line1 L_1, R_1	4.0 mH, 0.94 **Ω**
Line2 L_2, R_2	4.0 mH, 0.91 **Ω**
Control period T_s	102 μs

Table 2. Parameters og the same substation multiple loop system

Transmission capacity	6 kVA
Sending-end voltage v_s	200 V, 60 Hz
Load $R_{L1} R_{L2} R_{L3}$	20 **Ω**, 60**Ω**, 60**Ω**
Line 1 $L_{1a} R_{1a}$	3.0 mH, 0.75**Ω**
Line 1 $L_{1b} R_{1b}$	3.0 mH, 0.75**Ω**
Line 2 $L_2 R_2$	6.0 mH, 1.5**Ω**
Line 3 $L_3 R_3$	6.0 mH, 1.5**Ω**
Transformer ratio 1:n	1:1.07 (send:receive)
Control period T_s	204 μs

Case 1: Loss Minimization in Distribution System Connected to Linear Loads

The reference voltages are calculated as illustrated in (11) using the currents flowing through the lines and voltage of the source end. This is done to control the FACTS device in case of voltage compensatory scheme. UPFC effectively supplements the drop in the voltage across the line inductance as well as the voltage difference between the sources. The simulation waveforms of voltage difference between the source ΔV, UPFC reference voltage Vc, current flowing through the line 1 IL1 , current flowing through the line 2 $I_{L2,}$ current passing the loop I_{loop} are shown in Figure 8.

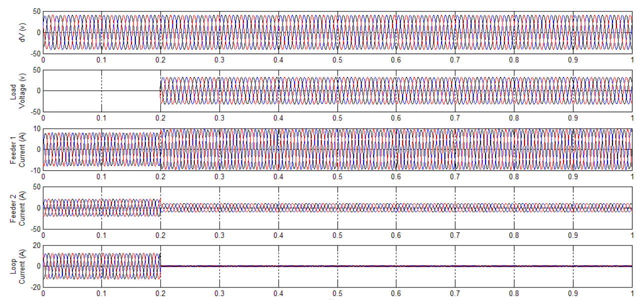


Figure 8. Simulation waveforms of the distribution system with UPFC.

Case 2: Loss Minimization in Distribution System Connected to Non-Linear Load

The proposed scheme is also extended to non-linear loads. Non-linear loads greatly affect power quality and tend to initiate the dangerous problem of harmonics. It may be sometimes deliberate or voluntary switching action which may be momentary in nature and might lead to fluctuations in system voltage or current waveform. These fluctuations are called harmonics. The order and magnitude of the harmonics injected into the system depends mainly on the type of load connected to the system. Linear loads, however do not result in generation of harmonics. For instance, daily home based appliances such as television sets, fridges, air conditioners, computer stationery, etc are few of the examples of non-linear loads. The presence of harmonics in the current waveform results in detrimental effect on power factor.

UPFC installed in the system apart from loss minimization, will also mitigate the problem of harmonics, thereby delivering quality power.

Figure 9 shows the simulation results for distribution system under two feeder considerations. From Figure 9(a) we observe that the harmonics generated by usage of non-linear load. And because of this harmonics the system may to damage. In order to protect the system from these problems an UPFC is helpful. From Figure 9(b), we observe that the shunt converter is act at a particular time of 2s, so that the harmonics compensated.

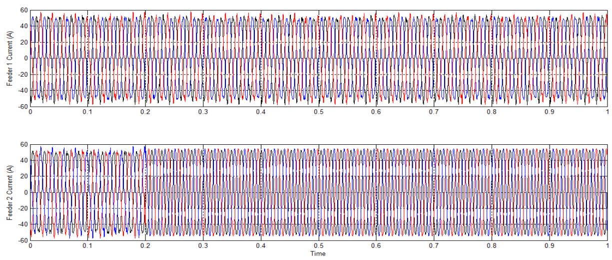


Figure 9. Simulation waveforms of feeder 1 current and feeder 2 current.

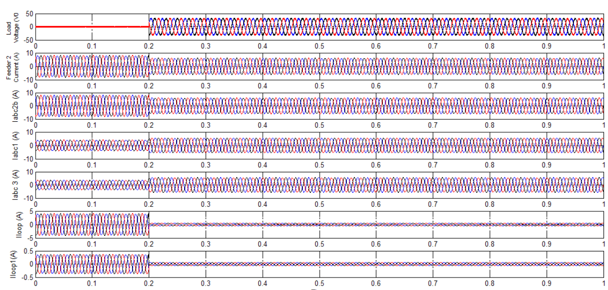


Figure 10. Simulation waveforms of distribution system with Non-Linear Load.

Figure 11 shows the simulation results for distribution system under two feeder considerations. From Figure 11(a) we observe that the harmonics generated by usage of non-linear load. And because of this harmonics the system may to damage. In order to protect the system from these problems an UPFC is helpful. From Figure 11(b), we observe that the shunt converter is act at a particular time of 2s, so that the harmonics compensated.

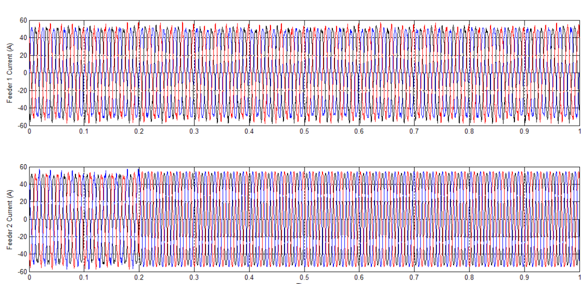


Figure 11. Simulation Waveforms of feeder current 1 and feeder 2 current.

5. Conclusion

The distribution system loss reduction and control schemes with installation of UPFC are discussed in detail. The mathematical analysis is also presented for the proposed schemes. The control schemes effectively compensate the voltage variations in the system and minimize the loop current, which ultimately results in system loss minimization. UPFC is effective FACTS device which acts constant voltage source connected in series with the loop, in other words, it acts as a series compensator. The simulation study is presented in detail to validate the theoretical hypothesis. Non-linear loads are also considered in this paper in addition to linear loads. It is seen that UPFC mitigates the problem of harmonics which arise due to presence of non-linear loads. UPFC is best suited device for loss reduction in case of single isolated and multiple loop substations and also tackle the problem of harmonics if any due to presence of arbitrary fluctuations or presence of non-linear loads.

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