Load Voltage Regulation and Line Loss Minimization of Loop Distribution Systems using UPFC

Joohi Darji¹ Anjali Rana² Jyoti Swamy³
¹, ², ³Department of Electrical Engineering
L. D. College of Engineering, Ahmedabad.

Abstract---This paper presents a new method for achieving load voltage regulation and line loss minimization in the loop distribution systems, simultaneously. First, the line loss minimum conditions in the loop distribution systems are presented. Then, load voltage regulation is achieved by using shunt compensation. To achieve these two objectives simultaneously, the Unified Power Flow Controller (UPFC) is used. The UPFC shunt converter is used as a shunt compensator to regulate the load voltage, and the UPFC series converter is used to control the power flow to achieve line loss minimization. The proposed control schemes of UPFC shunt and series converter are also investigated. The effectiveness of the proposed control schemes has been verified experimentally using laboratory prototype in a 200V, 6kVA system.

Key words: Loop distribution system, Voltage regulation, Line loss minimization, Series and shunt compensation, Unified Power Flow Controller (UPFC)

I. INTRODUCTION

Concerns over the global environment have led to an increase in using clean power sources such as photovoltaic and wind power generation systems using nature’s energy and cogeneration systems using waste heat. These power sources are generally dispersed in the distribution systems. However, the dispersed power sources complicate the power flow in distribution systems. Controlling the active and reactive power requires the installation of power electronic devices such as SVG (Static Var Generator) in the distribution systems.

Distribution networks may be classified as either radial or loop. The radial distribution systems are more desirable than loop distribution systems, and distribution engineers have preferred them because they use simple, inexpensive protection schemes. Radial distribution systems are used in Japan because when a fault occurs in the distribution system, the part of the fault can be isolated fast from the distribution system to avoid the influence of the fault.

Much of the recent research on distribution systems has been focused on voltage regulation and minimization of the power loss. Many researchers used distributed generation, series capacitors and shunt capacitor, connected in strategic location, to regulate the load voltage and minimize line loss by compensating the reactive power required by the loads. Other researches minimize the line loss and regulate the voltage in distribution system by reconfiguring the existing system using the sectionalizing switches. Also, many papers dealing with loss reduction and voltage regulation using FACTS devices have been introduced. Most of the papers used STATCOM, shunt active filter and series-shunt power converter to regulate and balance the voltage at the customer side and reduce the losses by reactive power injection. But in recent years, UPFC has been proposed to increase the power flow as well as an aid for system stability through the proper design of its controller. It is becoming the most important FACTS device since it can provide various types of compensation like voltage regulation, phase shifting regulation, impedance compensation and reactive compensation.

In this paper, achieving voltage regulation and total line loss minimization, simultaneously, in the loop distribution systems is investigated by using UPFC series and shunt converters. The shunt converter is used to regulate the load voltage, whereas the series converter is used to minimize the total line loss of the loop distribution system. The proposed control schemes of the UPFC series and shunt converters are also presented. Total line loss minimization and voltage regulation of the loop distribution system are investigated experimentally by using laboratory prototype in a 200kV, 6kVA system.

II. SIMPLIFIED MODEL OF DISTRIBUTION NETWORK

Taking account of the long transmission lines and multi-load nodes, the distribution network is often designed as a loop in order to ensure the reliability of power supply but usually operated in the radiation way. For convenient Illustration, a simplified distribution system model is adopted as an example in this paper, as shown in fig.1.

In fig.1, two lines are fed from substation. The first line supplies power to load 2 by line 3 and second one line 2 supplies power to load 1 directly. Under normal circumstances, the switch is off. When it is on, the grid in fig.1 forms a loop. In this model, impedances of line 1, 2, 3,
IV. LOAD VOLTAGE REGULATION

Load voltage regulation problems in distribution systems are commonly solved by using STATCOM, which has the ability to control voltage magnitude by compensating reactive power. However, STATCOM cannot control the line loss in loop distribution systems. On the other hand, series compensators like UPFC have the ability to regulate the load voltage and to minimize line loss simultaneously in the loop distribution system.

Fig. 3(a) shows the distribution system, represented by single phase Thevenin equivalent circuit, from the load terminal, with the shunt compensator. The shunt compensator is represented by a current source that injects a current $I_c$. $V_s$ and $V_r$ are source voltage and load voltage, respectively. The load current $I_l$, which equals the source current $I_s$ before installation of the shunt compensator, is assumed to be constant. Fig. 3(b) shows the phasor diagram of the whole system before installation of the shunt compensator. The load voltage is assumed to be the reference voltage. The voltage drop $ΔV$ at the load terminal and the load current $I_l$ can be formulated as follows[8]:

$$ΔV = V_s - V_r = (R_s + jX_s)I_l$$  \hspace{1cm} (1.4)

So that,

$$\bar{V}_r = \left|\bar{V}_r\right| \angle 0.0^\circ$$  \hspace{1cm} (1.4)

$$I_l = \frac{R_s - jX_s}{V_r}$$  \hspace{1cm} (1.4)

Thus, voltage drop can be divided into two components, $ΔV_r$ in phase with the load voltage, and $ΔV_x$ in quadrature with the load voltage.

After installing the shunt compensator, the source current can be calculated as follows:

$$I_s = I_l + I_c$$  \hspace{1cm} (1.7)

From (1.4) and (1.5),

$$|V_s|^2 = |V_r|^2 + \left|\frac{(R_s I_s + X_s Q_c)}{V_r}\right|^2 + \left|\frac{(X_s I_s - R_s Q_c)}{V_r}\right|^2$$  \hspace{1cm} (1.8)

Where,

$$Q_c = Q_l + Q_e$$  \hspace{1cm} (1.9)

Fig. 3(c) shows the phasor diagram of the whole system after installing the shunt compensator. By controlling the shunt compensator current $I_c$, it is possible to make the load voltage to be equal in magnitude to the source voltage, $|V_r| = |V_s|$; then the compensator reactive power, $Q_c$, can be calculated.

Load voltage regulation problems in the loop distribution systems can be solved by D-STATCOM that connected in parallel with the distribution lines to inject a controlled leading or lagging reactive power. The STATCOM is a voltage source converter that converts a dc voltage at its input terminals into a 3-phase set of ac voltages at fundamental frequency with controllable
magnitude and phase angle, and it is used as a reactive power compensator by absorbing or supplying reactive power. Under light load conditions, the controller is used to minimize or completely diminish line over voltage. Under heavy load conditions, it is used to maintain certain voltage levels.

In this paper, the main function of the UPFC series converter is to control the power flow in order to eliminate the loop current and hence minimize the total line loss of the loop distribution system. The function of the shunt converter is to regulate the dc link voltage and to regulate the load voltage to be equal in magnitude to the source voltage using reactive power injection simultaneously.

VI. PROPOSED CONTROL SCHEMES

A. Series converter control schemes

Two power flow control schemes are proposed to obtain the reference voltage $\hat{V}_c$ of the UPFC series converter for minimizing the total line loss of loop distribution system according to the system line parameters. These schemes are Line Inductance Compensation and Line voltage compensation. The shunt converter control scheme is also presented in this paper for regulating the load voltage.

1) Line Inductance Compensation

This scheme is used to compensate the line parameters of the loop distribution system to realize the relation shown in equation (1.2). This method can be used if the condition shown in equation (1.2) is realized for all loop lines except one. In this case, the relation of the line impedance parameters of the loop system in fig.2 is:

$$ R_1 \neq R_2 \neq R_3 \quad L_1 \neq L_2 \neq L_3 $$

In this case, the UPFC can be controlled to compensate line 1 inductance by inserting a series inductance, $L_c$. It is calculated as follows:

$$ L_c = \frac{R_1}{L_1 + L_c} $$

Considering the value of the inserted series inductance, $L_c$, the reference voltage of the UPFC series converter, $\hat{V}_c$ can be calculated, in the steady state as follows:

$$ \hat{V}_c = -j\omega L_c I_l $$
In order to achieve fast and accurate response of the UPFC, the reference voltage of the UPFC series converter will be formulated in the transient state as follows:

\[ v_c = -L_C \frac{di_1}{dt} \]  

(1.14)

2) Line voltage compensation scheme
This scheme is used to compensate the inductance voltage drop in each line of the loop system in order to achieve the condition shown in (1.3). This control scheme can be used if the relation of the line impedance parameters of the loop system shown in fig.2 is:

\[ \frac{R_1}{L_1} \neq \frac{R_2}{L_2} \neq \frac{R_3}{L_3} \]  

(1.15)

In this case, UPFC can be controlled to cancel the summation of the reactance voltage drop by inserting a series voltage, \( \Delta v \), equal in magnitude to the summation of the reactance voltage drop, but in the opposite direction. The value of \( \Delta v \) can be calculated using (1.3) as:

\[ \Delta v = \sum_{i=1}^{3} \Delta v_i \]  

(1.16)

\[ \sum_{i=1}^{3} \Delta v_i = 0 \]  

(1.17)

In order to achieve fast and accurate response of the UPFC, the reference voltage of the UPFC series converter will be formulated as:

\[ v_c = \sum_{i=1}^{3} L_i \frac{di_i}{dt} \]  

(1.18)

B. Shunt converter control scheme
Regulating the reactive power injected by the shunt converter is used to achieve a constant regulated voltage at its bus. Fig. 5 shows the block diagram of the proposed direct output voltage control scheme in which the AC and DC voltage regulation are realized by PI controllers. The commanded reactive power current \( I_q^* \) is determined by a conventional PI controller which regulates the magnitude of the bus voltage that the shunt converter connected to. The currents \( I_d^* \) and \( I_q^* \) can be used to calculate the reference voltage of the shunt converter.

\[ I_q^* = \frac{1}{3} \sum_{i=1}^{3} I_q^i \]  

\[ I_d^* = \frac{1}{3} \sum_{i=1}^{3} I_d^i \]  

Fig. 5: Control circuit of UPFC shunt converter

VII. EXPERIMENTAL SYSTEM CONFIGURATION
Fig.6 shows the 6kVA, 200V laboratory model of the distribution system and the UPFC. The distribution system consists of two sets three phase lines, line 1 and 2. The load supplied by the line 1 and line 2 is a pure resistance. \( R_1, L_1 \) and \( R_2, L_2 \) are the parameters of line 1 and line 2, respectively. The parameters of the whole system are listed in Table 1. The line parameters shown in Table 1 are chosen in order to obtain large difference between the resistance to inductance ratio of line 1 and 2, which causes a large loop current to flow in the loop system. In the practical distribution systems, the resistance to inductance ratio of each line is slightly different. The shunt converter connected

\[ V_{dc} = 250V \]  

\[ \frac{V_{dc}}{V_{source}} = 1:3 \]  

\[ \frac{V_s}{V_{source}} = 2:1 \]  

\[ T_s = 102 \mu s \]  

Table 1: System Parameters (6kva Base)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source voltage vs</td>
<td>200V, 60Hz</td>
</tr>
<tr>
<td>Load RL</td>
<td>10Ω (1.5p.u.)</td>
</tr>
<tr>
<td>Input L of shunt converter</td>
<td>3mH (0.16p.u.)</td>
</tr>
<tr>
<td>Line 1 L1</td>
<td>6mH (0.34p.u.)</td>
</tr>
<tr>
<td>Line 2 L2</td>
<td>0.15 Ω (0.02p.u.)</td>
</tr>
<tr>
<td>R2</td>
<td>0.85 Ω (0.13p.u.)</td>
</tr>
<tr>
<td>Capacitor C</td>
<td>3000μF</td>
</tr>
<tr>
<td>DC link voltage Vdc</td>
<td>250V</td>
</tr>
<tr>
<td>Transformation ratio</td>
<td>1:3 (system: series)</td>
</tr>
<tr>
<td>Transformation ratio</td>
<td>2:1 (system: shunt)</td>
</tr>
<tr>
<td>Switching time Ts</td>
<td>102μs</td>
</tr>
</tbody>
</table>

Control parameters of shunt converter

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC voltage regulator kp</td>
<td>0.30A/V</td>
</tr>
<tr>
<td>k</td>
<td>0.03A/Vs</td>
</tr>
<tr>
<td>DC voltage regulator kp</td>
<td>0.30A/V</td>
</tr>
<tr>
<td>k</td>
<td>0.30mA/Vs</td>
</tr>
</tbody>
</table>

VIII. EXPERIMENTAL RESULTS
A. Before installing UPFC
Experimental measurements are carried out to the laboratory model as shown in fig.6 before installation of UPFC. Table
2 shows a comparison between the theoretical and experimental values of each line current $i_1$, $i_2$, loop current $i_{loop}$, line load voltage $v_r$, UPFC shunt converter current $i_c$, series voltage $v_c$, each line loss $P_{1L}$, $P_{2L}$, total line loss $P_L$. From 0 to T1, Fig.7 and Fig.8 show the experimental waveforms of line 1 current, line 2 current, loop current, UPFC shunt converter current, actual and reference line to line load voltage $v_r$, voltage reference of the UPFC series converter $v_c$ and dc link voltage $v_{dc}$ in the loop system before installing the UPFC. From 0 to T1, only UPFC shunt converter is used to regulate the dc link voltage, and its current is negligibly small.

B. After installing UPFC shunt converter

Experimental measurements are carried out after installing shunt converter in the loop distribution system. Table 3 shows the experimental results of different line parameters. From T1 to T2 in fig.7 and 8 show the experimental waveforms of the currents and voltages in the loop system with the effect of the UPFC shunt converter only. In this period, the shunt converter is increased to compensate the load voltage. From these results, it is cleared that the UPFC shunt converter regulates the dc link voltage to be 250V and regulates the load voltage to be equal in magnitude to the source voltage, but the loop current increases to be 7.28A which causes the total line loss to increase to be 259W.Although the UPFC shunt converter reduces the load voltage, it is cleared that the series converter reduces the source voltage by using UPFC shunt converter. From T2 to T3, the UPFC series converter is used to eliminate the loop current and to achieve line loss minimum condition by using Line Inductance compensation scheme, while the shunt converter is used to regulate the dc link voltage and the load voltage. In this period, the loop current is eliminated from the loop system and the total line loss is reduced to be 79.14W by using UPFC shunt converter, and the load voltage is still equal in magnitude to the source voltage by using the UPFC shunt converter. From the waveforms, it is cleared that the series converter reduces the total line loss of the loop system by 43.54% from its original value before installation of shunt converter, 139.83W.

C. After installing UPFC shunt and series converter

In this case, UPFC series converter is inserted simultaneously with the shunt converter to eliminate the loop current, and hence to achieve minimum total line loss in the loop system.

1) Controlling series converter with Line Inductance Compensation scheme:

In fig.6, in order to apply the Line Inductance Compensation scheme to control the UPFC series converter, the values of the line 1 current and $L_c$ are needed to calculate the reference voltage of the UPFC series converter $v_c$, shown in (1.14). The line 1 current can be detected by a current sensor. The value of $L_c$ can be calculated from (1.12) as follows:

$$L_c = \frac{\alpha_1}{\alpha_2} \left( L_2 - L_1 \right) = \frac{0.15}{0.85} \times 3 - 6 = -5.47 \text{mH} \quad (1.19)$$

From T2 to T3, the UPFC series converter is used to eliminate the loop current and achieve the line loss minimum condition by using Line Inductance compensation scheme, while the shunt converter is used to regulate the dc link voltage and the load voltage. In this period, the loop current is eliminated from the loop system and the total line loss is reduced to be 78.95W by using UPFC series converter, and the load voltage is still equal in magnitude to the source voltage by using UPFC shunt converter. The reference voltage of UPFC series converter $v_c$ can be calculated as follows:

$$v_c = L_1 \frac{di_1}{dt} + L_2 \frac{di_2}{dt} \quad (1.20)$$

In fig.8, from T2 to T3, the UPFC series converter is used to eliminate the loop current and to achieve line loss minimum condition by using line voltage compensation scheme, while the shunt converter is used to regulate the dc link voltage and load voltage. In this period, the loop current is eliminated from the loop system and the total line loss is reduced to be 79.14W by using UPFC series converter, and the load voltage is still equal in magnitude to the source voltage by using UPFC shunt converter. Thus the series converter reduces total line loss by 43.4% from its original value before installation of UPFC shunt converter. From the experimental results, it is cleared that UPFC shunt converter has the capability to regulate the load voltage and UPFC series converter has a capability to minimize total line loss in the loop distribution system.

<table>
<thead>
<tr>
<th>Shunt converter only</th>
<th>Series and shunt converter</th>
</tr>
</thead>
<tbody>
<tr>
<td>$i_{loop}$</td>
<td>5.42 A</td>
</tr>
<tr>
<td>$v_r$</td>
<td>192.2 V</td>
</tr>
<tr>
<td>$i_c$</td>
<td>0.2 A</td>
</tr>
<tr>
<td>$v_c$</td>
<td>0.0 V</td>
</tr>
<tr>
<td>$P_{1L}$</td>
<td>8.63 W</td>
</tr>
<tr>
<td>$P_{2L}$</td>
<td>124.95 W</td>
</tr>
<tr>
<td>$P_L$</td>
<td>133.58 W</td>
</tr>
</tbody>
</table>

Table 2: Loop System Before Installation of UPFC Shunt And Series Converter

<table>
<thead>
<tr>
<th>Shunt converter only</th>
<th>Series and shunt converter</th>
</tr>
</thead>
<tbody>
<tr>
<td>$v_c$</td>
<td>190.5 V</td>
</tr>
<tr>
<td>$i_c$</td>
<td>13.1 A</td>
</tr>
<tr>
<td>$v_r$</td>
<td>0.0 V</td>
</tr>
<tr>
<td>$P_{1L}$</td>
<td>64.26 W</td>
</tr>
<tr>
<td>$P_{2L}$</td>
<td>14.69 W</td>
</tr>
<tr>
<td>$P_L$</td>
<td>78.95 W</td>
</tr>
</tbody>
</table>

Table 3: Experimental Results After Installation Of Upfc Shunt And Series Converter

<table>
<thead>
<tr>
<th>Circuit</th>
<th>Experimental</th>
<th>Theoretical</th>
</tr>
</thead>
<tbody>
<tr>
<td>$i_1$</td>
<td>4.12 A</td>
<td>4.38 A</td>
</tr>
<tr>
<td>$i_2$</td>
<td>7.2 A</td>
<td>7.0 A</td>
</tr>
</tbody>
</table>
IX. CONCLUSION

This paper has represented line loss minimum conditions, Line Inductance Compensation scheme and Line Voltage Compensation scheme of the UPFC to realize load voltage regulation and total line loss minimization simultaneously. So UPFC has the great capability to regulate load voltage and minimize total line loss in the loop distribution system simultaneously.

REFERENCES


