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

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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 230V, 6kVA system.*

Key Words: **Loop distribution system,Voltage regulation, loss minimization, Series compensation, Shunt compensation, and Unified Power Flow Controller (UPFC)**

1.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 230kV, 6kVA system.

2. 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.

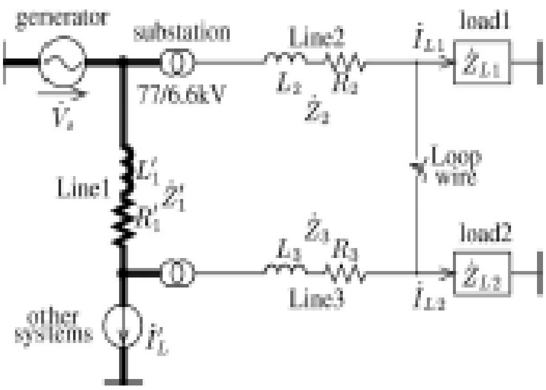


Fig-1: Model of Loop Distribution System

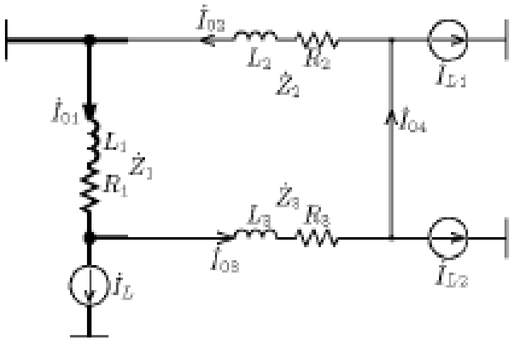


Fig-2: Approximate Model of Loop Distribution System

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, 3,4 are $\dot{Z}1' = R1' + j\omega L1'$, $\dot{Z}2 = R2 + j\omega L2$, $\dot{Z}3 = R3 + j\omega L3$ and $\dot{Z}4 = 0$, respectively. The load impedances are $\dot{Z}L1$ and $\dot{Z}L2$. The other systems that connected to loop system are represented by a current source $\dot{I}L'$. Fig- 2 shows the approximate model of the system shown in fig-1. The load currents $\dot{I}L1$ and $\dot{I}L2$, and the other systems current $\dot{I}L$ are assumed to be constant.

3. LINE LOSS MINIMUM CONDITIONS

Total line loss minimum conditions can be obtained in the loop distribution system from the total line loss equation that can be formulated by using the line currents that flow in the loop distribution system lines. The mathematical deviation process[5] is used for achieving total line loss minimum conditions. The change in the line currents is defined as the loop current $\dot{I}loop$, which circulates in the loop distribution system in the same direction (clockwise) and can be formulated as follows:

$$\dot{I}loop = \sum_{i=1}^{3} j\omega Li\, \dot{I}0i \Big/ Rloop \quad .....(1)$$

Total line loss minimum conditions can be realized by eliminating the loop current $\dot{I}loop$ from the loop system. Two conditions can be obtained by equating the loop current with zero. The first condition is:

$$\frac{R1}{L1} = \frac{R2}{L2} = \frac{R3}{L3} \quad ......(2)$$

In other words, if the lines of the loop distribution system are constructed by the same line type, the total line loss minimum is realized without using any controller.

The second condition is:

$$\sum_{i=1}^{3} j\omega Li\, \dot{I}0i = 0 \quad .... (3)$$

In other words, if the summation of the reactance voltage drop in the loop system is zero, the total line loss minimum is realized. Equations (2) and (3) have the same object because both of them eliminate the loop current from the loop distribution system and minimize the total line loss. The loop current can be eliminated by using the UPFC series converter.

4. 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.

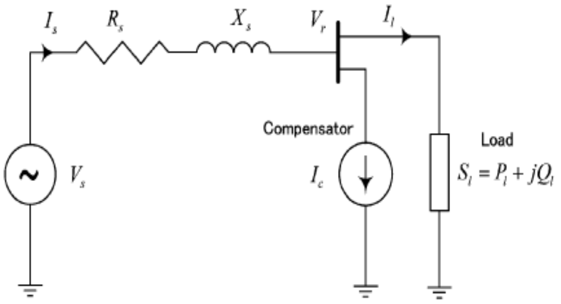


Fig-3: Single Phase Thevenin Circuit

Fig.-3 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 Ic. Vs and Vr are source voltage and load voltage, respectively. The load current Il, which equals the source current Is before installation of the shunt compensator, is assumed to be constant.

Fig-4 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 Il can be formulated as follows[8]:

$$\Delta\dot{V}=\dot{V}s-\dot{V}r=(Rs+jXs)\dot{I}l \quad ......(4)$$

$$\dot{V}r=|Vr|\angle 0^{\circ} \quad .....(4)$$

$$\dot{I}l=\frac{Pl-jQl}{\dot{V}r} \quad .....(4)$$

So that,

$$\Delta\dot{V}=(Rs+j\,Xs)\,\frac{Pl-jQl}{\dot{V}r}$$

$$=\frac{RsPl+XsQl}{\dot{V}r}+j\frac{XsPl-RsQl}{\dot{V}r} \quad .....(5)$$

$$=\Delta V_R+j\,\Delta V_X \quad .....(6)$$

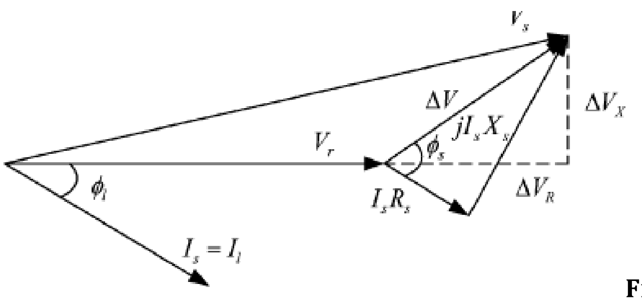


Fig -4: Phasor Diagram of System before installation of Shunt Compensator

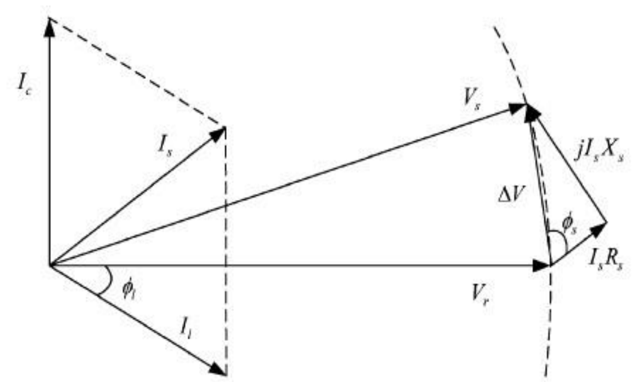


Fig-5: Phasor Diagram of System after installing Shunt Compensator

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:

$$\dot{I}s=\dot{I}l+\dot{I}c \quad ......(7)$$

From (4) and (5),

$$|Vs|^2=\left|\dot{V}r+\frac{RsPl+XsQs}{\dot{V}r}\right|^2 \quad ......(8)$$

Where,

$$Qs=Ql+Qc \quad .....(9)$$

Fig-5 shows the phasor diagram of the whole system after installing the shunt compensator. By controlling the shunt compensator current Ic, it is possible to make the load voltage to be equal in magnitude to the source voltage, $|Vr|=|Vs|$; then the compensator reactive power, Qc, 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, since the UPFC shunt converter has the same circuit configuration of the D-STATCOM, the function of the D-STATCOM to regulate the load voltage is achieved by using the UPFC shunt converter. It is used to regulate the dc link voltage and load voltage simultaneously. The load voltage is regulated to be equal in magnitude to the source voltage.

5. CONFIGURATION OF UPFC

Fig-6 shows the general configuration of the UPFC. It is the combination of series and shunt converters connected back to back to each other through a common dc link capacitor. The series converter, which acts a controllable voltage source, υc is used to inject a controllable voltage in series with the line and thereby to force the power flow to a desired value. So, the series converter exchanges the active and reactive power with the line while performing this duty. The reactive power is electronically provided by the series inverter itself, and the active power is transmitted to the dc terminals.

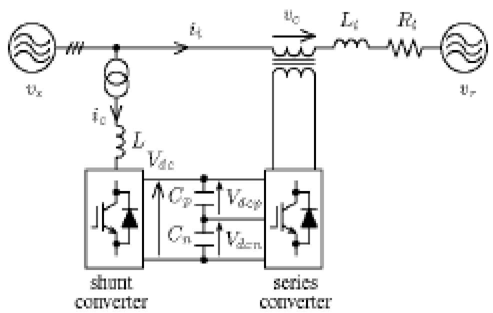


Fig-6: Configuration of UPFC

The shunt converter, which acts a controllable current source ic, is used to regulate dc link voltage by adjusting the amount of the active power drawn from the transmission line to meet the real power needed by the series converter. The shunt converter is also able to control the reactive power.

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.

6. PROPOSED CONTROL SCHEMES

6.1 Series converter control schemes

Two power flow control schemes are proposed to obtain the reference voltage 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.

6.1.1 Line Inductance Compensation

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

$$\frac{R1}{L1} \neq \frac{R2}{L2} = \frac{R3}{L3} \quad \text{......... (10)}$$

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

$$\frac{R1}{+Lc} \neq = \quad \text{...... .(11)}$$

$$Lc = \frac{R1}{R2} L2 - L1 \quad \text{...... (12)}$$

Considering the value of the inserted series inductance, Lc, the reference voltage of the UPFC series converter, can be calculated, in the steady state as follows:

$$\dot{V}c = -j\omega Lc\dot{I}1 \quad \text{.......(13)}$$

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:

$$\upsilon c = -Lc\frac{di1}{dt} \quad \text{..... (14)}$$

6.1.2 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 (3). This control scheme can be used if the relation of the line impedance parameters of the loop system shown in fig.-2 is:

$$\neq \quad \neq \quad \text{....... (15)}$$

In this case, UPFC can be controlled to cancel the summation of the reactance voltage drop by inserting a series voltage, , equal in magnitude to the summation of the reactance voltage drop, but in the opposite direction. The value of can be calculated using (3) as:

$$-\sum_{i=1}^{3} j\omega LiIi + \;\; = 0 \quad \text{. ...... (16)}$$

$$= \sum_{i=1}^{3} j\omega LiIi \quad \text{........ (17)}$$

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

$$\upsilon c = \sum_{i=1}^{3} Li\frac{dIi}{dt} \quad \text{......(18)}$$

6.2 Shunt converter control scheme

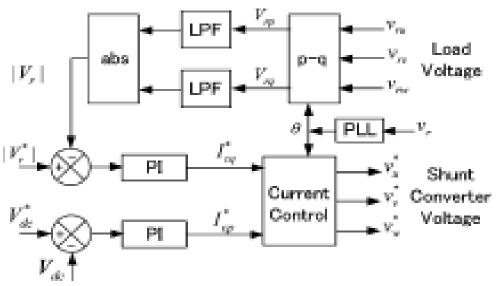


Fig-7: Control Circuit of UPFC Shunt Converter

Regulating the reactive power injected by the shunt converter is used to achieve a constant regulated voltage at its bus. Fig. 7 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 Iq* is determined by a conventional PI controller which regulates the magnitude of the bus voltage that the shunt converter connected to. The currents Id* and Iq* can be used to calculate the reference voltage of the shunt converter.

7. EXPERIMENTAL SYSTEM CONFIGURATION

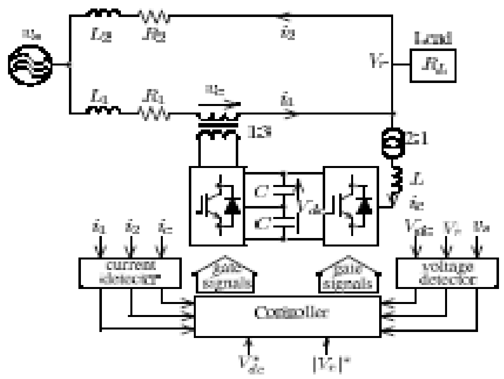


Fig-8 : Experimental System Configuration

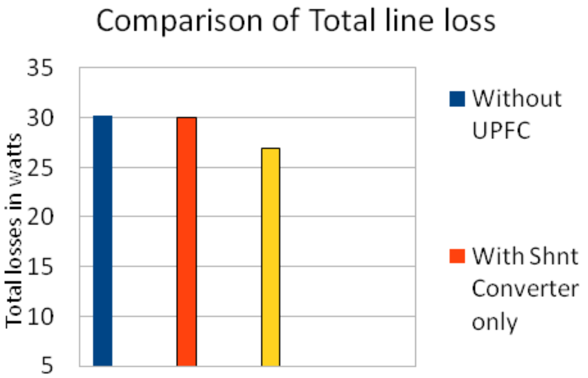
TABLE-1: System Parameters (6kVA Base)

Source voltage	230V, 60Hz
Load RL	10Ω (1.5p.u.)
Input L of shunt converter	3mH (0.16p.u.)
Line 1 L1	6mH (0.34p.u.)
R1	0.15 Ω (0.02p.u.)
Line 2 L2	3mH (0.16p.u.)
R2	0.85 Ω (0.13p.u.)
Capacitor C	3000μF
DC link voltage Vdc	250V
Transformation ratio	1:3 (system: series)
Transformation ratio	2:1 (system: shunt)
Switching time Ts	102μs
Control parameters of shunt converter	
AC voltage regulator kp	0.30A/V
ki	0.03A/Vs
DC voltage regulator kp	0.30A/V
ki	0.30mA/Vs

Fig-8 shows the 6kVA, 230V 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. R1, L1 and R2, L2 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 and2, 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 in parallel with the distribution line via a 3-phase transformer with turns ratio of 2:1 to regulate dc link voltage as Vdc=250V and to regulate the load voltage to be equal in magnitude to the source voltage. The series converter consists of three single phase H-bridge voltage source converters. The ac terminals of each H-bridge converter are connected in series to the distribution line through a single phase transformer with a ratio of 3:1 to minimize the total line loss of the loop system. The switching and sampling frequency for the series and shunt converters are 4.9 and 9.8 kHz, respectively.

8. EXPERIMENTAL RESULTS

	Without using UPFC	With Shunt Converter Only	With Shunt and Series Converter (With UPFC)
I1	22.4A	22.385A	20A
I2	13.43A	13.43A	11.5A
Iloop	8.97A	8.9550A	8.5A
Vc	-	-	132.785V
Vr	119.4V	119.45V	119.65V
Pl1	75.2640W	75.1632W	60W
Pl2	45.0912W	45.0912W	33.0625W
Pl	30.1728W	30.0720W	26.9375W



9. CONCLUSIONS

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.

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