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Transmission Loss Minimization using UPFC

Banakar Basavaraj[1], Ronad Basangouda[2], Jangamshetti Suresh.H[3]
[1]Student Member IEEE, [2]Member IEEE, [3]Senior Member IEEE

Abstract: *The paper focuses on the issue of transmission loss allocation and transmission loss minimization. To meet the power demand it is essential to increase the transmitted power by reducing transmission losses. This can be achieved by adding Flexible AC Transmission System (FACTS) controllers. The annual, weighted average transmission and distribution loss in India is about 30-35%. To investigate the effect of the UPFC on the steady state condition of the system, different models can be used. The Unified Power Flow Controller (UPFC) injection model is incorporated in load flow by Newton Raphson algorithm. Loss allocation is an important aspect in determining the cost of transmission. Z-bus loss allocation technique is used to achieve the same. Currents rather than powers are emphasized in the allocation process. Optimal location to place UPFC is identified based on active power loss Sensitivity factors. The changes in the system are studied to see the impact of the UPFC. The impact of UPFC is analyzed by using 5-bus test system, IEEE 14-bus and 30-bus test systems. The results conclude that considerable amount of losses can be reduced. The analysis is achieved through developing a program using MATLAB.*

Index Terms: *LFA (load flow analysis), UPFC (unified power flow control), Z bus Allocation, Sensitivity factors*, *Flexible AC transmission systems (FACTS).*

I. INTRODUCTION

In the present pace of power system, transmission systems are being required to provide increased power transfer capability to accommodate a much wider range of possible generation patterns. Environmental, right-of-way, and cost problems are major hurdles for power transmission network expansion. Hence, there is an interest in better utilization of available power system capacities by installing FACTS controllers. Power systems today are highly complex in nature. The requirements to provide a stable, secure, controlled quality of power are becoming vitally important with the rapid growth in industrial area. To meet the demand in a power system it is essential to increase the transmitted power by reducing losses in the transmission line. Moreover installation of new transmission lines in a power system leads to the technological complexities increased cost and delay in construction. Considering these factors it is necessary to modify the existing transmission system instead of constructing new transmission lines.

II. UNIFIED POWER FLOW CONTROLLER (UPFC)

A .Circuit Arrangement of UPFC

The UPFC consists of two voltage source converters, which are connected back to back through a DC link. The series voltage converter is connected to the transmission line by means of a series transformer and the shunt voltage converter by means of shunt transformer. The series voltage converter injects an AC voltage into the transmission line with Controllable magnitude and phase angle.

The shunt converter can exchange active and reactive powers with the system, which enables the system to do shunt compensation independently. Converter 2 provides the main function of the UPFC by injecting an AC voltage with controllable magnitude and phase angle in series with the transmission line via a series transformer. The basic function of converter 1 is to supply or absorb the real power demand by converter 2 at the common DC link. It can also generate or absorb controllable reactive power and provide independent shunt reactive compensation for the line. Converter 2 supplies or absorbs locally the required reactive power and exchanges the active power as a result of the series injection voltage [2].

Converter 2 is used to generate a voltage source at the fundamental frequency with variable amplitude and phase angle, which is added to the ac transmission line by the series-connected boosting transformer. The inverter output voltage injected in series with line can be used for direct voltage control, series compensation, phase shifter, and their combinations.

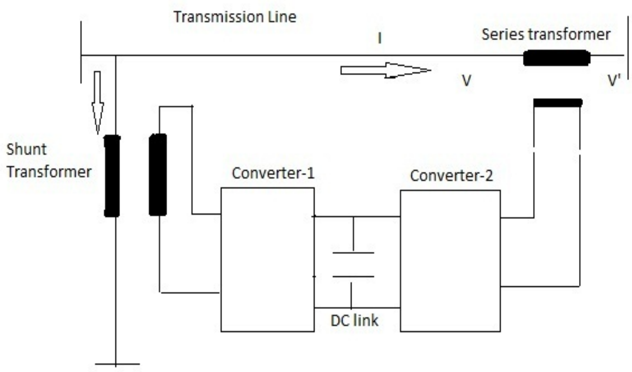

Fig.1. Schematic diagram of UPFC [1].

Converter 2 is used to generate a voltage source at the fundamental frequency with variable amplitude and phase angle, which is added to the ac transmission line by the series-connected boosting transformer. The inverter output voltage injected in series with line can be used for direct voltage control, series compensation, phase shifter and their combinations. This voltage source can internally generate or absorb all the reactive power required by the different type of controls applied and transfers active power at its dc terminal.

B. UPFC injection model for power flow studies.

Model for UPFC, which will be referred as UPFC injection model is derived. This model is helpful in understanding the impact of the UPFC on the power system in the steady state. Further, the UPFC injection model can easily be incorporated in the steady state power flow model. The series voltage source converter does the main function of the UPFC by injecting voltage in series with transmission line [1].Series connected voltage source converter model: Suppose a series connected voltage source is located between nodes i and j in a power system. The series voltage source converter can be modeled with an ideal series voltage V_s in series with a reactance X_s as shown in fig below.

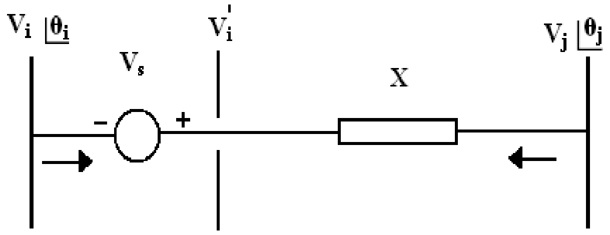

Fig.2.Representation of a series connected VSC

$$V_i^1 = V_S + V_i \quad (1)$$

where

V_i^1 = voltage behind the series reactance.

V_S = series source voltage.

V_i = voltage at i'th node.

The series voltage source V_S is controllable in magnitude and phase

$$V_S = rV_i e^{i\gamma} \quad (2)$$

where r = series voltage source co-efficient. $(0 < r < r_{\max})$

γ = series voltage source angle. $(0 < \gamma < 2\pi)$

The injection model is obtained by replacing the equivalent circuit of series connected voltage source as Norton's equivalent circuit as shown in fig.5 .The current source,

$$I_S = -jb_S V_S \quad (3)$$

Where,

$b_S = 1/X_S$

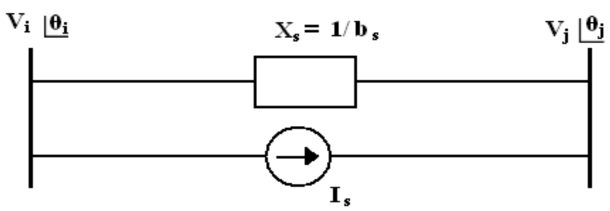

Fig.3. Equivalent Norton's circuit of a series connected VSC.

The power injected into the j[th] bus

$$\overline{S_{js}} = \overline{V_j}(-\overline{I_s})^* \quad (5)$$

$$S_{js} = V_j[-jb_s r \overline{V_i} e^{j\gamma}]^*$$

$$S_{js} = b_s r V_i V_j \sin(\theta_{ij} + \gamma) + jb_s r V_i V_j \cos(\theta_{ij} + \gamma)$$

Where $\theta_{ij} = \theta_i - \theta_j$

From above equations, the injection model of series connected voltage source can be sent as two dependent loads as shown in fig.4. In UPFC, the shunt connected voltage source (converter1) is used mainly to provide the active power, which is injected to the network via the series connected voltage source.

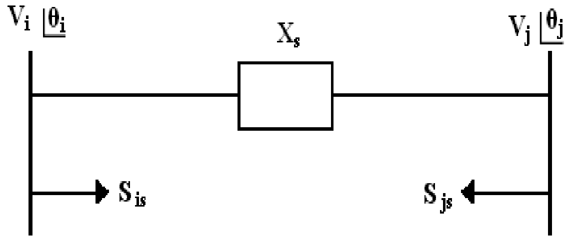

Fig.4 .Injection model for a series connected VSC.

When the losses are neglected [1]

$$P_{conv1} = P_{conv2}$$

The apparent power supplied by the series voltage source converter is

$$S_{conv2} = \overline{V_S}\,\overline{I_{ij}}^* = re^{j\gamma}\overline{V_i}[\frac{\overline{V_i^1} - \overline{V_j}}{jX_S}]^* \quad (6)$$

After simplification, the active and reactive power supplied by converter 2 is

$$P_{conv2} = rb_S V_i V_j \sin(\theta_i - \theta_j + \gamma) - rb_S V_i^2 \sin(\gamma)$$

$$Q_{conv2} = -rb_S V_i V_j \cos(\theta_i - \theta_j + \gamma) + rb_S V_i^2 \cos(\gamma) + r^2 b_S V_i^2 \quad (7)$$

The reactive power delivered or absorbed by converter 1 is independently controllable by UPFC and can be modelled as a separate controllable shunt reactive source. In view of above, it is assumed that $Q_{conv1} = 0$. The UPFC injection model is constructed from the series connected voltage source model with the addition of a power equivalent to $P_{conv1} + j0$ to node i.

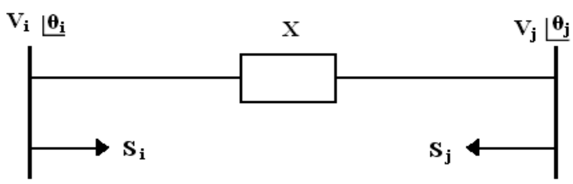

Fig.7 . Complete UPFC model.

Thus, the complete UPFC injection model is shown in fig.7.

$$Q_{si} = rb_s V_i^2 \cos(\gamma) + Q_{shunt}$$
$$Q_{sj} = -rb_s V_i V_j \cos(\theta_{ij} + \gamma)$$
$$P_{si} = rb_s V_i V_j \sin(\theta_{ij} + \gamma)$$
(8)
$$P_{sj} = -rb_s V_i V_j \sin(\theta_{ij} + \gamma)$$

III. Methodology

A.***Incorporation of UPFC in Newton Raphson Power flow algorithm:***

The Steps to Incorporate UPFC in Newton-Raphson Algorithm are as follows

- Read the system input data; line data, bus data, generator and load data.
- Formation of admittance matrix 'Y' bus of the transmission line between the bus i and j.
- Combining the UPFC power equations with network equation, the conventional power flow equation is given as:

$$P_i + jQ_i = \sum_{j=1}^{n} V_i V_j Y_{ij} \angle(\theta_{ij} - \delta_i + \delta_j) + P_i^1 + jQ_i^1 \quad (9)$$

- The conventional jacobian matrix are formed. Due to the inclusion of UPFC the dimensions of the jacobian matrix is increased.
- In this step, the jacobian matrix is modified and power equations are mismatched. The Bus bar voltages are updated at each iteration and convergence is checked. If convergence is not achieved in the next step the algorithm goes back to the step 5 and the jacobian matrix is modified and the power equations are mismatched until convergence is attained.
- If the convergence achieved in earlier step, the output load flow is calculated for PQ bus that includes the Bus bar voltages, generation, transmission line flow and losses.

B. Sensitivity analysis of total active power loss

A method based on the sensitivity of the total system active power loss with respect to the control variables of the FACTS device UPFC is considered. For UPFC placed between buses i and bus j, the considered control parameter is the injected series voltage of controllable magnitude and its phase angle. The active power loss sensitivity factor with respect to these control variables may be given as, loss sensitivity with respect to control parameter of UPFC placed between buses i and bus j[3].

$$a_{ij} = \frac{\partial P_L}{\partial V_{ij}} \quad (10)$$

And this can be deduced from the above equation as,

$$\frac{\partial P_L}{\partial V_{ij}} = 2V_i V_j \cos(\delta_i - \delta_j) + 2V_i V_j \sin(\delta_i - \delta_j) \quad (11)$$

Thus from the above equation the sensitivity factors with respect to active power loss are obtained.

C.Z-Bus loss allocation method

The goal of the Z-bus loss allocation method, is to take a solved power flow and systematically distribute the system transmission losses, among the network buses. The loss component, L_k is the fraction of the system losses allocated to the net real power injection at bus K[4]. The Z-bus loss allocation algorithm is as follows

- Solve load flow; get bus voltage vector V and total power loss.
- Obtain bus current vector I from V and complex power injection.

$$S = (P_i + jQ_i) \quad (12)$$

- Obtain the vector RI.

$$RI = Re\{Z\} I.$$
$$RI = Re\{Z[Re(I)]\} + Re\{Z[Im(I)]\} \quad (13)$$

- Calculate the component of total loss due to current injection Ik at the jth bus.

$$L_k = \Re\left[I_k^* \left(\sum_{j=1}^{nb} R_{kj} . I_j \right) \right] \quad (14)$$

IV. SIMULATION RESULTS

The simulation is carried out for IEEE 14 and 30 bus systems.

A. Simulation result for IEEE-14 bus system.

Table .1.Voltage profile & distribution of active power Loss cost without UPFC.

Bus Number	**Voltage (p.u.)**	**Angle (degree)**	**Distribution of active power loss in \$/hr**	**Distribution of active power loss in ₹/hr**
1	1.0600	0.000	388	19400
2	1.0350	-4.8589	7	350
3	0.9922	-12.6963	144	7200
4	1.0026	-10.2365	45	2250
5	1.0082	-8.7363	4	200
6	1.0610	-14.3841	6	300
7	1.0313	-13.3617	0	0
8	1.0313	-13.3711	0	0
9	1.0357	-14.9825	27	1350
10	1.0371	-15.2613	9	450
11	1.0471	-14.9944	3	150
12	1.0511	-15.3826	6	300
13	1.0471	-15.5190	15	750
14	1.0299	-16.4270	22	1100
			677	**33,850**

Table 1 depicts the voltage, phase angle and distribution of active power loss cost in the system before incorporating UPFC in the system. Before incorporating UPFC in the system, the total real power loss in the system is 13.5272 MW. The generator 1(i.e, at Bus-1) with about 85% of the total generation always gets allocated with highest cost,

which is proportional to the highest loss taking place in that Bus-1(slack bus generator).
Since, the sensitivity factors are calculated with respect to the active power loss in the system the sensitivity factor at that Bus-1 will be reasonably high as it can be seen in the Table 2.The sensitivity factors from the Table 2 indicate that the line-4, line-5, and line-10 are selected as the best lines for locating UPFC based on their highest sensitivity factors.

Table.2. Sensitivity factors:

Bus Number	UPFC in line-4		UPFC in line-5	
	Voltage (p.u)	Angle (degree)	Voltage (p.u)	Angle (degree)
1	1.0600	0.0000	1.0600	0.0000
2	1.0350	-4.6739	1.0350	-4.8228
3	0.9922	-12.5313	0.9923	-12.6407
4	1.0026	-10.0904	1.0028	-10.1648
5	1.0083	-8.6033	1.0085	-8.6533
6	1.0610	-14.2468	1.0612	-14.3026
7	1.0313	-13.2177	1.0315	-13.2864
8	1.0313	-13.2272	1.0315	-13.2959
9	1.0357	-14.8397	1.0359	-14.9055
10	1.0372	-15.1194	1.0373	-15.1833
11	1.0471	-14.8548	1.0473	-14.9146
12	1.0511	-15.2449	1.0513	-15.3010
13	1.0471	-15.3809	1.0473	-15.4377
14	1.0299	-16.2863	1.0301	-16.3476

Table .3.Comparisons of voltage and phase angle profile with UPFC.

Bus Number	UPFC in Line-4	UPFC in Line-5
	Distribution of active power loss cost in $ / hr	Distribution of active power loss cost in $ / hr
1	369.1634	382.2617
2	10.1278	7.2548
3	143.4611	144.1806
4	44.4162	44.1990
5	3.9037	3.0096
6	6.0450	5.9372
7	0.0000	-0.0000
8	0.0919	0.0914
9	26.9393	26.7652
10	8.9313	8.8719
11	2.9764	2.9481
12	5.7665	5.7077
13	14.5446	14.4183
14	22.4375	22.3233
Total cost	**659**	**668**
Total loss	**13.1968 MW**	**13.3774 MW**

Table 3 shows the comparisons of voltage and phase angle profiles after incorporating UPFC in the line-4, line-5 and line-10. From the Table 3 it can be seen that the voltage and phase angles has been improved considerably better in the selected line-4, line-5 and line-10 than compared to without UPFC results as shown in Table 1

The Table 4 shows the comparisons of loss allocation costs at each bus for the three lines namely line-4, line-5 and line-10. On Comparison, it is found that the system losses have considerably reduced. Thus, placing UPFC in line-4 gives efficient and better results than in other lines. The reduction in losses is 0.3304 MW/hr its respective cost reduction is 17 $/hr [3].

Table.4.Comparisons of Loss minimization and Loss allocation with UPFC

Line Number	From Bus	To Bus	Sensitivity factor
1	2	4	2.2607
2	2	5	2.2234
3	2	3	2.3147
4	**1**	**2**	**2.3722**
5	**1**	**5**	**2.4373**
6	3	4	1.9023
7	5	4	2.0740
8	4	7	2.1776
9	4	9	2.2415
10	**5**	**6**	**2.3397**
11	6	11	2.2454
12	6	12	2.2689
13	6	13	2.2654
14	7	8	2.1275
15	7	9	2.1958
16	9	10	2.1588
17	9	14	2.1865
18	10	11	2.1618
19	12	13	2.2063
20	13	14	2.1906

V. CONCLUSION

REWRITE THE CONCLUSION. Include the results of the 30 bus system in conclusion. Once again check the technical part of the paper thoroughly. The results are obtained for IEEE 14-bus and 30-bus test system. The transmission losses are reduced satisfactorily. UPFC is optimally placed using active power loss sensitivity factors which were calculated after performing the load flow analysis. UPFC's role in loss minimization and its influence for loss allocation is verified. Minimization of power losses can be achieved with out generation scheduling. By controlling the angle and magnitude of injected voltage, power flow through transmission line can be controlled.

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BIOGRAPHY

Basavaraj Bankar. was born in Karnataka, India on 17 February1988. HE obtained B.E (Electrical) from Visweshwaraiah techhnological University, Karnataka.,India. He is currently persuing M.Tech Degree in Power and Energy Systems in Electrical and Electronics Engineering, Basaveshwar Engineering College, Bagalkot, India.

Basangoud.F.Ronad Was born in Badami, Karnataka, India on 22 July 1986. He obtained B.E (Electrical and Electronics) from Visveswaraih Technological University, Belgaum, Karnataka India in 2008 and M.Tech (Power and Energy System) from Basaveshwar Engineering College, Bagalkot, Karnataka, India in 2010. His areas of interest include Power Electronics, Power system and Renewable Energy Sources. Presently he is working as faculty in the Department of Electrical & Electronics Engineering at Basaveshwar Engineering College, Bagalkot, India.

Dr. Suresh. H. Jangamshetti: (S'88, M'90, SM'97) was born in Bijapur, Karnataka, India on May 28, 1963. He obtained his B.E (Electrical) degree from Karnataka University Dharwad in 1985 and M.Tech. (Power Systems) & Ph.D (Wind Energy Systems) from IIT Kharagpur in 1989 & 2000 respectively.

His areas of interest include Wind-Solar Energy Systems, Energy Conservation, Computer Applications to Power System and FACTS He won the "Outstanding IEEE Student Branch Counsellor" award for the year 1996(R10) and 2010 (IEEE Bangalore Section) at Basaveshwar Engineering College, Bagalkot, Karnataka, India. He was Fulbright-Nehru Visiting Lecture Fellow at Michigan Technological University, Houghton MI USA during Fall 2011. He is working as Professor in the department of E&E at Basaveshwar Engineering College, Bagalkot.