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POWER FLOW CONTROL BY USING UPFC BASED QUASI-NEWTON OPTIMIZATION IN A DISTRIBUTION SYSTEM

[1]Poornima Reddy A, [2]Hari T

[1] PG Student, Department of EEE, SVPCET, Puttur, Andhra Pradesh, India.
[2] Assistant Professor, Department of EEE, SVPCET, Puttur, Andhra Pradesh, India.

Abstract: **This paper deals with an alternative proposition for the steady state modeling of unified power flow controller (UPFC). Since current limitations are determinant to FACTS apparatus design, the proposed current based model (CBM) assumes the current as variable, allowing easy manipulation of current restrictions in optimal power flow evaluations. The performance of the proposed model and of the power injection model (PIM) are compared through a Quasi-Newton optimization approach. Two operating situations of a medium size network with 39 busbars were studied from the point of view of optimization and current limits, observing the performance of the UPFC modelling.**

Keywords: **FACTS, optimal power flow, Quasi-Newton method, UPFC.**

1. INTRODUCTION

Power flow studies and optimization techniques are essential tools for the safe and economic operation of large electrical systems. The FACTS equipment appeared in the 1980s and, in the early 1990s, voltage source inverters (VSI) were developed. The UPFC is one of the most complete equipment of this new technological family, allowing the regulation of active and reactive powers, substantially enlarging the operative flexibility of the system [1]–[7].

Steady state models of UPFC described in the literature employ the power balance equation, resulting in the equality of the series and shunt active power of converters assuring no internal active power consumption or generation.

One of the first proposed models [8] uses this condition, but only in particular cases, when power and voltage are admittedly known, is the implementation of the model in traditional power flow program viable.

The employed models in [9] and [10] represent the active elements through equivalent passive circuits, including the power balance equation. In [11], the passive model consists of a susceptance and an ideal voltage transformer and the fundamental power balance equation is intrinsically included. Voltage source models employed in [12]–[15] consist of series and shunt volt- ages presented in the equations as control variables.

The model described in [16], known as power injection model (PIM), is quite spread in the literature, representing the effect of active elements by equivalent injected power.

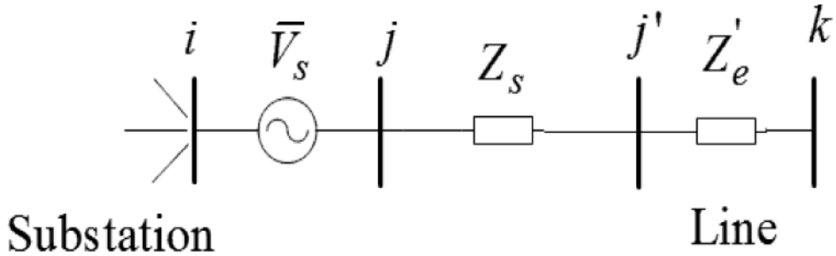

Fig. 1.UPFC and network

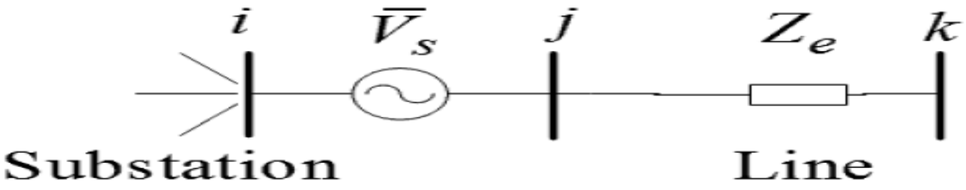

Fig. 2. Equivalent model of UPFC in the electric network

The model of [17] deals with currents and voltages relations through the nodal admittance matrix in an intermediate stage of the equations, but currents are eliminated in the formulation, voltages remaining as variables.

In the existing models, the current is not explicitly treated in the equations. Since in the specification of FACTS converters one of the main restrictions lies on current limitation, it is convenient to have a model that uses the current as a variable, which will be the purpose of this paper.

Hence, in Section II, the equations of a current based model (CBM) are presented. In Section III, an optimization approach of the developed model is presented, comparing its performance with that of a PIM, seeking to analyze the behavior of UPFC in the New England network, of 39 busbars. In Section IV, the conclusions are presented.

II. POWER INJECTION MODEL

From the power electronics viewpoint, FACTS employs self-commutated, voltage-sourced switching converters to realize rapid controllable, static, synchronous ac voltage or current sources. This approach provides superior performance characteristics and uniform applicability for transmission voltage, effective line impedance, and angle control. From the power system viewpoint, it also offers the unique potential to exchange active power directly with the ac system, in addition to providing the independently controllable reactive power compensation, thereby giving a powerful new option for flow control and the counteraction of dynamic disturbance.

III. CURRENT BASED MODEL

The developed model represents the UPFC in steady state, introducing the current in the series converter as variable (see Fig.1).

Series voltage:V_S

Series transformer impedance:Z_S

Transmission line impedance:$Z_e^{'}$

Let us consider busbar i and k existent in the transmission line where the UPFC will be located, with impedance$Z_e^{'}$. Fictitious busbars j and$j^{'}$ are created in order to include the UPFC in the system. The series impedance of UPFC coupling transformer $z_s$and the transmission line are added, resulting in the equivalent impedance $z_e = z_e^{'} + z_s$ connected to the internal node j and node $j^{'}$ is eliminated. This association is quite simple, even in case of two port lines represented by π circuits.

he equivalent network is presented in Fig. 2, with the series voltage inserted between busbars i and j.

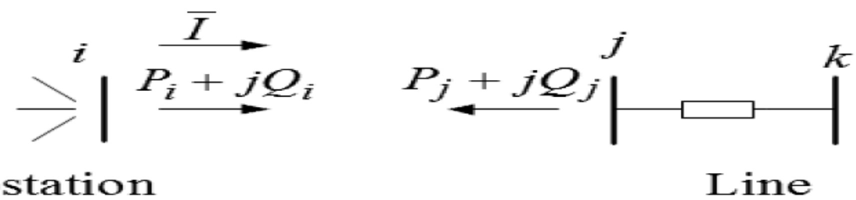

Fig. 3. Injected power due to current in busbars i and j

A. Injected Power Due to Current:

The power consumption of the system load at busbar i is calleds_i^0.

Additional powers s_i^c and s_i^c due to current I are easily calculated according to Fig. 3. Current I introduces two variables I,ψ related to module and phase of the current.

We can write the new power terms due to current:

$$\begin{aligned} S_i^c &= \bar{V}_i \bar{I}^* & S_j^c &= -\bar{V}_j \bar{I}^* \\ P_i^c &= V_i I \cos(\varphi - \theta_i) & Q_i^c &= V_i I \mathrm{sen}(\varphi - \theta_i) \\ P_j^c &= -V_j I \cos(\varphi - \theta_j) & Q_j^c &= -V_j I \mathrm{sen}(\varphi - \theta_j) \end{aligned}$$

and we have

$$\begin{aligned} P_i &= P_i^0 + P_i^c & P_j &= P_j^c \\ Q_i &= Q_i^0 + Q_i^c & Q_j &= Q_j^c. \end{aligned}$$

Putting the new variables ψ and I at n and 2n position, respectively, the new vector of variables can be written:

$$[x^t] = [\theta_1, \theta_2, \ldots, \theta_{n-1}, \varphi, V_1, V_2, \ldots, V_{n-1}, I].$$

B. Series Voltage Equations:

The following treatment of the series voltages for the UPFC is general for FACTS devices that can employ this feature. The main example is the SSSC and, as a consequence, other equipment such as IPFC and GIPFC that use series voltage can be modelled as well.

Writing the voltage equation between nodes i and j,we obtain

$$\bar{V}_j - \bar{V}_i = \bar{V}_s.$$

The series voltage will be treated similarly to the PIM model of [10]:

$$\bar{V}_s = r V_i e^{j\delta}$$

Where r is the factor for series voltage and δ is the series voltage angle.

That equation substituted in (2.2) results

$$\bar{V}_j - (1 + re^{j\delta})\bar{V}_i = 0.$$

If r and δ are constants, in a regular power flow case, calling the complex variable

$$A\angle\alpha = -(1 + r\angle\delta)$$

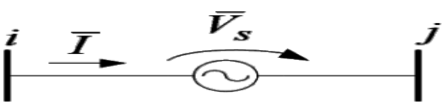

Fig. 4. UPFC series voltage power

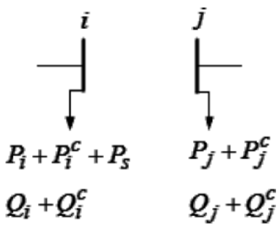

Fig. 5. Injected powers in the bus bars with the inclusion of UPFC

We can write

$$\bar{V}_j + A\angle\alpha\cdot\bar{V}_i = 0.$$

We obtain the equations, relative to the real and imaginary parts, F_n=0 and G_n=0, respectively:

$$F_n = AV_i\cos(\alpha+\theta_i) + V_j\cos\theta_j$$
$$G_n = AV_i\text{sen}(\alpha+\theta_i) + V_j\ \text{sen}\theta_j.$$

These equations will be put at the end of the equation system. If r and $^{\delta}$ are variables in an optimization case, we have

$$[x^t] = [\theta_1, \theta_2, \ldots, \theta_{n-1}, \varphi, \delta, V_1, V_2, \ldots, V_{n-1}, I, r]$$

$$F_n = V_j\cos\theta_j - V_i[\cos(\theta_i) + \cos(\theta_i+\delta)]$$
$$G_n = V_j\sin\theta_j - V_i[\sin(\theta_i) + \sin(\theta_i+\delta)].$$

C. Power Balance:

In order to complete the UPFC model, it is necessary to introduce the power balance equation between series and shunt converters. The series power will be added to the shunt power of bus bar i , similarly to [10] (see Fig. 4)

Let us calculate the power in the series converter:

$$S^s = re^{j\delta}\bar{V}_i I\angle - \varphi.$$

Splitting the previous expression in active and reactive powers:

$$P^s = rV_iI\cos(\theta_i+\delta-\varphi)$$
$$Q^s = rV_iI\text{sen}(\theta_i+\delta-\varphi).$$

Active power is included in node (see Fig. 5).

D. Complete Jacobian:

Calling the Jacobian matrix, without UPFC power addition [17]

$$J_c^0 = \begin{bmatrix} H^0 & N^0 \\ j^0 & L^0 \end{bmatrix}.$$

Let us add the injected power due to current in bus bars i and j and also the voltage equations F_n and G_n. The additional correction of the Jacobian matrix, due to the power balance equation, is also included, complementing the formulation

$$[J] = [J_c^0] + [J^c] + [J^s].$$

E. Optimization Approach:

The behavior of the proposed model was studied with an optimization power flow code based on the Quasi-Newton method. The Quasi-Newton method was used in order to compare time answers of PIM and CBM models, adopting the same initial conditions and trying to obtain similar results as possible, although some differences in the equations of both cases can lead to small discrepancies in some variables of the system.

The approximation formula used in the Quasi-Newton method is given by [19]

$$E_{k+1} = \left[I_d - \frac{p_k y_k^T}{p_k^T y_k}\right] E_k \left[I_d - \frac{y_k^T p_k}{p_k^T y_k}\right] + \frac{p_k p_k^T}{p_k^T y_k}$$

Where,

E_{k+1} inverse of approximation of Taylor series expansion of the gradients of in x_{k+1};

P_k=$Ek + 1y_K$ secant relationship or Quasi-Newton;

y_k Taylor series expansion

I_d identity matrix.

Current restrictions are introduced in the formulation. In the CBM, current module and angle are the variables of the problem, while for PIM current equation is introduced according to

$$\bar{I} = \left(V_i \angle \theta_i + r V_i \angle(\theta_i + \delta) - V_j \angle \theta_j\right)\left(j b_s\right).$$

Equation (2.17) would be a little more complex if the series admittance Y_s=1/$Z_s$was not simplified to Y_s=jb_s disregarding series impedance losses.

IV. RESULTS

Several comparative tests performed with CBM e PIM models presented identical results in power flow analysis using a Matlab code. An additional comparison with the model of [8] was made, using the Power World program.

Some modifications in the New England System of 39 bus- bars were introduced with the purpose of highlighting the optimization results. The modified New England system is represented in Appendix B. Generator 2 is the swing bus bar, and the other generators are considered power variable generators and generation costs are also presented. In the modified network, the base case does not converge and convergence can only be attained if the power generation cost is optimized. If current restrictions are used in some lines, convergence is only attained with UPFCs in the network.

Voltage results were considered inside the range 0.95 to 1.05 pu for network busbars. In order to make a fair comparison between the two models, the same initial conditions were adopted.

The network was analyzed with 3 and 6 UPFCs.

TABLE 1: CURRENTS LIMITS FOR 3 UPFCS

LINE	UPFC	CURRENT LIMITS
32-31	1	0 – 4 pu
39-38	2	0 – 3 pu
13-14	3	0 – 2 pu

TABLE 2: NEW ENGLAND WITH 3 UPFCS

	PIM	CBM	Difference PIM*CBM(%)
Cost generation	672.9195	672.9178	0.00025
Time(sec)	0.660122	0.28730	56.47
r1	0.7800	0.2300	70.51
$\delta 1$	0.9870	0.4540	53.29
r2	0.9800	0.1600	83.67
$\delta 2$	0.9230	0.4670	49.40
r3	0.8600	0.1400	83.72
$\delta 3$	0.9840	1.8662	89.65
Current 1	3.9900	4	0.25
Angle 1	-0.4470	-0.9520	-112.9
Current 2	2.9900	3	0.334
Angle 2	-0.4560	-0.2840	37.71
Current 3	2.0000	2	0
Angle 3	-0.4760	-0.4470	6.092
P loss	31.7093	31.9580	0.7843
Q loss	987.2300	968.5900	1.888

A. Network with 3 UPFCs:

The lines with UPFC and their respective minimum and maximum current limits are presented in Table I.

The generation cost and computation time comparison are presented in Table II showing the critical operative condition, with the currents through the selected lines within range values, which is only possible with the inclusion of UPFCs in the network.

In Table II, the same generation cost presented by the two models and the lower computation time of the CBM model can be verified.

With 3 UPFCs, despite the higher Jacobian dimension of CBM, its convergence time is lower since limitations on current treated as a variable enable fast convergence. Most variables such as voltage, current and angle obtained in the convergence of three UPFCs are identical in both models, but this is not true if current limits are increased. Reducing the current band limits, PIM does not usually converge.

Additionally, we also performed some tests with the IEEE 118 bus bars with 3 UPFCs. The same trend of lower times for CBM was observed, although more analysis should be performed with this system in order to compare numerical values.

B. Network with 6 UPFCs:

The lines with UPFC and their respective minimum and maximum current limits are presented in Table III.

Table IV shows that by increasing the number of UPFCs to 6, the lower convergence time of CBM is still more evident. The results of the variables of the two models are not similar but generation costs are almost the same for these limits. If the limits are increased, different generation costs can be yielded for the models.

In several cases, it was observed that for all the set of current limits that allow convergence for the PIM models also leads the CBM model to convergence. On the other hand, the inverse is not true, with CBM presenting a better performance in cases of difficult convergence due to current limitations, mainly in cases with narrower current limits.Here the losses are decreased when compared to 3 upfcs.

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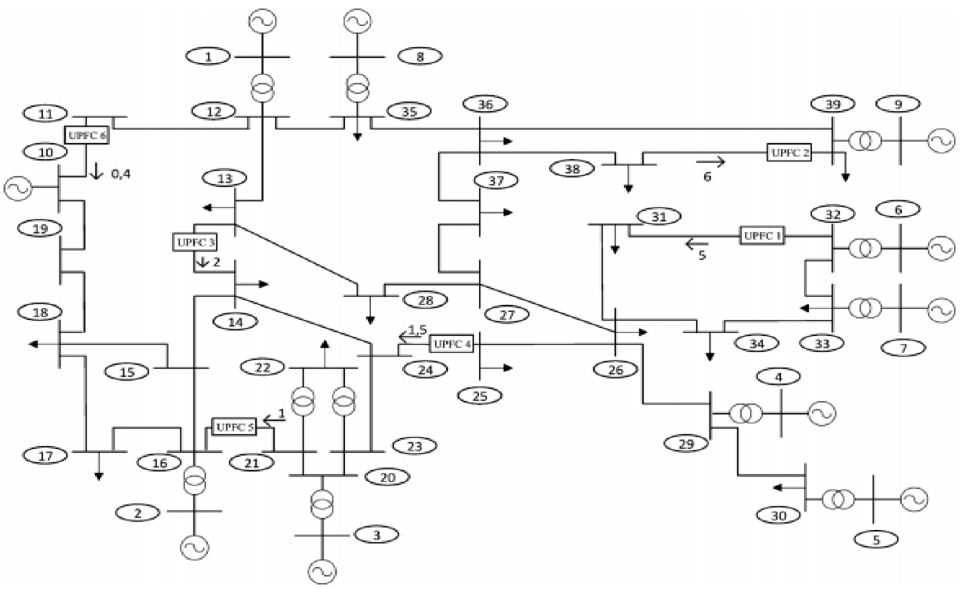


Fig. 6. Modified New England network with 6 UPFC

TABLE 3: CURRENTS LIMITS FOR 6 UPFCS

LINE	UPFC	CURRENT LIMITS
39-38	1	0-5pu
13-14	2	0-6pu
32-31	3	0-2pu
25-24	4	0-1.5
16-21	5	0-1pu
11-10	6	0-0.4pu

TABLE 4: NEW ENGLAND WITH 6 UPFCS

	PIM	CBM	Difference PIM*CBM(%)
Cost generation	533.7700	533.7541	0.0029
Time(sec)	400.271	41.886	89.53
Power 1	3.4757	3.5153	1.13
Power 2	2.1070	2.0998	0.341
Power 3	7.0336	7.0466	0.1848
Power 4	9.8240	9.8094	0.1486
Power 5	3.1780	3.7108	16.765
Power 6	2.8237	2.8331	0.332
Power 7	3.2996	3.2843	0.5418
Power 8	14.423	14.847	0.16
Power 9	3.5572	3.5112	1.2931
r1	0.15	0.15	0
δ1	0.45710	0.45767	0.03
r2	0.24340	0.21720	10.7641
δ2	-0.25460	-0.27393	7.07
r3	0.19990	0.24640	18.85
δ3	1.8006	1.7882	0.6886
r4	0.3	0.3	0
δ4	1.6836	1.6813	0.14
r5	0.15	0.15	0

δ5	1.3844	1.3727	0.85
r6	0.24781	0.3	17.40
δ6	1.6751	1.7060	2.05
Current 1	5	5	0
Angle 1	-0.9529	-0.95000	0.05
Current 2	6	6	0
Angle 2	-0.28404	-0.29976	5.24
Current 3	2	2	0
Angle 3	-0.44740	-0.46539	3.86
Current 4	1.5	1.5	0
Angle 4	0.30260	0.30224	0.17
Current 5	1	1	0
Angle 5	0.10672	0.0669	37.25
Current 6	0.2019	0.2019	1.05
Angle 6	-1.4102	-1.1581	17.88
P loss	30.4600	30.1200	1.162
Q loss	832.600	831.471	0.1355

C. Network with 8 UPFCS:

The lines with UPFC and their respective minimum and maximum current limits are presented in Table V.

Table VI shows that by increasing the number of UPFCs to 8, the increase convergence time of CBM is still more evident. The results of the variables of the two models are not similar but generation costs are almost the increased for these limits. And here the losses are decreased compared to3& 6 upfcs. If the limits are increased, different generation costs can be yielded for the models.

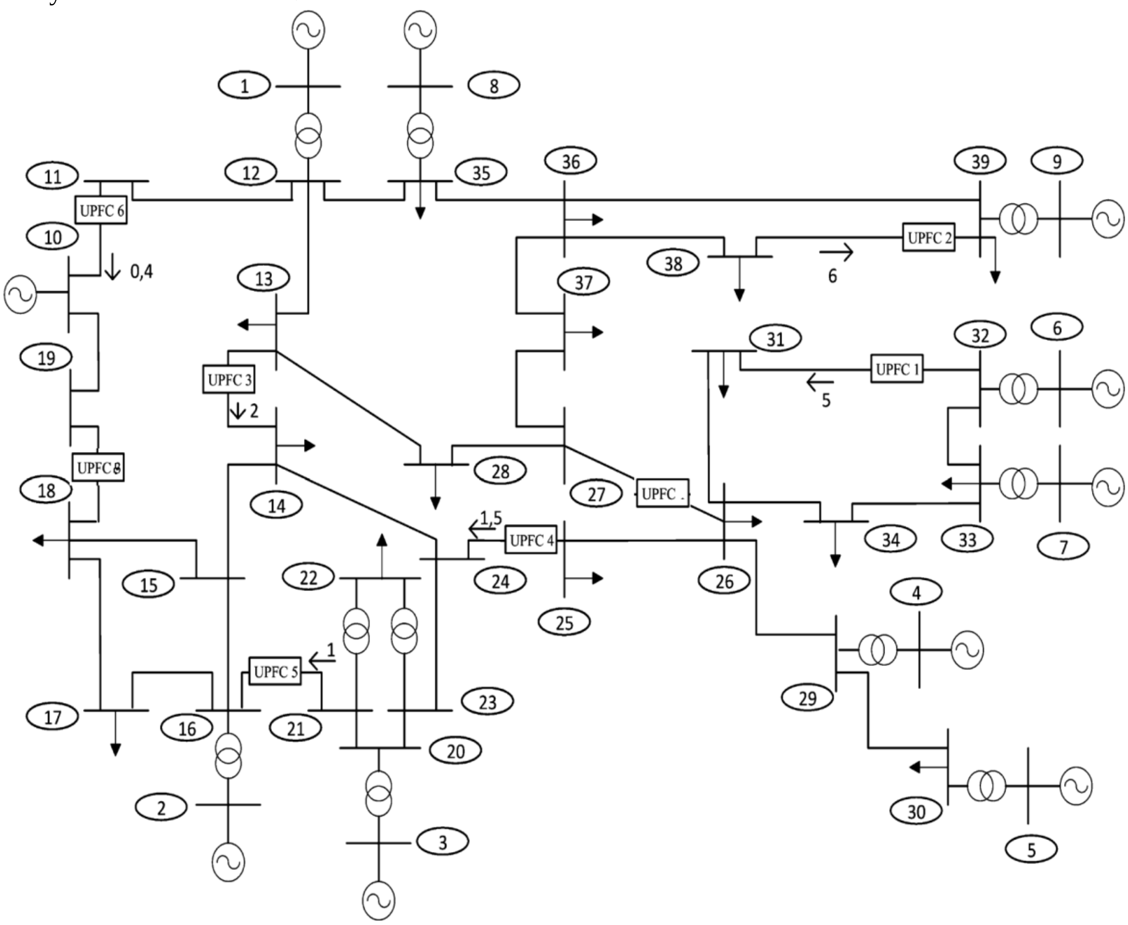


Fig. 7. Modified New England network with 8 UPFC

TABLE 5: CURRENTS LIMITS FOR 8 UPFCS

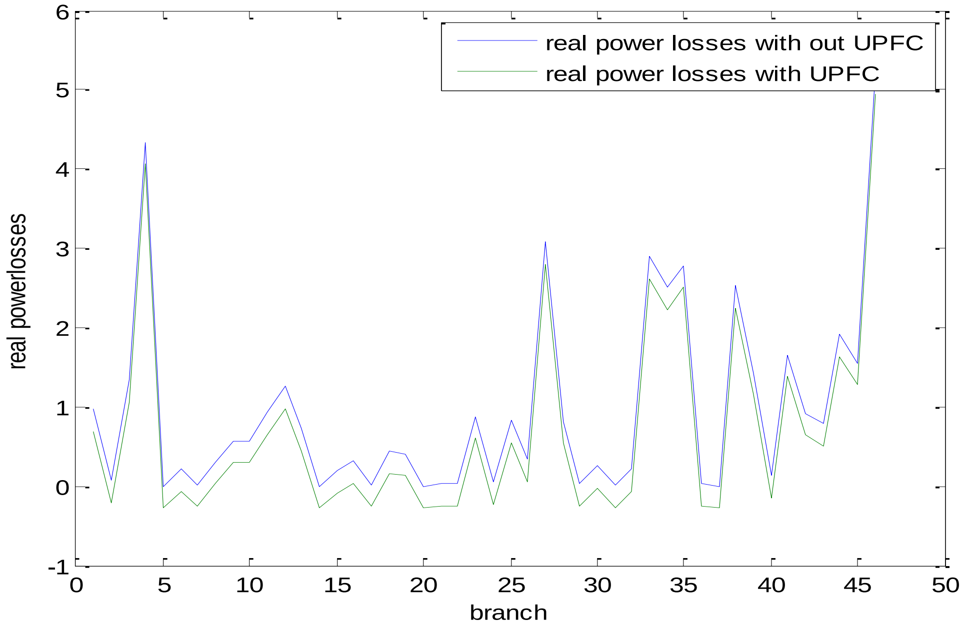
LINE	UPFC	CURRENT LIMITS
32-31	1	0-5 pu
39-38	2	0-6pu
13-14	3	0-2pu
25-24	4	0-1.5pu
26-21	5	0-1pu
11-10	6	0-0.2pu
27-28	7	0-0.32pu
17-18	8	0-3pu

TABLE 6: NEW ENGLAND WITH 8 UPFCS

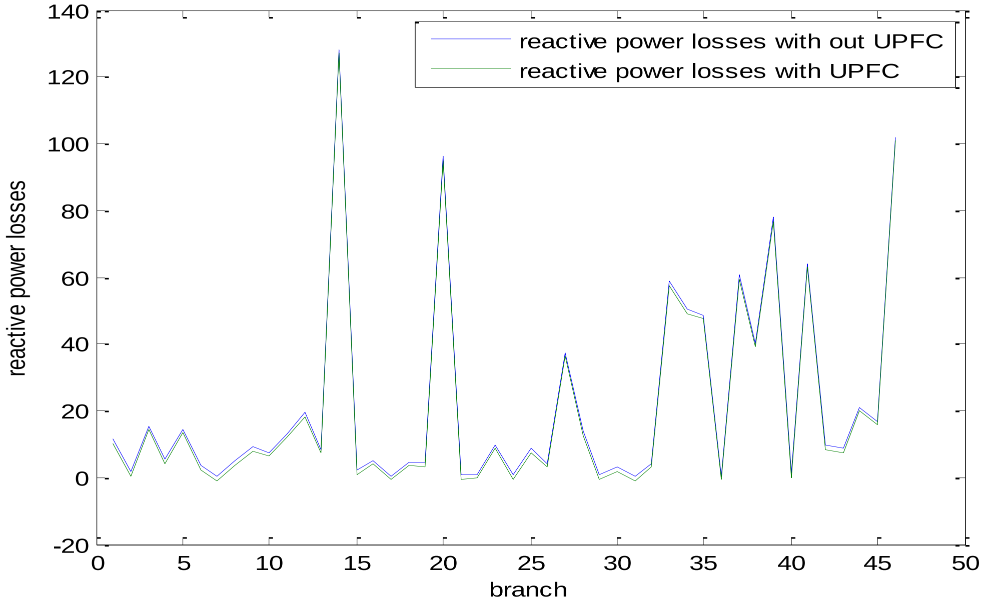
	CBM
Cost generation	633.4560
Time(sec)	48.7976
Power 1	3.5153
Power 2	2.0998
Power 3	7.0466
Power 4	9.8094
Power 5	3.7108
Power 6	2.8331
Power 7	3.2843
Power 8	14.847
Power 9	3.5511
r1	0.15
$\delta 1$	0.4576
r2	0.2434
$\delta 2$	-0.2730
r3	0.1999
$\delta 3$	1.7880
r4	0.3
$\delta 4$	1.6813
r5	0.15
$\delta 5$	1.3700
r6	0.247
$\delta 6$	1.5120
r7	0.26
$\delta 7$	1.6400
r8	0.23
$\delta 8$	1.2300
Current 1	5
Angle 1	-0.9533
Current 2	6
Angle 2	-0.3422
Current 3	2
Angle 3	-0.4470
Current 4	1.50
Angle 4	-0.4231
Current 5	1
Angle 5	0.36

Current 6	0.204
Angle 6	0.2013
Current 7	0.32
Angle7	0.2452
Current 8	3
Angle 8	0.343
P loss Q loss	29.381 830.9

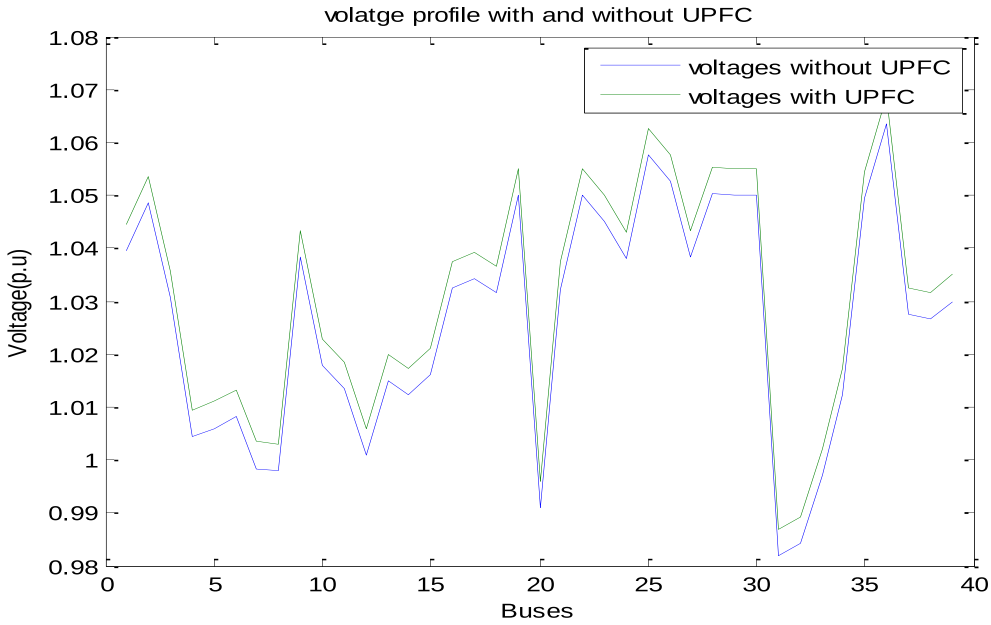
GRAPH 1: Real power, reactive power, and voltage profile for 8 UPFC



(a) Real power losses with and without UPFC



(b) Reactive power loss with and without UPFC



(c) Voltage profile with and without UPFC

V. CONCLUSION

In this paper the proposition of an alternative formulation for the modeling of UPFC was presented, considering the current in the series converter as a variable. The CBM model was compared with the traditional power injection model PIM, showing coincident results in power flow evaluations.

In an optimization approach, despite working with two additional equations for each UPFC, the CBM model reduces the computational time and losses. Where as in 8 UPFC in CBM model the time increases and losses are decreased. In this paper we are mainly reducing the losses. when current limitations are introduced in the series converters, mainly when dealing with several UPFC in the system, which is a very important issue in FACTS design.

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AUTHORS PROFILE:

A.POORNIMA REDDY She received her B.Tech (Electrical and Electronics Engineering) degree from Jawaharlal Nehru technological university in 2012, at Seshachala institute of technology puttur and currently she is pursuing M.Tech (Electrical Power System)at S.V.P.C.E.T,Puttur,India.

T.HARI He received his B.Tech (Electrical and Electronics Engineering) degree from JNTU,Hyderabad, at In A.V.S.C.E.T ,Nellore and M.Tech (PE) from the G.P.R.E.C;Kurnool He is currently working as Assistant Professor at Dept. of Electrical and Electronic Engineering, S.V.P.C.E.T,Puttur. His area of interest power electronics.