

A COMPREHENSIVE LOAD FLOW MODEL FOR UPFC AND ITS COMBINATION WITH ESS

Ahad Kazemi Ahmad Esmailie Mohammad.T Hassanzade R.Rezaiepour
e-mail: kazemi@iust.ac.ir e-mail: mhasanzadeeng@yahoo.com email: rrezatepour@yahoo.com
Iran University of Science and Technology
Faculty of Engineering, Department of Electrical & Electronics Engineering, Tehran, Iran

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ABSTRACT

A reliable Power flow model is required to study Unified Power Flow Controller (UPFC) effects on power system steady state behavior. A few models such as decoupled model, power injection and voltage source model are introduced for this purpose. In this paper a comprehensive, robust, complete and flexible load flow model considering existing decoupled power flow model is presented. For the first time, UPFC combination with energy storage system, ESS, is introduced to improve UPFC capability and performance. The presented model is incorporated in two different networks to show the newly developed model to be far more flexible and efficient. The simulations show the model capabilities and applications in different UPFC control strategies considering UPFC losses. Finally, influence of UPFC location and energy storage system on converters ratings are studied.

I. INTRODUCTION

IN the end of 1980s, appearance of FACTS controllers opened new ways in power systems. Various factors such as increasing daily demand, deregulated power systems and power marketing motivate FACTS controllers' usage. In power marketing, it is required to control the whole power flow of transmission lines. FACTS controllers are the prime contender to provide many control functions to handle a wide range of dynamic and steady-state problems encountered in electrical power networks. UPFC (Unified Power Flow Controller) is one the most comprehensive FACTS devices which controls line active and reactive power flows independently as well as local bus voltage [1]. However, very little work has been carried in developing suitable models to assess UPFC behavior in large-scale power networks and most of them suffer from restrictions. Therefore, an accurate and comprehensive model seems to be necessary. In this paper, existing models such as decoupled, power injection and voltage source model are reviewed briefly

and considering decoupled power flow model, a comprehensive, complete, robust and flexible model is presented and generalized for UPFC combined with ESS.

The model is implemented in two power networks to show its effectiveness in various UPFC control strategies considering UPFC losses. Finally, different parameters effects such as UPFC impedance, location and energy storage system on UPFC converters rating are investigated.

II. POWER FLOW MODELS REVIEW

A power flow model is required to study devices effects on network. In spite of significant importance of these models, a few UPFC power flow models are proposed. Decoupled power flow model [4], injection model [3, 7] and voltage source model [5, 6] can be mentioned as presented models.

IV. THE PROPOSED POWER FLOW MODEL OF UPFC

In spite of decoupled model simplicity, it is more robust than the others and contains unique capabilities. Some shortcomings such as additional nonlinear equation set necessity, UPFC parameter initial value choices and simultaneous control of UPFC objective parameters (i.e. all three P , Q and V must be varied at the same time) can be eliminated after some substantial modifications in this model. Moreover, limit revision of UPFC parameters would be easily possible in iteration process. In power flow solution, P_i or one of the Q_i or V_i should be known in every bus. Assuming network stability, power flow always provides unique solution. In other words, if the connected elements to the desired bus act neutral to bus parameters, power flow answer would be constant. However, power system operation conditions should be far from critical points.

Having connected UPFC, the receiving end always injects $P_{Bt}-Q_{Bt}$ to bus j , and sending end voltage maintain V_{Et} in bus I (see Fig. 5).

According to the above, if UPFC is replaced by elements which are neutral to the known bus parameters, power flow answers remain constant. These elements should inject P_{Bt} - Q_{Bt} to bus j and keep V_{Et} at bus i. A load model together with a generator is capable of injecting P_{Bt} - Q_{Bt} to bus j while maintaining V_{Et} at bus i. The UPFC model is shown in Fig. 6.

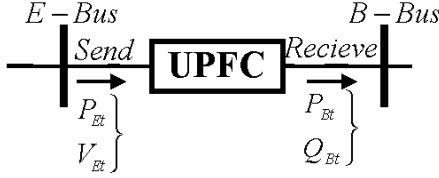


Fig. 5. Network control by UPFC

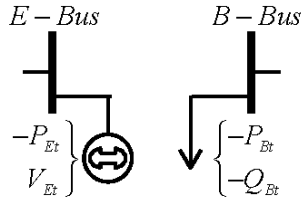


Fig. 6. UPFC model for Fig. 5

Assuming free loss UPFC, injected and absorbed power values to bus j and i would be equal. It can be seen in Fig. 5 that V_{Et} and P_{Et} are known values of the sending end of the UPFC.

Contrary to the voltage or reactive power, real power always is specified in UPFC. In this case, arbitrary values could be chosen for bus parameter. It is better to choose 1 p.u for voltage or reactive power of the bus. Accordingly, the following models (see Fig. 7) can be considered for UPFC. Regarding to power flow, if the type of bus i and j are known before UPFC insertion, they would also be known after insertion. In other words, a P-Q bus remain P-Q after inserting UPFC if P and Q in UPFC ends are known, otherwise the bus always remain P-V bus. Therefore, power flow solution is always applicable for a power system embedded with UPFC.

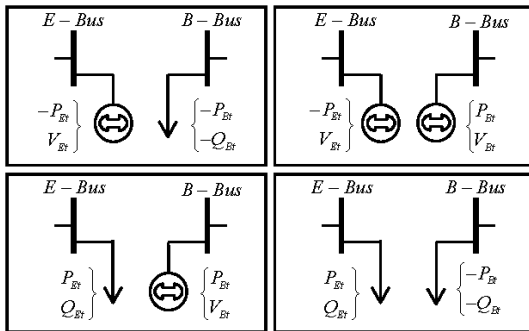


Fig. 7. UPFC applicable power flow models

Unknown system parameters are obtained after power flow solution, and UPFC parameters would be calculated considering voltage source model in Fig. 8. The currents are calculated as follows:

$$\bar{I}_B = \frac{P_{Bt} - jQ_{Bt}}{\bar{V}_{Bt}^*} \quad (1)$$

$$\bar{I}_E = \frac{P_{Et} - jQ_{Et}}{\bar{V}_{Et}^*} - I_B \quad (2)$$

Series source voltage is (3).

$$\bar{V}_B = V_{Bt} - V_{Et} + Z_B I_B \quad (3)$$

Substituting I_B from (1) to (3) results in phase and magnitude of series voltage source. Similarly, for parallel voltage source (4), substituting I_E from (2) to (4), provides phase and magnitude.

$$\bar{V}_E = \bar{V}_{Et} - Z_E \bar{I}_E \quad (4)$$

Therefore, UPFC parameters are obtained as mentioned above. Note that, in this approach, UPFC parameters are calculated by linear equations without numerical solution, so initial values estimation, the main defect of previous methods, is eliminated.

R_B and R_E show transformers and power switches losses, respectively [4]. UPFC losses are calculated by (5) after power flow solution. Considering power flow solution inflexibility, it is necessary to assume free loss UPFC. Also, UPFC losses are so small. Therefore, its effect on power flow can be ignored. If limit revision of power flow results is possible in whole iteration process and verification can be applied on load flow program, UPFC unknown parameters can be determined easily by the mentioned equations and their limits can easily be checked. If the parameters exceed the boundaries, some strategies seem to be useful during iteration process contrary to the decoupled model. For example, if V_B increases, Q_{Bt} or V_{Et} can be reduced and if V_E increases, Q_{Et} would be reduced [9].

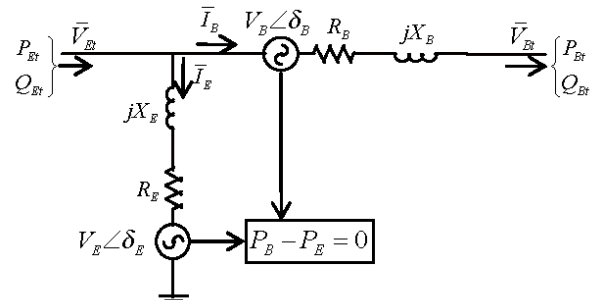


Fig. 8. UPFC voltage source model

$$P_{loss} = R_E I_E^2 + R_B I_B^2 \quad (5)$$

Considering above, losses would be calculated accurately by (5) for each iteration and P_{Bt} changed to $P_{Bt} - P_{loss}$ for the next value. Therefore, in the next iterations accurate solution is achieved for losses.

If UPFC is installed at the beginning or end of the line, depending on the UPFC model, a bus should be added to the network. The added bus model can be determined according to the previous discussion. If a UPFC is installed in the middle of the line, two buses should be added to the network. Their models would be determined considering UPFC models at the two ends.

V. THE PROPOSED GENERALIZED UPFC POWER FLOW MODEL FOR UPFC/ESS

In spite of various UPFC characteristics involved in power system efficiency improvement, it suffers from active power injection disability. Adding this capability significantly enhances UPFC steady-state performance [9]. The capability can be achieved by combining energy storage systems or distributed power generators with UPFC. There are various systems which can be combined with UPFC (e.g. combustion turbines or compact air storage system). UPFC/ESS steady-state model is shown in Fig. 9[9].

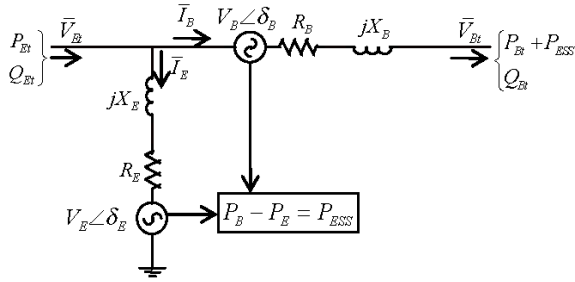


Fig. 9. UPFC/ESS voltage source model

It can be seen that power constraint is shown by $P_B - P_E = P_{ESS}$, therefore UPFC/ESS power flow model is as shown in Fig. 10.

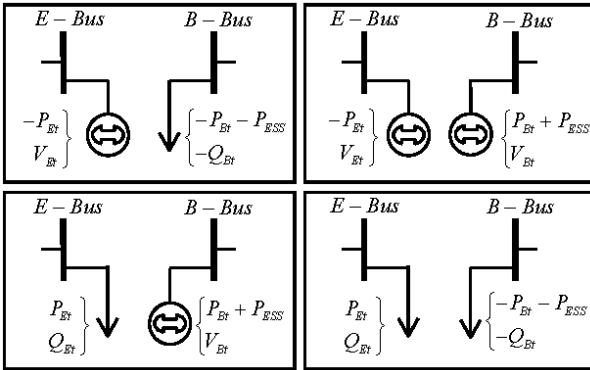


Fig. 10. UPFC/ESS applicable power flow models

VI. POWER FLOW MODEL EVALUATION

In this section, power flow model applications and efficiency is assessed in two different networks. At first, a five-bus network is considered (Fig. 11(a)) [10] to show the most important property of decoupled model, i.e. carrying out capability in common power flow programs. It is assumed to transfer 40 MW and 2MVAR from bus 3 to bus 4 and keep voltage of bus 4 in 1 p.u. Therefore, UPFC is modeled as Fig. 11(b) and power flow is implemented by Power World Simulator®. UPFC parameters are calculated by (3) and (4) (see table 1-part A). Assuming UPFC impedance as $Z_B = Z_E = 0.05 + j0.1$ p.u., UPFC losses are 0.0096 p.u. The

receiving power would be $P_{Bt} = 40 - 0.0096 = 39.9904$. It is obvious that, loss value can be ignored.

Assume that a 10MW energy storage system is combined with the UPFC. UPFC/ESS model is shown in Fig. 11(c); UPFC parameters are shown in table 1-part B.

Easy implementation of this model in load flow program as well as UPFC parameters easy calculation significantly shows the priority of the model to the others. The second network is shown in Fig. 12. Assume that UPFC is installed at the beginning of the line between buses 5 and 6. It can be controlled to absorb 30 MW from bus 5 and inject 100 MW to bus 6 in addition to keep terminal voltages in 1.05 p.u. UPFC parameters and their losses in each iteration are shown in table 2. Power flow results are shown in Fig. 12(b). It can be seen that UPFC parameters are calculated easily without initial values requirement and their limits can be revised easily.

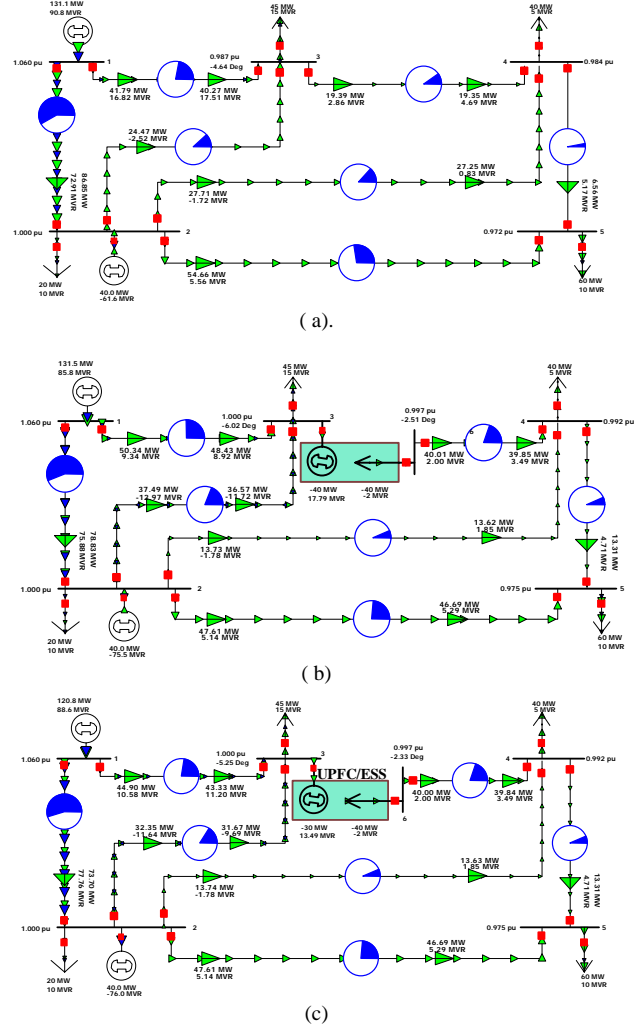


Fig. 11. The studied five bus network: (a) without UPFC ;(b) with UPFC at the beginning of the line, between 3rd and 4th bus; (c) with UPFC/ESS at the beginning of the line, between 3rd and 4th bus

TABLE I
CALCULATED UPFC PARAMETERS

	V_B	δ_B	V_E	δ_E
Part A	0.101 ^{pu}	86.99°	1.017 ^{pu}	-6.01°
Part B	0.091 ^{pu}	87.48°	1.013 ^{pu}	-4.67°

The parameters calculations impose no influence on number of iterations for power flow solution convergence. Also, losses can be calculated easily.

VII. INFLUENCE OF VARIOUS FACTORS ON UPFC CONVERTERS RATINGS

Various factors influence UPFC performance, converters ratings and range of UPFC parameters variations. These factors are studied in previous papers for special case of two machine system [1, 8]. The offered model can be used to perform these studies in a real network without simplifying and the results would be more reliable. On the contrary of two machines system, the main advantage of real networks studies is to consider network

TABLE II
UPFC PARAMETERS IN EACH ITERATION

n	V_B (pu)	δ_B (°)	V_E (pu)	δ_E (°)	P_{loss} (pu)
1	0.27	72.5	1.24	-8.1	0.060
2	0.30	72.0	1.22	-9.5	0.058
3	0.29	71.0	1.23	-8.6	0.060
4	0.29	71.4	1.23	-8.8	0.059
5	0.29	71.3	1.22	-8.8	0.059
6	0.29	71.3	1.22	-8.8	0.059
7	0.29	71.3	1.22	-8.8	0.059
8	0.29	71.3	1.22	-8.8	0.059

Operational restrictions and UPFC parameters constraints effect on UPFC performance. For instance, in some cases, network topology-structure as well as constraints makes UPFC unable to increase lines transmission capacity.

UPFC can be installed in every point of a line. UPFC location affects on converters ratings and parameters range. Assume that UPFC is installed between buses 5 and 6 to transfer 30 MW (see Fig. 12). UPFC converters ratings variations in terms of UPFC location in a line is shown in Fig. 13(a). On the contrary of significant changes of series converters rating, parallel converter rating can be ignored. Parallel converters have minimum rating at 70% of line sending end of the line. Also, converters voltages increase at the end of the line,

but it is not so significant to restrict UPFC location. UPFC can be installed in vast range of a line considering low variations of rating and voltage UPFC converters.

A UPFC is installed in the middle of the line between buses 5 and 6 to study transferring power effects on UPFC converters (see Fig. 12). UPFC converters rating in terms of transferred power of UPFC are shown in Fig. 13(b).

Transferring power increment results in almost linear increment of converters rating. Therefore, converters rating limitation affect severely on maximum transferring power. The increment affect ignorantly parallel converters voltage, but severely affects series converters voltage. Series converters voltage is another constraint for maximum transferring power.

Now, consider energy storage influence on UPFC converters ratings. Assume that UPFC is installed between buses 5 and 6 (see Fig. 12) and absorbs 30MW at the receiving end and deliver the same amount plus exiting energy storage power at another end. UPFC converter ratings in terms of energy storage delivered power are shown in Fig. 13(c).

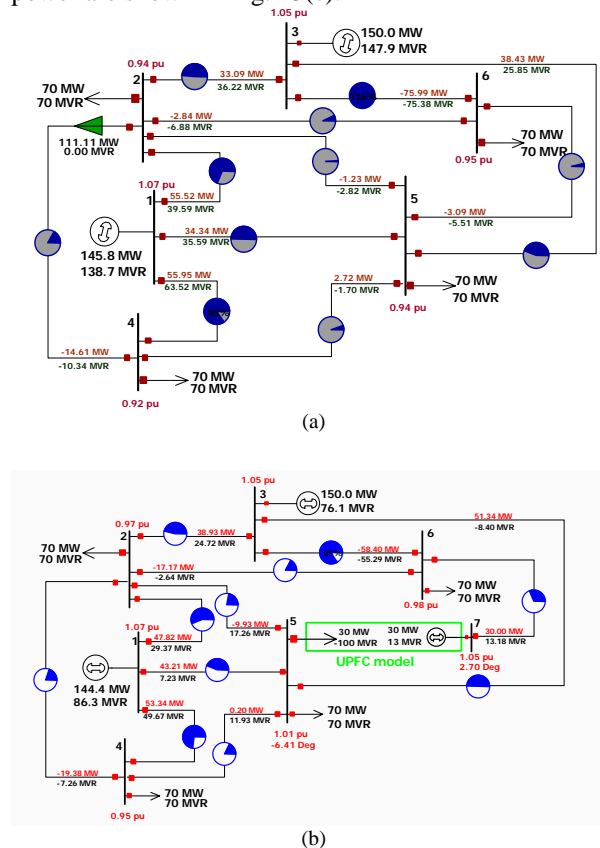


Fig. 12. The studied 6 bus network: (a) without UPFC; (b) with UPFC at the beginning of the line between bus 5 and 6

Both series and parallels converters ratings almost increase equal to injected power of energy storage system. Therefore, converters ratings limitation restricts energy storage system power injection. Converters voltages vary in terms of injecting power of energy storage system. Parallel converters variation can be ignored, but series one increases rapidly. Voltage

constraint of series converter is another limiting factor for injection power of energy storage system.

Another effective parameter is UPFC parallel impedance. A 30MW UPFC is installed on a line between buses 5 and 6 (Fig. 12) to assess UPFC converters ratings (Fig13(d)).

VIII. CONCLUSION

Investigating various power flow models shows their shortcoming and constraints. Decoupled power flow model is modified to a comprehensive and robust one to eliminate available defects and limitations. Model capability to implement in available load flow programs without changing the context is considered as a unique property. In the proposed model, two decoupled buses are added for each UPFC. Therefore, Jacobean matrix dimension increases by two and convergence speed changes, but especially in large networks this case can be ignored. In this model, UPFC constraints and losses are considered. Also, the model can be easily performed in power networks and UPFC combined with ESS. The performed simulations confirmed the two proposed models capabilities and efficiencies in various UPFC control strategies.

According to the investigation performed on UPFC converters rating using the offered models in this research, converters rating, voltages, limitations of converters voltage and rating affect severely the maximum transferring power. These limitations restrict injection power of energy storage system as well.

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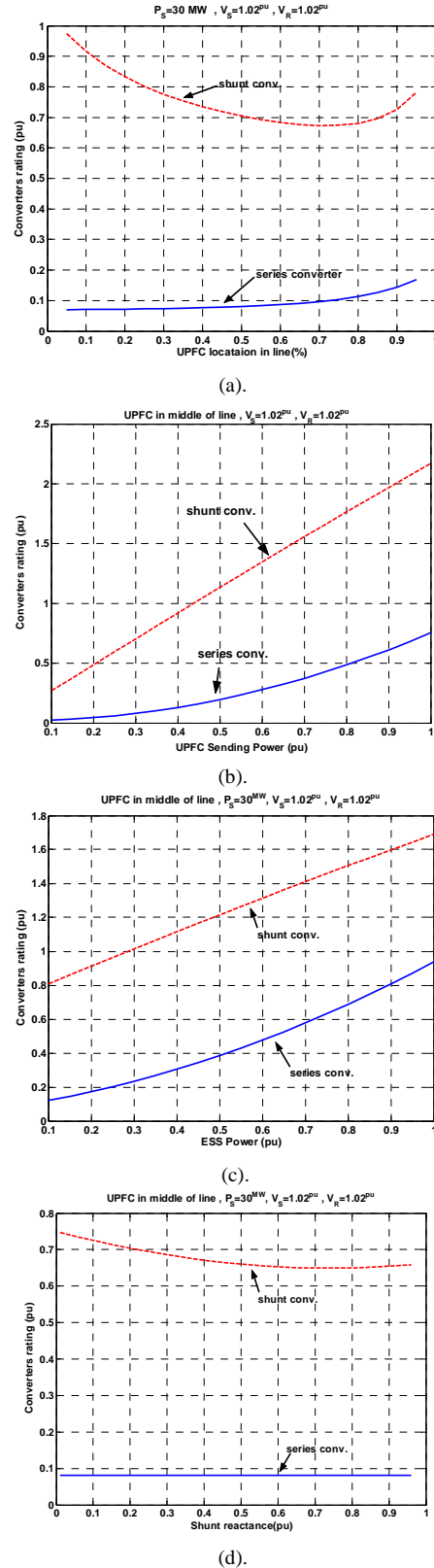


Fig. 13-UPFC converters ratings related to : (a) location;(b) transferring power ;(c) ESS delivered power ;(d) parallel reactance