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Comparison of various UPFC models for power flow control

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ABSTRACT

This paper presents a comparative study on various implementation techniques of Unified Power Flow Controller (UPFC) in load flow algorithms. The comparison is done among; decoupled technique, comprehensive technique, load injection technique, π load injection technique, indirect technique, and matrix partitioning technique. The merits and demerits of these techniques are presented. Beside these techniques, the paper presents a developed UPFC model based only on current injection approach. The model is implemented in Newton–Raphson current injection load flow method (NR-CIM). This model addresses the main drawbacks of previous techniques. Test results are presented using IEEE standard systems which demonstrate the effectiveness of the developed model.

1. Introduction

Flexible Alternating Current Transmission Systems (FACTS) devices have been widely used in power systems around the world. These devices are used to enhance the controllability and increase the power transfer capability of the electrical network. The semiconductor devices such as diodes, transistors, thyristors and gate turn-off thyristors (GTO) are applied to develop the various types of FACTS. The FACTS devices have the ability to control many parameters of transmission systems such as; the series impedance, the shunt impedance, the current, the voltage magnitude, and the phase angle. Also it can be used for damping the oscillations of system at various frequencies below the rated frequency. In general, there are two generations of FACTS devices, the first generation is based on the conventional thyristor switched capacitors reactors, and quadrature tap changing transformers. This generation has resulted the Static Var Compensator (SVC), the Thyristor-Controlled Series Capacitor (TCSC), and the Thyristor-Controlled Phase Shifter (TCPS). While, the second generation employs the gate turn off thyristor switched converters as voltage source converters. This generation has produced the Static Shunt Compensator (STATCOM), the Static Synchronous Series Compensator (SSSC), the UPFC, the Interline Power Flow Controller (IPFC), and the Generalized Unified Power Flow Controller (GUPFC). In general, these two groups have distinctly different operating and performance characteristics.

The UPFC is considered one of the most important of FACTS devices. The configuration of this device is based on the concept of voltage source converter (VSC) which has several attractive features, such as to work together with energy storage devices, allowing both active and reactive power to be simultaneously exchanged with the ac system.

The UPFC can be considered as a multi-function controller which is capable of providing the performance of one or two FACTS devices. Where, this device can be viewed as a coordinated combination of SSSC on the series part and STATCOM on the shunt part. Although UPFC utilizes the same technology as SSSC and STATCOM, its operational principle is different from them. The UPFC can be used to control the line power flow and voltage bus individually or simultaneously [1–5].

Now, the implantation of FACTS devices in load flow algorithms is considered as a fundamental requirement in planning, operation, and control. Generally, the existing load flow programs need to be modified to incorporate these devices. The required modifications

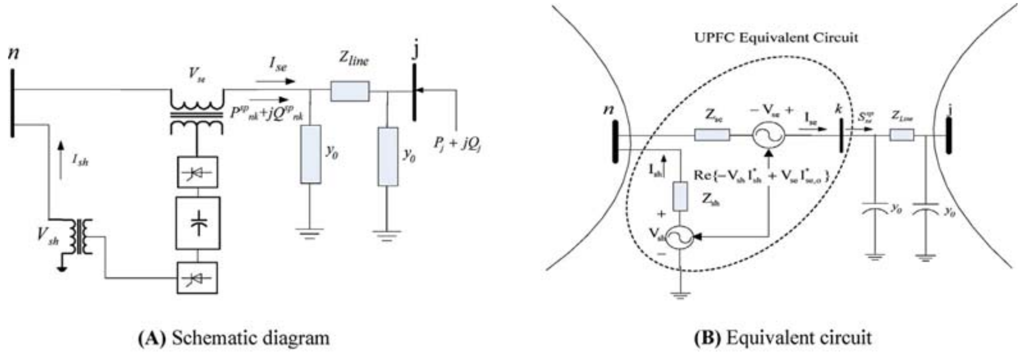


Fig. 1. *N* bus system with UPFC connected between buses *n* and *j*.

been done to reduce the complexity of load flow programs with the UPFC device [3–14].

In this paper, comparison study on the UPFC modeling techniques (the decoupled technique, the comprehensive technique, the load injection technique, the π load injection technique, the indirect technique, and the matrix partitioning technique) is presented. The advantages, the disadvantages and the main idea for each technique are described. Also, the paper presents an easy modeling for UPFC controller into NR-CIM load flow method. The developed model is only based on current injection approach. This model addresses the main drawbacks of previous techniques.

2. Decoupled UPFC technique

Fig. 1A describes the schematic diagram of UPFC (two voltage source converters connected with common dc link). The equivalent circuit of UPFC as two voltage sources (V_{sh}, V_{se}) with series impedances (representing the coupling transformers) can be given as in Fig. 1B [3–5].

Based on this equivalent circuit, Nabavi-Niaki and Iravani proposed a simple UPFC model based on decoupled approach [7]. In this technique, the UPFC and coupling transformers are assumed to be lossless. The sending and receiving ends of the UPFC are separated. The receiving bus is transformed into a PQ bus while the sending is transformed into a PV bus. The injected active and reactive power loads at PQ bus and the voltage magnitude at the PV bus are set at the pre-request values as shown in Fig. 2A. A standard load flow is carried out to determine the load flow solution with the new representation of UPFC. After the convergence of load flow algorithm, the power flow solution is used to solve the UPFC steady-state equations to determine parameters of UPFC (V_{sh}, V_{se}).

2.1. Advantages of decoupled UPFC technique

The simplicity is considered the main advantage of this technique. Where, the modification of original Jacobian matrix is avoided, only the power mismatch vector has to be changed.

2.2. Disadvantages of decoupled UPFC technique

- The problem of selecting the suitable UPFC parameters initial values still exists. Where, these parameters are computed after the converge using a set of non-linear equations.
- The technique did not take in account the situation when the UPFC is the only link between two sub-networks.

3. Comprehensive UPFC technique

Ref. [8], has presented a new and comprehensive UPFC model to circumvent the limitations of decoupled technique. In this model, The UPFC is considered a straightforward extension of the power flow equations. Where, the UPFC control parameters are taken as independent variables and their values are calculated during the iterative process. The comprehensive technique is considered a unified approach links the alternating current network and UPFC state variables in a single system of simultaneous equations. As a result of that, the Jacobian matrix is increased according to the number of UPFCs. In general, the structure of the modified Jacobian matrix with UPFC can be given in Fig. 2B.

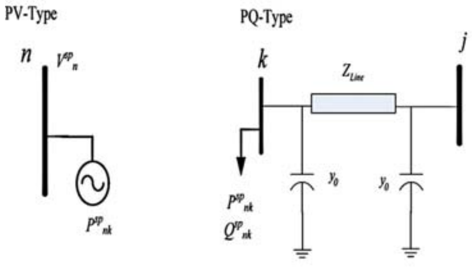
3.1. Advantages of comprehensive UPFC technique

The main advantages of comprehensive approach compared to decoupled technique can be summarized as follows:

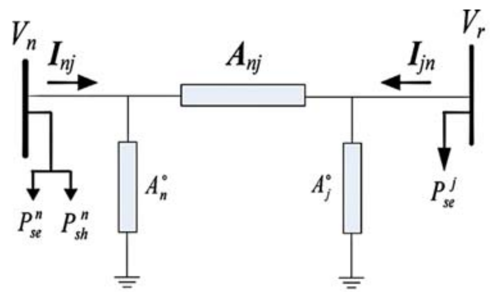
- Due to the incorporating of UPFC state variables inside the Jacobian matrix and mismatch vector, a good convergence characteristic can be obtained.
- The approach gives the ability to control the voltage, active and reactive power simultaneously or individually.
- The approach gives a solution when the UPFC is the only link between two sub-networks.

3.2. Disadvantages of comprehensive UPFC technique

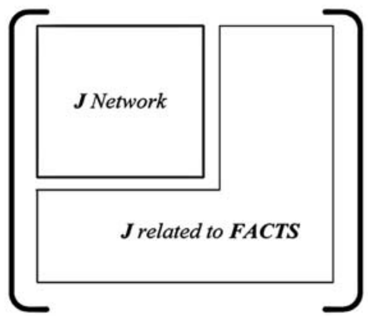
This technique presents the UPFC control parameters as independent variables and their values are calculated during the iterative process. Hence, the size of the Jacobian matrix is increased in order to accommodate the additional independent UPFC state



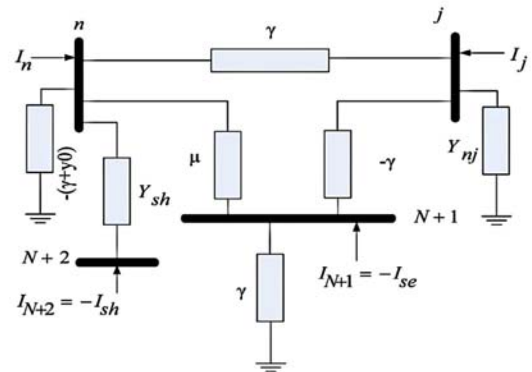
(A) Decoupled model.



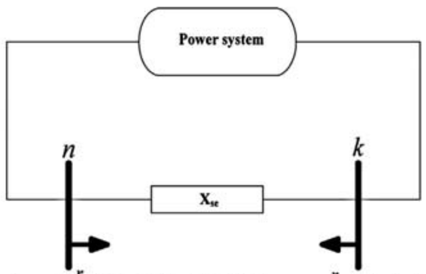
(E) π load injection model.



(B) Comprehensive model



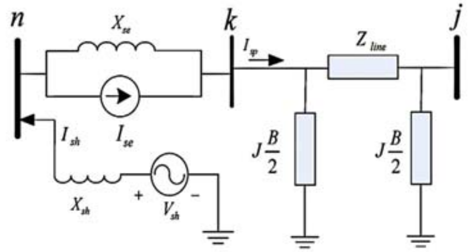
(F) An indirect model.



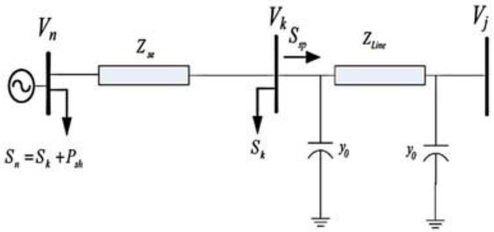
$$P_{n,upfc} = \frac{r}{X_{se}} V_n V_k \sin(\theta_n - \theta_k + \beta) \quad P_{k,upfc} = -\frac{r}{X_{se}} V_n V_k \sin(\theta_k - \theta_n + \beta)$$

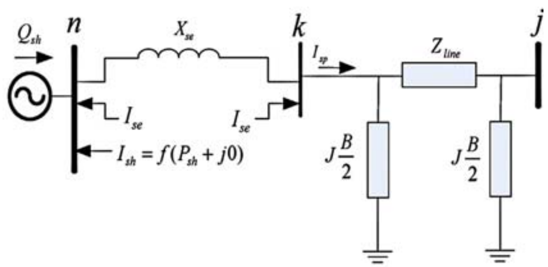
$$Q_{n,upfc} = \frac{r}{X_{se}} V_n^2 \cos\beta \quad Q_{k,upfc} = -\frac{r}{X_{se}} V_n V_k \cos(\theta_n - \theta_k + \beta)$$

(C) Load injection model.



(G) Current sources representation of UPFC.





to $rV_n \angle \beta$, where $0 < r < r_{max}$ and $0 < \beta < 360°$. r and β represent the control parameters of UPFC. The UPFC model can easily be incorporated into load flow algorithm. Where, the admittance matrix is modified by adding the series reactance of UPFC (X_{se}) between nodes n and k. Then, the Jacobian matrix is modified by adding the appropriate injected powers. To make this more clearly, the linearized load flow model can be considered as:

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} H & N \\ J & L \end{bmatrix} \cdot \begin{bmatrix} \Delta\theta \\ \dfrac{\Delta V}{V} \end{bmatrix} \quad (1)$$

The Jacobian matrix has to be modified as follows:

$$\begin{bmatrix} J_{old} & A_{12} \\ A21 & A22 \end{bmatrix} \begin{bmatrix} X_1 \\ X2 \end{bmatrix} = \begin{bmatrix} B_1 \\ B2 \end{bmatrix} \quad (2)$$

Where, the superscript (•) indicates the elements of Jacobian matrix without UPFC. Based on this technique, Haque and Yam proposed a simple UPFC model to eliminate the modifications of Jacobian matrix [10]. In this model, the injected loads are updated during the iterative process based on the terminal voltages of UPFC and the pre-request values for line power flow and shunt voltage magnitude. The control parameters of UPFC can be updated during the iterative process. Fig. 2D shows the simple UPFC model based on load injection approach.

Where:

$$S_n = V_n \left(\frac{P_{sp} + jQ_{sp}}{V_k}\right)^* - \left(\frac{V_n - V_k}{Z_{se}}\right) \quad (3)$$

$$S_k = -V_k \left(\frac{P_{sp} + jQ_{sp}}{V_k}\right)^* - \left(\frac{V_n - V_k}{Z_{se}}\right) \quad (4)$$

$$P_{sh} = Re\left\{V_{se}\left(\frac{V_n + V_{se} - V_k}{Z_{se}}\right)^*\right\} \quad (5)$$

where, the superscripts (sp), (se) and (sh) indicate the specified, series and shunt values, respectively.

4.1. Advantages of load injection UPFC technique

By using the load injection technique, the implementation of UPFC into power flow program can be done easily compared to the comprehensive approach. Also, this technique solved the problem when the UPFC compensator is the only link between two sub-networks.

4.2. Disadvantages of UPFC injection model

The main drawback of this approach is the modification of Jacobian matrix to include the related elements of UPFC controller. Also, the UPFC parameters are adjusted by trial and error in order to achieve the power flow solution.

5. π load injection UPFC technique

the pre-request values. The π load injection model of the embedded UPFC can be given as in Fig. 2E [11,12].

Where,

$$P_{se}^{n} = V_n V_{se} \frac{(1 - y_0 X_L)}{(X_{se} - y_0 X_{se} X_L + X_L)} \sin(\theta_n - \theta_{se}) \quad (6)$$

$$P_{se}^{j} = \frac{-V_j V_{se}}{(X_{se} - y_0 X_{se} X_L + X_L)} \sin(\theta_j - \theta_{se}) \quad (7)$$

$$A_{nj} = -\frac{1}{Z_{se}(1 + jZ_L - y_0) + Z_L} \quad (8)$$

$$A_n^o = -(j2y_0 - Z_L {y_0}^2) + \frac{(1 + jZ_L y_0)(1 + Z_{se}(j2y_0 - Z_L {y_0}^2) + (1 + jZ_L y_0))}{Z_{se}(1 + jZ_L - y_0) + Z_L} \quad (9)$$

$$A_j^o = \frac{Z_{se}(j2y_0 - Z_L {y_0}^2) + jZ_L y_0}{Z_{se}(1 + jZ_L - y_0) + Z_L} \quad (10)$$

$$P_{sh}^{n} = \frac{V_n V_{sh}}{X_{sh}} \sin(\theta_n - \theta_{sh}) \quad (11)$$

5.1. Advantages of π load injection UPFC technique

In this model, the reactance of the coupling transformers and the line charging susceptance are considered in the load flow solution. The original structure and symmetry of the admittance matrix can still be kept. The Jacobian matrix can keep the block-diagonal properties. Hence, the sparsity technique can be easy applied for load flow solution.

5.2. Disadvantages of π load injection UPFC technique

In this technique, the UPFC variables are adjusted simultaneously with the variables of network to achieve the required control targets. Hence, the Jacobian matrix has to be modified to include the related elements of UPFC. Also, this method needs good initial conditions for the UPFC state variables to obtain a good convergence.

6. An indirect UPFC technique

Ref. [13], tried to reduce the complexities of the load flow program codes with UPFC controller. This target has been done by developing an indirect approach for modeling of UPFC in NR load flow algorithm. In this approach, the power system network with the UPFC is represented with amended equivalent network without this device. Then, the standard load flow program can be used to find the load flow solution and the required voltage parameters of UPFC.

By assuming, an N bus power system network incorporated with (K) UPFCs. The new equivalent circuit of power system network with UPFCs can be represented as $N + 2K$ bus system without UPFC. In Fig. 1, an UPFC is connected between buses n and j of an existing (N) bus system. Based on that, the equivalent $(N + 2)$ bus system can be given as in Fig. 2F.

Where,

$$I_{N+2} = -I_{sh} = \sum_{k=1}^{N+2} Y_{(N+2),k} V_k \tag{15}$$

6.1. Advantages of indirect UPFC technique

The main advantage of the indirect approach is the reducing of load flow complexity when contains UPFC device. This reducing has been done by transform the power network with UPFC to equivalent network without UPFC.

6.2. Disadvantages of indirect UPFC technique

The main disadvantage of this approach is the increasing in the size of Jacobian matrix in order to accommodate the additional state variables of UPFC. As a result of that, the Jacobian elements related to UPFC have to be modified.

7. UPFC modeling using matrix partitioning technique

Ref. [14], has applied the matrix partitioning approach to model UPFC in NR load flow algorithm. This approach tried to avoid the modification of original Jacobain matrix (J_{old}) and achieve the reusability. This approach based on partitioning of the Jacobian matrix into original matrix and new sub-matrices related to UPFC, as described in (16).

$$\left[\begin{array}{c|c} J_{old} & A_{12} \\ \hline A21 & A22 \end{array}\right] \left[\begin{array}{c} X_1 \\ \hline X2 \end{array}\right] = \left[\begin{array}{c} B_1 \\ \hline B2 \end{array}\right] \tag{16}$$

Eq. (16) can be rewritten as follows:

$$J_{old} X_1 + A_{12} X_2 = B_1 \tag{17}$$

$$A_{21} X_1 + A_{22} X_2 = B_2 \tag{18}$$

Eq. (19) can be obtained by rearranging (17).

$$X_1 = J_{old}^{-1}(B_1 - A_{12} X_2) \tag{19}$$

By substituting (19) into (18), Eq. (19) can be obtained as follows:

$$X_2 = [A_{22} - A_{21} J_{old}^{-1} A_{12}]^{-1} [B_2 - A_{21} J_{old}^{-1} B_1] \tag{20}$$

In order to get the value of X_1, X_2 is solved first and then substituted into (19).

7.1. Advantages of UPFC modeling using matrix partitioning technique

The matrix partitioning approach is based on the comprehensive UPFC model; hence, the advantages of the comprehensive approach have been collected in this technique. Moreover, the adding and changing in load flow codes can be done with some modification in the original codes.

8. Developed UPFC model for (NR-CIM) load flow method

The equivalent circuit of UPFC is comprised of series and shunt voltage sources as shown in Fig. 1A. In the developed model, the series voltage source is represented by Norton's equivalent circuit. Where, the current source (I_{se}) is in parallel with the series reactance (X_{se}), as shown in Fig. 2G.

The current source can be separated and injected at buses n and k, respectively, as shown in Fig. 2H. This injected current can be calculated as a function of the updated voltages at these buses, series UPFC reactance and pre-request active and reactive line flow (P_{sp}, Q_{sp}) as follows;

$$I_{se} = \left(\frac{P_{sp} + jQ_{sp}}{V_n}\right)^* - \left(\frac{V_k - V_n}{jX_{se}}\right) \tag{21}$$

The real (r) and imaginary (m) components of the injected currents at buses (i and k) can be calculated as follows:

$$I_{se}^r = \frac{P_{sp} V_n^r + Q_{sp} V_n^m}{(V_n^r)^2 + (V_n^m)^2} - \frac{(V_k^m - V_n^m)}{X_{se}} \tag{22}$$

$$I_{se}^m = \frac{P_{sp} V_n^m - Q_{sp} V_n^r}{(V_n^r)^2 + (V_n^m)^2} + \frac{(V_k^r - V_n^r)}{X_{se}} \tag{23}$$

The shunt converter can be modeled as a synchronous condenser which produces the reactive power (Q_{sh}) and zero active power to maintain the voltage magnitude of sending bus (n) at the pre-request value. In general, this shunt converter neither supplies nor absorbs the active power from the system. Therefore, the real power exchange of this converter must be zero as in (24).

$$PE_t = P_{sh} + P_{se} = 0 \tag{24}$$

As a shown in Fig. 2H, the shunt injected current (I_{sh}) at the sending bus (n) can be calculated using (25).

$$I_{sh} = \left(\frac{P_{sh} + j0}{V_n}\right)^* \tag{25}$$

Based on (24), the active power (P_{sh}) can be calculated using (26).

$$P_{sh} = -(P_{se}) \tag{26}$$

P_{se} can be calculated from the following equation;

$$P_{se} = Re\left\{V_{se}\left(\frac{V_i + V_{se} - V_k}{jX_{se}}\right)^*\right\} \tag{27}$$

The final form of (P_{se}) can be calculated using (28).

$$P_{se} = \frac{V_{se}^r}{X_{se}}(V_n^m + V_{se}^m - V_k^m) - \frac{V_{se}^m}{X_{se}}(V_n^r + V_{se}^r - V_k^r) \tag{28}$$

The injected real and imaginary components of shunt current at bus (n) can be calculated as follows:

$$I_{sh}^r = \frac{V_n^r P_{sh}}{(V_n^r)^2 + (V_n^m)^2} \tag{29}$$

8.1.1. Series converter

The real and imaginary components of series injected voltage can be calculated using the following simple equations;

$$V_{se}^{r} = -I_{se}^{m} X_{se} \tag{31}$$

$$V_{se}^{m} = I_{se}^{r} X_{se} \tag{32}$$

8.1.2. Shunt converter

The real and imaginary components of shunt injected voltage can be calculated using the following equations;

$$V_{sh}^{r} = V_{n}^{r} + \frac{X_{se}}{(V_{n}^{r})^2 + (V_{n}^{m})^2}(V_{n}^{r} Q_{sh} - V_{n}^{m} P_{sh}) \tag{33}$$

$$V_{sh}^{m} = V_{n}^{m} + \frac{X_{se}}{(V_{n}^{r})^2 + (V_{n}^{m})^2}(V_{n}^{r} P_{sh} + V_{n}^{m} Q_{sh}) \tag{34}$$

Where,

$$Q_{sh} = \sum_{i=1}^{N} |V_n||V_i|(G_{n,i} \sin\theta_{n,i} - B_{n,i} \cos\theta_{n,i}) + Q_{load}^{n} \tag{35}$$

8.2. Implementation of UPFC model in (NR-CIM)

The developed UPFC model can be implemented easily into the new formulation of NR load flow which based on current injections approach (NR-CIM) [15–18]. This load flow formulation is considered a faster than the conventional NR load flow method which based on power mismatches approach. This due to the most elements of Jacobian matrix is constant and equals to the elements of admittance matrix. In this load flow method, the PV and PQ buses are represented by two equations comprising the real and imaginary components of the injected currents expressed in terms of the voltage rectangular coordinates. Regarding to the PV bus, an additional equation is needed to represent the voltage mismatch of this bus.

Table 1
Solution algorithm of NR-CIM load flow with the developed UPFC model.

The algorithm	
123	| Initialize voltages and angles. | Form **Y-Bus** | Convert the sending bus of UPFC to PV-type with the specified value. | Add the reactance of UPFC to original admittance matrix. | Determine the current mismatch vector (ΔI) as given in (36). **If** (ΔP_{max} and $\Delta Q_{max} \leq$ tolerance) | Go to step 4 **Otherwise** | Solve the power flow equation of NR-CIM [15–18]. | Update the required parameters of UPFC as given in (31)–(33). | **end if** If $h \geq$ maximum number of iterations.
4	| Go to step 4 Otherwise | Go to step 3 | **end if** Print **Results** included the final values of UPFC parameters.

The incorporating of the developed UPFC model in this load flow algorithm became simple with avoiding the modification of original Jacobian matrix as presented in Table 1. It can be observed that the current mismatch vector is only needed to modify as follows:

$$\Delta I = [\Delta I_1^m \, \Delta I_1^r \ldots (\Delta I_n^m - I_{se}^m + I_{sh}^m)(\Delta I_n^r - I_{se}^r + I_{sh}^r)\Delta V_n^2 \ldots (\Delta I_k^m + I_{se}^m)(\Delta I_k^r + I_{se}^r) \ldots \Delta I_N^m \, \Delta I_N^r] \tag{36}$$

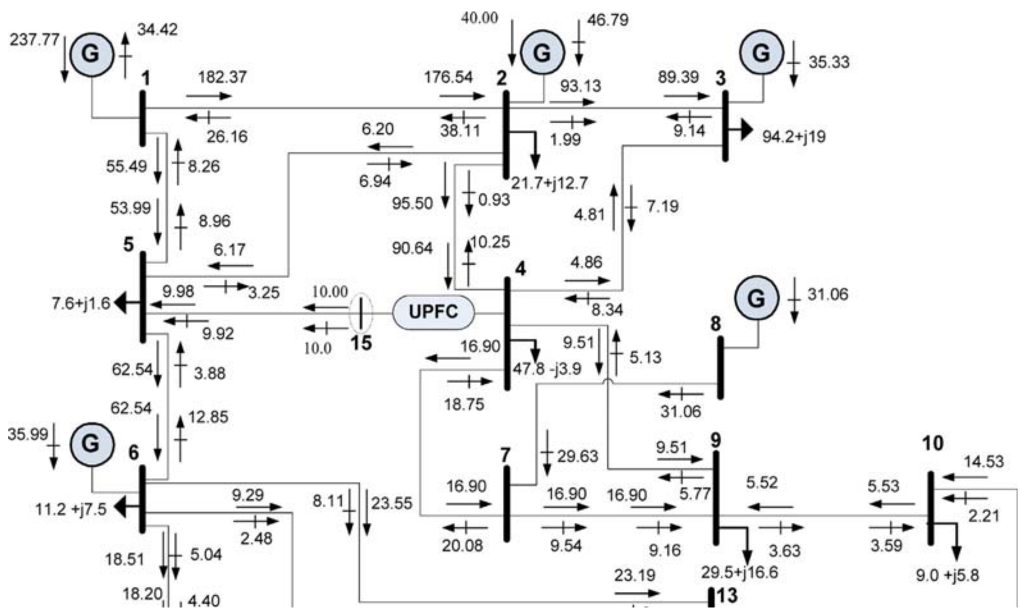


Table 2
Voltage magnitudes (p.u) and phase angles (°) for IEEE 14-bus system with and without UPFC.

Bus no.		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
W/o UPFC	V	1.0600	1.0450	1.0100	1.0295	1.0349	1.0700	1.0559	1.0900	1.0497	1.0458	1.0543	1.0547	1.0495	1.0315	–
	φ	0.0	−5.0	−12.6	−10.4	−9.0	−14.7	−13.6	−13.6	−15.2	−15.4	−15.1	−15.5	−15.6	−16.4	–
With UPFC	V	1.0600	1.0450	1.0100	1.0000	1.0501	1.0700	1.0398	1.0900	1.0299	1.0286	1.0446	1.0536	1.0458	1.0182	1.0554
	φ	0.0	−5.8	−15.8	−15.0	−6.5	−14.6	−17.0	−17.0	−17.9	−17.6	−16.2	−15.7	−15.9	−18.1	−6.4

Where,

$$\Delta I_n^m = I_n^{m,\mathrm{sp}} - I_n^{m,\mathrm{cal}} \tag{37}$$

$$\Delta I_n^r = I_n^{r,\mathrm{sp}} - I_n^{r,\mathrm{cal}} \tag{38}$$

8.3. Advantages of developed UPFC model

The developed UPFC model can be incorporated easily into the NR load flow algorithm without any modification in the original Jacobian matrix. The model solves many problems due to the implementation of UPFC in load flow algorithm such as:

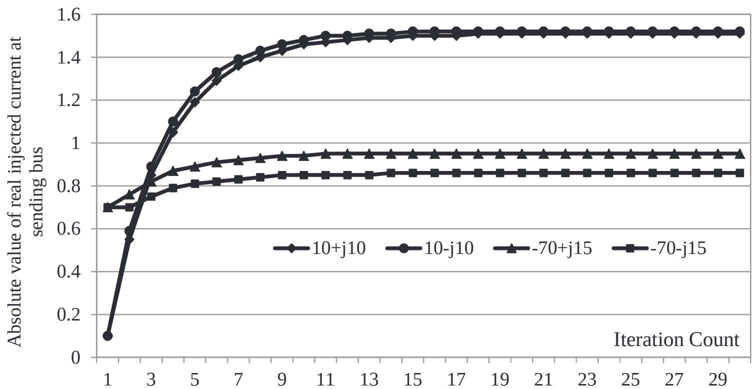
- The problem which exists when UPFC is the only link between two sub-networks.
- The control of voltage, active and reactive power simultaneously or individually can be done.
- The parameters of UPFC can be updated during the iterative process.
- The original structure and symmetry of admittance and Jacobian matrices can still be kept.
- The sparsity technique can be easily applied in load flow program with UPFC device.

8.4. Disadvantages of developed UPFC model

The load flow convergence with the developed UPFC model needs a few more iterations compared to the uncontrolled case. Anyway, the addition iterations in the case of load flow control are not considered a big problem.

9. Results and discussions

The proposed UPFC model has been investigated on standard IEEE 14-bus and IEEE 30-bus test systems to validate its feasibility. The developed model is incorporated into the NR based on current injection (NR-CIM) load flow algorithm. The NR-CIM load flow algorithm with the UPFC model has been written using the C++ language. The developed model is more flexible. It can be used to control any combination of voltage, active and reactive line flows according to the operating requirements. A convergence tolerance



(A) Variation of real injected current at bus (4)

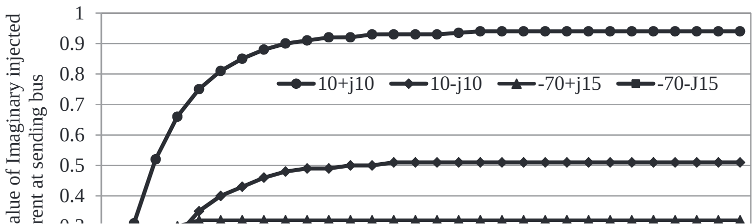


Table 3
IEEE 14-bus system with UPFC at various specified line flows.

Specified power flow (MVA)		Complex voltage (p.u)				
Psp	Qsp	Bus (4)	Bus (15)	Bus (5)	Series converter	Shunt converter
10	10	1.000 ∠ −15.00	1.055 ∠ −6.39	1.050 ∠ −6.54	0.177 ∠ 58.10	0.966 ∠ −14.97
10	−10	1.000 ∠ −14.50	1.034 ∠ −5.94	1.037 ∠ −6.24	0.162 ∠ 71.51	0.968 ∠ −14.62
−70	15	1.000 ∠ −9.81	1.035 ∠ −11.07	1.038 ∠ −9.39	0.102 ∠ −72.28	0.986 ∠ −9.70
−70	−15	1.000 ∠ −9.52	1.001 ∠ −10.68	1.017 ∠ −9.13	0.091 ∠ 70.71	0.986 ∠ −9.50

equals to 10^{-5} p.u for the maximal absolute bus active and reactive power mismatches has been chosen. The source impedances have values of $X_{se} = X_{se} = 0.1$ p.u. and the system base MVA is 100.

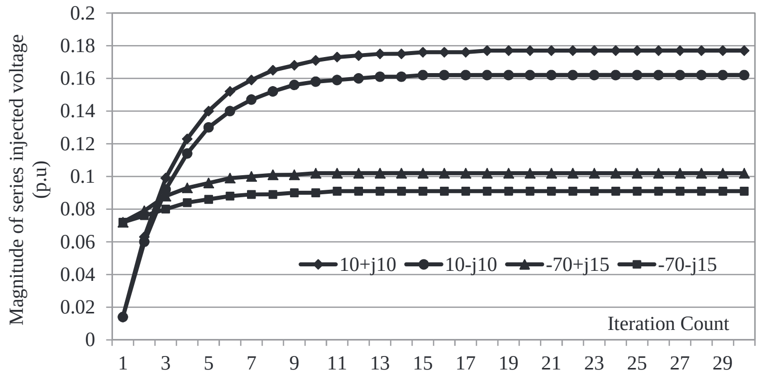
9.1. Case I: IEEE 14-bus test system

In this case, an UPFC (operated in voltage, active and reactive control mode) is connected between buses (4) and (5), near bus (4) in IEEE 14-bus system [19]. The control objective is to keep the voltage at bus (4), active and reactive power flow from bus (4) to (5) equal to 1.0 p.u, 10 MW and 10 MVar, respectively. New auxiliary bus (15) is added to the original system and taken as reference bus. The results shown in Table 2 give the voltage magnitude and phase angle for all buses of the system with and without UPFC. The power flows results have shown the ability of NR based on current injection approach (NR-CIM) in solving the load flow including the developed UPFC model in the electrical system. In Fig. 3, the load flow solution is fulfilling the control objectives of voltage, active and reactive power flows. This can be proven by calculating the line flow between buses (4) and (15) by using the obtained voltage and phase angle of the related buses.

With the same location of UPFC in IEEE 14-bus system, the capability of the developed model in NR-CIM load flow algorithm to work at different power flow references has been validated in this test. The UPFC is used to control the voltage at bus (4) to be 1.0 p.u, at the various specified line flows toward bus (5) which are presented in Table 3. The developed model in NR-CIM load flow program converged successfully to find the solutions for all test cases. The complex voltage of sending bus (4) and reference bus (15) for all cases of various specified line powerflows are given in Table 3. It can be observed that the obtained voltages of buses 4 and 15 are highly affected by the pre-request line flows.

The variation of the total injected currents at bus (4) against the iterations count for various specified line flows is shown in Fig. 4A as a real component and Fig. 4B as imaginary component. These components have to be added to the original current mismatches and sending bus (4). While, only series current (I_{se}) should be added at the reference bus (15). It can be observed that the convergence characteristics of the injected currents change fast for the first iterations and reach to the final value after a few iterations.

The variation of the magnitude and phase angle for series converter voltage against the iterations count for different specified



(A) Variation of magnitude of series injected voltage.

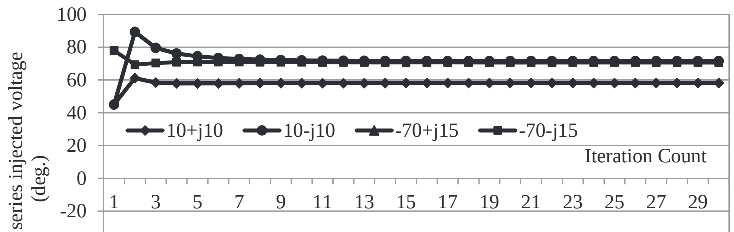


Table 4
Test results of IEEE30-bus system.

Parameters	UPFC1	UPFC2	UPFC3
Send → receive	6 → 4	19 → 18	27 → 25
P_{se} (MW)	7.00	10.00	15.00
Q_{se} (MVar)	2.50	−5.00	8.00
V_{se} (p.u.)	0.203 ∠ 66.84	0.182 ∠ 67.87	0.199 ∠ 42.20
V_{sh} (p.u.)	0.956 ∠ −17.52	0.924 ∠ −22.52	0.911 ∠ −24.35
V_n (p.u.)	1.000 ∠ −17.03	1.000 ∠ −22.44	1.000 ∠ −24.33
V_k (p.u.)	1.039 ∠ −6.21	1.020 ∠ −12.67	1.088 ∠ −15.43
V_j (p.u.)	1.037 ∠ −6.34	1.021 ∠ −13.56	1.057 ∠ −16.55
$I_{se}+I_{sh}$ (p.u.)	−1.87 + j0.8	−1.67 + j0.68	−1.34 + j1.48

line flows is shown in Fig. 5A and B, respectively. It can be seen that variation of series injected voltage as a magnitude and angle are smoothly without oscillation. But the required number of iterations is a few more than the load flow solution without UPFC. This is because in the developed model, two injected currents at the ends of UPFC need to be updated during the iterative process. Anyway, the required few number of iteration in the case of load flow control is not considered a big problem.

9.2. Case II: IEEE 30-bus test system

In this test case, three UPFC are located at different places in the IEEE 30-bus system [19]. The UPFCs are embedded in transmission lines between buses (6) and (4) for the first controller (UPFC1), (19) and (18) for the second controller (UPFC2), and (27) and (25) for the last one (UPFC3). The UPFC1 is used to control the transfer power flow in the first line to be 7 MW and 2.5 MVar respectively. The UPFC2 is implemented in the second line to adjust the active and reactive powers to be $10 - j5$ MVar. Finally the UPFC3 is used to control the active and reactive power toward bus (25) to be 15 MW and 8 MVar respectively. For all UPFCs, the pre-request voltage magnitude of sending bus is fixed at 1.0 p.u. The final values of series and shunt voltages, voltage of sending bus, auxiliary and receiving buses voltage and the final values of total injected current at the sending bus are presented in Table 4. This test shows the ability of the developed model to work with several UPFCs at different locations and control references.

10. Conclusions

In this paper, many of previous techniques that interested to implement the UPFC controller into load flow algorithms have been presented. The advantage and drawbacks of the decoupled model, the comprehensive model, the load injection model, the indirect model, and the UPFC modeling using matrix partitioning technique have been described. Also, a simple UPFC model based on current injection approach has been developed. This model has addressed many problems due to the implementation of UPFC in load flow algorithm such as; the problem which exists when the UPFC is the only link between two sub-networks, the parameters of UPFC can be updated the iterative process, the control of voltage, active and reactive power simultaneously or individually can be done, the original structure and symmetry of admittance and Jacobian matrices is still unchanged and the sparsity technique can be applied. Consequently, the incorporating of UPFC in load flow code became easy without any modification in the original Jacobian matrix.

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