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Determination of IPFC operating constraints in power flow analysis

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ABSTRACT

In recent years, the Flexible AC Transmission System (FACTS) controllers have been widely used to enhance the controllability, security and flexibility in power transmission networks. Interline power flow controller (IPFC) is a versatile member of FACTS devices that can be used to control the power flow in multiple lines in network. Modeling of IPFC with handling its operating constraints is an important issue to determine the practical capabilities of this device. This paper presents a simple modeling with strategies for handling all operating constrains of IPFC in Newton–Raphson (NR) load flow algorithm. The various operating constraints such as; the injected series voltages, injected line currents passing through the converters and exchanged powers among the series converters are investigated. The developed IPFC model with these constraints is validated using standard IEEE 30-bus and IEEE 118-bus test systems.

Introduction

The Flexible AC Transmission System (FACTS) controllers are elegant devices which have been used to control the power system parameters such as; the voltage magnitude, the active power, reactive power, the line impedance and the phase angle. Hence, these devices can improve the operation, the security and the stability of power system [1–3]. Due to continuous progress and development of the power electronic devices, many types of FACTS devices are produced such as: SVC, PS, TCR, TCSC, STATCOM, TCPST, IPC, SSSC, IPFC, UPFC, CUPFC and GUPFC [4–6].

Due to the excellent influences of FACTS devices on power system performance, modeling of these devices became important topic. Consequently, various elegant efforts have been done for modeling of FACTS. In coupled models, the FACTS are represented by injected voltage sources and series impedances with transmission line. The FACTS control parameters are embedded in load flow equations as state variables so some modifications in Jacobian matrix are mandatory [12,13]. In power injection models, the injected voltage sources in coupled models are represented by injected powers at FACTS terminals buses. These powers are embedded in Jacobian matrix and updated during the iteration process of load flow algorithm. Hence, the Jacobian matrix should be modified [14,15]. In decoupled models, the FACTS terminals are separated and represented by PQ and PV buses. However, modifications in Jacobian matrix also required [16].

Reference [17] has presented a simple modeling of UPFC in Newton–Raphson and Gauss seidel load flow algorithms without modification of Jacobian matrix while references [18,19], have presented easy modeling for IPFC and SSSC in revised Newton–Raphson current injection load flow solution without modification in Jacobian matrix. In these models, the FACTS devices have been represented using current injection approach. The injected currents at FACTS terminals are calculated as a function of required specified values to avoid the modification of Jacobian matrix. However, the operating constraints have not been handled in the above models.

Inter line power flow controller (IPFC) is an advanced FACTS member. It can be used to control the active and reactive powers flow in multiple transmission lines to maximize utilization of these lines and it can handle problem of the congested lines by transfer the power from line to another. However, modeling of FACTS devices with handling violations of their operating constraints are needed to determine the practical capabilities of these devices. References [8–11] have presented some FACTS devices and methods for handling their violated limits. In these references, when one of operating constraints is violated, the required specified values of FACTS must be changed precisely to adjust the violated value to its maximum limit. Hence, the utilization of these devices will be maximized.

This paper presents an easy developed modeling for IPFC controller in NR load flow algorithm. This model is based on power injection approach. The modification of Jacobian matrix of load

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Nomenclature

Acronyms

AC	alternating current
FACTS	flexible AC transmission systems
IPC	interphase power controller
IPFC	interline power flow controller
NR	Newton–Raphson
PS	thyristor-controlled phase shifter
SSSC	synchronous series compensator
TCR	thyristor-controlled reactor
SVC	static var compensator
STATCOM	static synchronous compensator
TCPST	thyristor controlled phase shifting transformer
UPFC	unified power flow controller
T	transformer
Line	transmission line
CUPFC	center-node unified power flow controller
GUPFC	generalized unified power flow controller
TCSC	thyristor-controlled series capacitor
NPV	number of PV buses
M	master line or master converter
S	slave line or slave converter
Δ	mismatch
p.u	per unit
MVA	mega volt ampere
MW	mega watt
MVAR	mega var
PV	generator bus
PQ	load bus
No.	number
θ	bus voltage angle

Superscripts

max	maximum value
Im	imaginary value
Re	real value
M	master line
S	slave line

Subscripts

sp	specified values
m, *n*, *j*, *k*, *h*	bus name
ex	exchanged value
*se*1, *se*2	series value of master, slave converter
re	released value
*Line*1	master line
*Line*2	slave line
M, *S*	master converter, salve converter
Inj	injected value

Variables

V	voltage
I	current
Φ	voltage angle
R, X, Z	resistance, reactance and impedance
P, Q, S	active, reactive and apparent powers

flow algorithm can be avoided using this model. Consequentially, the complexities of incorporating IPFC in load flow algorithm are avoided. This paper also proposes simple strategies for handling the IPFC operating constraints to maximize utilizations of this controller. The operating constraints are including; the injected series voltages, the injected line currents passing through the converters and exchanged powers among series converters. The developed strategies are based on modifying the controlled specified values with the maximum limits of the required constraints. The rest of paper is organized as follows: Section "Concept of IPFC controller" describes the construction and operating principals for IPFC controller. Section "Developed IPFC model" discusses the proposed model of IPFC and its equivalent circuits. Section "Handling of IPFC operating constraints" gives the solution process of the violated operating constraints of IPFC. In Section "NR load flow solution with IPFC model and operating constraints determination", the numerical results based on standard IEEE test system are presented. Finally, the conclusions are presented in Section "Simulation results".

Concept of IPFC controller

IPFC is an advanced combined series-series FACTS controller. It consists of two or more converters connected in series with transmission lines and coupled together though common DC link. However, two or more static synchronous series compensators (SSSC) can be connected to produce this recent device that can be used to control the transmitted powers of multiple lines. Each converter could absorb or deliver reactive power independently. The exchanged powers among the converters are balanced at the DC link. Hence, the net active power in IPFC equals to zero. This means that the active powers which have been transferred to line are directly compensated from another line i.e. the IPFC doesn't consume or generate active power. In case of IPFC consists of three converters, it can be used to control three parameters; active and reactive powers flow of primary line and active power or reactive power of another line while the last parameter in the second line would be released to achieve the exchanged power condition [7,18].

Developed IPFC model

Fig. 1 shows a simple construction of IPFC that consists of two converters (master and slave converters) connected to AC system through coupling transformers ($T1, T2$). These converters are connected together through a common DC link. The master converter is connected in series with the master line between buses m and n to control the active and reactive power flow of this line to be specified values ($S_{sp}^{M} = P_{sp}^{M} + jQ_{sp}^{M}$). The salve converter is connected in

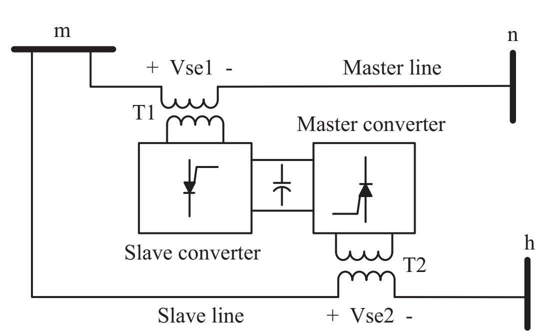

Fig. 1. IPFC schematic diagram.

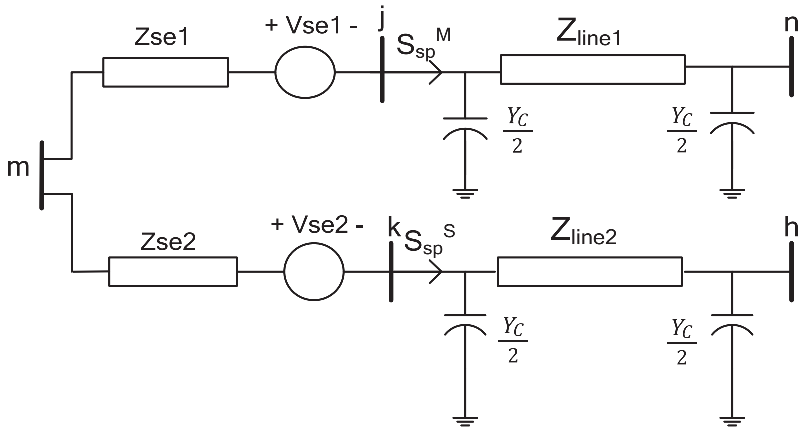

Fig. 2. IPFC equivalent circuit based on voltage source representation.

series with the slave line between buses m and h to control the active power of this line at a specified value P_{sp}^{S}. The equivalent circuit of IPFC can be given by two injected voltage sources (V_{se1}, V_{se2}) connected in series with impedances of transformers (Z_{se1}, Z_{se2}) as shown in Fig. 2. Two buses (j, k) are added to represent the IPFC's terminals.

In the developed IPFC model, the voltage sources can be transformed to current sources in parallel with the series impedances as shown in Fig. 3.

The current sources between buses (m,j) and buses (m,k) can be replaced by three shunt current sources as shown in Fig. 4. By applying Kirchhoff's current law at points (j,k), the shunt injected currents $(I_{M,inj}, I_{S,inj})$ can be obtained as a function of specified master and slave line currents (I_{sp}^{M}, I_{sp}^{S}) as follows:

$$I_{M,inj} = I_{sp}^{M} - I_{mj} = \left(\frac{S_{sp}^{M}}{V_j}\right)^{*} - \left(\frac{V_m - V_j}{Z_{se1}}\right) \quad (1)$$

$$I_{S,inj} = I_{sp}^{S} - I_{mk} = \left(\frac{S_{sp}^{s}}{V_k}\right)^{*} - \left(\frac{V_m - V_k}{Z_{se2}}\right) \quad (2)$$

where,

$$S_{sp}^{M} = P_{sp}^{M} + jQ_{sp}^{M} \quad (3)$$

$$S_{sp}^{s} = P_{sp}^{s} + jQ_{re}^{s} \quad (4)$$

$$V_{se1} = I_{M,inj} Z_{se1} \quad (5)$$

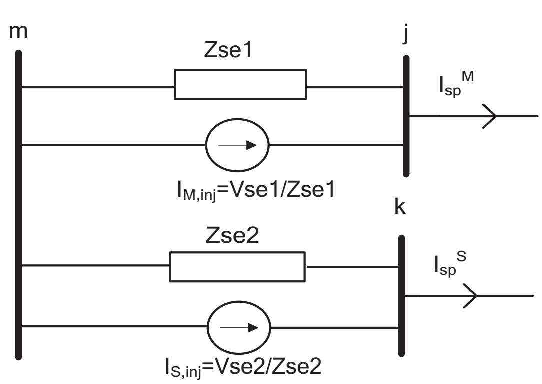

Fig. 3. IPFC equivalent circuit based on current source representation.

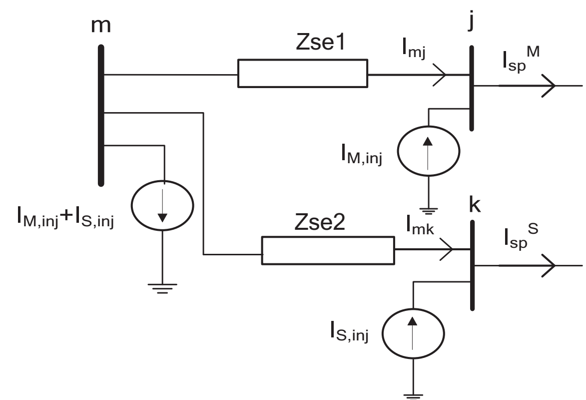

Fig. 4. IPFC model based on the shunt injected currents representation.

$$V_{se2} = I_{S,inj} Z_{se2} \quad (6)$$

$$V_m = V_m^{Re} + jV_m^{Im} \quad (7)$$

$$V_j = V_j^{Re} + jV_j^{Im} \quad (8)$$

$$V_k = V_k^{Re} + jV_k^{Im} \quad (9)$$

$$I_{se1} = I_{sp}^{M} = \left(\frac{S_{sp}^{M}}{V_j}\right)^{*} \quad (10)$$

$$I_{se2} = I_{sp}^{S} = \left(\frac{S_{sp}^{s}}{V_k}\right)^{*} \quad (11)$$

The resistances of coupling transformers can be neglected. Hence, $Z_{se1} = jx_{se1}$ and $Z_{se2} = jx_{se2}$. The shunt injected current at bus m equals to summation of the shunt injected currents at buses (j,k) which can be given by:

$$I_m = I_{M,inj} + I_{S,inj} \quad (12)$$

The shunt injected currents at buses (m,j,k) can be easily converted to three injected fictitious loads (S_m, S_j, S_k) as shown in Fig. 5. These injected loads are updated during iteration process of load flow program according to following equations:

$$S_j = -V_j I_{M,inj}^{*} \quad (13)$$

$$S_k = -V_k I_{S,inj}^{*} \quad (14)$$

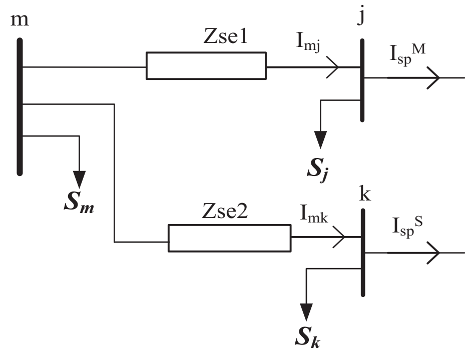

Fig. 5. Developed IPFC model based on injected fictitious loads approach.

$$S_m = V_m I_m^* \tag{15}$$

As mentioned before that the exchanged real power among the converters must be balanced at the DC link of the IPFC. Hence, the net power exchange must equal zero as given in (16).

$$\sum P_{ex} = P_{ex1} + P_{ex2} = 0 \tag{16}$$

where,

$$P_{ex1} = Re(V_{se1} I_{se1}^*) \tag{17}$$

$$P_{ex2} = Re(V_{se2} I_{se2}^*) \tag{18}$$

By substituting the values of P_{ex1} and P_{ex2} from (17) and (18) in (16), the net exchanged power can be formulated as follows:

$$P_{ex1} + P_{ex2} = Re(V_{se1} I_{se1}^*) + Re(V_{se2} I_{se2}^*) = 0 \tag{19}$$

By substituting the values of $V_{se1}, V_{se1}, I_{se1}$ and I_{se2} from (5), (6), (10), and (11) respectively in (19), Eq. (19) can be expressed as follows:

$$Re\left(I_{M,inj} Z_{se1} \left(I_{sp}^M\right)^*\right) = -Re\left(I_{S,inj} Z_{se2} \left(I_{sp}^S\right)^*\right) \tag{20}$$

$$Re\left(I_{M,inj} Z_{se1} \left(I_{sp}^M\right)^*\right) = -Re\left(I_{S,inj} Z_{se2} \left(\frac{S_{sp}^s}{V_k}\right)\right) \tag{21}$$

By substituting the value of $I_{S,inj}$ from (2) in (21)

$$Re(I_{M,inj} Z_{se1} \left(I_{sp}^M\right)^*) = -Re\left(\frac{S_{sp}^{s*} S_{sp}^s}{V_k^* V_k} Z_{se2} - (V_m - V_k) \frac{S_{sp}^s}{V_k}\right) \tag{22}$$

By substituting the values of V_m , V_k and S_{sp}^s from (7), (9) and (4) respectively in (22), Eq. (22) can be expressed as follows:

$$\left(-Re(I_{m,inj} Z_{se1} I_{sp}^{M*}) - P_{sp}^s\right)\left(\left(V_k^{Re}\right)^2 + \left(V_k^{Im}\right)^2\right) + P_{sp}^s\left(V_m^{Re} V_k^{Re} + V_m^{Im} V_k^{Im}\right) = Q_{re}^s\left(V_m^{Im} V_k^{Re} - V_m^{Re} V_k^{Im}\right) \tag{23}$$

Then,

$$Q_{re}^s = \frac{\left(-Re(I_{m,inj} Z_{se1} I_{sp}^{M*}) - P_{sp}^s\right)\left(\left(V_k^{Re}\right)^2 + \left(V_k^{Im}\right)^2\right) + P_{sp}^s\left(V_m^{Re} V_k^{Re} + V_m^{Im} V_k^{Im}\right)}{V_m^{Im} V_k^{Re} - V_m^{Re} V_k^{Im}} \tag{24}$$

Q_{re}^s represents the released value to ensure that the net exchanged power equals to zero. Where, the IPFC is used to control only three parameters (the specified active and reactive power of a master line and the specified active or reactive power of the other line).

Handling of IPFC operating constraints

The IPFC operating constrains can be categorized as follows:

1- Series currents constraints of master and slave converters $(I_{se1}^{max}, I_{se2}^{max})$
2- The injected series voltages constraints of master and slave converters $(V_{se1}^{max}, V_{se2}^{max})$
3- The exchanged power constraint between the converters (P_{ex}^{max})

In the developed IPFC model, the operating constraints are checked with achieving the balancing of exchanged powers condition ($\sum P_{ex} = 0$). However, the following steps can be used to handle the three above categories as:

Series injected current violation handling of master converter

The injected current (I_{se1}) of master converter is the first value must be checked in the developed model. If I_{se1} is violated, it will be adjusted to its maximum value I_{se1}^{max} as given in (25).

$$I_{se1} - I_{se1}^{max} = 0 \tag{25}$$

This can be achieved by releasing the specified active and reactive powers of master line converter to capture maximum current rating using (26).

$$S_{sp}^M = V_j \left(I_{sp}^M\right)^* = V_j (I_{se1})^* \tag{26}$$

By substituting value of I_{se1} from (25) in (26)

$$S_{sp}^M = V_j (I_{se1}^{max})^* = P_{sp}^M + jQ_{sp}^M \tag{27}$$

Hence,

$$P_{sp}^M = Re(V_j (I_{se1}^{max})^*) \tag{28}$$

$$Q_{sp}^M = Im(V_j (I_{se1}^{max})^*) \tag{29}$$

P_{sp}^M and Q_{sp}^M act as new specified set points to adjust the injected current of master line to its maximum value. The main advantage of this developed technique compared with reference [8] is avoiding the reducing of Q_{sp}^M or P_{sp}^M to be zero to handle the violation of I_{se1}.

Series injected current violation handling of slave converter

In the developed model, If the injected current (I_{se2}) of slave converter is violated, it will be adjusted to its maximum value I_{se2}^{max} according to (30) by releasing the specified active and reactive powers of slave line converter as follows:

$$I_{se2} - I_{se2}^{max} = 0 \tag{30}$$

$$S_{sp}^S = V_k (I_{se2})^* = V_k (I_{se2}^{max})^* \tag{31}$$

Hence,

$$P_{sp}^S = Re(V_k (I_{se2}^{max})^*) \tag{32}$$

$$Q_{sp}^S = Im(V_k (I_{se2}^{max})^*) \tag{33}$$

P_{sp}^S and Q_{sp}^S act as new specified set points to adjust the injected current of slave line to its maximum value. Note that the specified reactive power of slave line is released to balance the exchanged powers among the converters. However, the balancing of exchanged power condition can be lost in case of using the previous equations. Hence, the reactive power of master line must be released with releasing the specified values of slave line as follows:

$$P_{ex1} = -P_{ex2} \tag{34}$$

By substituting the value of P_{ex1} and P_{ex2} from (17) and (18) in (34)

$$Re(V_{se1}(I_{se1})^*) = -Re(V_{se2}(I_{se2})^*) \tag{35}$$

By substituting the values of I_{se1}, V_{se2} and I_{se2} from (10), (6) and (30) respectively in (35)

$$Re\left(V_{se1}\left(I_{sp}^M\right)^*\right) = -Re(I_{s,inj}Z_{se2}(I_{se2}^{max})^*) \tag{36}$$

By substituting the value of V_{se1}, I_{sp}^M , $I_{s,inj}$ from (5), (10) and (2) respectively in (36)

By make some manipulations in (36).Hence, the released reactive power of master line (Q_{re}^M) which balance the exchanged power condition in case of handling the violation of I_{se2} can be given as:

$$Q_{re}^M = \frac{P_{sp}^M\left(V_m^{Re}V_j^{Re} + V_m^{Im}V_j^{Im}\right) - \left(\left(V_j^{Re}\right)^2 + \left(V_j^{Im}\right)^2\right)\left(Re(I_{S,inj}Z_{se2}(I_{se2}^{max})^*) + P_{sp}^M\right)}{V_m^{Im}V_j^{Re} - V_m^{Re}V_j^{Im}} \tag{37}$$

where, $V_m = V_m^{Re} + jV_m^{Im}, V_j = V_j^{Re} + jV_j^{Im}, S_{sp}^M = P_{sp}^M + jQ_{re}^M, Z_{se2} = jx_{se2}$

Series injected voltage violation handling of master converter

After handling the series currents violation of IPFC, the series injected voltages will be checked. If the injected voltage (V_{se1}) is violated, it will be enforced to its maximum rating according to (38) by releasing the specified active and reactive powers of master line.

$$V_{se1} - V_{se1}^{max} = 0 \tag{38}$$

By using (1) and (5), the new value of master line injected current can be formulated as follows:

$$I_{M,inj} = \left(\frac{S_{sp}^M}{V_j}\right)^* - \left(\frac{V_m - V_j}{Z_{se1}}\right) = \frac{V_{se1}}{Z_{se1}} = \frac{V_{se1}^{max}}{Z_{se1}} \tag{39}$$

Hence,

$$S_{sp}^M = V_j\left[\frac{V_{se1}^{max} + V_m - V_j}{Z_{se1}}\right]^* \tag{40}$$

Then,

$$P_{sp}^M = Re\left(S_{sp}^M\right) = Re\left(V_j\left[\frac{V_{se1}^{max} + V_m - V_j}{Z_{se1}}\right]^*\right) \tag{41}$$

$$Q_{sp}^M = Im\left(S_{sp}^M\right) = Im\left(V_j\left[\frac{V_{se1}^{max} + V_m - V_j}{Z_{se1}}\right]^*\right) \tag{42}$$

where, P_{sp}^M and Q_{sp}^M act as new specified values to handle V_{se1} violation.

Series injected voltage handling violation of slave converter

If the series voltage of slave converter (V_{se2}) is violated, it can be adjusted to it maximum limit according to (43) by releasing the specified active and reactive of slave line by the same way of handling V_{se1} violation as follows:

$$V_{se2} - V_{se2}^{max} = 0 \tag{43}$$

By using (1) and (5), the new value of slave line injected current can be formulated as follows:

$$I_{S,inj} = \left(\frac{S_{sp}^s}{V_k}\right)^* - \left(\frac{V_m - V_k}{Z_{se2}}\right) = \frac{V_{se2}}{Z_{se2}} = \frac{V_{se2}^{max}}{Z_{se2}} \tag{44}$$

Hence,

$$S_{sp}^s = V_k\left[\frac{V_{se2}^{max} + V_m - V_k}{Z_{se2}}\right]^* \tag{45}$$

Then,

$$P_{sp}^S = Re\left(S_{sp}^S\right) = Re\left(V_k\left[\frac{V_{se2}^{max} + V_m - V_k}{Z_{se2}}\right]^*\right) \tag{46}$$

$$Q_{sp}^s = Im\left(S_{sp}^S\right) = Im\left(V_k\left[\frac{V_{se2}^{max} + V_m - V_k}{Z_{se2}}\right]^*\right) \tag{47}$$

P_{sp}^S and Q_{sp}^s are the new specified values which handle violation of V_{se2}. However, the balancing of exchanged power condition can be lost in case of using the previous equations. Hence, the reactive power of master line and the specified values of slave line must be released. The value of the released reactive power of master line can be deduced using (35) by the same way of handling I_{se2} violation in Section "Series injected current violation handling of slave converter" except substituting V_{se2} to be V_{se2}^{max}. Hence, the released reactive power of master line (Q_{re}^M) which balances the exchanged power can be given as:

$$Q_{re}^M = \frac{P_{sp}^M\left(\left(V_m^{Re}\right)\left(V_j^{Re}\right) + \left(V_m^{Im}\right)\left(V_j^{Im}\right)\right) - \left(\left(V_j^{Re}\right)^2 + \left(V_j^{Im}\right)^2\right)\left(Re\left(V_{se2}^{max}\frac{S_{sp}^s}{V_k}\right) + P_{sp}^M\right)}{V_m^{Im}V_j^{Re} - V_m^{Re}V_j^{Im}} \tag{48}$$

Exchanged power violation handling of IPFC

The exchanged power among the master and slave converters is also checked in the developed model. If the exchanged power is violated, it can be limited to its maximum value according to (49). This can be achieved by releasing the specified reactive power of master line for handling P_{ex1} and releasing the specified reactive power of slave line for handling P_{ex2} at same time as follows:

$$P_{ex1} - P_{ex}^{max} = 0 \tag{49}$$

By substituting value of P_{ex1} from (17) in (49)

$$Re(V_{se1}I_{se1}^*) - P_{ex}^{max} = Re\left(I_{M,inj}Z_{se1}\left(I_{sp}^M\right)^*\right) - P_{ex}^{max} = 0 \tag{50}$$

By substituting value of $I_{M,inj}$ and I_{sp}^M in (50) and doing some manipulations in (50), the released reactive power of master line can be formulated as follows:

$$Q_{re}^M = \frac{P_{sp}^M\left(V_m^{Re}V_j^{Re} + V_m^{Im}V_j^{Im}\right) + \left(P_{ex}^{max} - P_{sp}^M\right)\left(\left(V_j^{Re}\right)^2 + \left(V_j^{Im}\right)^2\right)}{V_m^{Im}V_j^{Re} - V_m^{Re}V_j^{Im}} \tag{51}$$

By the same way, the released specified reactive power of slave line which handles P_{ex2} violation can be formulated as follows:

$$Q_{re}^S = \frac{P_{sp}^S\left(V_m^{Re}V_k^{Re} + V_m^{Im}V_k^{Im}\right) + \left(P_{ex}^{max} - P_{sp}^S\right)\left(\left(V_k^{Re}\right)^2 + \left(V_k^{Im}\right)^2\right)}{V_m^{Im}V_k^{Re} - V_m^{Re}V_k^{Im}} \tag{52}$$

NR load flow solution with IPFC model and operating constraints determination

The following steps illustrate the NR load flow algorithm with the developed IPFC model with its operating constraints determination.

Step 1: Readcontroller with its maximum operating constraints.
Step 2: Construct the admittance matrix and set the iteration number equals to zero.
Step 3: Calculate the injected loads (S_j, S_k, S_m) according to (13)–(15).
Step 4: Calculate the Jacobian matrix and mismatch vector.
Step 5: Find the load flow solution and update the buses voltage.
Step 6: Repeat the steps from (3) to (5) until the convergence of load flow is achieved.
Step 7: Check all of the operating constraints and handling the violated constraints as follows:

(1) If I_{se1} is violated, it will be handled by modifying (P_{sp}^M, Q_{sp}^M) using (28) and (29) according to Section "Series injected current violation handling of master converter".
(2) If I_{se2} is violated, it will be handled by modifying (P_{sp}^S, Q_{sp}^S) with releasing (Q_r^M) using (32), (33) and (37) according to Section "Series injected current violation handling of slave converter".
(3) If V_{se1} is violated, it will be handled by modifying (P_{sp}^M, Q_{sp}^M) using (41) and (42) according to Section "Series injected voltage violation handling of master converter".
(4) If V_{se2} is violated, it will be handled by modifying (P_{sp}^S, Q_{sp}^S) with releasing (Q_{re}^M) using (46)–(48) according to Section "Series injected voltage handling violation of slave converter".
(5) If P_{ex} is violated, it will be handled by releasing (Q_{re}^M, Q_{re}^S) using (51) and (52) according to Section "Exchanged power violation handling of IPFC".

Step 8: If the load flow algorithm is converged and all constraints are enforced. Then stop algorithm and print the results.

The above steps can be summarized in Fig. 6.

Simulation results

The NR load flow program with developed model and operating constraints determination of IPFC controller is written using M-file programming in MATLAB 7.8. This section produces the studied cases and numerical results which have been carried out on IEEE 30-bus and IEEE 118-bus test systems to verify the performance and capability of IPFC model. For all studies cases, the coupling transformers reactance of IPFC equals to 0.1 p.u and convergence tolerance is 10^{-6} with system base MVA is 100.

IEEE 30-bus system

The original data of IEEE 30-bus test system can be obtained from [20]. Algorithm convergence can be assessed by calculating magnitude increments speed and angles increments speed according to (53) and (54). Master converter of an IPFC controller is connected between bus No. 6 and bus No.10 where, the slave converter is connected between bus No. 6 and bus No. 28. The power flows of master and slave lines without IPFC are equal to 15.832 + j0.653 MVA and 18.823-j9.618 MVA, respectively.

$$Speed(\Delta V) = \sqrt{\sum\nolimits_{i=1}^{N-NPV-1} (\Delta V)^2} \quad (53)$$

$$Speed(\Delta\theta) = \sqrt{\sum\nolimits_{i=1}^{N-1} (\Delta\theta)^2} \quad (54)$$

Seven studied cases described in Tables 1 and 2, are used to assess the performance of developed IPFC model. The specified active and reactive powers of master line (P_{sp}^M, Q_{sp}^{SM}) and active power (P_{sp}^S) of the slave line are tested with different values. The different values of specified active and reactive powers are arbitrary selected to be more or less than the original values (if there is no FACTS are embedded) to verify the effectiveness and the control capabilities of the developed IPFC model. From Tables 1 and 2, it can be observed that the injected series voltage magnitudes, angles and exchanged powers of IPFC are changed with variation of specified powers to force the flow powers in lines as required. The final values of injected loads and voltages of IPFC's auxiliary buses are also changed with the variation of specified powers. The exchanged powers of master and slave converters are identical but with opposite sign i.e. the net exchanged powers are balanced in all studied cases. Figs. 7 and 8 show the convergence characteristics using the speed of voltage magnitude and angle increments which are decreased rapidly in first five iterations.

IEEE 118-bus test system

The details of IEEE 118-bus test system are given in [21]. Seven studied cases are used in this section to verify the strategies handling of IPFC constraints. All results of studied cases are shown in Table 3. The bold values in Table 3 indicate the maximum constraints limit and the modified specified values which enforce the operating constraints in each case.

Case (1): The master line converter of IPFC is located between bus No. 100 and bus No. 103 with specified active and reactive power equal to 100 MW and 20 MVAR respectively. While, the slave line converter of IPFC is located between bus No. 100 and bus No. 104 with specified active power equals to 60 MW. In this case, there is no any handling for IPFC operating constraints.
Case (2): This case is similar to case (1) except, the maximum limit of I_{se1} is 0.5 p.u. In this case, the I_{se1} can be enforced to its maximum value by releasing the specified active and reactive powers of master line as explained in Section "Series injected current violation handling of master converter".
Case (3): This case is similar to case (1) except, the maximum limit of I_{se2} is 0.4 p.u. In this case, the I_{se2} can be enforced to its maximum value by releasing the specified active and the reactive powers of slave line with releasing the reactive power of master line, at same time as explained in Section "Series injected current violation handling of slave converter".
Case (4): This case is similar to case (1) except, the maximum limit of V_{se1} equals to 0.02 p.u, it can be enforced by releasing the specified active and reactive power for master line as explained in Section "Series injected voltage violation handling of master converter".
Case (5): This case is similar to case (1) except, the maximum limit of V_{se2} is equals to 0.04 p.u. In this case, the V_{se2} can be enforced to its maximum value by releasing the specified active and the reactive powers of slave line with releasing the reactive power of master line, at same time as explained in Section "Series injected voltage handling violation of slave converter".
Case (6): This case is similar to case (1) except, the maximum limit of P_{ex} is equals to 2 MW. In this case, the P_{ex} can be

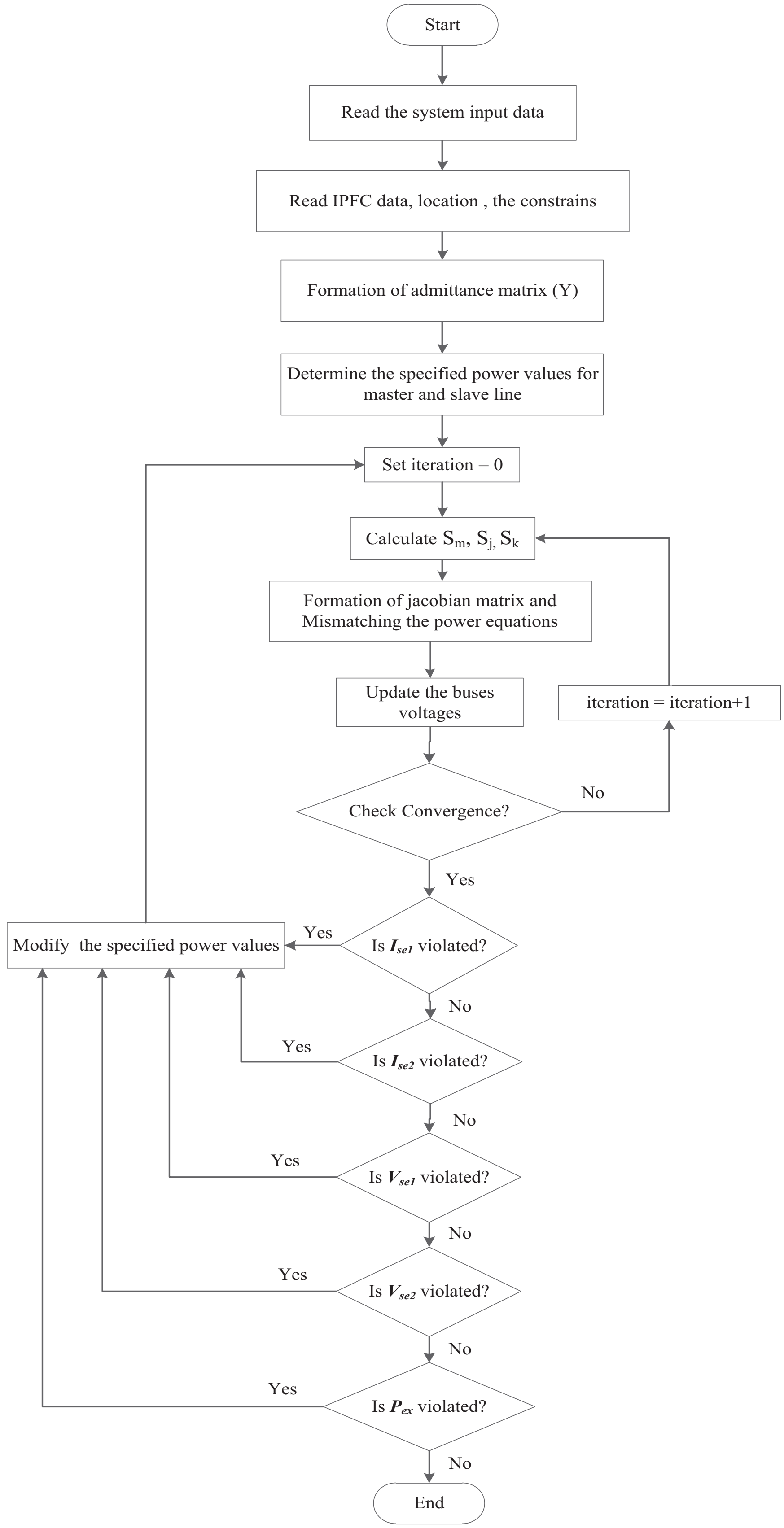

Fig. 6. NR load flow algorithm with developed IPFC model and operating constraints determination.

Table 1
IPFC parameters with different specified values.

Case	P_{sp}^{M} (MW)	Q_{sp}^{M} (MVAR)	P_{sp}^{s} (MW)	Master converter parameters			Slave converter parameters		
				V_{se1} (p.u)	φ_{se1} (deg)	P_{ex1} (MW)	V_{se2} (p.u)	φ_{se2} (deg)	P_{ex2} (MW)
(1)	10	1.5	10	0.0345	−87.169	0.1457	0.0177	−115.02	−0.1457
(2)	20	1.5	10	0.0458	72.100	0.0578	0.0160	−96.43	−0.05778
(3)	20	2.5	10	0.0463	63.602	0.1471	0.0151	−122.57	−0.1471
(4)	20	−1.5	10	0.0505	96.953	−0.2191	0.0292	−57.798	0.2191
(5)	25	0	10	0.0871	85.73	−0.1375	0.0236	−62.232	0.1375
(6)	−20	−1.5	15	0.0665	116.58	−0.2259	0.0358	−22.204	0.2259
(7)	25	−5	−15	0.0968	108.58	−0.6702	0.1213	−88.945	0.6702

Table 2
The injected loads and auxiliary buses voltage of IPFC for studied cases.

Case	P_{sp}^{M} (MW)	Q_{sp}^{M} (MVAR)	P_{sp}^{s} (MW)	Injected loads		Auxiliary buses voltage	
				$S_{M,inj}$ (MVA)	$S_{S,inj}$ (MVA)	V_j (p.u)	V_k (p.u)
(1)	10	1.5	10	33.73 −j10.07	17.57 +j3.77	1.019∠−13.7	1.014∠−12.90°
(2)	20	1.5	10	−46.10 −j6.44	16.25 −j1.83	1.016∠−9.94	1.018∠−12.86°
(3)	20	2.5	10	−45.40 −j13.32	14.47 +j5.20	1.022∠−9.99	1.013∠−12.77°
(4)	20	−1.5	10	−48.25 +j14.58	21.20 −j21.44	0.997∠−9.79	1.030∠−13.11°
(5)	25	0.0	10	−87.24 +j5.54	18.43 −j15.88	1.004∠−7.90	1.027∠−12.99°
(6)	−20	−1.5	15	−49.67 +j14.95	0.92 −j16.01	0.997∠−9.71	1.028∠−12.27°
(7)	25	−5	−15	−52.22 +j 38.15	6.19 −j36.72	0.971∠−8.00	1.033∠−17.17°

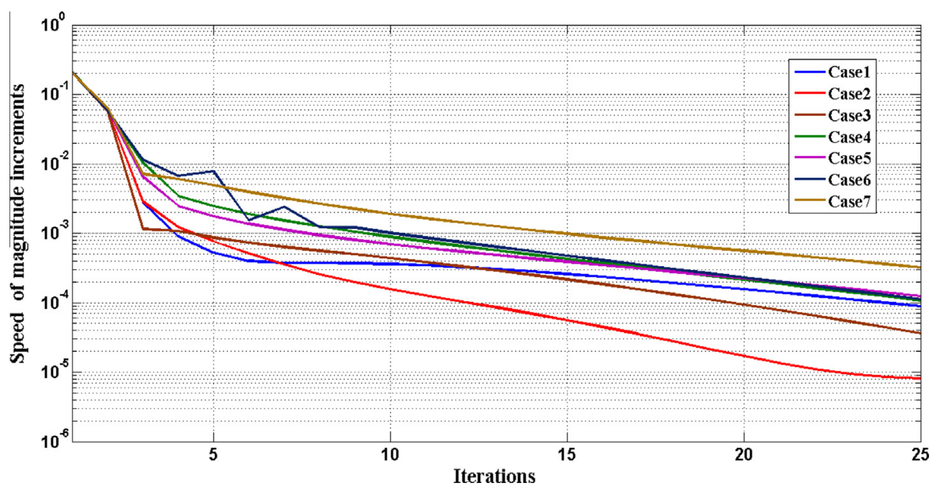

Fig. 7. Magnitude increments speed of IPFC model.

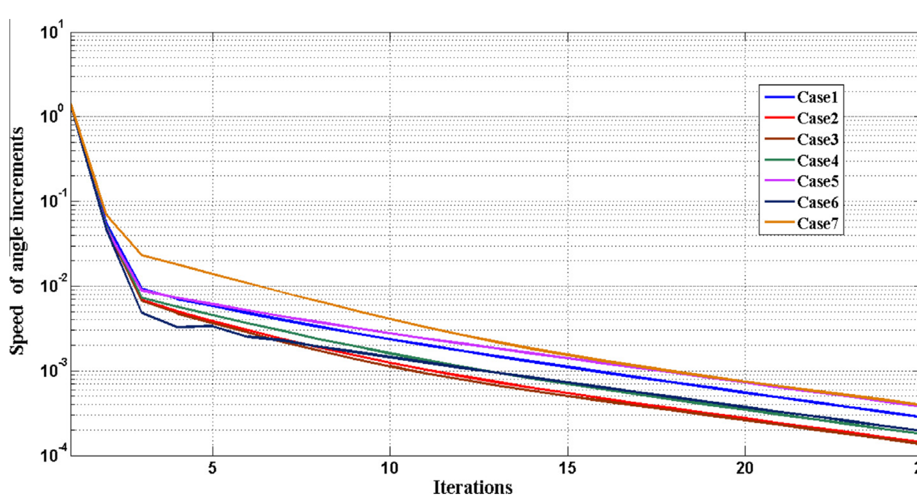

Fig. 8. Angles increments speed of IPFC model.

Table 3
Numerical results of IEEE 118-bus test system with constraints handling.

	Case1	Case2	Case3	Case4	Case5	Case6	Case7
P_{sp}^{M} (MW)	100.00	**49.98**	100.00	**95.86**	100.00	100.00	**59.64**
Q_{sp}^{M} (MVar)	20.00	**8.66**	**−13.69**	**9.43**	**−11.71**	**12.41**	**−7.30**
P_{sp}^{s} (MW)	60.00	60.00	**38.60**	60.00	**56.99**	60.00	**78.03**
Q_{sp}^{s} (MVar)	−13.18	−12.33	12.81	−3.40	**15.35**	**−4.45**	**7.59**
I_{se1} (p.u)	0.983	**0.500**	1.009	0.943	1.006	0.994	**0.600**
I_{se2} (p.u)	0.641	0.638	**0.400**	0.607	0.569	0.616	0.765
V_{se1} (p.u)	0.043	0.268	0.049	**0.020**	0.030	0.026	0.135
V_{se2} (p.u)	0.081	0.145	0.134	0.031	**0.040**	0.042	**0.020**
φ_{se1} (deg)	29.34	−68.33	−94.59	0.00	167.71	57.68	−76.42
ϕ_{se2} (deg)	179.96	−94.10	−60.154	−172.01	0.0	169.99	0.0
P_{ex1} (MW)	4.08	4.94	2.670	1.80	2.25	**2.00**	−1.45
P_{ex2} (MW)	−4.08	−4.94	−2.670	−1.80	- 2.25	**−2.00**	1.45
V_j (p.u)	1.037	1.015	1.000	1.021	1.001	1.013	0.998
V_k (p.u)	0.957	0.959	1.017	0.989	1.036	0.976	1.024
$P_{m,inj}$	−5.10	266.26	45.35	7.75	−17.69	−15.27	134.9
$Q_{m,inj}$	−44.93	−55.78	20.51	−18.89	24.61	−22.43	7.81
$P_{s,inj}$	−35.09	130.99	133.9	−9.26	16.88	−24.55	8.07
$Q_{s,inj}$	70.07	48.95	−27.19	29.97	−37.85	33.60	−18.83

enforced to its maximum value by releasing the reactive power of master and slave lines at the same time as illustrated in Se ction "Exchanged power violation handling of IPFC".

Case (7): This case is similar to case (1) except, the maximum limits of I_{se1} and V_{se2} are 0.6 p.u and 0.02 p.u respectively.In this case, the values of specified values are modified twice. The first one for handling the violation of I_{se1} and the second modification for handling the violation of V_{se2}. The specified active and reactive powers of master line are 59.642 + j13.243MVA to handle the I_{se1} according to Section "Series injected current violation handling of master converter". but V_{se2} stills violated. Hence, a second modification is required to handle V_{se2}. The final modifications are illustrated in Table3.

Conclusions

This paper has presented a simple modeling of IPFC in Newton–Raphson load flow algorithm. The developed model based on power injection approach. Complex injected loads at the terminals of IPFC are calculated as function of the specified active and reactive powers in master line and the specified active power in slave line, where the reactive power in salve line is released to balance the exchanged active powers between master and slave converters of IPFC. The main advantage of this model is that the original structure of Jacobian matrix can still be kept. Consequentially, the complexities of incorporating IPFC in load flow algorithm are avoided. Also in this paper, the operating constraints of IPFC including; the series injected voltage, the series injected currents flows through IPFC and the exchanged powers of converters have been handled successfully and determined at their maximum limits to maximize utilizations of IPFC. Simple strategies are presented for enforcing the constraints of IPFC which are based on modifying the controlled specified values with the maximum limits of the required constraints. The developed IPFC model and strategies for handling its operating constrains are validated using IEEE 30 bus and IEEE 118 bus test systems. The obtained numerical results have proved the effectiveness of developed IPFC model and strategies for handling IPFCs' constrains.

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