IMPACT OF FACTS CONTROLLERS ON SYSTEM LOADABILITY IN PRESENCE OF BILATERAL CONTRACTS IN A COMPETITIVE ENVIRONMENT

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Abstract – Under a deregulated environment, electricity consumers and suppliers are permitted to establish various bilateral contracts. The transmission company, however, has only to honor and execute these bilateral contracts as far as the system design and operating conditions permit. A fundamental question is then to what extent these contracts could affect the system loadability and what kinds of system reinforcements will be required to meet the future contracts needs. This paper describes a series of studies modeling bilateral contracts by means of further constraints added to an OPF model representing the Maximum Load Increase (MLI). Numerical experiments are then presented to illustrate how the use of FACTS devices installed in the transmission network allows improving the system loadability, conversely eventually limited by the presence of bilateral contracts.

Keywords: Bilateral contracts, FACTS devices, Maximum Load Increase

1 INTRODUCTION

Power utilities around the world are slowly undergoing a significant transformation towards a deregulated environment. The driving forces of deregulation are aiming to establish a more competitive market in order to achieve lower rates for consumers and higher efficiency for suppliers. Traditional power companies are therefore gradually divested into independent business entities by unbundling and privatization of their generation, transmission and distribution functions. Power suppliers are actively competing with one another for customers. The customers can therefore establish various contracts with any supplier in order to obtain the lowest rate and most desirable service. Bilateral contracts specifying the amount of power, the time and duration of the service and the associated rate are negotiated and agreed upon between suppliers and customers [1].

The next step is to deliver the power from suppliers to their respective consumers. Power transmission under a deregulated environment is generally handled by an independent entity, whose network is open to all users. Although there are different rules governing the role and responsibility of the transmission company, a basic requirement is to serve the needs of all users in the network as much as the system design and operating conditions permit, given the constraints of meeting the required security standards.

The following discussion assumes that any bilateral contract will have to be honored and executed by the transmission company unless the system security is endangered. Based on this operational requirement, a fundamental question is to what extent these contracts could affect the system loadability and what kinds of system reinforcements will be required to meet the future contracts needs.

In this context, the traditional tools adopted for security assessment have to be updated to take into account the possibility of new control strategies, such as the fast regulating capacity of FACTS devices.

Even if the most practical applications of FACTS devices have been devoted, until now, to the exploitation of their dynamic performances [2], it is very important to highlight their capability to solve network security problems within abnormal operating conditions (line overflows or voltage limit violations) [3-6].

Therefore, in this paper, the steady-state model of FACTS devices is considered, with the aim of making easier the redirection of power flows [7] towards the branches affected by lighter load. This will improve the system security level, making more flexible the transmission grid.

In particular, the present paper investigates on how the presence of the most powerful FACTS device, the Unified Power Flow Controller (UPFC) [8, 9], may allow the increase of the system loadability, conversely eventually limited by the presence of bilateral contracts. The choice of a UPFC instead of another device, such as a TCSC or even a Phase Shifting Transformer, is due to the interest of the authors in modeling the most complete device, eventually able also to deal with reactive security problems, included in the OPF formulation presented in the paper, but not here explicitly discussed.

In this paper, first the presentation of the UPFC steady state model in terms of injection model [8] is recalled. Then the formulation of the optimal power flow representing the objective of enhancing the system load, namely Maximum Load Increase (MLI), is proposed, embedding the presence of FACTS controllers in terms of further constraints and by modifying the MLI power flow equations.

A bilateral contracts model is then provided and embedded into the MLI formulation.

The complete MLI is then applied to a number of fictitious operational problems to demonstrate how the use of a FACTS device may enhance the loadability of an electric power system likely decreased by the satisfaction of superimposed bilateral contracts.

2 STATIC MODELING OF FACTS CONTROLLERS

Nowadays, FACTS technology *(Flexible AC Transmission Syste*m), based on power electronic components, represents an attractive tool for the control of power flows, providing the possibility of operating the transmission grid with increased flexibility and efficiency. Even if the most practical applications of FACTS devices have been devoted, until now, to the exploitation of their dynamic performances, it is very important to highlight their capability to solve network security problems (line overflows or voltage limit violations).

Therefore, in this paper, the steady-state model of FACTS devices is considered, with the aim of making easier the redirection of power flows towards the branches affected by lighter load. In particular, the present paper investigates on how the presence of the most powerful FACTS device, the *Unified Power Flow Controller* (UPFC) [8, 9], will improve the system security level, making more flexible already existing lines, especially in presence of firm bilateral contracts between generators and loads.

Basically, an UPFC consists of two voltage source converters (VSCs), operating from a common dc link provided by a dc storage capacitor (Fig. 1). One converter, in particular, is connected in series with the transmission line via a series boost transformer with a leakage reactance X_{se}, operating as a Static Synchronous Series Compensator (SSSC). The other one is connected in shunt with the transmission line via a shunt boost transformer with a leakage reactance X_{sh}, operating as a Static Synchronous Compensator (STATCOM).

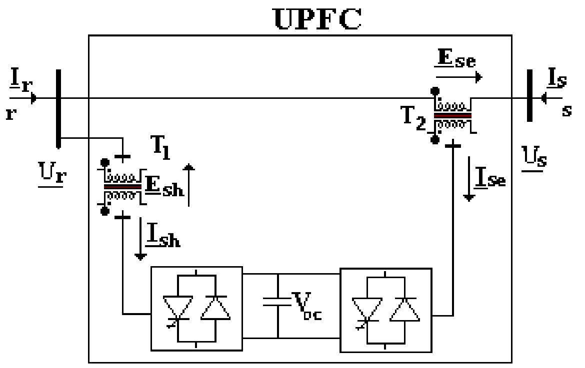

Figure 1: UPFC scheme.

It is noteworthy to underline that the main objective of the series converter is to control the active and reactive power flows on the transmission line, by regulating phase and magnitude of its output voltage. Conversely, the shunt converter can independently supply/absorb reactive power, in order to provide a voltage regulation at the connection point. Besides, it can provide the eventually required active power by the series converter through the dc link terminals. In this way, the active power freely flows between the shunt and the series converters ac terminals, via the common dc link, and the net active power interchange between UPFC and power system is zero in steady state (neglecting converters losses).

Representing the effect of the two VSCs in terms of voltage sources, controllable in magnitude and in phase, $\underline{E}_{se} = m_{se} e^{j\varphi_{se}} \underline{U}_r$ and $\underline{E}_{sh} = m_{sh} e^{j\varphi_{sh}} \underline{U}_r$ respectively, an equivalent circuit of UPFC can be obtained, as depicted in Fig. 2.

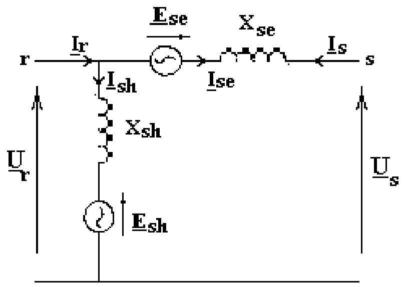

Figure 2: UPFC equivalent circuit

Using the UPFC representation of Fig. 2, a model for the UPFC device can then be derived and easily incorporated into the steady state power flow model. The UPFC can be modeled either by means of its transmission matrix model, then deriving the relating admittance matrix, as described in [4], or by a classic injection model [6], as it will be shown in the following.

Let us suppose a series connected voltage source is located between nodes r and s in a power system. The series voltage source converter can be modeled with an ideal series voltage, $\underline{E}_{se}$, in series with a leakage reactance, X_{se}. As in Fig. 3, the injection model is so obtained by replacing the voltage source $\underline{E}_{se}$ by the current source $\underline{I}_{se} = (-jb_{se})\underline{E}_{se}$, in parallel with the reactance leakage X_{se}, with b_{se} equal to the inverse of the reactance X_{se}. Let us indicate with $\check{A}$ the conjugate of the generic complex vector $\underline{A}$.

The current source $\underline{I}_{se}$ corresponds to the injection complex powers $\dot{S}_{r\_se} = \underline{U}_r(-\check{I}_{se})$ and $\dot{S}_{s\_se} = \underline{U}_s \check{I}_{se}$, while the shunt side absorbs from bus r a complex power $\dot{S}_{r\_sh} = P_{r\_sh} + jQ_{r\_sh}$. The total injections at buses *r* and *s*, as well as the UPFC functional constraint, are then:

$$\begin{aligned} P_r &= P_{r\_se} - P_{r\_sh} = \\ &= -U_r U_s m_{se} b_{se} \sin(\varphi_{se} + \delta_r - \delta_s) \end{aligned} \quad (1)$$

$$Q_r = Q_{r\_se} - Q_{r\_sh} = \\ = -U_r^2 m_{se} b_{se} \cos\varphi_{se} - U_r^2 b_{sh}(1 - m_{sh}\cos\varphi_{sh}) \quad (2)$$

$$P_s = P_{s\_se} = U_r U_s m_{se} b_{se} \sin(\varphi_{se} + \delta_r - \delta_s) \quad (3)$$

$$Q_s = Q_{s\_se} = U_r U_s m_{se} b_{se} \sin(\varphi_{se} + \delta_r - \delta_s) \quad (4)$$

$$\mathrm{Re}\left\{ \underline{E}_{sh} \cdot \overset{v}{I}_{sh} \right\} = \mathrm{Re}\left\{ - \underline{E}_{se} \cdot \overset{v}{I}_{s} \right\} \quad (5)$$

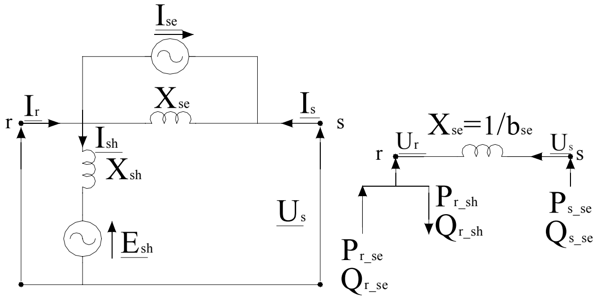

Figure 3: Shunt and series sides of the UPFC converted into two power injections at buses r and s.

3 THE MAXIMUM LOAD INCREASE FORMULATION WITH AN EMBEDDED FACTS DEVICE

The Maximum Load Increase (MLI) model has been formulated by the authors as an OPF model with the objective of maximizing the system loading parameter, λ, i.e. the percentage of load increase.

The whole MLI model formulation with an embedded FACTS device can then be described as follows:

Max λ (6)

Subject to the following constraints:

Equality constraints for each bus i:

- percentage of homothetic load increase definition

$\lambda = P_{cTot}/ P_{coTot}$ (7)

where P_{cTot} and P_{coTot} are, respectively, the total system load after an increment of λ and at the base case;

- active and reactive Load Flow equations for each i-th bus, where the underscripts g and c stand for generator and load respectively, while N is the number of buses.

$$P_i = P_{gi} + P_{ci} = U_i \sum_{j=1}^{N} U_j \left(G_{ij}\cos\theta_{ij} + B_{ij}\sin\theta_{ij} \right)$$
$$Q_i = Q_{gi} + Q_{ci} = U_i \sum_{j=1}^{N} U_j \left(G_{ij}\sin\theta_{ij} - B_{ij}\cos\theta_{ij} \right) \quad (8)$$

where $P_{ci} = P_{coi}\left(1 + \dfrac{P_{cTot}}{P_{coTot}}\right) = P_{coi}(1+\lambda)$ (9)

is the active load consumption at bus i after a power increase of λ

and $Q_{ci} = Q_{coi}\left(1 + \dfrac{Q_{cTot}}{Q_{coTot}}\right) = Q_{coi}(1+\lambda)$ (10)

is the reactive load consumption at bus i after a power increase of λ.

Inequality constraints:

- upper and lower bounds on voltage magnitude for each bus *i*

$U_i^m \le U_i \le U_i^M$ (11)

- upper and lower bounds on voltage phase for each bus i

$\delta_i^m \le \delta_i \le \delta_i^M$ (12)

- upper and lower bounds on active power for each generation bus i

$P_{gi}^m \le P_{gi} \le P_{gi}^M$ (13)

- upper and lower bounds on reactive power for each generation bus i

$Q_{gi}^m \le Q_{gi} \le Q_{gi}^M$ (14)

- upper bound on the square of apparent power for each generation bus i

$P_{gi}^2 + Q_{gi}^2 \le \left(S_i^M\right)^2$ (15)

- upper and lower bounds on the difference of voltage phases for each line l

$\theta_l^m \le \theta_l \le \theta_l^M$ (16)

- upper bound on the square of line current for each line l of buses i and j and impedance $\dot{Z}_{ij}$

$$I_{ij}^2(U,\theta) = \frac{U_i^2 + U_j^2 - 2U_iU_j\cos\theta_{ij}}{\left|\dot{Z}_{ij}\right|^2} \le \left(I_{ij}^M\right)^2 \quad (17)$$

When an UPFC device is installed in the system, Load Flow equations can be modified by adding the UPFC injection model (eqs. (1) to (4)), while the UPFC active power balance equation, (5), has to be embedded within the equality constraints.

Moreover, upper and lower bounds on the UPFC control parameters, eqs. (18) to (21), have to be added to the inequality constraints:

- upper and lower bounds on UPFC shunt magnitude

$m_{sh}^m \le m_{sh} \le m_{sh}^M$ (18)

- upper and lower bounds on UPFC series voltage magnitude

$m_{se}^m \le m_{se} \le m_{se}^M$ (19)

- upper and lower bounds on UPFC shunt voltage phase shift

$\varphi_{sh}^m \le \varphi_{sh} \le \varphi_{sh}^M$ (20)

- upper and lower bounds on UPFC series voltage phase shift

$\varphi_{se}^m \le \varphi_{se} \le \varphi_{se}^M$ (21)

In compact form, the MLI can be written as follows:

H_{MLI}=max λ (22)

s.t.

$LF(P_g, \lambda, T, X, m_{se}, m_{sh}, \varphi_{se}, \varphi_{sh}) = 0$ (23)

$D(P_g, \lambda, T, X, m_{se}, m_{sh}, \varphi_{se}, \varphi_{sh}) \le 0$ (24)

where T and X represent the vectors of the decision, except for P_g and λ, and of the dependent variables respectively.

4 MLI IN PRESENCE OF BILATERAL CONTRACTS

In a restructured electricity market, bilateral transactions may take place between a group of seller buses and a group of buyer buses. Let us suppose that the real and reactive loads may be homothetically increased by a loading factor λ if all constraints represented by (23) and (24) are met. The formulation that will be shown in the following is of course valid for bilateral contracts among a generic number of sellers and a generic number of buyers. Anyway, for clarity sake, in the exposition let us suppose to have a simple contracts configuration, as described in Fig. 4.

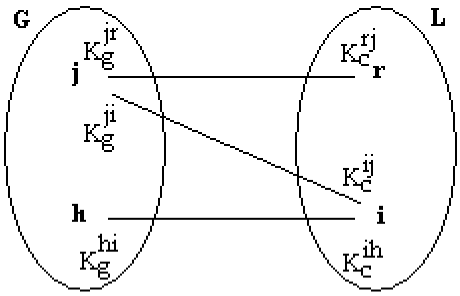

Figure 4: Set of contracts between a set of buyers' loads, **L**, and a set of sellers' generators, **G**.

Let **G** be the set of generation buses having at least one contract with a load and **L** the set of load buses, having at least one contract with a generator.

A first observation is that if a generator belongs to **G** then the loads with which it has a contract should be in **L** and, vice versa, if a load belongs to **L** the generators with which it planned to have a transaction should belong to **G**.

As far as **G**, , it is supposed that if a generic generation bus **j** has a contract with two generic load buses **r** and **i**, from the example in Fig. 4, the power produced by **j** not necessary must represent the whole production of **j**, meaning that

$$\sum_{t \in LC} k_g^{jt} = k_g^{jr} + k_g^{ji} \leq 1 \tag{25}$$

where LC is the set of loads with which generator **j** has a contract, and k_g^{jr} and k_g^{ji} are participation factors standing for the percentage of its own power production to be produced by generator **j** according to its contracts with loads **r** and **i,** respectively.

If $\sum_{t \in LC} k_g^{jt} < 1$, a part of **j** production meets the rest of the system load power not bilaterally contracted, always according to Load Flow equations (8). Obviously, also the power bilaterally contracted has to satisfy Load Flow equations, but further constraints must be met and added to the MLI formulation in order to model the contract.

Hence, for each generic generation bus **j**, a constraint is needed saying that all the power bilaterally contracted by **j** with the generic loads **r** and **i** must coincide with the contracted amount of power demand of loads **r** and **i**, according to the following:

$$P_{gj}(k_g^{jr} + k_g^{ji}) = (k_c^{rj} P_{cor} + k_c^{ij} P_{coj})(1+\lambda) \tag{26}$$

where k_c^{rj} and k_c^{ij} are participation factors representing the percentage of power consumption, $P_{cor}(1+\lambda)$ and $P_{coj}(1+\lambda)$, respectively requested by loads **r** and **i** that multiplied by $P_{cor}(1+\lambda)$ and $P_{coj}(1+\lambda)$ signify the active power generator **j** has to produce according to its contracts with **r** and **j**.

As far as **L** as well, let us suppose that a generic load bus **i** may contract to be fed partially or totally by two generic generators buses **j** and **h**, so that:

$$\sum_{t \in GC} k_c^{it} = k_c^{ij} + k_c^{ih} \leq 1 \tag{27}$$

where GC is the set of generators with which load **i** has a contract.

If $\sum_{t \in GC} k_c^{it} < 1$, a part of **i** demand has to be met by the system generators, always according to Load Flow equations (8). Also for loads, the power bilaterally contracted has to satisfy Load Flow equations, but further constraints are needed in the MLI formulation. Indeed, for each generic load bus **i**, a constraint is needed saying that all the power bilaterally contracted by **i** with the generic generators **j** and **h** must coincide with the contracted amount of power produced by generators **j** and **h**, according to the following:

$$(k_c^{ij} + k_c^{ih}) P_{coi}(1+\lambda) = P_{gj} k_g^{ji} + P_{gh} k_g^{hi} \tag{28}$$

Conversely, for each generic load **r**, having a unique bilateral contract with a generator **j,** no further constraint is needed to be added to the MLI since it would be redundant because already written for generator **j** with (26).

Some remarks have now to be made as far as the constraints representing the presence of bilateral contracts.

From the second member of (26) it can be noted that if there should be an increment of λ in the system load, also the amount of power bilaterally contracted would take advantage of this power increase.

Moreover an observation has to be made as far as the loads participation factors.

In the paper they are maintained fixed, in general different from bus to bus and given as input data. It is so assumed that bilateral contracts are firm i.e. it is known a priori that they meet the security constraints so that they must be satisfied with priority before any increment λ of load.

As far as the reactive power, further constraints similar to (26) and (28) should be added but this represent one of the future aims of the paper.

Different simulations could be also made leaving variable some loads and generators participation factors with the objective of looking for those amount of powers that can be bilaterally contracted and that maximize the loadability of the power system. Of course constraints like (25) and (27) should be added to the MLI formulation in case of variable participation factors, that is a generator cannot contract more than its own production and a load cannot request more than its own consumption. Anyway, at the moment, this alternative represents another further future aim in the authors' research activity.

5 NUMERICAL EXPERIMENTS

In order to illustrate how an UPFC may increase the loadability of a power system in a competitive environment in presence of bilateral contracts, some numerical experiments have been carried out on a 5-bus test power system, whose data in p.u. are shown in Fig. 5. As future aim, the authors intend to obtain results from simulation on larger test power systems, even if the peculiarities of the model proposed are exhaustively discussed in the following.

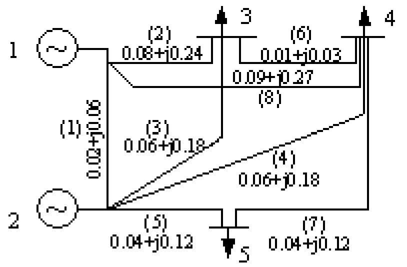

Figure 5: Test power system (1 to 5: buses, (1) to (8): lines) Base power 100 MVA, base voltage 150kV

For sake of simplicity, six different relevant tests are reported in the paper, in order to illustrate the effectiveness of the proposed approach. Computational results obtained by the solution of the proposed optimization problem modeled by MLI are illustrated and commented in the following.

The thermal limit for all lines is assumed equal to 1.000 p.u.

5.1 First test: no UPFC- no contracts

As first test, let us consider the power system in Fig. 5 with no UPFC installed and with no bilateral contract between any load and generator.

All power demand is dispatched according to the satisfaction of all the constraints described by (7)- (17) with the objective to maximize the system loadability λ, as described in (6). Data relative to generators and loads base case are provided in Tab. 1 in p.u.

Bus	P_g	P_{co}	Q_{co}
1	1.9000	-	-
2	0.37500	-	-
3	-	0.60000	0.30000
4	-	0.80000	0.10000
5	-	0.80000	0.20000

Table 1: Generators and loads data base case

From the MLI solution, a loadability λ of 0.48452 is achieved, with a corresponding increase of power provided by generators at buses 1 and 2, whose new production is shown in Tab. 2, together with loads consumptions after the increment, always in p.u.

System load power cannot be further augmented since lines 1-2 and 2-5 reach their thermal limit.

Bus	P_g	P_c	Q_c
1	2.3089	-	-
2	1.1087	-	-
3	-	0.89072	0.44536
4	-	1.1876	0.14845
5	-	1.1876	0.29691

Table 2: Generators and loads data after an increase of λ=0.48452

5.2 Second test: a UPFC installed on line 3-4- no contracts

Let us suppose that a UPFC is installed on line 3-4 as depicted in Fig. 6.

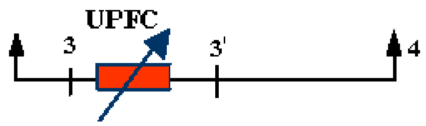

Figure 6: Line 3-4 scheme with an UPFC installed in correspondence of node 3.

For precision sake, it is underlined that the STATCOM is installed at node 3 while the SSSC is installed between nodes 3 and 3'. X_{se} and X_{sh} are taken equal to 0.00100 p.u, approximately corresponding to a device of base power 100 MVA and base voltage 150 kV.

From the MLI solution, the optimum λ results equal to 0.54884, greater than in case of absence of UPFC (λ=0.48452 from the first test).

Lines 1-2 and 2-5 always result loaded at their maximum while the generation power scheduling together with the power consumptions after the increase are provided in Tab. 3.

Bus	P_g	P_c	Q_c
1	2.3676	-	-
2	1.1999	-	-
3	-	0.92931	0.46466
4	-	1.2391	0.15489
5	-	1.2391	0.30977

Table 3: Generators and loads data after an increase of λ=0.54884

The UPFC parameters (m_{se} and m_{sh} in p.u., φ_{se} and φ_{sh} in rad.) at the optimum are given in Tab. 4.

m_{se}	m_{sh}	φ_{se}	φ_{sh}
0.00000	1.0008	0.00161	0.00000

Table 4: UPFC parameters at optimum

What can be highlighted in this second test is that according to the base case configuration (Tab. 1), to the topology and to the line impedances of the power system, the UPFC parameters at the optimum show that m_{se} is 0.00000 p.u. and φ_{sh} is 0.00000 rad. m_{se} equal to 0.00000 p.u. means that $\underline{E}_{se} = m_{se} e^{j\varphi_{se}} \underline{U}_3$ has magnitude 0.00000 p.u. so that the UPFC works as a STATCOM with only injection of reactive power at bus 3. Being φ_{sh} equal to 0.00000 rad., $\underline{E}_{sh} = m_{sh} e^{j\varphi_{sh}} \underline{U}_3$ results in phase with $\underline{U}_3$. Since m_{sh} is equal to 1.0008 p.u. at the optimum, with reference to Fig. 2, a current $\underline{I}_{sh}$ is absorbed from bus 3 so that a reactive contribute $\mathrm{Im}\left\{\underline{E}_{sh} \cdot \overset{v}{I}_{sh}\right\} = -1.0000$ p.u. is provided.

5.3 *Third test: no UPFC- a contract between 1-3*

Let us now assume that a bilateral contract exists between generator 1 and load 3, with participation factors given in Tab.5

k_g^{13}	k_c^{31}
0.06500	0.20000

Table 5: Generators and loads participation factors

Since load 3 has only a contract, with generator 1, only one constraint like (26) for generator 1 has to be added to the MLI.

Having to meet this constraint, the generation scheduling changes if compared with the one of the first test according also to the new load increase λ=0.18517 reached at the optimum, as shown in Tab. 6.

Bus	P_g	P_c	Q_c
1	2.1880	-	-
2	0.52464	-	-
3	-	0.71110	0.35555
4	-	0.94813	0.11852
5	-	0.94813	0.23703

Table 6: Generators and loads data after an increase of λ=0.18517

In this case, the thermal limit of line 1-2 constraints the optimization process to stop and the load increase λ reached in this case is less than the one obtained in the case no contract is established (0.18517 <0.48452 from the first test).

5.4 *Fourth test: a UPFC installed on line 3-4- a contract between 1-3*

A bilateral contract exists between generator 1 and load 3 but, comparing with the third test, in addition, a UPFC is installed on line 3-4, as depicted in Fig. 6 and whose data are known from the second test.

Participation factors characterizing the contract are assumed the same as in the third test, so already given in Tab. 5.

From the MLI solution, line 1-2 reaches its thermal limit and the optimum λ results equal to 0.20297, greater than in case of absence of UPFC (λ=0.18517 from the third test) but always smaller than in case of absence of contracts (λ=0.54884 from the second test).

The new generation scheduling and loads after the increment are given in Tab. 7.

Bus	P_g	P_c	Q_c
1	2.2209	-	-
2	0.53835	-	-
3	-	0.72179	0.36090
4	-	0.96239	0.12030
5	-	0.96239	0.24060

Table 7: Generators and loads data after an increase of λ=0.20297

The UPFC parameters (m_{se} and m_{sh} in p.u., φ_{se} and φ_{sh} in rad.) at the optimum are given in Tab. 8.

m_{se}	m_{sh}	φ_{se}	φ_{sh}
0.01315	1.0008	0.01103	0.00000

Table 8: UPFC parameters at optimum

Having assumed an accuracy of 0.0001, from the observation of the power contributes of the shunt and of the series side, two reactive contributes, in p.u., $\mathrm{Im}\left\{\underline{E}_{sh} \cdot \overset{v}{I}_{sh}\right\} = -1.0000$ and $\mathrm{Im}\left\{\underline{E}_{se} \cdot \overset{v}{I}_{3'}\right\} = 0.00730$ are provided.

5.5 *Fifth test: no UPFC- a contract between 1-3 and a contract between 1-4*

In this test, generator 1 is supposed to have two contracts, one with load 3 and another with load 4, according to participation factors given in Tab.9

k_g^{13}	k_g^{14}	k_c^{31}	k_c^{41}
0.06500	0.08800	0.20000	0.20000

Table 9: Generators and loads participation factors

Only one constraint like (26) has to be added to the MLI relative to generator 1.

The new generation scheduling needed to meet also the constraints imposed by the bilateral contracts and that maximizes λ are provided in Tab.10, together with loads after the increment.

Bus	P_g	P_c	Q_c
1	2.0945	-	-
2	0.54602	-	-
3	-	0.69117	0.34559
4	-	0.92156	0.11520
5	-	0.92156	0.23039

Table 10: Generators and loads data after an increase of λ=0.15195

The maximum load increase obtained in this case, λ=0.15195, is smaller than the one of test three (λ=0.18517), where only one contract exists. The load increment in presence of the aforesaid constraints can be further increased if a UPFC is installed in the transmission network, as test six will show below.

5.6 Sixth test: a UPFC installed on line 3-4 - a contract between 1-3 and a contract between 1-4

With the same contracts of the previous test, a UPFC is installed on line 3-4, as depicted in Fig.6.

From the MLI solution, line 1-2 reaches its thermal limit and the optimum λ results equal to 0.19000, greater than in case of absence of UPFC (λ=0.15195 from the fifth test), but smaller than in case of presence of only one contract (λ=0.20297 from the fourth test).

The new generation scheduling and loads after the increment are given in Tab. 11.

Bus	P_g	P_c	Q_c
1	2.1636	-	-
2	0.56562	-	-
3	-	0.71400	0.35700
4	-	0.95200	0.11900
5	-	0. 95200	0.23800

Table 11: Generators and loads data after an increase of λ=0.19000

As to the UPFC parameters (m_{se} and m_{sh} in p.u., φ_{se} and φ_{sh} in rad.) at the optimum, they are given in Tab. 12.

m_{se}	m_{sh}	φ_{se}	φ_{sh}
0.01635	1.0000	0.00077	0.00000

Table 12: UPFC parameters at optimum

From the observation of the power contributes of the shunt and of the series side, active and reactive contributes, in p.u., $\text{Im}\left\{\underline{E}_{sh}\cdot\overset{v}{I}_{sh}\right\}$=-0.14314 and $\text{Im}\left\{\underline{E}_{se}\cdot\overset{v}{I}_{3'}\right\}=0.00081$ are provided.

6 CONCLUSIONS

The numerical experiments carried out have proved that the presence of a FACTS device in the transmission system can increase system loadability. This peculiarity can be particularly appreciated in presence of bilateral contracts among generators and loads. Line flows tend indeed to distribute in order to meet the aforesaid bilateral transactions often moving closer to the corresponding thermal limits. An UPFC installed in the transmission network may help in reaching a more balanced distribution of line flows. In the future, the authors intend to focus their attention also on reactive security aspects, not here discussed even if embedded in the MLI formulation. Moreover, N-1 security problems relating load curtailments would be also a topic of great interest.

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