A Novel Modeling Approach for Exploring the Effects of UPFC on Restructured Electricity Market

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Abstract— A new steady state modeling of unified power flow controller (UPFC) is proposed in this paper. Using this model, factors that affect the objective function of electricity market as a result of UPFC installation in power grid has been decomposed into four components, including line series impedance increase, shunt reactive power compensation, in-phase component of series voltage and quadrature component of series voltage. A UPFC has been placed in different points of a test system and impact of each component on objective function of electricity market has been measured by simulation and compared with results from analytical method. Both active and reactive power spot prices are calculated and their relation with settings of UPFC series part has been studied. Also, numerical results shows that the necessary cost to improve security of electricity market decreases by UPFC installation.

Index Terms-- **Unified power flow controller, optimal power flow, LMP, quadratic decomposition**

I. INTRODUCTION

Limitations in transmission and generation system expansion, such as right-of-way and environmental problems, have made it an inevitable essential to use the current network capacity as much as possible [1]. The competitive nature of the electricity market tends to optimize it, as the market continuously seeks new ways to reduce costs. Flexible AC transmission systems (FACTS), which are developed as a result of recent progress in power electronic technology and communication systems, have opened alternative ways of coping with these problems, better controlling the network and reducing costs. FACTS devices can be used for congestion management [5], energy loss minimization [7], power flow control [8], security enhancement [1], and maximizing the social welfare [3] from steady state point of view and network stability improvement from dynamic point of view.

In the United States to manage power pricing in the PoolCo power market, ISO solves optimal power flow (OPF), whose main objective is to maximize the social welfare subject to network constraints [9,10]. FACTS settings in steady state applications are determined together with optimal power flow variables in a single unified framework. Among FACTS devices, UPFC is able to simultaneously compensate reactive power, control active and reactive power flow of line [11]. Several techniques have been proposed to determine UPFC settings in optimal power flow [1,2,6].

The impact of UPFC installation on power system has been discussed in [1-4]. Generation cost and active power loss are reduced by installation of UPFC [1-3]. Using UPFC for minimization of electricity market objective function leads to reduction in spot prices of load buses [3]. Real and reactive power spot prices change drastically due to placement of UPFC [3]. The UPFC operation also has an impact on transmission cost allocation in power market [4]. But, to our knowledge, so far no discussion has been presented about the chosen UPFC settings and degree of effect of each UPFC function, including reactive power compensation, active and reactive power flow control, on the OPF objective function.

This paper is organized in five sections. In section II, the optimal power flow and security constrained optimal power flow approaches and their implementation are presented. Then, in section III a new modeling of UPFC in electricity market has been proposed, which decomposes factors influencing the objective function of electricity market resulting from UPFC installation into four components. These include line series impedance increase, shunt reactive compensation, in-phase component of series voltage and the quadrature component of series voltage. Also, the relation between UPFC series part settings and locational marginal prices (LMP) has been studied.

In section IV, to validate the proposed approach, a UPFC has been placed on all possible points of a test system to measure the impact of each prementioned components on improving the objective function of the electricity market. This measurement has been done by OPF simulation for different UPFC positions in the system and the results have been compared with the ones coming from a sensitivity analysis. The UPFC allocation is also discussed. Taking into account the security constraint in power market's system has been studied with and without UPFC in another part of case studies. Numerical studies showed that security improvement from alert mode to normal mode will cost less through the use of UPFC in proper location of the system. Test results show the effectiveness of the proposed method. Finally, a summery of the paper is presented in section V.

II. SECURITY CONSTRAINED POWER MARKET MODEL

A. Optimal power flow

Maximization of social welfare as the main objective of the electricity market consists of offer prices of generators (Sellers) and bid prices of loads (Buyers). Optimal power flow solution in this paper is based on separating control variables, u, from state variables, x [12]. The proposed algorithm of optimal power flow is shown in Fig. 1.
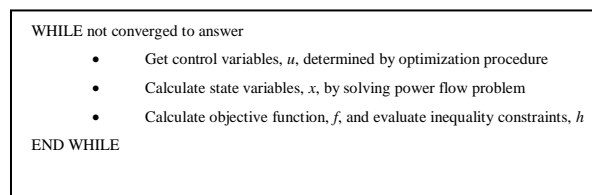
WHILE not converged to answer
- Get control variables, *u*, determined by optimization procedure
- Calculate state variables, *x*, by solving power flow problem
- Calculate objective function, *f*, and evaluate inequality constraints, *h*
END WHILE

Fig. 1: Implementation flowchart of optimal power flow

B. Security constraint

From power system security viewpoint, ordinary optimal power flow in which only the base case limitations maintained, normally leads to alert mode. To assure operating in normal mode, it is necessary to plan the power market in a way that system limitations not only be maintained in base case but also be taken care in case of single contingenci(es) occurrence; such a problem is known as the Security Constrained Optimal Power Flow (SCOPF). To add security constraint to the flowchart of OPF in Fig. 1, it is necessary to do load flow in post contingency network with the same given control variables and to evaluate the constraints.

In comparison to SCOPF cost function, OPF cost function is always less or equal because SCOPF is an OPF with some more constraints.

$$f_{\mathrm{OPF}} \leq f_{\mathrm{SCOPF}} \tag{2}$$

If no constraint of post contingency is binding, equality occurs in equation 2, otherwise inequality happens. So the difference between the resulting cost function of OPF and SCOPF, Δf in (3), means an additional cost for ancillary services that enhance the network security to normal mode.

$$\Delta f = f_{\mathrm{SCOPF}} - f_{\mathrm{OPF}} \tag{3}$$

III. UPFC MODELING AND FUNCTION ANALYSIS IN POWER MARKET

A. New UPFC modeling in OPF

A modified version of the comprehensive steady state UPFC [2,13] modeling has been used in this paper. In the comprehensive UPFC modeling, control parameters of UPFC are amplitude and angle of series converter voltage phasor, (U_{s}, Φ_{s}) and amplitude and angle of shunt converter voltage phasor (U_{p}, Φ_{p}). The model is shown in Fig. 2 where

δ_{1} and δ_{2} represent former-side and end-side voltage angles respectively.

V_{1} and V_{2} denote former-side and end-side bus voltage magnitudes, respectively.

Z_{s} and Z_{p} represent series and shunt transformers leakage impedances.

I_{s} and I_{p} are series and shunt converter currents, respectively and Q_{p} is reactive power generated by shunt converter.
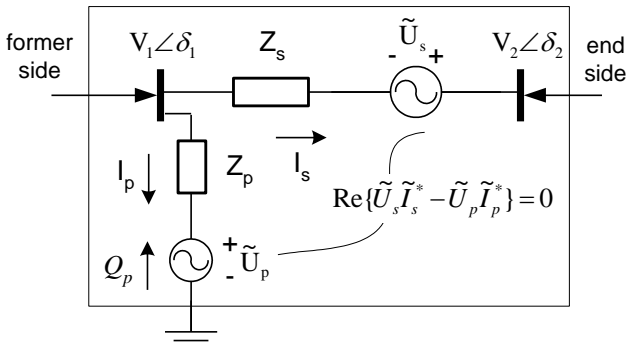

Fig. 2: UPFC equivalent circuit

However, in this paper, in-phase and quadrature components of series voltage converter (U_{sx}, U_{sy}) as shown in Fig. 3, and

in-phase and quadrature components of shunt voltage converter (U_{px}, U_{py}) as shown in Fig. 4, are used as UPFC control parameters. These parameters can mathematically be expressed as (4) and (5).
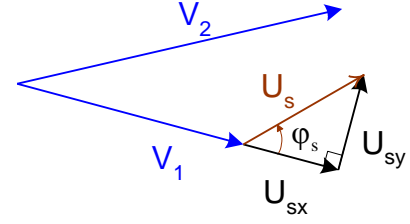

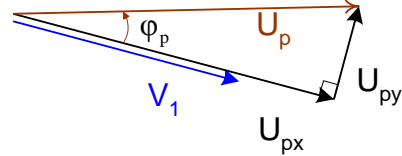Fig. 3: voltage phasor diagram of series converter

Fig. 4: voltage phasor diagram of shunt converter

$$\tilde{U}_{s} = (U_{sx} + jU_{sy}) \times 1\angle\delta_{1} \tag{4}$$

$$\tilde{U}_{p} = (U_{px} + jU_{py}) \times 1\angle\delta_{1} \tag{5}$$

Parameters in [2] have been replaced with these new parameters, as the UPFC steady state controllable parameters, because in normal operating conditions of the power system $\delta_{1} - \delta_{2}$ and V_{1}-V_{2} are small and resistance of Z_{s} and Z_{p} are also small; therefore, 1) U_{sx} changes just the reactive power flowing from bus 1 to bus 2 . U_{sy} modifies the power flow from bus 1 to bus 2. In other words, in-phase and quadrature components of UPFC series voltage are comparable in operation to tap changer and phase-shifter respectively (Fig.3) U_{px} and U_{py} are responsible for controlling reactive and active power flow respectively in the shunt part of UPFC's equivalent circuit in Fig. 2; whereas none of control parameters of UPFC model in [2] separately changes active or reactive power flow.

In order to incorporate UPFC in proposed optimal power flow implementation presented in the previous section, three UPFC parameters in (6) should be added to the set of optimization control variables, u, and at the same time, left parameter, U_{py}, should be added to the set of state variables, x. According to U_{py} function, it is adjusted in load flow problem to satisfy the active power balance equation in UPFC.

$$u_{\mathrm{UPFC}} = \{U_{sx} \quad U_{sy} \quad U_{px}\} \tag{6}$$

Also UPFC limitations given below should be added to optimization inequalities.

$I_{s} \leq I_{s}^{\max}$ (Maximum current of series part)

$I_{p} \leq I_{p}^{\max}$ (Maximum current of shunt part)

$U_{s} \leq U_{s}^{\max}$ (Maximum voltage magnitude of the series converter)

$U_{p} \leq U_{p}^{\max}$ (Maximum voltage magnitude of the shunt converter)

IV. UPFC FUNCTION ANALYSIS IN POWER MARKET

By choosing U_{sx}, U_{sy}, U_{px}, and U_{py} as UPFC parameters that separately affect active and reactive power, the effect of UPFC installation in transmission system of power market can be known as the total impacts of four functions.

- *Line impedance increase caused by UPFC series transformer impedance*
- *Reactive power injection, Q_p, to former side bus*
- *Reactive power flow in the series part because of U_{sx}*
- *Active power flow in the series part because of U_{sy}*

Among four mentioned components, just the first one tends to increase the OPF objective function; others, in contrast, are variables of optimization and used to decrease the objective function of optimization.

Given UPFC installed at the sending end of a transmission line, the quadrature component of series voltage, Usy, should be positive when power price (active LMP) at the sending bus of the line is cheaper than price at the receiving end and vice versa since Usy>0 makes active power transfered from first-side bus to end-side bus. Also the in-phase component of series voltage, Usx, should be positive when reactive power LMP at the sending bus of the line is less than its value at the receiving end and vice versa because Usx>0 makes reactive power transfer from first-side bus to end-side bus.

For the line on which the UPFC is installed, active and reactive power flow caused by the U_{sy} and U_{sx} functions are in the same direction as the natural active and reactive power flow. Functions U_{sx} and U_{sy} increase the total active and reactive power flow. Meanwhile, if maximum current limits overexceeded before applying U_{sx} and U_{sy}, violations of the maximum line current constraint occures. In this case, U_{sx} and U_{sy} settings do not obey the LMP rule and are so selected in OPF to decrease the line current.

V. CASE STUDIES

A. UPFC PLACEMENT

Validation tests are performed in a six bus test system shown in Fig. 5 which has 11 lines [9]. OPF results of the test system are summarized in Table I. where the social welfare in this electricity market, f^0_{OPF}, is 3131.25R/hr. (R is monetary unit as used in [9]). Reactive power generation of G3, Q^{max}_{G3} and current of the line 2-4, I^{max}_{12-4}, are set to their maximum values.
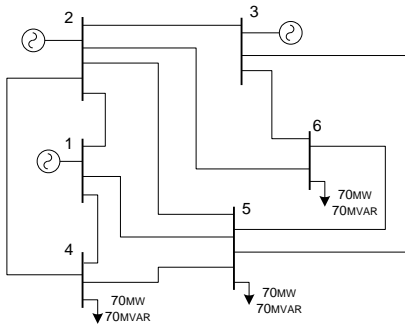

Fig. 5: Six bus test system diagram

TABLE I
OPF RESULTS OF THE SIX BUS TEST SYSTEM WITHOUT UPFC

Generation Bus	P [MW]	Q [MVAR]	V [pu]	Binding inequalities
1	55.54	59.19	1.05	Q^{max}_{G3}
2	84.74	60.35	1.0312	I^{max}_{12-4}
3	76.67	60.00	1.0304	
f^0_{opf} =	3131.25 R/hr			

In order to allocate UPFC in a system, all possible points of the system should be evaluated and number, location and size of UPFCs should be determined. Considered points for UPFC installation are both ends of all lines of the six bus system which involves 22 cases. Optimal power flow is solved in the system for different UPFC installation cases and the resulting social welfare is compared.

Since the maximum current rating of the system's 11 lines is on average 40MVA, the size of series and shunt converter of the UPFC is chosen as 4MVA with the aim of setting the maximum UPFC compensation to 0.1pu of line voltage. However the maximum UPFC compensation can be up to 0.5 pu of line voltage [14] or more. It is obvious that it is an unrealistic choice in UPFC allocation. Here the converters are sized to be relatively small so that OPF cost reduction can be an indicator of OPF cost function sensitivity with respective to UPFC installation. Based on this outcome, UPFC locations can be determined. Also a constant UPFC cost allows the result to be seam as an economic sensitivity measure. .

Apart from converter size, other UPFC ratings may differ with placement at candidate points. Maximum voltage magnitude of shunt converter, U^{max}_p, is always slightly higher than line nominal voltage which here is chosen 1.2 pu in all cases. Since U_P is normally about 1pu, maximum current of shunt converter, I^{max}_p, will be the same as converter apparent power per unit rating, 4MVA. Maximum current of the series part, I^{max}_s, is maximum per unit line current. Given nominal power and maximum current of series converter, (7) calculates maximum voltage magnitude of series converter, U^{max}_s. Resistance and reactance levels of the coupling transformers are chosen based on their voltage level and power.

$$U^{max}_s = \frac{MVA_{series}}{I^{max}_s} \qquad (7)$$

The following steps are carried out for all 22 UPFC placement cases.

Step1: By setting three UPFC's control parameters free, run optimal power flow and obtain UPFC settings (U^*_{px}, U^*_{sx}, U^*_{sy}) and OPF cost function, f^4_{OPF}

Step2: Put UPFC in zero compensation mode ($Q_p=0$, $U_{sx}=0$, $U_{sy}=0$) and obtain OPF cost function, f^1_{OPF}.

Step3: Put UPFC in the condition of (Q_p is free, $U_{sx}=0$, $U_{sy}=0$) and obtain OPF cost function, f^2_{OPF}.

Step4: Put UPFC in the condition of (Q_p is free, $U_{sx}=U^*_{sx}$ and $U_{sy}=0$) and obtain OPF cost function, f^3_{OPF}.

In each of the pre-mentioned steps, one of the four UPFC's elements in affecting the OPF cost function is enabled and social welfare of the step, f^k_{OPF}, is obtained. So the change in OPF cost function caused by enabling the element y_k computed by simulation, Δf^k_{sim}, is

$$\Delta f^k_{sim} = f^k_{opf} - f^{k-1}_{opf} \quad ,k=1,\cdots,4 \qquad (8)$$

The change in OPF cost function made by enabling element y_k can also be calculated by sensitivity analysis, Δf^k_{sen}, as shown in (9).

$$\Delta f^k_{sen} = \frac{\partial f}{\partial y_k} \times y^*_k \quad ,k=1,\cdots,4 \qquad (9)$$

Where in (9), y^*_1 is the series transformer leakage impedance; y^*_2 denotes the reactive power injection by shunt converter, Q_p, y^*_3 and y^*_4 are U^*_{sx} and U^*_{sy} settings respectively obtained in step 1; $\frac{\partial f}{\partial y_k}$ is OPF cost function sensitivity with respective to element y_k. In order to obtain sensitivity factors, UPFC installation is not necessary and they are calculated using just OPF results of the main system without UPFC. Δf^k_{sim} and Δf^k_{sen} for k=1,…,4 are shown in Table II through V. it can be seen that Δf^k_{sen} gives a relatively good estimation of Δf^k_{sim} in most cases. For instance for the case of UPFC installation at receiving end of the line 2-6, which is underlined in Table II to V, the difference between Δf^k_{sen} and Δf^k_{sim} is respectively 0.11, 0.59, 0.43 and 0.53R/hr. Therefore the effect of UPFC installation can be approximated. Subsequently, simulation results of each four steps have been reviewed.

VI. LINE IMPEDANCE INCREASE

It can be noted from Table II that firstly, the change in OPF cost function corresponding to insertion of UPFC series transformer, Δf^1_{sim}, is comparatively small in most cases and secondly, this value remains almost the same in UPFC installation on both ends.

TABLE II
OPF COST INCREASE BECAUSE OF SERIES PART IMPENDENCE INSERTION IN LINE

Line number	Line	Impedance	Δf^1_{sim} [R/hr]		$\frac{\partial f}{\partial X_l}$	Δf^1_{sen} [R/hr]
			Sending End	Receiving End		
1	1-2	0.050	-0.77	-0.99	-23.70	-1.18
2	1-4	0.022	5.62	6.15	214.1	4.75
3	1-5	0.050	0.9	1.18	12.31	0.62
4	2-3	0.050	-0.13	0.1	-0.30	-0.01
5	2-4	0.022	-4.59	-4.64	-318.3	-7.07
6	2-5	0.089	3.33	3.81	37.38	3.32
7	2-6	0.010	0.21	0.25	15.58	0.15
8	3-5	0.016	0.08	0.1	-0.68	-0.01
9	3-6	0.013	1.29	1.31	74.65	0.93
10	4-5	0.200	0.14	-1.72	-5.51	-1.10
11	5-6	0.050	0.29	0.10	4.18	0.21

VII. SHUNT REACTIVE POWER COMPENSATION

By comparing Δf^2_{sim} in Table III in 22 cases, it can be seen that connecting UPFC to a specific bus, by insertion of UPFC on all lines connected to the bus, would lead to the same amount of compensation. For example in UPFC installation at the receiving end of the line 2-3, sending ends of the line 3-5 and 3-6 in which UPFC is connected to the bus 3, Δf^2_{sim} takes very closed values, 3.25, 3.09 and 3.03R/hr respectively. Consequently, rows of Table III are grouped based on the six buses of the system; in each group, cases of UPFC installation on the lines connected to the bus are mentioned. Also it can be seen that whenever UPFC is connected to one of the load buses, shunt converter current has been set to the maximum value. These cases are marked by * in Table III. It is reasonable because generated reactive power by generating units should be delivered through lines that lead to some active power loss which means more generation, whereas supplying reactive power by UPFC is almost lossless.

TABLE III
SHUNT REACTIVE POWER COMPENSATION IN 22 UPFC PLACEMENT CASES

UPFC On bus	Line of UPFC	Q_p [MVAR]	Δf^2_{sim} [R/hr]	$\frac{\partial f}{\partial Q_p}$	Δf^2_{sen} [R/hr]
1	1-2		0		
	1-4	0	0	0	0
	1-5		0		
2	1-2		0		
	2-3		0		
	2-4	0	0	0	0
	2-5		0		
	2-6		0		
3	2-3	3.25	-0.34		-0.62
	3-5	3.09	-0.3	-0.193	-0.59
	3-6	3.03	-0.29		-0.58

TABLE III
SHUNT REACTIVE POWER COMPENSATION IN 22 UPFC PLACEMENT CASES (CONTINUED)

UPFC On bus	Line of UPFC	Q_p [MVAR]	Δf^2_{sim} [R/hr]	$\frac{\partial f}{\partial Q_p}$	Δf^2_{sen} [R/hr]
4	1-4		-5.35*		
	2-4	3.89	-1.61*	-1.225	-4.76
	4-5		-3.92*		
5	1-5		-2.31*		
	2-5		-2.49*		
	3-5	3.84	-2.22*	-0.728	-2.79
	4-5		-1.94*		
	5-6		-2.23*		
6	2-6		-1.4*		
	3-6	3.89	-1.42*	-0.4975	-1.93
	5-6		-1.34*		

VIII. IN-PHASE AND QUADRATURE COMPONENTS OF SERIES VOLTAGE, U_{sx} AND U_{sy}

U_{sx} and U_{sy} compensation results are presented in Tables IV and V. the first and the second row of each line of both tables are related to placing UPFC at sending and receiving end of the line respectively. By reviewing Δf_{sim}^3 and Δf_{sim}^4 in Tables IV and V, it can be seen that in-phase and quadrature components of series voltage always cause objective function of electricity market to be decreased. Also, by comparing the values of U_{sx}^* in both UPFC installation cases of a line, it is often observed that U_{sx}^* value in sending end of a line is very near to minus U_{sx}^* in receiving end of the line. This situation holds true about U_{sy}^* whereas maximum difference about U_{sx}^* in Table IV is 0.009pu and about U_{sy}^* in Table V is 0.016pu. Maximum U_{sx} and U_{sy} compensations take place in UPFC installation on the lines 1-4 and 1-2 respectively that are presented in bold type.

TABLE IV
COMPENSATION OF IN-PHASE COMPONENT OF SERIES VOLTAGE IN THE SIX BUS SYSTEM

Line	U_{sx}^* [pu]	Δf_{sim}^3 [R/hr]	$\dfrac{\partial f}{\partial U_{sx}}$	Δf_{sen}^3 [R/hr]
1-2	-0.013	-1.24	150	-1.87
	0.009	-0.89	-155	-1.42
1-4	0.057	**-12.79**	-384	-21.9
	-0.052	**-8.16**	350	-18.3
1-5	0.054	-1.96	-17.4	-0.94
	-0.050	-1.65	13.4	-0.66
2-3	0.053	-2.06	-36.5	-1.94
	-0.054	-2.03	36.6	-1.97
2-4	-0.017	-0.44	-1066	18.1
	0.017	-0.4	996	17.3
2-5	0.026	-2.91	-100	-2.63
	-0.026	-2.29	79.5	-2.07
2-6	0.034	-1.26	-8.3	-0.28
	-0.027	-0.8	9.01	-0.24
3-5	0.011	-0.11	-0.88	-0.01
	-0.002	0	1.01	0
3-6	0.031	-1.61	-2.8	-0.09
	-0.026	-0.75	-8.12	0.21
4-5	-0.025	-1.73	162	-4.02
	0.022	-1.57	-156	-3.49
5-6	-0.037	-1.26	28.3	-1.05
	0.039	-1.42	-25.3	-0.99

TABLE V
COMPENSATION OF QUADRATURE COMPONENT OF SERIES VOLTAGE IN THE SIX BUS SYSTEM

Line	U_{sy}^* [pu]	Δf_{sim}^4 [R/hr]	$\dfrac{\partial f}{\partial U_{sy}}$	Δf_{sen}^4 [R/hr]
1-2	-0.041	**-2.8**	102	-4.14
	0.041	**-2.94**	-108	-4.44
1-4	0.031	-0.83	-180	-5.64
	-0.038	-1.31	217	-8.15
1-5	-0.010	-0.45	15.7	-0.16
	-0.006	-0.02	-18	0.1
2-3	0.028	-0.5	-20	-0.57
	-0.028	-0.5	20.2	-0.56
2-4	-0.017	-0.37	-442	7.52
	0.010	-0.13	494	4.74
2-5	0.028	-1.79	-44	-1.2
	-0.038	-2.69	47.8	-1.81
2-6	0.000	0	-0.1	0
	-0.006	-0.04	0.78	0
3-5	-0.006	-0.04	5.77	-0.04
	0.000	0	-5.1	0
3-6	0.038	-1.89	11.4	0.44
	-0.043	-2.76	-4.8	0.2
4-5	-0.017	-0.25	76.4	-1.26
	0.021	-0.43	-74	-1.57
5-6	-0.043	-1.4	20.8	-0.89
	0.044	-1.4	-20	-0.87

In order to examine the proposed UPFC function analysis presented in previous section, active and reactive LMPs of each system bus are shown in a square beside the bus in Fig. 6. LMPs resulted from evaluating the OPF on the system without UPFC. Illustrated arrows at two ends of each line show the direction of active and reactive power flow as result of Usy and Usx operation respectively. Also magnitude of the settings U*sx and U*sy presented in Tables IV and V are shown above each arrow.

The previously mentioned approach of relationship between U*sx and U*sy settings and LMPs is applicable to all 22 cases except two cases of UPFC insertion on line 2-4 whose current is set to maximum value. It is observed that the rule satisfies all the 20 cases about U*sx and 18 cases among 20 about U*sy setting. Violating cases are depicted by bold arrows in Fig. 6. These violations of the rule are not illogical because optimal power flow is a problem of high degree nonlinearity.

Line 2-4 drawn by bold line in Fig. 6, was set to its maximum current in optimal power flow on the system without UPFC. Also active and reactive power naturally flows from bus 2 to 4. Here the second rule of the proposed analysis truly predicts the sign of U*sx and U*sy settings in both cases of UPFC installation on this line and the settings are so chosen to reduce line 2-4 current.

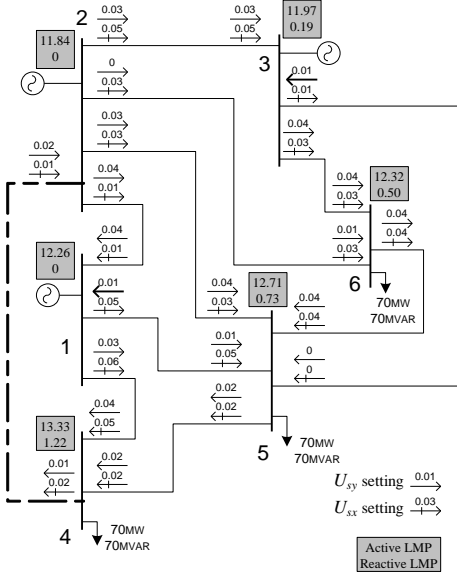Fig. 6: active and reactive LMPs in main power market and U^*_{sx}, U^*_{sy} settings in UPFC placement on the system

IX. TOTAL EFFECTS & UPFC CANDIDATE POINTS

Impacts of the four elements on OPF cost function in 22 cases have been summarized in the stacked column chart shown in Fig. 7. There are two columns for each of 11 transmission line in Fig. 7. Left and right columns are related to UPFC installation on sending and receiving ends of the line respectively. Each column consisted of four stacked columns related to four elements. The first stacked column represents impact of the line impedance increase illuminated by vertical arrows. This element in some cases, like the cases of UPFC insertion on line 2-4, has a positive effect and in other cases, like the cases of UPFC installation on line 1-4, has a negative effect in OPF cost function reduction. Other elements, however, always have positive effect. Every element, according to its impact on OPF cost function, raises the column.

By comparing total column heights, the total compensations of UPFCs can be identified. It can be seen that UPFC installation in all the 22 cases totally decreases OPF cost. By comparing heights of two columns related to UPFC installation on lines whose one end is a generation bus and another is a load bus, including the lines 1-4, 1-5, 2-4, 2-6, 3-5 and 3-6, it is always observed that UPFC installation on load bus end of the line makes more compensation than the generation bus one. The reason is that reactive compensation is much more in load bus end though this is specific to this test system that reactive loads have not been compensated.

Six cases from 22 cases in that UPFC produced most compensation are marked by * in Fig. 7. These six cases are connected with UPFC installation on both ends of lines 1-4, 2-4 and 4-5. since UPFC insertion on both ends of a line is unrealistic suggestive candidate points to install UPFC in the six bus system are receiving end of the lines 1-4, 2-4 and sending end of the line 4-5.

C. Security provision cost reduction by UPFC installation

Impact of UPFC on power market security has been studied in the second part of case studies. OPF objective function increase resulting from security improvement, Δf in (3), have been calculated for some cases. The first case is the main power market without UPFC. Three other cases are selected from 22 UPFC placement cases of which have made maximum compensation. Contingency is assumed to be the typical example of the line 5-6 outage. Results are presented in Table VI. It can be seen that Δf for system with UPFC is less than one without UPFC. Therefore cost of security improvement has been reduced by UPFC installation in proper location.

TABLE VI
SECURITY IMPROVEMENT COST FOR DIFFERENCE CASES

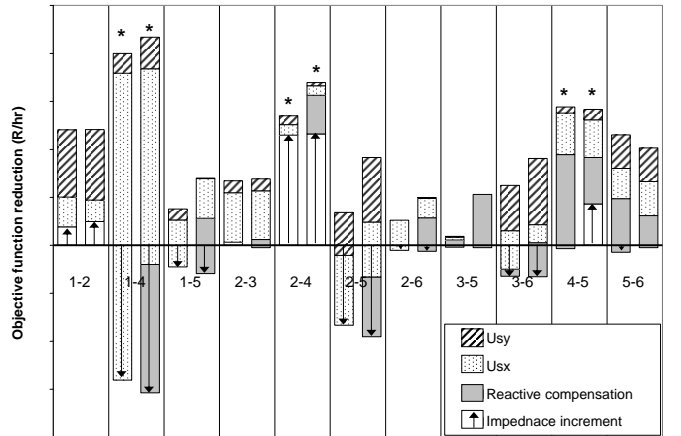| Case	Security improvement cost Δf [R/hr]
Main system without UPFC	1.88
UPFC installed on the receiving end of the line 1-4	0.55
UPFC installed on the receiving end of the line 2-4	1.44
UPFC installed on the sending end of the line 4-5	1.64

Fig. 7: UPFC four elements compensation for 22 cases

X. CONCLUSIONS

In this paper, a new steady state modeling of a Unified Power Flow Controller (UPFC) has been proposed whose parameters are directly and separately connected to active and reactive power flow in series and shunt parts of the UPFC. Using the developed model, UPFC settings and power prices in a competitive power market have simultaneously been determined to maximize the social welfare. Also, based on the proposed model, the impact of UPFC installation on social welfare has been divided into four elements, including the line impedance increase, reactive power injection because of U_{px} operation, reactive power flow in the series part resulting from U_{sx} effect and active power flow in the series part resulting from U_{sy} effect. By studying the test system with different UPFC positions, the impact of each element on power market

objective function has been seen and compared with approximated results obtained by sensitivity approach.

Also, by comparing total UPFC compensations in different cases, suitable UPFC insertion points were suggested. Since the approximated results of the effect of each element are calculated without repeating the Optimal Power Flow (OPF), the method can be used to allocate UPFC. Based on U_{sx} and U_{sy} function, two rules for predicting the sign of U_{sx} and U_{sy} settings have also been proposed and their effectiveness has been practically validated by case studies. Furthermore, test results have shown that the cost of security enhancement from alert mode to normal mode in power market is reduced by UPFC installation.

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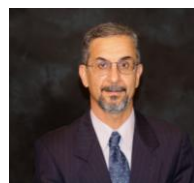
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