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Congestion Management Using UPFC in Deregulated Power System

P.Suganya[1], S. Nandini[2], Mrs. K. Muthulakshmi[3]

PG Student, Department of EEE, Kamaraj College of Engineering and Technology, Virudhunagar, India[1, 2]

Associate Professor, Department of EEE, Kamaraj College of Engineering and Technology, Virudhunagar, India[3]

Abstract—Congestion in the transmission lines is one of the technical problems that appear particularly in the deregulated environment. There are two types of congestion management methodologies to relieve congestion in transmission lines. One is non-cost free methods and another is cost-free methods, among them later method relieves the congestion technically whereas the former is related more with the economics. In this paper congestion is relieved using cost free method. Among the various cost free methods, use of FACTS devices method is considered in this paper. The unified power flow controller (UPFC) integrates properties of both shunt and series compensations, and can effectively alter power system parameters in a way that increases power transfer capability and stabilizes system. The above method is tested on modified IEEE 30-bus system and it can be readily extended to any practical systems.

Keywords-Congestion management (CM); Unified Power Flow Controller (UPFC); optimal power flow (OPF); scheduling coordinators (SCs);

I. INTRODUCTION

With the growing demand of electricity, the transmission network also needs expansion to transfer power. The transmission network with growing concerns of environment, right of way problems, and pressure for effective use of existing facilities in competitive electricity market environment can cause to violate the physical limits of transmission system more frequently to carry more power which leads to the congestion. This congestion in the network may hamper market efficiency, forcing the customers to back down power consumption due to rise in electricity prices and may threaten security of the system making system vulnerable to lower stability margins. Thus, it is the utmost duty of the ISO to mitigate congestion utilizing different techniques may be cost free or cost based [1]. The basic concepts of transmission management and its importance, dispatch model, role of the ISO and its model are presented in [2].

Techniques based on prices, rescheduling of generators, zonal based methods, sensitivity based approaches, financial transmission rights, and FACTS applications to congestion management has been presented in [3–17]. Fang and David [3,4] proposed a transmission dispatch methodology as an extension of spot pricing theory in a pool and bilateral as well as multilateral transaction m del. Prioritization of electricity transactions and willingness-to-pay for minimum curtailment strategies has been investigated as a practical alternative to deal with the congestion. Authors in [5] proposed FACTS based curtailment based strategy based on [4] for congestion management. Singh et al. [6] proposed approaches for congestion management based on OPF, which utilizes DC load flow model to minimize the congestion cost for pool model and bilateral model. The nodal pricing theory has been applied in the pool model whereas a method based on congestion cost allocation has been suggested for bilateral model. An optimal power flow based approach using nodal congestion price signals for computing the optimal power output of generators has been proposed in [6].

An OPF approach based on DC load flow as well as AC load flow has been formulated to minimize the net cost of re-dispatch to manage internzonal and intrazonal congestion [7]. Fast LP algorithm to manage congestion by rescheduling generation in Chinese electricity market is presented in [8]. An augmented Lagrangian Relaxation based algorithm has been proposed in [9]. A congestion management approach based on real and reactive power congestion distribution factors based zones and generator's rescheduling was proposed in [10].Many authors presented FACTS based model for re-dispatching during congestion management [11–17]. However, the congestion management methods have been applied for pool market model. Some of the authors have taken bilateral model into account; however, the ISO must ensure secure bilateral transactions negotiations so that congestion in the network is avoided. In the project, optimal power flow based generation rescheduling approach for congestion management approach has been presented using power flow controllers viz. UPFC.

II. CONGESTION PROBLEM

In this section, the problem of congestion is considered and how it is relieved in regulated and deregulated framework of electricity power markets, it is also discussed [2].

The condition where overloads in transmission lines or transformers occur is called congestion. When the producers and consumers of electric energy desire to produce and consume ill amounts that would cause the transmission system to operate at or beyond one or more transfer limits, the system is said to be congested. Congestion management, that is, controlling the transmission system so that transfer limits are observed, is perhaps the fundamental transmission management problem. Congestion could prevent system operators from dispatching additional power from a specific generator. Congestion could be caused for various reasons, such as transmission line outages, generator outages, changes in energy demand and uncoordinated transactions. Congestion may result in preventing new contracts, infeasibility in existing and new contracts, additional outages, and monopoly of prices in some regions of power systems and damages to system components. Congestion may be prevented to some extent by means of reservations, rights and congestion pricing. Congestion is a term that has come to power systems from economics in conjunction with deregulation, although congestion was present in power systems before deregulation. There it was discussed in terms of steady-state security, and the basic objective was to control generator output so that the system remained secure at the lowest cost. When dealing with power flow within its operating area, one entity, the vertically integrated utility, controlled both generation and transmission, gained economically from lower generation costs, and was responsible or the consequences and expected costs when less secure operation resulted in power outages. Conflicts between security and economics could be traded off within one decision-making entity.

There are two broad paradigms that may be employed for congestion management.

A.Cost-free means

(i) Out-aging of congested lines.
(ii) Operation of transformer taps/phase shifters.
(iii) Operation of FACTS devices particularly series devices.

B. Non-cost-free means:

(i) Re-dispatch of generation in a manner different from the natural settling point of the market. Some generators back down while others increase their output. The effect of this is that generators no longer operate at equal incremental costs.
(ii) Curtailment of loads and the exercise of (not-cost-free) load interruption options.

Among the above two main techniques cost-free means have the advantages like it is not going to affect economical matters, so to relieve the congestion GENCOs and DISCOs will not come into picture. In this paper, FACTS devices are used to relieve the congestion because they possess many advantages as compared with the other techniques.

II. MODELLING OF UNIFIED POWER FLOW CONTROLLER (UPFC)

Flexible AC transmission systems (FACTS) devices are transfer capability of the transmission systems, to enhance continuous control over the voltage profile and/or to damp power system oscillations. The ability to control power rapidly can increase stability margins as well as the damping of the power system, to minimize losses, to work within the thermal limits range, etc. In this chapter, injection model of the Unified Power Flow Controller (UPFC) is discussed.

3.1. BASIC PRINCIPLES OF UNIFIED POWER FLOW CONTROLLER

The UPFC, which was first proposed by Gyugi in 1991 [3], consists of shunt (exciting) and series (boosting) transformers as shown in Fig. 1. Both transformers are connected by two-gate turn off (GTO) converters and a DC circuit represented by the capacitor. Converter 1 is primarily used to provide the real power demand of converter 2 at the common DC link terminal from the AC power system. Converter 1 can also generate or absorb reactive power at its

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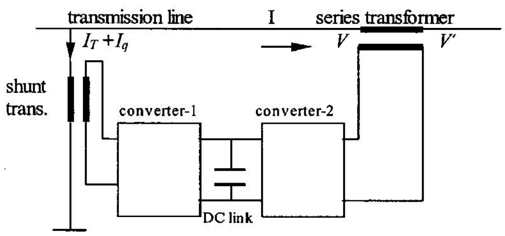

Fig.1 The UPFC basic circuit arrangement.

AC terminal, which is independent of the active power transfer to (or from) the DC terminal. Therefore with proper control, it can also fulfil the function of an independent advanced static VAR compensator providing reactive power compensation for the transmission line and thus executing indirect voltage regulation at the input terminal of the UPFC.

Converter 2 is used to generate a voltage source at the fundamental frequency with variable amplitude ($0 \leq V_T \leq V_{Tmax}$) and phase angle ($0 \leq \varphi_T \leq 2\pi$_), which is added to the AC transmission line by the series connected boosting transformer. The inverter output voltage injected in series with line can be used for direct voltage control, series compensation, phase shifter and their combinations. This voltage source can internally generate or absorb all the reactive power required by the different type of controls applied and transfers active power at its DC terminal.

With these features, UPFC is probably the most powerful and versatile FACTS device which combines the properties of TCSC, TCPAR and SVC. It is only FACTS device having the unique ability to simultaneously control all three parameters of power flow: voltage, line impedance and phase angle. Therefore, when the UPFC concept was developed in 1991, it was recognized as the most suitable and innovative FACTS device.

3.2 MODELLING OF UNIFIED POWER FLOW CONTROLLER (UPFC)

The UPFC can provide simultaneous control of all basic power system parameters (transmission voltage, impedance and phase angle). The controller can fulfill functions of reactive shunt compensation, series compensation and phase shifting, meeting multiple control objectives.

The voltage at the bus i is taken as reference (all other angles are taken with respect to the bus angle)

$$V_i = |V| \angle 0^\circ \qquad (1)$$

And voltage up to UPFC is $V_i' = V_i + V_{se}$. The voltage sources, V_{se} and V_{sh}, are controllable in both magnitude and phase angles. The values of γ and r are defined within the limits as

$$0 \leq r \leq r\max$$

$$0 \leq \gamma \leq 2$$

V_{se} is defined in terms of reference bus voltage (i.e),Vi.

$$V_{se} = r^* V_i * e^\wedge(j\gamma) \qquad (2)$$

For finding the power fed by the UPFC we go for superposition theorem. First considering the series voltage source and then the shunt one.

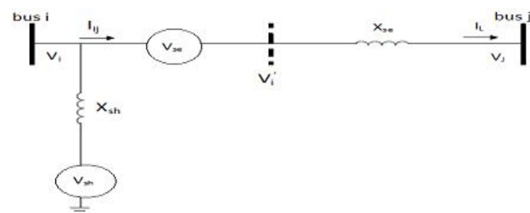

Fig.2 Two voltage source model of UPFC

By considering the series source the circuit is as below the steady-state UPFC mathematical model is developed by replacing V_{se} by a current source using duality principle. Which is connected in parallel with the transmission line, where $b_{se} = 1/X_{se}$.

$$I_{se} = -j * b_{se} * V_{se} \qquad (3)$$

The convention for flow of current is if the current leaves the node it is negative and if it enters the node it is positive.

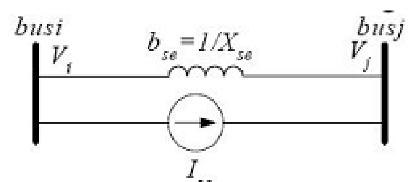

Fig.3 Replacement of voltage source by current source

As the power is equal to the product of voltage and current conjugate

$$P + jQ = V_{j^*}(I') \qquad (4)$$

$$S_{is} = V_i(-I_{se})' \qquad (5)$$

$$S_{js} = V_j(I) \qquad (6)$$

The injected powers S_{is}, S_{js} can be simplified according to following operations

$$S_{is} = V_i(j_{bse} \quad r \quad V_i e^\wedge(j\gamma))' \qquad (7)$$

From Euler's identity

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$$e^\wedge(j\gamma) = \cos\gamma + j\sin\gamma \qquad (8)$$

$$S_{is} = V_i(e^\wedge(-j(\gamma+90)\times b_{se}rV_i^{'}) \qquad (9)$$

so

$$S_{is} = -rb_{se}V_i^2[\cos(-\gamma-90) + j\sin(-\gamma-90)$$

(10) $S_{is} = -rb_{se}V_i^2\sin\gamma - jb_{se}rV_i^2\cos\gamma$ (11)

Since

$$S_{is} = P_{is} + jQ_{is} \qquad (12)$$

Comparing above equations,

$$P_{is} = -rb_{se}V_i^2\sin\gamma \qquad (13)$$

$$Q_{is} = -rb_{se}V_i^2\cos\gamma \qquad (14)$$

The voltage $V_j = V_j\angle\theta_j$ and $V_i = V_i\angle\theta_i$

$$S_{js} = V_j(I_{se})'$$

$$S_{js} = V_j\angle\theta_j(-j \;\; r \;\; V_i\angle\theta_j e^\wedge(j\gamma))$$

$$S_{js} = V_i \;\; V_j \;\; b_{se} \;\; r\sin(\theta_i - \theta_j + \gamma) +$$
$$jIV_j b_{se} r\cos(\theta_i - \theta_j + \gamma)$$

(15)

And $S_{js} = P_{js} + Q_{js}$

Comparing above equations we get

$$P_{js} = V_i \;\; V_j \;\; b_{se} \;\; r\sin(\theta_i - \theta_j + \gamma) \qquad (16)$$

$$Q_{js} = V_i \;\; V_j \;\; b_{se} \;\; r\cos(\theta_i - \theta_j + \gamma) \qquad (17)$$

Consider the shunt source, in UPFC; the shunt branch is used mainly to provide both the real power, P_{se}, which is injected to the system through the series branch, and the total losses within the UPFC. The total switching losses of the two converters is estimated to be about 2% of power transferred, for Thyristor based PWM converters, if losses are included in real power injection of shunt connected voltage source at bus I , P_{sh} is equal to 1.02 times the injected series real power through the series connected voltage source to the system.

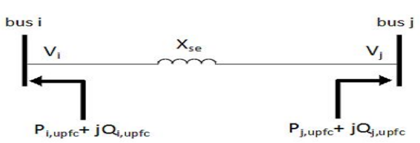

Fig.4 Steady state mathematical model

IV. MATHEMATICAL MODELLING OF CONGESTION MARKET MODEL

In this proposed optimal power flow based generation rescheduling approach for congestion management approach has been presented using power flow controllers viz UPFC (Unified power flow controller).

4.1 CONGESTION MANAGEMENT MODEL BASED ON BID FUNCTION

For congestion management, GENCOs submit bids to the ISO along with their maximum and minimum limits of rescheduling. The bid function can be constant bid or linear bid function. In this work, linear bid function has been considered. Based on the qualifying bids, the ISO send signals to the GENCOs to regulate their output during congestion hours to mitigate congestion for which the generators are paid according to their qualified bids. For the generators to reschedule their generation up/down, their base case generation information is essential. This has been obtained solving optimal power flow problem with minimization of fuel cost.

4.2 CONGESTION MANAGEMENT MODEL

min $F(x, u, p, \xi_{FACTS})$ (18)

S.t $h(x, u, p\ \xi_{FACTS}) = 0$ (19)

$g(x, u, p, \xi_{FACTS}) \le 0$ (20)

An objective function F is minimization of congestion cost and is subjected to power flow equality constraints represented as vector h and all inequality constraints represented as vector g. Vector x represents state variables, u represents control variables, and p represents fixed parameters, FACTS is the integer variable that represents set of {0,1} with 0 as absence and 1 as presence of power flow control devices.

Objective function: Minimize congestion cost CC

$$CC = \sum_{d=1}^{nd} \Delta C\,(P_g^{up}) + \sum_{d=1}^{nd} \Delta C\,(P_g^{down}) \qquad (21)$$

The components of the congestion cost CC are the sum of the linear bid functions of the GENCOs increment and decrement generation submitted to the ISO for congestion management.

$\Delta C(P_g^{up}) = k1 * \Delta P_g^{up} * bsmva + R_g^{up}$ (22)

$\Delta C(Pgdown) = k2 * \Delta P_g^{down} * bsmva + R_g^{down}$ (23)

Where k1 and k2 are inc./dec. bid cost coefficients in \$/MW h of generation scheduling bid function submitted to the ISO.

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4.3 EQUALITY CONSTRAINTS

Let complex voltages at bus-i and bus-j are Vi\di and Vj\dj respectively. The power injection equations at each bus can be written as:

$P_i = \sum_{j=1}^{Nb} V_i V_j \, [G_{ij}\cos(\delta_i - \delta_j) + B_{ij}\sin(\delta_i - \delta_j)] \quad \forall\, i = 1, 2, \ldots N_b$ $Q_i = \sum_{j=1}^{Nb} V_i V_j [G_{ij}\sin(\delta_i - \delta_j) - B_{ij}\cos(\delta_i - \delta_j)] \quad \forall\, i = 1, 2, \ldots N_b$ (24)

These power injection equations can be suitably modified with the incorporation of UPFC and ST modifying the power equations to determine the respective power injection equations.

$\sum_{g=1}^{Ng} \Delta P_g^{up} - \sum_{g=1}^{Ng} \Delta P_g^{down} = 0$ (25)

$P_{gni} = P_g + \Delta P_g^{up}$ or $P_{gni} = P_g - \Delta P_g^{down}$ (26)

$P_i = P_{gni} - P_d$ (27)

$Q_i = Q_{gi} - Q_{di}$ (28)

Power flow equation for real and reactive power are:

$P_{ij} = V_i V_j Y_{ij} \cos(\theta_{ij} + \delta_j - \delta_i) - V_i^2 Y_{ij} \cos\theta_{ij}$ (29)

Case	P (MW)	Q(MVAr)	P(MW)	Q(MVAr)
Nominal Case	192.06	105.08	189.20	107.20
Proposed case	191.73	100.24	189.20	107.20

$Q_{ij} = -V_i V_j Y_{ij} \sin(\theta_{ij} + \delta_j - \delta_i) + V_i^2 Y_{ij} \sin\theta_{ij} - (V_i^2 Y_{sh}/2)$

(30)

4.4 INEQUALITY CONSTRAINTS

(i) Up/down demand limits for demand management: The limits for up and down demand management are given by

$\Delta P_{gmin}^{down} \leq \Delta P_g \leq \Delta P_{gmax}^{down}$ (31)

$\Delta P_{gmin}^{up} \leq \Delta P_g \leq \Delta P_{gmax}^{up}$ (32)

$P_{gn}^{min} \leq P_{gn} \leq P_{gn}^{max}$ (33)

$Q_g^{min} \leq Q_g \leq Q_g^{max}$ (34)

$V_i^{min} \leq V_i \leq V_i^{max}$ (35)

$\delta_i^{min} \leq \delta_i \leq \delta_i^{max}$ (36)

(ii) Power flow limits

$P_{ij}^2 + Q_{ij}^2 \leq (S_{ij}^{max})^2$ (37)

(iii)Inequality constraints with integer variable ξ for UPFC control parameters:

$V_{se,min} < \xi_{UPFC} * V_{se} < V_{se,max}$ (38)

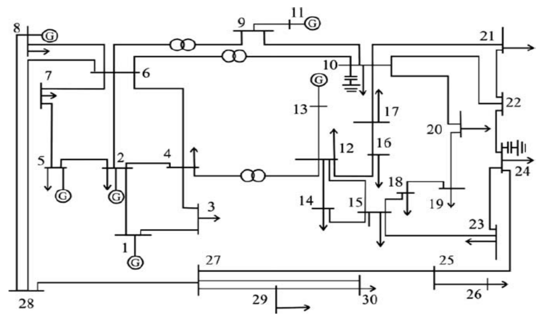
$\delta_{se,min} < \xi_{UPFC} * \delta_{se} < \delta_{se,max}$ (39)

$V_{sh,min} < \xi_{UPFC} * V_{sh} < V_{sh,max}$ (40)

$\delta_{sh,min} < \xi_{UPFC} * \delta_{sh} < \delta_{sh,max}$ (41)

V. RESULTS AND DISCUSSIONS

The proposed congestion management system is programmed using MATLAB script



programming

Fig.5 modified IEEE 30 bus system

language. The proposed method is implemented on modified IEEE 30bus system. The bus data is given in table I. Line (8, 28) get congested (exceeding flow limit of 12 MVA) if outage of line (6,28) is considered.

TABLE I GENERATOR DATA

BUS	(MW)	(MW)	(MVAR)	(MVA)	A	B	C
1	50	200	-20	250	0.0	2.0	0.00375
2	20	80	-20	100	0.0	1.75	0.0175
5	15	50	-15	80	0.0	1.0	0.0625
8	10	35	-15	60	0.0	3.25	0.00834
11	10	30	-10	50	0.0	3.0	0.025
13	12	40	-15	60	0.0	3.0	0.025

Where Generating cost $f_i = a_i + b_i PG_i + c_i PG_i^2$

TABLE II COMPARISON OF RESULTS UNDER NOMINAL AND PROPOSED CASE(UPFC)

5.1 NOMINAL CASE

Voltage at bus 29 is 29.810 mu at nominal case without using facts devices (table III).

TABLE III VOLTAGE CONSTRAINTS FOR NOMINAL CASE

BUS	Vmin mu	Vmin	Vmag	Vmax	Vmax mu
29	-	0.950	1.050	1.050	29.810

The maximum branch flow of the line between bus 10 and bus 8 is 32 MVA. At from end of the line 10, MVA limit is 2.387mu and at to end of the line 35 line, flow limit is 0.024mu.The line flow limit between bus 25 and bus 27 is 0.024 mu (table IV)

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TABLE IV BRANCH FLOW CONSTRAINTS FOR NOMINAL CASE

Branch	From bus	From end |sf|mu	From end |sf|	limit |smax|	To end |st|	To end |st|mu	To bus
10	6	2.387	32.00	32.00	31.63	-	8
35	25	-	15.62	16.00	16.00	0.024	27

5.2 PROPOSED CASE (UFPC)

With UPFC device, the bus voltage at bus 29 is enhanced to 135.851 mu from 29.810 mu (table V). The line flow limit between bus 6 and bus 8 is enhanced to 27.08mu form 2.387 mu.

TABLE V VOLTAGE CONSTRAINTS FOR PROPOSED CASE

BUS	Vmin mu	Vmin	Vmag	Vmax	Vmax mu
29	-	0.950	1.050	1.050	135.851

The line flow limit between bus 25 and bus 27 is enhanced to 6.608 mu from 0.024 mu (table VI)

TABLE VI BRANCH FLOW CONSTRAINTS FOR PROPOSED CASE

Branch	From bus	From end |sf|mu	From end |sf|	limit |smax|	To end |st|	To end |st|mu	To bus
10	6	27.08	32.00	32.00	31.64	-	8
30	15	-	15.58	16.00	16.00	1.433	23
35	25	-	15.60	16.00	16.00	6.608	27

VI. CONCLUSION

In this paper, congestion management was implemented using FACTS devices (UPFC). The increment in line flow limits and their corresponding values are shown above. With the history of more than three decades and widespread research and development, FACTS controllers are now considered a proven and mature technology. The operational flexibility and controllability that FACTS has to offer will be one of the most important tools for the system operator in the changing utility environment. In view of the various power system limits, FACTS provides the most reliable and efficient solution. The high initial cost has been the barrier to its deployment, which highlight the need to device proper tools and methods for quantifying the benefits that can be derived from use of FACTS. The generators are set to lower preferred schedules with FACTS applications. With power flow control devices, the congestion cost can be optimized with higher level of congestion cases in complex system.

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