The Power Flow Control of UPFC for Cost Minimization

Jung-Uk Lim and Seung-Il Moon

Abstract - This paper presents a new operation scheme of UPFC to minimize both generation costs and active power losses in a normal operation state of power system. In a normal operation, cost minimization is a matter of primary concern among operating objectives. This paper considers two kinds of costs, generation costs and transmission losses. The total generation cost of active powers can be minimized by optimal power flow, and active power losses in the transmission system can be also minimized by power flow control of UPFC incorporated with minimization of generation costs. In order to determine amounts of active power reference of each UPFC required for the cost minimization, an iterative optimization algorithm based on the power flow calculation using the decoupled UPFC model is proposed. For verification of the proposed method, intensive studies have been performed on a 3-unit 6-bus system equipped with a UPFC.

Keywords - UPFC, normal operation state, generation costs, transmission losses, decoupled model

1. Introduction

Since the concept of UPFC characteristics has been established by L. Gyugyi for the first time[1], the power flow computation for UPFC embedded power systems appears to be fundamental need for power system operation and planning purposes. Mathematical models of UPFC for power flow analysis have been proposed by many researchers[2,3]. The proposed models can be classified into two types, a coupled model and a decoupled model. The decoupled model has been used in this paper because it has advantage of assigning the desired values of the active and reactive power at both ends of UPFC.

The optimal power flow(OPF) formulation of power system including UPFC has been tackled so far by applying the proposed UPFC models to the conventional OPF problem. M. Noroozian has proposed a steady-state UPFC model referred as UPFC injection model, and it was used to apply to power loss minimization[4]. H.A. Perez has achieved considerable progress in UPFC modeling and OPF solving procedure, and has minimized the generation cost and active power losses as a objective function respectively[5]. And S.Y. Ge and T.S. Chung have considered three types of FACTS devices such as TCSC, TCPS, and UPFC in formulating a OPF problem and have solved security-constrained OPF problem[6].

This paper presents a new operation scheme of UPFC which is based on OPF to minimize the total power generation cost and the total loss of active powers simultaneously in a normal operation state of power system. Both generation costs and losses in the transmission system can be additionally reduced by active power control of UPFC. In order to determine amounts of active power reference of each UPFC required for cost minimization, an iterative optimization algorithm based on the power flow calculation using the decoupled UPFC model is used.

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2. Mathematical Model of UPFC

Fig. 1 shows power system including UPFC, of which equivalent circuit can be divided into two models, a coupled model and a decoupled model respectively.

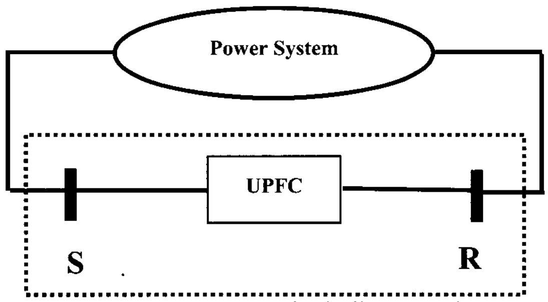

Fig. 1 Power System including UPFC

2.1 A Coupled Model

The UPFC is made of a series inverter, a shunt inverter, and two transformers. The series inverter and the shunt inverter of UPFC are modeled by ideal voltage sources, and the transformers are modeled as the impedances respectively as Fig. 2[7]. This mathematical model for UPFC is defined as a coupled model. In the coupled model, the voltage or current sources at both ends of the UPFC and impedance between them can be assigned with the desired values.

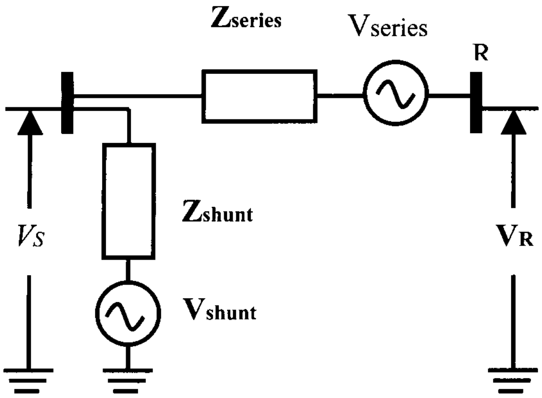

Fig. 2 A Coupled Model of the UPFC

2.2 A Decoupled Model

Fig. 3 shows a decoupled model of the UPFC for power flow analysis. As shown in Fig. 3, both ends of the UPFC were decoupled, and specified as PV bus and PQ bus, respectively[7]. The UPFC cannot generate real power or absorb it, then the sum of PSR and PRS is equal to zero. The decoupled model has advantage of assigning the desired values of the active and reactive power at both ends of UPFC.

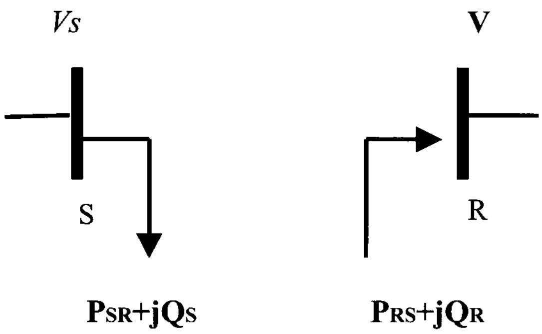

Fig. 3 A Decoupled Model of the UPFC

3. The Process of Costs Minimization

The total power generation cost which represents the total cost of active power generation is a function of amount of power generation at each bus. The minimum value of total generation cost is determined by solving OPF on generation cost minimization. The additional cost reduction can be made by the power flow control of UPFC. But somewhat higher losses would be incurred since cheaper generating sources generally located away from load centers would be predominantly used to meet the demands. In this context, the generation cost may increase against loss reduction. In other words, there can be a conflict between generation cost minimization and transmission loss minimization. Comparing the size of both costs, the cost caused by economic dispatch is dominant over the cost by loss reduction. Further, the power loss can be easily reduced by the power flow control of UPFC. Therefore, It is reasonable to minimize the total generation cost first, and then to minimize the total loss by control of UPFC. The process to minimize the generation cost and the transmission loss is shown in Fig. 4.

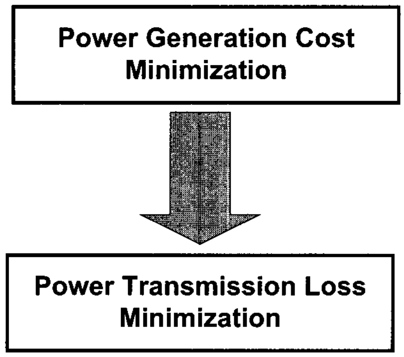

Fig. 4 Process of Costs Minimization

3.1 The Power Generation Cost

The power generation cost represents the cost of active power generation, which is a function of amount of power generation at each bus. The OPF problem to minimize the total generation cost can be formulated as follows.

$$\text{Minimize } GC = \sum_{i=1}^{NG}(a_i + b_i P_{gi} + c_i P_{gi}^2) \tag{1}$$

Subject to,

Equality constraints:

$$P_{gi} - P_{di} = \sum_{j=1}^{N}|V_i||V_j||Y_{ij}|\cos(\theta_{ij} + \delta_j - \delta_i) \quad \text{for } i = 1,\ldots,N \tag{2}$$

$$Q_{gi} - Q_{di} = \sum_{j=1}^{N}|V_i||V_j||Y_{ij}|\sin(\theta_{ij} + \delta_j - \delta_i) \quad \text{for } i = 1,\ldots,N \tag{3}$$

Inequality constraints:

$$P_{gi}^{\min} \le P_{gi} \le P_{gi}^{\max} \quad \text{for } i = 1,\ldots,NG \tag{4}$$

$$Q_{gi}^{\min} \le Q_{gi} \le Q_{gi}^{\max} \quad \text{for } i = 1,\ldots,NG \tag{5}$$

$$V_i^{\min} \le V_i \le V_i^{\max} \quad \text{for } i = 1,\ldots,N \tag{6}$$

$$P_{ij}^{\min} \le P_{ij} \le P_{ij}^{\max} \quad \text{for } i,j \in N, i \ne j \tag{7}$$

where

GC Total generation cost

N Total number of buses

NG Number of generating buses
i, j Index of buses
P_{gi} Real power generation at bus i
Q_{gi} Reactive power generation at bus i
P_{di} Real power demand at bus i
Q_{di} Reactive power demand at bus i
V_i Voltage at bus i
Y_{ij} Element of network admittance matrix
θ_{ij} Phase angle of Y_{ij}
δ_i Voltage angle at bus i
P_{ij} Real power transfer on line i-j
$P_{gi}^{\min}$, $P_{gi}^{\max}$ Real power generation limits at bus i
$Q_{gi}^{\min}$, $Q_{gi}^{\max}$ Reactive power generation limits at bus
$V_i^{\min}$, $V_i^{\max}$ Voltage limits at bus i
$P_{ij}^{\min}$, $P_{ij}^{\max}$ Real power transfer limits on line i-j

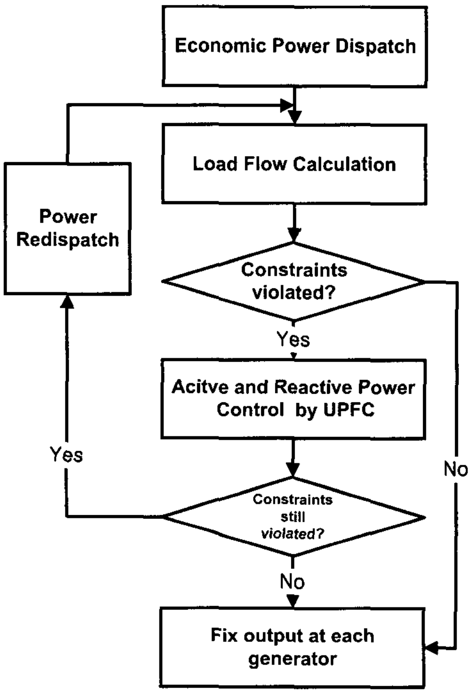

Fig. 5 Power Generation Cost Minimization

Observing OPF formulation for generation cost minimization, line flow control of UPFC almost cannot change economic power dispatch. In normal state, the most importance objective of power system operation is to satisfy the total demand at the minimum cost. Therefore, economic power dispatch for generating units is prior to the power flow control of UPFC when the total generation cost is minimized. Each generating unit, independent of UPFC operation, produces output according to power dispatch result. But, in the insecure state of power system, the different operation scheme should be applied. Fig. 5 shows the process of power generation cost minimization by UPFC operation.

3.2 The Transmission Loss of Active powers

The transmission loss indicates the surplus of power generation in comparison with the amount of total load. Therefore, it requires additional generation cost. The OPF problem to minimize the total loss of active powers in the transmission system can be formulated as follows.

$$\text{Minimize } LOSS = \sum_{k=1}^{NL} C_k (P_{ij} + P_{ji}) \quad (8)$$

Subject to,

Equality constraints:

$$P_{gi} - P_{di} = \sum_{j=1}^{N} |V_i||V_j||Y_{ij}| \cos(\theta_{ij} + \delta_j - \delta_i)$$
$$\text{for } i = 1, \ldots, N \quad (9)$$

$$Q_{gi} - Q_{di} = \sum_{j=1}^{N} |V_i||V_j||Y_{ij}| \sin(\theta_{ij} + \delta_j - \delta_i)$$
$$\text{for } i = 1, \ldots, N \quad (10)$$

Inequality constraints:

$$P_{gi}^{\min} \le P_{gi} \le P_{gi}^{\max} \quad \text{for } i = 1, \ldots, NG \quad (11)$$

$$Q_{gi}^{\min} \le Q_{gi} \le Q_{gi}^{\max} \quad \text{for } i = 1, \ldots, NG \quad (12)$$

$$V_i^{\min} \le V_i \le V_i^{\max} \quad \text{for } i = 1, \ldots, N \quad (13)$$

$$P_{ij}^{\min} \le P_{ij} \le P_{ij}^{\max} \quad \text{for } i, j \in N, i \ne j \quad (14)$$

where
$LOSS$ Total Transmission Loss
NL Total number of lines.

Fig. 6 shows the process of minimization of the total transmission loss by UPFC control.

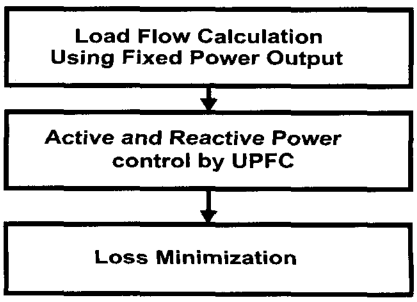

Fig. 6 Transmission Loss Minimization

4. Case Studies

The developed operation scheme has been tested on the 6-bus system equipped with a UPFC shown in Fig. 7[8].

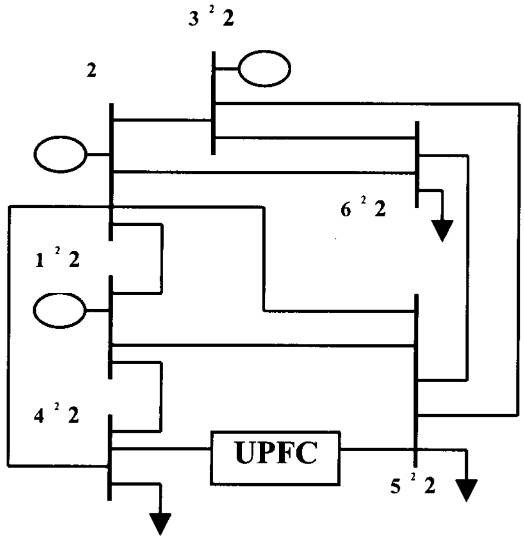

Fig. 7 3-unit 6-bus Sample System

Let the fuel cost curves for the 3 units in the 6-bus system be given as

$$F_1(P_{G1}) = 213.1 + 11.669P_{G1} + 0.00533P_{G1}^2 \ \$/h$$
$$F_2(P_{G2}) = 200.0 + 10.333P_{G2} + 0.00889P_{G2}^2 \ \$/h$$
$$F_1(P_{G3}) = 240.0 + 10.833P_{G3} + 0.00741P_{G3}^2 \ \$/h$$

with unit dispatch limits of active power

$$50.0MW \le P_{G1} \le 200\ MW$$
$$37.5.MW \le P_{G2} \le 150\ MW$$
$$45.0MW \le P_{G3} \le 180\ MW$$

and line flow limits of active power

$0 \le P_{line} \le 40MW$ for all lines.

Table 1 shows the active power outputs at each unit and the total power generation cost by economic dispatch(ED), OPF results without UPFC operation, and OPF results with UPFC operation, respectively. In case of ED, all of inequality constraints are ignored. In this example, active power flow from bus 2 to bus 4 is bounded by line flow constraints. The UPFC operation can alleviate the line flow between bus 2 and bus 4. Therefore, active power at each bus can be re-dispatched, and the power generation cost is reduced.

Once the generation cost was minimized, the total transmission loss can be also minimization. The transmission loss of active powers can be easily reduced by the power flow control of UPFC as shown in Fig. 8.

Table 1 Total Generation Cost on a Sample System

	ED Results	OPF Results	OPF Results with UPFC Operation
P_{G1}	50 MW	93.2MW	71.8MW
P_{G2}	115MW	77.1MW	98.4MW
P_{G3}	45MW	47.7MW	47.9MW
Total Gen. Cost	\$3058.2	\$3170.7	\$3157.2

In order to determine amounts of active power reference of a UPFC required for the cost minimization, Marquardt method based on the power flow calculation was used[9].

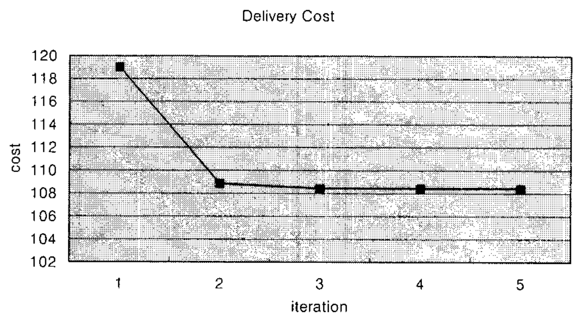

Fig. 8 Loss Minimization on a 6-bus system

5. Conclusions

This paper presents a new operation scheme of UPFC to minimize both the total generation cost and the total transmission losses of active powers in a normal operational state.

- The generation cost of active powers can be minimized by OPF calculation.
- The total transmission loss can be minimized by power flow control of UPFC.
- Considering the size of both costs, it is reasonable to minimize the generation cost first, and to minimize the transmission loss by control of UPFC successively.
- In order to determine amounts of active power reference of each UPFC required for cost minimization, Marquardt method based on the power flow calculation using the decoupled UPFC model was used.

The proposed scheme for cost minimization has been applied to a 6-bus system, and the results of numerical examples were presented and reviewed.

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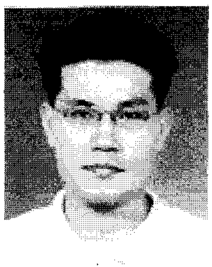

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