PSerc 99-03

Optimal Power Flow Formulation in Market of Retail Wheeling

Taiyou Yong, Student Member, IEEE Robert Lasseter, Fellow, IEEE
Department of Electrical and Computer Engineering,
University of Wisconsin at Madison,
Madison, Wisconsin, USA

Abstract: Power system deregulation along with retail wheeling was proposed in legislation for the future power system operation. Retail wheeling implies customers have more choices. One important option is the power supplier providing cheaper power. In this paper we introduce new concepts of generation sets and load sets to model the behavior of power supply and load distribution in the new retail wheeling market. Formation of optimal power flow (OPF) problem, in which the public interests are maximized, is demonstrated.. IEEE-14 bus system is used as an example.

Key words: Power System Deregulation, Retail Wheeling, Optimal Power Flow, Generation and Load Shifting

1. Introduction

Electric power system deregulation is underway in the US. The heart of deregulation is retail wheeling. Retail wheeling will create an open market to encourage vigorous and fair competition in electric supply. Past power system structures are vertical. One utility controls the power generation, transmission and distribution in an area. The rate of electricity is regulated. The market is monopoly. Retail wheeling allows customers to choose power suppliers. The utilities have to provide better services and cheaper power to attract customers.

The deregulation has already allowed free access to the generation market. The power suppliers are the agencies who sell power to customers. They may not produce power, but they buy shares from generation units. Retail wheeling may allow distribution agencies to enter the distribution market. They represent a group of customers and buy distribution right to acquire power from transmission system.

This restructuring of power system challenges the old concepts of power system analysis. Optimal power flow is an optimizing tool for power system planning, energy management etc. Use of the optimal power flow is becoming more important in the deregulated power industry to deploy the resources optimally. In the past time, researchers focused on how to formulate some practical constraints, such as bus voltage range, generation limits, line transfer capability, contingency constraints, environment concerns etc. and how to solve the optimal power flow problem efficiently. Techniques such as Newton method, sequential linear and quadratic programming method, PQ de-coupling method etc[1,2]are used. However some new concerns on optimal power flow arise in the retail wheeling market. In the deregulated power system, Suppliers and Customers exchange power in the energy market. The price of power is determined in the market. The Independent System Operators (ISO) will manage the transmission system operation to ensure completion of the business transactions. Public interest is the objective of the ISO.

In this paper, we introduce some new concepts in the formulation of optimal power flow to meet the new environment. A simple IEEE-14 bus system is used to establish the new optimal power flow problem.

2. Description of new concepts

Power systems are restructuring to create a more competitive power market. Power systems include two interactive parts, physical transmission system and the power market. Power suppliers and customers are the basic elements in the power market. Power suppliers will sell power to customers through physical transmission system. In the future, the power system structure can be described in the Fig 1.

It’s possible for power suppliers to be different from the power producers. They make their profits by buying power from the producers, such as hydro power plants, nuclear power plants etc and selling power to consumers. The suppliers have contracts with customers promising the power supply.

Here we define a *generation set* to model the relationship between power suppliers and power generation.

Definition of generation set: Generation set is a group of generators where the suppliers can obtain the generation.

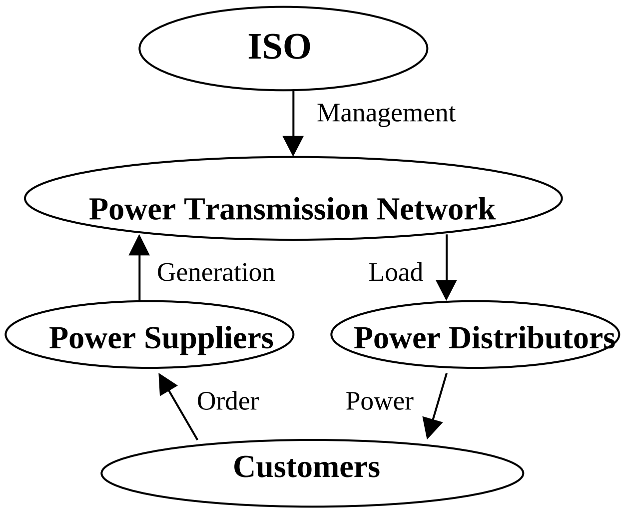

Fig. 1 Restructured electric power system

Using this definition, it's easy to include the power plants which are regulated by states, such as nuclear power plants, large hydro power plants, along with small power plants.

Retail wheeling would allow end-use electricity consumers, individually or in aggregate (together with other consumers), to choose among different energy suppliers and place a demand order. This could include terms and condition as quantities, times, prices, and other factors.

The power distributors don't control the power level. They maintained the distribution system to ensure the load flow from the transmission system to customers. The distribution systems absorb the power from one or more buses of the transmission system. The load at transmission system may shift between a group of load buses (physically power substations). We can call the group of buses where the load shifts as a *load set*. Typically the geographical range of loads is limited. The load can only shift among buses in the neighborhood. The *load set* can also be called as neighborhood set of load.

Definition of load set: Load set is a group of load buses with shifting demand.

The concept of load set can model the aggregate consumers, or some large electricity consumers, such as large manufacturers.

All the transactions of power supply contracts have to be completed through the transmission system. At the system level, public interests concerns, both technically and economically are dominated. Technical aspects, power flow must be satisfied. Electricity must be produced at the instant it is to be used. Large quantities of electric energy cannot be economically stored. Reliability in the supply of electricity is crucial to many applications, and absolutely essential to others. Any reduction in system reliability must be weighed against the potential damage to our economy, our standard of living, and our national security. The transmission system must be maintained at a safe level. Independent System Operator will manage the transmission system in the public interests.

Once the new concepts are introduced, some concerns are raised.

· The loads at transmission system buses are not constant. But the load demand of customers is a fixed value over a period. This constraint, $\sum_j L_{ij} = L_i$ where $L_{ij} = s_{ij} L_i$; i: index of load, j: index of elements in the load set of load i; s_{ij} is the share of loads at bus j, And $\sum_i \sum_j L_{ij} = D$. D is the total consumer demand, which is equal to the load absorbed by distributors from load buses.

· The power injection of generator buses to the transmission system is still constrained by the possible output range of generators. But the price of power at each power plant may be different among shares of suppliers. The summation of shares of different suppliers must be in the range of generator output. $\sum_j G_{ij} = G_i$, where $G_{ij} = h_{ij} G_i$; i: index of power suppliers, j: index of generators where power suppliers can obtain power to inject into transmission system. h_{ij} is the generator j's shares held by supplier i. The generated power must be equal to the supply requirement $\sum_i \sum_j G_{ij} = S$, where S means the total power supply.

· Market clearing (electricity must be consumed instantly) implies that total supply must be equal to the total load demand S=D. The system loss is compensated by some physical swing buses which maintain the system frequency. The price of power is determined in the market.

3. New Formulation of OPF

Retail wheeling causes many complex implications for the existing interconnected transmission and distribution systems in terms of reliability, quality of service, and responsibility for restructured services. Moreover, this transaction has significant financial and implications for electric providers, shareholders, consumers, local units of government, and states.

For current systems, important economic benefits are being realized through the coordinated planning and operation of the highly integrated electric generation and transmission systems. These benefits are the result of reduced generation capacity margin requirements and the ability to schedule generation on a lowest incremental cost basis over broad geographical areas.

The in the old OPF formulation, the production cost is the objective to minimize, and at the same time, some constraints, including entire power flow equations, generation limits, voltage ranges and line transfer capability etc., has to be satisfied. The production cost typically is considered as quadratic functions or as a piecewise linear approximation. For a quadratic cost function, the OPF problem we can formulate as

Min $Cost=\Sigma(\alpha_i*Pg_i^2+\beta_i*Pg_i+\gamma_i)$

i: index of generators, α_i, β_i, γ_i are the coefficients of quadratic production cost functions.

S.T.

- Entire AC Power Flow
  $f(Pg,Qg,V,\delta) = 0$

- Line Flow Constraints
  $Line(Pg,Qg,V,\delta) \le Line_{max}$

- Bus Voltage Magnitude Range
  $V_{min} \le V \le V_{max}$

- Real Power Output Range of Each Unit
  $Pg_{min} \le Pg \le Pg_{max}$

- Reactive Power Output Range OF Each Unit
  $Qg_{min} \le Qg \le Qg_{max}$

Other constraints, such as contingency can be added.

As discussed in the previous section, we need to reconsider the objective to achieve and the constraints applied to the supply side and demand side.

ISOs have to manage the transmission system to benefit all the consumers with considering the system safety. The objective is to maximize the public interests, i.e. to minimize the total transmission loss. The other objective fun can be set to maximize the public interests, such as maximize the social welfare. In this paper, to simplify the formulation, we take the cost minimization as objective function.

Generally the constraints of optimal power flow still include the entire AC power flow, generation output range, bus voltage limits, transmission line transfer capabilities. Additional constraints related to the retail wheeling need to be added.

For a system with N buses, L lines, J generators, K loads and an associated power market with I suppliers, M customers, mathematically we formulated the OPF in market of retail wheeling as,

Min $Loss=\sum_l P_l(S, D, s, h, V, \delta)$

P_l is the line power load in two directions.

S.T.

- Entire AC Power Flow
  $f(S, D, s, h, V, \delta) = 0$, f is a 2Nx1 vector which contains the real power and reactive power balances at N buses transmission system.

- Line Flow Constraints
  $Line(S, D, s, h, V, \delta) \le Line_{max}$, Line is a 2Lx1 vector, which contains the magnitude of 2-direction flow in all the transmission lines.

- Bus Voltage Magnitude Range
  $V_{min} \le V \le V_{max}$

- Power Output Range of Each Generation Unit
  $G_{jmin} \le \sum_i G_{ij} \le G_{jmax}$, $G_{ij} \ge 0$. G_{ij} is the power generated by generator j for supplier i,. i: index of Suppliers, j: index of generators.

- Load Set Constraints
  $real(\sum_k L_{km} = L_m)$, $L_{km} = s_{km} L_m \Rightarrow \sum_k s_{jk} = 1$, m: index of customers, k: index of buses in load set of customer m.

- Generation Set Constraints
  $real(\sum_j G_{ij} = G_i)$, $G_{ij} = h_{ij} G_i \Rightarrow \sum_j h_{ij} = 1$, i: index of suppliers, j: index of generators in generator set of supplier i

- Elements in Shares s and h are between 0 and 1.
  $1 \ge s_{km} \ge 0$, $1 \ge h_{ij} \ge 0$,

  In the formulation, S is a vector representing all the suppliers' power injection through generation sets. D is a vector representing all customers' demand absorbed from load set. s and h are the shares of generation of suppliers and shares of load of customers. V and δ are Nx1 vectors, representing the magnitude and angle of each bus voltage.

And the other constraints, such as contingency constraints can also be formulated with variables $\{S, D, s, h, V, \delta\}$.

Those intermediate buses, where there is no supply and demand, are still treated as constant.

In the new formulation, the loads absorbed from the transmission system buses are not constants, but variables constrained by load sets, which define the distribution choices of customers.

In the power supply side, the power output is not only limited by generator ratings, but also constrained by the suppliers' choices. This models the free access to generation markets and transmission systems.

4. Sample system formulation

Using the proposed formulation, we can create a retail wheeling system. IEEE-14 bus system is used as the base transmission system. The topology of IEEE-14 bus system is shown in Fig2.

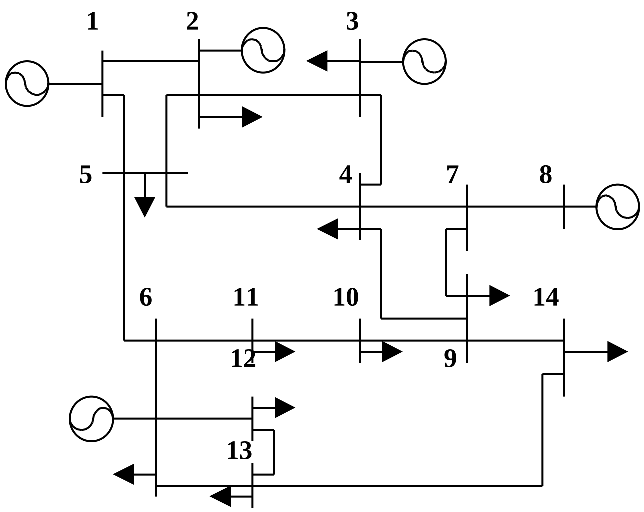

Fig.2 IEEE-14 bus system

This is a system with 14 buses, 20 lines and 5 generators {1, 2, 3, 6, 8}, and 11 load substations {2, 3, 4, 5, 6, 9, 10, 11, 12, 13, 14}, one intermediate bus {7}. Assume there are 2 suppliers {S1, S2} and 4 customers {D1, D2, D3, D4} in the energy market of this small system. Suppose the generation sets of suppliers are defined in Table 1. Load sets of customers are defined in Table 2.

Supplier	Generator Set
S1	1, 2, 3
S2	3, 6, 8

Table 1. Generator Set Definition

The overlap over generator at bus 3 means both suppliers S1 and S2 buy inject power to transmission system through generator at bus 3.

Customer	Load Set
D1	2, 3
D2	4, 5, 6
D3	6, 11, 12 , 13
D4	4, 9, 10, 14

Table 1. Load Set Definition

There is no power supply and demand at bus 7. The meaning of load set is, for example, D1 takes power from bus 2 and 3. The overlap of load set for D2 and d3 indicates both D2 and D3 may absorb power from bus 6.

Now the formulation of optimal power flow can be written as,

Min Loss=$\sum_{l} P_l(S, D, s, h, V, \delta)$

S.T.

- Entire AC Power Flow
  $f(S, D, s, h, V, \delta) = 0$. f is 28x1 function
- Line Flow Constraints
  $Line(S, D, s, h, V, \delta) \le Line_{max}$ Line is 40x1 function
- Bus Voltage Magnitude Range
  $V_{min} \le V \le V_{max}$ V is 14x1 voltage magnitude
- Power Output Range of Each Generation Unit
  $G_{jmin} \le \sum_{i} G_{ij} \le G_{jmax}$, i:1,2, j: index of generators {1, 2, 3, 6, 8}
- Load Set Constraints
  $\sum_{m} s_{km} = 1$, m:1,2,3,4, k index of elements in load set of m.
- Generation Set Constraints
  , i:1, 2, j: index of elements in generation set of supplier i.
- Elements in Shares s and h are between 0 and 1.
  $1 \ge s_{km} \ge 0$, $1 \ge h_{ij} \ge 0$,

Intuitively the flexibility of load and generation in the transmission system actually optimize the power delivery and increase the system marginal power range. Load flexibility releases the stress of high load buses and transmission lines. The voltage on high load buses will increase due to some load shifting.

5. Conclusion

Optimal power flow is formulated for competitive retail wheeling markets. With understanding of both technical and economic concerns, two important concepts of load sets and generation sets are presented. Under this assumption, optimal power flow is applied to maximize the public interests (e.g. minimize the transmission system loss). The solution of the proposed optimal power flow optimizes the load flow of transmission system by shifting the load from heavily loaded buses to the lightly loaded buses.

References

[1] M. Huneanult, F.D. Galiana, “A Survey of the Optimal Power Flow Literature”, IEEE Trans. On Power System, Vol.6, No. 2, May 1992

[2] J.A. Momoh etc, “Challenges to Optimal power flow”, IEEE Trans. On Power System, Vol. 12, No. 1, Feb,1997

[3] Hal R. Varian, “Microeconomic Analysis”, Third edition,1993

About Authors:

Taiyou Yong, (B.S. 91, M.S. 95), He is a PH.D candidate in University of Wisconsin and doing research on optimal power flow in deregulated environment, such as OPF in retail wheeling market, sparse techniques application. His interests also include power system analysis, control, and power electronics application.

Robert H. Lasseter (F'92) received the PH.D in physics at the University of Pennsylvania in 1971. He was a consultant Engineer at General Electric Co. until he joined the University of Wisconsin-madison in 1980.