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Economic Redispatch Considering Transmission Congestion for Optimal Energy Price in a Deregulated Power System

Muhammad Bachtiar Nappu and **Ardiaty Arief**
Department of Electrical Engineering
Faculty of Engineering, Universitas Hasanuddin
Makassar 90245, Indonesia
thiar@engineer.com, bachtiar@eng.unhas.ac.id, ardiaty@engineer.com

Abstract— **In a deregulated power system, energy prices throughout the network will be characterised and depending on the existence of transmission constraints. As power flow violates transmission constraints, redispatching generating units is required and this will cause the price at every node to vary. This manuscript introduces a scheme for economic redispatch model based on DC optimal power flow taking into account the transmission issue in order to obtain an optimal energy price, especially when transmission congestion takes place. A proposed scheme is discussed in this paper, to concisely evaluate the foremost indication in calculating the energy price, which is characterised by locational marginal price. The techniques used to incorporate transmission congestion into the model are examined as well.**

Keywords - Economic dispatch, transmission congestion, electricity market, locational marginal prices, optimal power flow, DC-OPF, nodal price, energy price, deregulated power system.

I. INTRODUCTION

Under an open access environment in a deregulated power system, transmission management holds a vital role in supporting transactions between suppliers and customers. Nevertheless, a transmission network has some constraints that should be addressed in order to ensure sufficient control to maintain the security level of a power system while maximising market efficiency. The most obvious drawback of transmission constraints is a congestion problem that becomes an obstacle of perfect competition among the market participants since it can influence spot market pricing [1-3].

The system becomes congested when the supplier and customer agree to produce and consume a particular amount of electric power, but this causes the transmission network to exceed its thermal limits. Congestion can cause the market players to exercise market power that is able to result in price volatility beyond the marginal costs [4-7]. Furthermore, if the systems are being heavily loaded than either preventive or protective actions must be taken to alleviate the system from further cascading failure. The preventive action in this case including DG penetration within congested zone, while the protective action can be in form of load shedding strategy [8-15]. Thus, it is important to manage congestion efficiently in the design of a power market.

One mechanism that has direct correlation with transmission management is market clearing price. In a competitive electricity market, energy prices throughout the network will be different and measured based on the existence of transmission constraints. When network losses are ignored and there is no congestion on the transmission lines, the power price will be the same at all nodes. This is known as uniform marginal pricing.

However, as the power flow violates transmission constraints, redispatching generating units is required and this will cause the price at every node to vary. This phenomenon is defined as locational marginal pricing. Therefore, the market-clearing price has a strong relationship with transmission management, which is needed to be assessed in order to obtain an efficient and transparent price but satisfying all market participants [16-22].

The authors in this paper introduce a scheme for economic redispatch model taking into account the transmission issue in order to obtain an optimal energy price, especially when transmission congestion occurs. In this manuscript, a proposed scheme is presented to briefly review the main idea behind the energy price calculation, which is represented by the so-called locational marginal price, and further discuss the techniques used to incorporate transmission congestion but ignoring network losses into the model.

II. ECONOMIC DISPATCH ON POWER GENERATION UNITS

The definition of economic dispatch as cited in [23] is "*the operation of generation facilities to produce energy at the lowest cost to reliably serve customers, recognizing any operational limits of generation and transmission facilities*". While reference [24] defines economic dispatch as "*the*

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process of allocating generation levels to the generating unit in the mix, so that the system load may be supplied entirely and most economically”. The production cost of generation is analysed during the dispatch, subject to data that is concerning fuel cost and electrical power output [25-34]. A quadratic equation is utilised to approximate the cost function along with several cost coefficients.

In evaluating the problems in connection with the economic operating of the power plant, the set of input-output characteristics of the thermal power generation units is essential. An ideal form of the input-output characteristic of a steam unit is sketched in Figure 1.

The following expressions are used to define the characteristic of the unit;

H : heat input (MBtu/h)
F : H times fuel cost = operating cost ($/h)
P : active power output (MW)

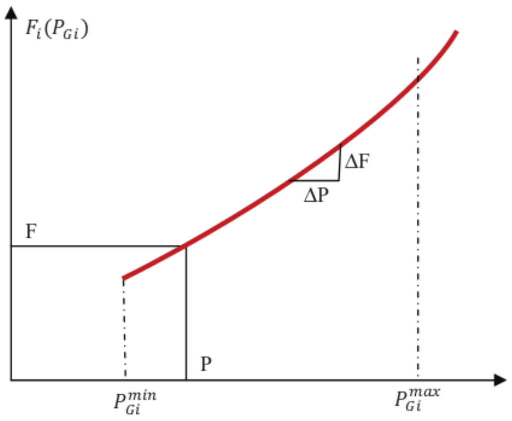

Fig. **1** Input-output curve of a steam turbine generator [35]

P_{Gi}^{max} is the upper limit of power output, and P_{Gi}^{max} reflects the lower operating limit which is technically an uneconomic point to run the unit. Opening a valve at the inlet to the steam turbine will allow the power output to rise. Consequently, the operating cost will perform a quadratic equation as a function of active power generation as follows

$$F_i(P_{Gi}) = a_i P_{Gi}^2 + b_i P_{Gi} + c_i \quad \$/h \tag{1}$$

III. LOCATIONAL MARGINAL PRICE

Locational marginal price (LMP) is the key factor to identify the spot price and to manage transmission congestion [36-38]. LMP methodology has been implemented or is under implementation at some independent system operators, such as: California ISO, PJM, New York ISO, ISO-New England, Midwest ISO, ERCOT, etc. LMP is defined in [39] as: “*…the marginal cost of supplying the next increment of electric energy at a specific bus considering the generation marginal cost and the physical aspects of the transmission system…*”.

In other words, the LMP is the cost to serve one additional MW of load at a specific location, using the lowest production cost of all available generators, while observing all transmission constraints. From the viewpoint of generation and transmission planning, it is fundamental to always calculate and forecast the value of LMP, which may be obtained using the traditional production cost optimisation model [40, 41]. However, the implementation of LMP must be able to manage various impracticalities, such as determining prices when systems run out of controls and transmission constraints are violated or there is an excess of generation or total generation is greater than total load [42].

IV. LMP IGNORING LOSSES BASED ON DC-OPF MODEL

The DC optimal power flow (DC-OPF) model is a common optimisation based technique that has been proposed by many market operators and is being broadly used in various ways, both for dispatching power and clearing energy markets to decide the LMP. This methodology has become the leading approach in electrical power markets. The DC optimal power flow model has been utilised in the electricity industry to compute the LMP due to its speed and robustness, particularly in market simulation and planning [43, 44].

Let the total production cost and the total consumer benefit are given by:

$$C_i(P_{Gi}) = a_i P_{Gi}^2 + b_i P_{Gi} + c_i \tag{2}$$

$$B_i(P_{Di}) = d_i P_{Di}^2 + e_i P_{Di} + f_i \tag{3}$$

The objective function is to maximise the total social welfare which also equals to minimise the total social cost;

$$Max \sum_{i=1}^{n_D} B_i(P_{Di}) - \sum_{i=1}^{n_G} C_i(P_{Gi}) \tag{4}$$

or

$$Min \sum_{i=1}^{n_G} [a_i P_{Gi}^2 + b_i P_{Gi} + c_i] - \sum_{i=1}^{n_D} [d_i P_{Di}^2 + e_i P_{Di} + f_i]$$

Social welfare is the difference between total production cost and total customer benefit, which is going to be maximised in the pool. The DC-OPF is basically employed to formulate LMP model without taking network losses into consideration. In pool-based dispatch mechanism using this methodology, an optimal solution is required with subject to a set of practical constraints as follows

- Bus power balance

$$P_i = \sum_{\substack{i=1 \\ (j\neq 1)}}^{Nbus} \left[B_{ij}\right]\left[\delta_i - \delta_j\right] \tag{5}$$

- Generator power output

$$P_{Gj}^{\,min} \leq P_G \leq P_{Gj}^{\,max} \qquad \text{for } i = 1, \ldots, N_G \tag{6}$$

- Active power demand

$$P_{Dj}^{\,min} \leq P_{Dj} \leq P_{Dj}^{\,max} \qquad \text{for } j = 1, \ldots, N_D \tag{7}$$

- Power transfer capability

$$flow_m(\delta) \leq flow_m^{\,max} \qquad \text{for } i = 1, \ldots, N_{bus} \tag{8}$$

From the objective function with subject to the constraints above, Lagrangian function is then implemented after selecting a reference node ($\delta_{ref} = 0$). Optimal condition will result a set of decision variables and multipliers;

$$z = [P_1\, P_2 \ldots P_n\; \delta_1\, \delta_2 \ldots \delta_{n-1}\; \lambda_1\, \lambda_2 \ldots \lambda_n\; \mu_1\, \mu_2 \ldots \mu_m\,]^{T} \tag{9}$$

Locational marginal price is represented through the Lagrangian multipliers;

$$LMP = \lambda \tag{10}$$

The Lagrangian multipliers may be considered to be the marginal cost or incremental cost at each generating bus to re-dispatch the generation in a manner to produce energy to serve loads in the modeled area at minimum cost. The merchandising surplus (MS) contains congestion revenue resulted from the violation of transmission constraints.

$$MS = \sum_{m} \mu_{max,flow,m} \cdot flow_m - \sum_{m} \mu_{min,flow,m} \cdot flow_m \tag{11}$$

where:

$flow_m^{\,max}$: upper limit of power flow on line m
C_i : production cost at bus i (\$/MWh)
B_i : customer benefit at bus i (\$/MWh)
P_{Gi} : active power output of i-th generator (MW)
P_{Di} : active power demand of i-th load (MW)
P_i : net injection at bus i
a_i, b_i, c_i : coefficients for production cost function
d_i, e_i, f_i : coefficients for customer benefit cost function
n_D : number of load.
N_{bus} : number of bus
b_{ij} : susceptance of the branch i-j
δ : voltage phase angle

V. RESULTS AND ANALYSIS

The LMP lossless scheme using DC-OPF method, which has been modeled in previous section, was implemented on the 3-bus system to determine the value of LMP at every node. The proposed method is implemented with a 3-bus system. Some important characteristics are evaluated to describe beneficial features of the proposed method. The system is required to deliver an aggregated load of 800 MW.

System details consisting of generation and branch profiles are given in Table 1. The scheme takes both energy price and transmission congestion costs in to account but ignoring the existence of network losses. This is to simplify the model in order to achieve optimal point. The simulation's results are shown at Figure 2 and 3.

TABLE I
BUS SYSTEM GENERATOR AND BRANCH DETAILS

Generator Profile

	b_i (\$/MWh)	m_i (\$/MW²h)	min G_i (MW)	max G_i (MW)
G_1	20	0.015	150	600
G_2	18	0.015	50	400

Branch Profile

	n'	n"	r p.u.	x p.u.	cap (MW)	μ_m (\$/MWh)
L1	1	2	0.0134	0.1335	200	2
L2	1	3	0.0067	0.0665	550	1
L3	2	3	0.0084	0.1002	350	1.25

a. *Unconstrained branch flow*

Figure 2 illustrates branch power flows on 3-bus system by ignoring network losses effects. Unconstrained branch power flow scheme is first simulated. Under this condition, it is found that transmission line *L1* flowing the power about 44.9 MW, while transmission line *L2* and *L2* are transmitting the power at 444.9 MW and 355.1 MW, respectively in order to fulfill the system load 800 MW. Since there is no transmission congestion on a particular line, this makes optimal energy price at every bus to be similiar, namely at \$26/MWh. This identical price is known as *uniform marginal price* or the UMP.

b. *Constrained branch flow*

Furthermore, when transmission lines are considered to have a security constraint as shown at Figure 3, there is a significant change of power flow on every transmission line.

Maximum capacity for line *L1, L2,* and *L3* are set to 200 MW, 550 MW, and 350 MW, respectively. As a result, the transmission line *L1* is transmitting power at about 38.54 MW. Meanwhile the transmission lines *L2* and *L3* are flowing the rest, which are 450 MW and 350 MW, correspondingly.

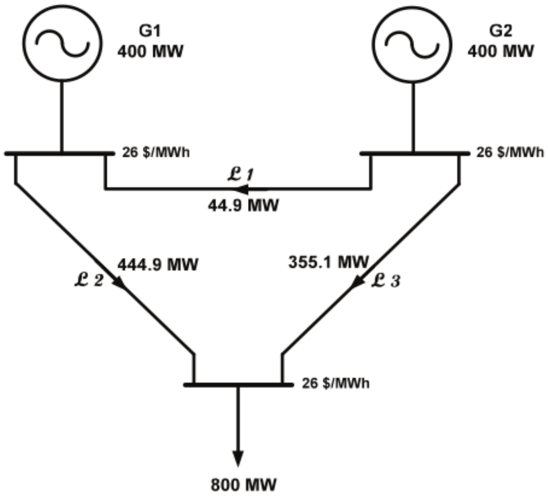

Fig. 2 Un-Constrained Branch Flow of 3-Bus System for LMP-lossless

It should be noted that transmission congestion happens on the transmission line *L3*. This congestion causes energy price differences at every bus. Optimal energy prices on every bus must undergo an adjustment along with changes in the composition of power generation in each generator to keep the 'security constraint' of the system is not violated. Hence, as the transmission congestion does exist on the network, the optimal energy prices now become $26.172/h at Bus 1, $23.828/h at Bus 2, and $27.339/h at Bus 3. Since the optimal energy prices are unique and different at every location, that is why such non-uniform circumstances is then well-known as *locational marginal price* or the LMP.

c. Objective Cost and Merchandising Surplus

In addition, simulation is continued to examine the value of objective cost for all possible reference bus. When Bus 1 was selected as the reference bus, the objective cost resulted was $17625/h. Similar values were also obtained as reference bus changing to either Bus 2 or Bus 3. This is confirming that even though DC-OPF method is a voltage phase-angle function, it does not depending on the selection of reference bus.

Moreover, it should be also considered that the selection of reference bus at a particular node would make the voltage phase-angle at that bus to be set at 0^o. However, since phase-angle differences between the reference bus and other buses are too small, the final objective cost obtained for all other reference buses do not change significantly. The same phenomenon is also found when the value of merchandising surplus obtained for all chosen reference buses is assessed.

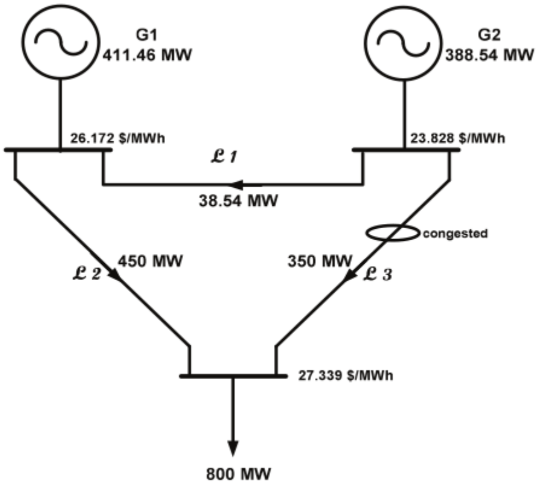

Fig. 3 Constrained Branch flow of 3-Bus System for LMP-lossless

It can be seen from the simulation that the outcome pattern of merchandising surplus tends to be flat and constant, similar to the pattern of objective cost values. As Bus 1 was selected as the reference node, the obtained merchandising surplus was about $1845/h. Furthermore, same situation happened when the reference bus was changed to either Bus 2 or Bus 3, the value of the merchandising surplus did not changed at all.

The results shown above give an indication that the implementation of the proposed DC-OPF method does not depend on the selection of reference bus in order to obtain better objective cost or merchandising surplus. Consequently, reference bus point can be set at any nodes. However, the reference bus is generally located at a bus in which generator with the largest capacity is connected.

VI. CONCLUSIONS

An economic redispatch scheme based on DC optimal power flow has been developed in order to obtain optimal energy prices particularly within a congested power system. The results proof that when unconstrained branch flow is simulated, there is no transmission congestion on a particular transmission line, and if network losses are ignored, the optimal energy prices at every bus will be the same. However since transmission lines are considered to have a security constraint, there is a significant change of power flow on every transmission line. Under this condition, once the transmission congestion takes place, then the energy price differences will be resulted at all buses. These two situations cause different results on objective cost and merchandising surplus of the power market.

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