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Performance Comparison of Optimal Power Flow Algorithms for LMP Calculations of the Full Scale Korean Power System

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Abstract – This paper proposes the comparison results of various optimal power flow algorithms (OPF) to calculate the locational marginal prices (LMP) of the unreduced full scale Korean transmission system. Five different types of optimal power flow models are employed: Full AC OPF, Cubic AC OPF, Quadratic AC OPF, Linear AC OPF and DC OPF. As the results, full AC OPF and cubic AC OPF model provides LMP calculation results very similar to each other while the calculation time of cubic AC OPF model is faster than that of the Full AC OPF. Other simplified OPF models, quadratic AC OPF, linear AC OPF and DC OPF offer erroneous results even though the calculation times are much faster than the Full AC OPF and the Cubic AC OPF. Given the condition that the OPF models sometimes fail to find the optimal solution due to the severe complexity of the Korean transmission power system, the Full AC OPF should be used as the primary OPF model while the Cubic AC OPF can be a promising backup OPF model for the LMP calculations and/or real-time operation.

Keywords: Optimal power flow, Locational marginal price, Full AC OPF, Cubic AC OPF, Quadratic AC OPF, Linear AC OPF, DC OPF

1. Introduction

Since J. Carpentier first introduced the mathematical formulation of the optimal power flow (OPF) problem in 1962, it has been one of the most challenging optimization problems in power system engineering [1]. The goal of OPF is to find the optimal settings of a given power system network that optimize the system objective functions such as total generation cost, system loss, bus voltage deviation, emission of generating units, number of control actions, and load shedding while satisfying its power flow equations, system security, and equipment operating limits, etc. [2].

If OPF problems can be solved in a reasonable computation time, the results can be utilized in several power system operations or planning problems: for example, real time economic dispatch in consideration with network constraints, optimal control of voltage and reactive power or calculation of locational marginal price (LMP), etc., are the most probable applications of the OPF. Transmission expansion planning and the economic evaluation of new investment of transmission lines are also possible applications of OPF models.

It is possible to formulate the OPF in various ways according to the objectives of the given problems, but the most frequently used formulation is to minimize the total fuel cost of the system satisfying several constraints such as voltage magnitudes / angles of the buses, active and reactive power limits of generators and transmission lines, etc. In order to calculate the active and reactive power outputs of the generators and power flow through transmission lines the nonlinear power flow equations should be incorporated in the constraints. The difficulty of finding optimal solution of OPF problem lies in the nonlinearity and complexity of power flow models which should be included inherently in the mathematical formulation to decide whether the constraints related to the active and reactive power outputs of generators, power flows through transmission lines and the voltage magnitudes and angles of buses.

In general, the full AC power flow model should be employed to find the exact solution of the OPF problem (dubbed full AC OPF hereafter). However, because of the severe nonlinearity of AC power flow equations the OPF model sometimes do not converge or requires significantly long computation time when applied to the large scale power system [3]. One of the detouring methods to avoid the problems that the full AC OPF has is to employ the DC power flow model based on the assumptions that the voltage magnitudes of all the buses are 1.0[pu] and voltage angles are very close to 0[rad]. Even though the OPF based on DC power flow model (DC OPF) is computationally faster and convergent, it has a critical weakness that the results are inexact and the constraints related to reactive power flows and voltage limits cannot be considered [4].

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Recently the relaxed AC OPF based on the Taylor approximation of AC power flow equations is extensively researched in order to overcome the slowness of AC OPF and the inexactness of DC OPF simultaneously [5, 6].

The main objective of this paper is to compare the performances of the five different types of OPF models. We calculate the LMPs of the Korean full scale power system using five different types of OPF models and compare the exactness of the results and the calculation times by each OPF model. The studied power system includes all the buses, transmission lines, transformers and synchronous compensators connected to networks higher than or equal to 66kV. The five OPF models are:

1) Full AC OPF model
2) Linearized AC OPF
3) Quadratic AC OPF model
4) Cubic AC OPF model
5) DC OPF model

The installed generation capacity of Korean power system is approximately 87GW (as of 2012) which is 14th in the world [7]. It is known, however, as one of the most difficult power systems to obtain the OPF solutions because of the complexity of the loop transmission network and concentration of electricity demand in the Seoul metropolitan area. Therefore, it is common practice to apply the OPF models to the reduced or simplified system and to consider only 765kV and 345kV networks (the Korean transmission system consists of 765kV, 345kV, 154kV and 66kV) in order to improve the convergence and computation time of the OPF models [8].

The OPF model based on the reduced or simplified network is mostly acceptable for the usual power system operation purposes, but the LMP calculations, the main objectives of this paper, based on the reduced power system may bring about some erroneous calculation results especially for the generators or demands connected to lower 154kV and 66kV voltage buses. Therefore, this paper proposes the LMP calculation results based on the OPF models with unreduced full scale power system in order to eliminate unnecessary conflicts between market participants who are very sensitive to small errors in calculation of market price.

One of the most significant problems to solve the OPF model and calculate the LMPs for the unreduced full scale Korean power system is that The numbers of buses and transmission lines increase drastically when the lower voltage networks are included in the OPF models. For example, the numbers of buses and transmission lines in 765kV and 345kV systems are 141 and 284, respectively, but they are increased to 1798 and 2331 if all the 154kV and 66kV systems are included. Therefore, the convergence and computation time for OPF model is significantly worsen.

The current wholesale electricity market in Korea, dubbed a Cost-Based Pool or CBP market, was commenced in 2001 when the generation sector was spun off from the vertically integrated Korea Electric Power Corporation (KEPCO). The CBP market was designed to operate temporarily because the original governmental plan for restructuring was to spin off the retail sector further in couple of years later and then to open a completely competitive wholesale market. However, as the restructuring has been delayed due to political reason the CBP market is still in effect. One of the most significant problems of CBP market is that the market operates based on a 'uniform pricing scheme'. Because the uniform pricing does not consider the network congestions, the uplift cost is significantly increased to compensate for the decreased and / or increased dispatch amounts due to transmission congestions. Furthermore, the uniform market prices cannot provide the newly built generators with price signals for the economical locations in terms of transmission congestion. Even though most of the advanced electricity markets adopt the LMP systems to solve the transmission congestion problem, it has not been adopted in Korea. One of the main reasons is a lack of practical method to solve the OPF, the most basic mathematical tool to calculate LMPs. Therefore, the result of this research can provide a very important milestone to introduce the LMP system in Korea.

This paper organizes as follows: Section 2 briefly explains the variables used in the paper. The mathematical formulations for the five OPF models and LMP calculation scheme are explained in Section 3. The unreduced full scale Korean power system studied in this paper is briefly introduced in Section 4. The performance comparisons between five OPF models and the LMP calculation results are provided in Section 5. Conclusions are given in the last section.

2. Nomenclature

i, j Index of bus
g Index of generator
N Number of total buses
N_g Number of total generators
N_l Number of total interchange transmission lines
i_g Index of bus where generator g is connected
a_{gi} Quadratic price coefficient of generator g connected to bus i
b_{gi} Linear price coefficient of generator g connected to bus i
c_{gi} No load price coefficient of generator g connected to bus i
P_{gi} Active power output of generator at bus i [MW]
P_{gi} max Max. active power output of generator i [MW]
P_{gi} min Min. active power output of generator i [MW]
Q_{gi} Reactive power output of generator at bus i [MVar]
Q_{gi} max Max. reactive power output of generator i [MW]

[MVar]
Q_{gi} min Min. reactive power output of generator i [MVar]
P_{di} Active power demand at bus i [MW]
Q_{di} Reactive power demand at bus i [MVar]
P_{ij} Active power flow between bus i and j [MW]
Q_{ij} Reactive power flow between bus i and j [MVar]
V_i Bus voltage magnitude at bus i [pu]
$V_{\max}$ Upper bound on the voltage magnitude[pu]
$V_{\min}$ Lower bound on the voltage magnitude[pu]
θ_i Bus voltage phase angle at bus i [rad]
θ_{ij} Difference in phase angle between i and j [rad]
$\theta_{\max}$ Upper bound on the voltage phase angle [rad]
$\theta_{\min}$ Lower bound on the voltage phase angle [rad]
G_{ij} Conductance of existing transmission line between i and j [pu]
B_{ij} Susceptance of existing transmission line between i and j [pu]
$S_{\max}$ Thermal limit of transmission line [MVA]
D_{ij} Direction power flow of interchange transmission line
$l_{\max}$ Upper bound on active power flow through interchange transmission line [MW]
LMP_i Locational marginal price at bus i [Won/kWh]
ℓ Lagrange function

3. OPF Formulation

3.1 OPF object function

We use the same forms of objective function for all five OPF models. The objective function is defined as the sum of total fuel costs of generators as given in Eq. (1), which is one of the most typically used objective functions in OPF problems:

$$Min \ : \sum_{i \in i_g}^{N_g} (a_{gi} P_{gi}^2 + b_{gi} P_{gi} + c_{gi}) \tag{1}$$

3.2 OPF constraints

Various technical constraints are applied in the OPF models as follows:

3.2.1 Power flow equations

The most significant difference between the five OPF models is what kind of power flow models are used in the models:

a) Full AC power flow model

Firstly, the Full AC OPF employs the most generally used rectangular form of nonlinear AC power flow equations defined as:

$$P_{ij} = |V_i|^2 G_{ij} - |V_i||V_j|(G_{ij} \cos\theta_{ij} + B_{ij} \sin\theta_{ij}) \tag{2}$$

$$Q_{ij} = -|V_i|^2 B_{ij} + |V_i||V_j|(B_{ij} \cos\theta_{ij} - G_{ij} \sin\theta_{ij}) \tag{3}$$

b) Linearized AC Power flow equation

Based on the assumption that the voltage deviation and the differences between voltage angles of adjacent buses are assumed to be very small, or $\Delta v_i \approx 0$, $\theta_{ij} \approx 0$, the following relationships can be obtained by applying the Taylor 1st order approximation [5]:

$$|V_i| = 1 + \Delta v_i \tag{4}$$

$$|V_i|^2 \approx 2\Delta v_i + 1 \tag{5}$$

$$|V_i||V_j| \approx 1 \tag{6}$$

$$\cos\theta_{ij} \approx 1 \tag{7}$$

$$\sin\theta_{ij} \approx \theta_{ij} \tag{8}$$

By applying the above Eqs. (4)~(8) into Eq. (2) and Eq. (3) the following linearized power flow equation can be obtained:

$$P_{ij} = (\Delta v_i - \Delta v_j) G_{ij} - B_{ij}\theta_{ij} \tag{9}$$

$$Q_{ij} = -(\Delta v_i - \Delta v_j) B_{ij} - G_{ij}\theta_{ij} \tag{10}$$

The OPF model based on Eq. (9) and (10) will be called *a Linear AC OPF model* hereafter.

c) Quadratic AC Power flow equation

It is found that one of the significant problems of the linearized version of OPF model given by Eq.(9) and Eq.(10) is that the products of voltage magnitudes of adjacent buses are significantly different from 1.0 at some buses. Given the circumstance we suggest that the accuracy of Linearized AC OPF model should be improved if the voltage deviation is extended to 1st order Taylor expansion, or $|V_i||V_j| = \Delta v_i + \Delta v_j + 1$, instead of Eq. (6). Then, Eq. (2) and Eq.(3) are to be modified as the following quadratic form of AC power flow equations:

$$|V_i||V_j| \approx \Delta v_i + \Delta v_j + 1 \tag{11}$$

$$P_{ij} = (2\Delta v_i + 1)G_{ij} - (\Delta v_i + \Delta v_j + 1)(G_{ij} + B_{ij}\theta_{ij}) \tag{12}$$

$$Q_{ij} = -(2\Delta v_i + 1)B_{ij} + (\Delta v_i + \Delta v_j + 1)(B_{ij} - G_{ij}\theta_{ij}) \tag{13}$$

We will call the OPF model based on Eqs. (11)~(13) *a Quadratic AC OPF model* due to the 2nd order nature of the power flow equations.

d) Cubic AC Power flow equation

It is obvious that the power flow equations Eq.(2) and Eq. (3) can be more exactly approximated if we apply higher order Taylor expansions to them. Because the OPF model based on the power flow equations with higher order approximation generally leads to poor convergence and longer computation times, we need to find a compromise between the exactness and computation speed. One possible compromise is to apply 1st and 2nd order Taylor expansion in a mixed way as follows:

$$P_{ij} = (2\Delta v_i + 1)G_{ij} - (\Delta v_i + \Delta v_j + 1)[(1 - \frac{\theta_{ij}^2}{2})G_{ij} + B_{ij}\theta_{ij}] \quad (14)$$

$$Q_{ij} = -(2\Delta v_i + 1)B_{ij} + (\Delta v_i + \Delta v_j + 1)[(1 - \frac{\theta_{ij}^2}{2})B_{ij} - G_{ij}\theta_{ij}] \quad (15)$$

The resulting equation has 3rd order (cubic) function with respect to the variable θ_{ij} and Δv_i, so we will call the OPF model based on Eq. (14) and Eq. (15) *a Cubic AC OPF model* hereafter.

e) DC power flow equation

The most extreme case of power flow equations is a DC power flow equation which is based on the assumption that the voltage magnitudes of all buses are 1.0 [pu] and the differences between the voltage angles of adjacent buses are very small ($\sin\theta_{ij} \cong \theta_{ij}$), and also the active losses of transmission lines are negligible ($G_{ij} = 0$). The DC power flow equation yields as follows:

$$P_{ij} = -B_{ij}\theta_{ij} \quad (16)$$

We will call the OPF model based on Eq.(16) *a DC OPF model* named after the DC power flow equation.

3.2.2 Node balances equations

The following equality constraints are employed to satisfy the demand and supply condition of active and reactive powers at each bus. However, as the DC OPF does not consider reactive power, Eq.(18) is not applicable in the DC OPF model.

$$P_{gi} - P_{di} - \sum_{j}^{N}(P_{ij}) = 0 \quad (17)$$

$$Q_{gi} - Q_{di} - \sum_{j}^{N}(Q_{ij}) = 0 \quad (18)$$

3.2.3 Generation limits

All the generators should satisfy the following inequality constraints which limit the active and reactive power outputs. The DC OPF model does not include Eq.(20):

$$P_{gi\min} \le P_{gi} \le P_{gi\max} \quad (19)$$

$$Q_{gi\min} \le Q_{gi} \le Q_{gi\max} \quad (20)$$

3.2.4 Transmission thermal limits

The following inequality constraint should be employed to limit the apparent power flowing through transmission lines:

$$Q_{ij}^2 + P_{ij}^2 \le S_{\max}^{\ 2} \quad (21)$$

However, because of severe nonlinearity of Eq. (21) the OPF models sometimes do not converge or take too long to converge to an optimal solution. Hence Eq. (21) is divided into two inequality constraints using a dummy variable α, which improves the convergence of OPF models significantly:

$$-S_{\max}\cos(\alpha_{ij}) \le P_{ij} \le S_{\max}\cos(\alpha_{ij}) \quad (22)$$

$$-S_{\max}\sin(\alpha_{ij}) \le Q_{ij} \le S_{\max}\sin(\alpha_{ij}) \quad (23)$$

Eq. (22) and Eq. (23) can further be linearized as shown in Fig. 1. We find that the linearization of the power curve as in Fig. 1 improves the convergence and computation time of OPF models significantly without making any noticeable difference in results.

Meanwhile, Eq. (21) and Eq. (22) should be replaced by the following inequality constraint in DC OPF due that reactive power flow cannot be considered in DC OPF model:

$$-S_{\max} \le P_{ij} \le S_{\max} \quad (24)$$

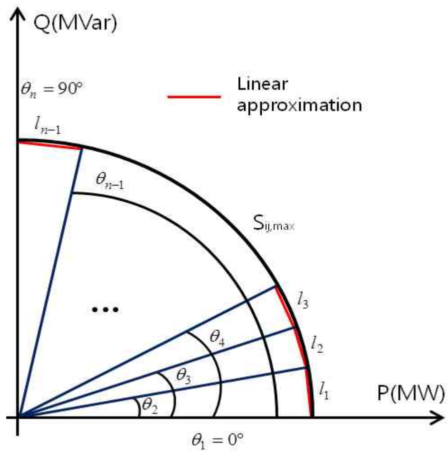


Fig. 1. Linear approximation for transmission flow limit [9]

3.2.5 Bus voltage constraints

The following inequality constraints are included to limit the magnitudes and angles of bus voltages. Similarly as the previous constraints, Eq. (25) is not considered in DC OPF:

$$V_{\min} \le V_i \le V_{\max} \quad (25)$$

$$\theta_{\min} \le \theta_i \le \theta_{\max} \quad (26)$$

3.2.6 Constraint on interchange power flow

In order for the Korean power system to secure the voltage stability a constraint on an interchange power flow between Seoul metropolitan area and outside is employed as follows:

$$\sum_{i,j\in i_l}^{N_l} P_{ij} D_{ij} \le l_{\max} \tag{27}$$

3.3 LMP calculation

Lagrange function of the full AC OPF including all the constraints explained above can be expressed as the following equation:

$$\begin{aligned}
\ell = & \sum_{i}^{N} (a_{gi}P_{gi}^2 + b_{gi}P_{gi} + c_{gi}) && \text{Fuel Cost} \\
& -\sum_{i}^{N} \pi_i (P_{gi} - P_{di} - \sum_{j}^{N} P_{ij}) && \text{Active Power Balance} \\
& -\sum_{i}^{N} \lambda_i (Q_{gi} - Q_{di} - \sum_{j}^{N} Q_{ij}) && \text{Reactive Power Balance} \\
& -\sum_{i}^{N} \hat{\tau}_i (P_{g\max} - P_{gi}) && \text{Real Power Output Upper Constraint} \\
& -\sum_{i}^{N} \breve{\tau}_i (P_{gi} - P_{g\min}) && \text{Real Power Output Lower Constraint} \\
& -\sum_{i}^{N} \hat{\omega}_i (Q_{g\max} - Q_{gi}) && \text{Reactive Power Output Upper Constraint} \\
& -\sum_{i}^{N} \breve{\omega}_i (Q_{gi} - Q_{g\min}) && \text{Reactive Power Output Lower Constraint} \\
& -\sum_{i}^{N} \hat{\mu}_i (g_{\max} - g_i) && \text{System Operating Upper Constraint} \\
& -\sum_{i}^{N} \breve{\mu}_i (g_i - g_{\min}) && \text{System Operating Lower Constraint}
\end{aligned} \tag{28}$$

where π_i, λ_i, $\hat{\tau}_i$, $\breve{\tau}_i$, $\hat{\omega}_i$, $\breve{\omega}_i$, $\hat{\mu}_i$ and $\breve{\mu}_i$ are the Lagrange multipliers of the corresponding constraints. Because the LMPs (Locational Marginal Prices) can be defined as the marginal cost of the total system with respect to the demand increase at each bus, the LMPs can be calculated by obtaining partial derivatives of Eq.(28) with respect to P_{di}, or the Lagrange multiplier of equality constraint on active power balance constraint defined by Eq.(17) [10]. Therefore, the LMP at the i th bus is defined by the following equation:

$$LMP_i = \frac{\partial \ell}{\partial P_{di}} = \pi_i \tag{29}$$

The Lagrange functions and LMPs of other OPF models can be calculated in similar ways and they are omitted here due to lack of space.

3. Study System

The power system studied in this paper is the unreduced full scale Korean power system as of the peak demand in the year of 2013 operated by KEPCO (Korea Electric Power Corporation). The system includes all the generators, buses, transmission lines, transformers and synchronous compensators connected to 66kV and higher voltage transmission networks. The practicality of the simulation results are improved by using the actual market data and peak demand at each bus in the year of 2013.

The study system consists of 1798 buses, 2331 transmission lines, 587 transformers and 363 generators with the voltage levels of 765kV, 345kV, 154kV and 66kV as shown in Fig 2. The detailed configurations are shown in Table 1.

As shown in Table 1, if study system includes the components in 154kV and lower voltage networks, the number of buses and transmission lines increase radically.

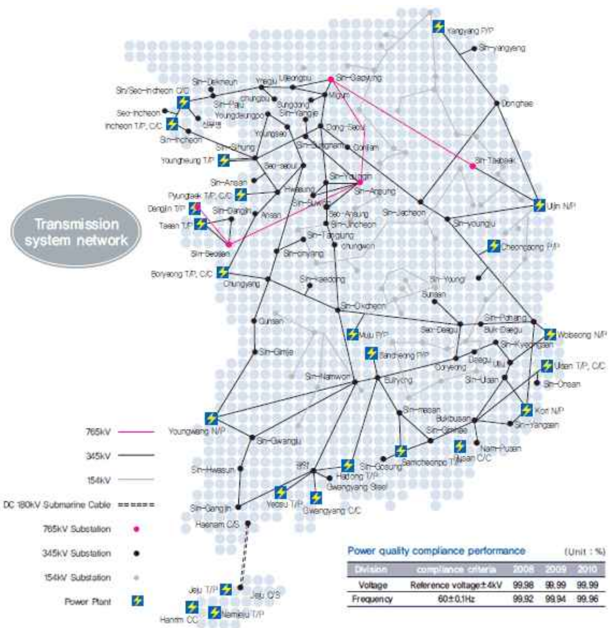


Fig. 2. Transmission map of Korean power system higher than 66kV (cited from KPX website, http://www.kpx.or.kr)

Table 1. Summary of korean power system (as of 2013)

Voltage(kV)	# of buses	# of lines	# of transformers	# of generators
765	6	7	24	
345	135	277	363	
154	1036	2047	200	363
66	621	0	0	
Total	1798	2331	587	

Hence, the system for OPF study is usually reduced or merged to 345kV or higher networks as explained in [8]. The OPF models based on the reduced or simplified network are acceptable in general for the usual power system operation purposes, but the LMP calculations, the main objectives of this paper, based on the reduced power system may bring about erroneous calculation results especially for the generators or demands connected to lower 154kV and 66kV voltage networks. Therefore, this paper proposes the LMP calculation results based on the OPF models with unreduced full scale power system in order to eliminate unnecessary conflicts between market participants who are very sensitive to small errors in market price calculations.

4. LMP Calculation Results

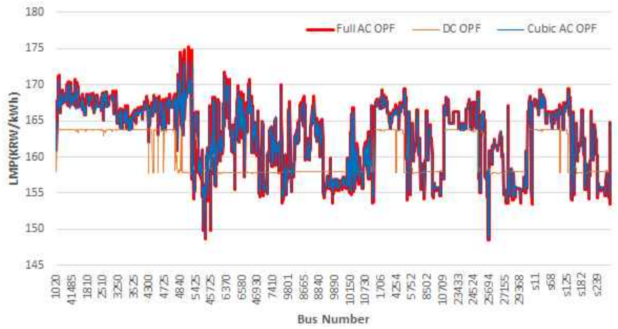
In order to solve the OPF models described in Eq.(1) ~ (27) and the LMPs calculated by Eq.(28), GAMS (General Algebraic Modeling System) version 24.2.2 is used [11][12]. Various solvers incorporating into GAMS, such as CONOPT, CPLEX, MINOS, KNITRO or BARON, etc., are tested and the performances are compared. Among the available solvers the MINOS solver derives the best convergence and computation time. Even though KNITRO provides the solution most quickly than other solvers, it sometimes converges to local optimal solutions. However, the superiority of MINOS solver cannot be guaranteed in all cases because we experienced that different cases exhibit different results.

All the variables are converted to per unit scales and the flat start (the initial voltage magnitudes and angles are set to 1.0 pu and 0.0 degrees, respectively) is used. To improve the convergence and computation time the constraints on the transmission lines thermal limits described in Eq.(22) and Eq. (23) are linearized by 8 straight lines. It should be noted that the load levels are intentionally scaled up for the Quad, Linear and DC OPF algorithms in order to compensate the errors due to losses which are not included in those three OPF algorithms. In general, the historical average loss amount is used for scale-up, but here we used the loss calculated by Full AC OPF algorithm.

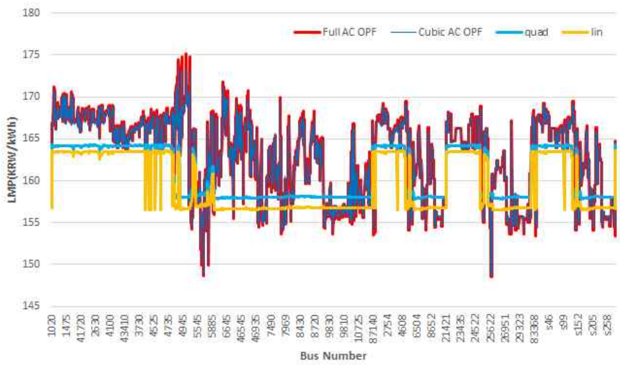
Table 2 shows the computation time (based on Intel i7-2600, 3.40GHz CPU, 8GB Memory) and the value of objective function by each OPF model. The LMPs calculated by each OPF models are compared in Fig. 3. As shown in Table 2, the Cubic AC OPF draws results very similar to those of the Full AC OPF in about 30.8% reduced computation time. Even though the values of objective function (total fuel costs) of OPF models are quite similar, the LMP calculation results are quite different from each other as shown in Table 2 and Fig. 3.

Table 2. Computation times and the values of objective functions (per one hour)

OPF Models	Full AC	Cubic AC	Quad. AC	Linear AC	DC
Total Fuel Cost (Billion Won)	5.211	5.206	5.210	5.210	5.210
Loss (MW)	1156	1123	-	-	-
Error w.r.t. Full AC OPF (Billion Won)	-	0.005	0.001	0.001	0.001
Time(sec)	65	45	40	29	17



(a) Full AC OPF vs. Cubic AC OPF vs. DC OPF



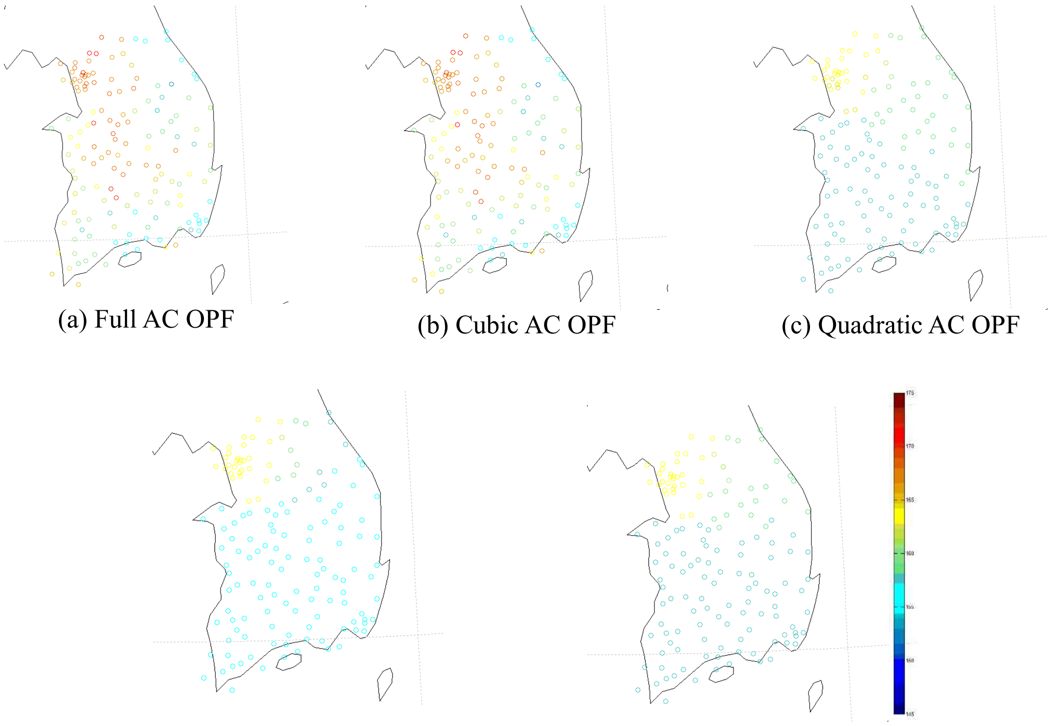
(b) Full AC OPF vs. Cubic, Quadratic, Linear AC OPFs

Fig. 3. LMP Calculation Results

The LMP maps calculated by each OPF models are shown in Fig. 4 (a) through (e). The LMP calculation results for selected buses are listed in Table A.1 in Appendix. As shown in the figures, the LMPs near to Seoul metropolitan areas are much higher than those of outside the metropolitan area due to the interchange power flow limits constraint described by Eq. (27). This phenomenon becomes much severer in Full AC OPF and Cubic AC OPF as shown in Fig. 4(a) and Fig. 4(b).

It is suggested that the differences are caused by transmission losses from the following reasons:

a) The LMP calculation results can be divided into two groups according to their similarity. The first group includes Full AC OPF and Cubic AC OPF, while the other group includes Quadratic AC OPF, Linear AC OPF and DC OPF. The main difference is that the OPF algorithms in the first group include network losses in the mathematical model, while the OPF algorithms in the latter group do not consider network losses.



(a) Full AC OPF (b) Cubic AC OPF (c) Quadratic AC OPF

(d) Linear AC OPF (e) DC OPF

Fig. 4. LMP maps calculated by five OPF models

b) Most of the inequality constraints related to voltage limits are inactive, which means the bus voltages do not influence the nodal prices. Furthermore, the results of Quadratic and Linearized AC OPF models are more similar to DC OPF even though they are AC based OPF models.

As the conclusion, it is suggested that the Cubic AC OPF can be one of the good alternatives to the Full AC OPF model in case that the faster computation time is required. The calculation results (the value of objective function and the LMPs) are very similar to those of the Full AC OPF, while computation time is reduced about 30%. Meanwhile, the Quadratic AC OPF, the Linear AC OPF and the DC OPF may not be appropriate for the purpose of LMP calculations due to the poor accuracy even though the convergence and computation time properties of the models are much better than the Full AC OPF and the Cubic OPF.

In order for the nodal pricing or LMP market rule is adapted in the actual electricity market, it is very important for the market operator to have a very stable and formidable OPF algorithm. During our experiment to apply various OPF algorithms to the full scale power system, we found that the computation time of the Full AC OPF is no longer than 1 minute. Therefore, the Full AC OPF model can be successfully used for the primary OPF model to calculate the LMP of the real-time market with 5 minute dispatch, while the Cubic AC OPF model can be used as the backup OPF model in case that the Full AC OPF model fails to converge or the calculation results of the Full AC OPF model is unreasonable.

5. Conclusion

In this paper, five different types of OPF models are tested and compared to calculate the Locational Marginal Prices of Korean power system. The five OPF models employed are the Full AC OPF, the Cubic AC OPF, the Quadratic AC OPF, the Linear AC OPF and the DC OPF. The OPF models are applied to the calculations of LMPs of the unreduced full scale KEPCO power system with actual market data and the peak demand in the year of 2013 which includes 1798 buses, 2331 transmission lines, 587 transformers and 363 generators.

As a result, the Cubic AC OPF suggests the LMPs almost similar to those of the Full AC OPF in slightly shorter computation time, while the Quadratic AC OPF, the Linear AC OPF and the DC OPF draws erroneous results though the computation times are greatly reduced.

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6. Appendix

Table A.1. The calculated LMPs(KRW/kWh) at some selected buses

Region	Full AC	Cubic AC		Quadratic AC		Linear AC		DC	
	LMP	LMP	Difference	LMP	Difference	LMP	Difference	LMP	Difference
West Seoul	166.2265	166.0644	0.1621	164.2577	1.9688	163.5399	2.6866	163.8141	2.4124
East Seoul	168.3117	168.1516	0.1601	164.1157	4.1960	163.3994	4.9124	163.6942	4.6176
West Incheon	164.7034	164.6676	0.0358	164.1949	0.5084	163.4783	1.2251	163.7593	0.9441
North Inchoen	164.1101	164.0624	0.0476	164.2073	-0.0972	163.4915	0.6186	163.7700	0.3401
Suwon	167.1421	166.9519	0.1902	164.1999	2.9422	163.4833	3.6588	163.7662	3.3759
Uijeongbu	166.9358	166.7724	0.1634	164.1909	2.7449	163.4733	3.4625	163.7569	3.1789
Wonju	168.0991	167.7507	0.3484	160.1985	7.9005	159.0911	9.0080	159.9669	8.1322
Gangneung	156.1395	156.3473	-0.2078	158.5735	-2.4339	157.2817	-1.1421	158.3917	-2.2522
Jeonju	162.8468	162.7176	0.1291	157.9688	4.8779	156.6383	6.2085	157.8379	5.0089
Naju	160.7057	160.7487	-0.0430	158.0229	2.6828	156.6913	4.0144	157.8843	2.8214
Gyeongju	162.6192	162.4851	0.1341	158.1749	4.4443	156.8520	5.7672	158.0223	4.5969
Sangju	163.4299	163.2214	0.2085	158.1737	5.2562	156.8570	6.5729	158.0272	5.4026
Chungju	161.6825	161.7005	-0.0179	158.4951	3.1874	157.2189	4.4636	158.3380	3.3445
Cheongju	169.2824	168.8427	0.4397	158.0922	11.1902	156.7743	12.5081	157.9559	11.3266
East Busan	156.7373	156.8265	-0.0892	158.0836	-1.3462	156.7534	-0.0161	157.9376	-1.2002
West Busan	155.4207	155.6002	-0.1795	158.0820	-2.6613	156.7519	-1.3312	157.9363	-2.5155
North Gwangju	157.9970	158.1061	-0.1090	158.0167	-0.0197	156.6851	1.3119	157.8789	0.1181
South Gwangju	161.6065	161.6397	-0.0332	158.0237	3.5829	156.6920	4.9145	157.8849	3.7216
North Daegu	164.1150	163.8946	0.2204	158.0928	6.0222	156.7639	7.3511	157.9464	6.1686
South Daegu	165.1442	164.8175	0.3267	158.0900	7.0542	156.7605	8.3838	157.9435	7.2007
West Daejeon	164.1994	163.9080	0.2914	158.0951	6.1043	156.7664	7.4330	157.9486	6.2508
East Daejeon	166.7319	166.4235	0.3084	158.0021	8.7298	156.6729	10.0590	157.8676	8.8643
Yeongheung#1G	164.6566	164.5296	0.1270	164.2202	0.4364	163.5028	1.1538	163.7819	0.8746
Uljin#1G	156.8921	157.0899	-0.1978	158.2388	-1.3466	156.9224	-0.0303	158.0833	-1.1911
Taean#1G	159.3581	159.4134	-0.0554	157.8632	1.4948	156.5343	2.8238	157.7482	1.6099
Boryeong#1G	163.5195	163.4458	0.0737	157.9329	5.5865	156.6020	6.9175	157.8064	5.7131
Dangjin#1G	160.9170	160.9412	-0.0242	157.8578	3.0592	156.5296	4.3874	157.7442	3.1727
Yeonggwang#1G	154.7641	155.0887	-0.3246	158.0175	-3.2534	156.6858	-1.9217	157.8793	-3.1152
Hadong#1G	153.6797	154.0298	-0.3500	158.0451	-4.3654	156.7132	-3.0335	157.9034	-4.2236
Wolseong#1G	157.1435	157.2834	-0.1399	158.1220	-0.9786	156.7937	0.3498	157.9721	-0.8286
Gori#1G	154.3295	154.5162	-0.1867	158.0848	-3.7553	156.7547	-2.4252	157.9387	-3.6092
Samcheonpo#1	155.0809	155.2985	-0.2176	158.0672	-2.9863	156.7365	-1.6556	157.9231	-2.8422

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