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Nodal Pricing in Deregulated Electricity Market

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ABSTRACT- The main methodologies used in electricity price has been reviewed in this paper. This study is an attempt to consistently present the current state of the locational marginal price (LMP) based congestion management, including issues that market and system operators are facing, and analyse new directions of the research. The recommendations are made on which areas are of high priority and should be addressed first. Besides giving a systematic description on how the LMPs are produced, the paper describes both the modelling and implementation challenges and solutions. This paper solely represents the view point.

Keywords- Locational marginal price, congestion management, optimal power flow

Nomenclature

K -number of transmission constraints
k -index of a transmission constraint
N -number of generators in the system
C -N-vector of generator offer prices
P -N-vector of generator output levels
D -vector of nodal loads
e -unit vector (all components equal to 1)
Loss- physical system losses
λ- balance constraint
μ- K-vector of the transmission constraints
i -generator/load index
T-(K * N) matrix of generator shift factors (GSF)
F^{max} – K-vector of transmission limits
P^{min}- N-vector of minimum generator capacity limits
P^{max} - N-vector of maximum generator capacity limits

I INTRODUCTION

Electricity Supply Industry throughout the world, is restructuring for better utilization of resources and providing quality service and choice to the consumer at competitive prices. Restructuring of the power industry abolishing the monopoly in the generation and trading sectors, thereby, introducing competition at various levels wherever it is possible. Electricity sector restructuring, also popularly known as deregulation, is expected to draw private investment, increase efficiency, promote technical growth and improve customer satisfaction as different parties compete with each other to win their market share and remain in business. Competitive electricity markets are complex systems with many participants who buy and sell electricity. Much of the complexity arises from the limitations of the underlying transmission systems and the fact that supply and demand must be in balance at all times. When the producers and consumers of electrical energy desire to produce and consume in amounts that would cause the transmission system to operate at or beyond one or more transfer limits, the system is said to be congested.

Location marginal pricing (LMP) has been one of the most popular means of congestion management in the large number of electricity markets worldwide. It became a part of the standard market design and every market in the country either implemented or in the process of implementing LBMP. The idea of using location-based spot pricing of electricity as the congestion management mechanism in electricity markets was proposed in [1, 2]. It was then developed into current locational marginal prices (LMP) framework in the works by Hogan [3] and Hogan et al. [4].LMP. Real markets had to deal with practical issues of implementing LMP and fine-tuning of both the theoretical foundation and practical market design. Some of these issues are adequacy of the models and tools being used for economic dispatch, unit commitment and LMP calculation; addressing infeasibilities; interpreting LMP components; physical and marginal loss pricing; recovering ‘as bid’ costs for the generators etc. LMPs have been used not only for pricing energy, but, with the so-called optimization, such ancillary services as reserves and regulation as well. Despite the comparatively large volume of publications dedicated to different topics of location-based spot pricing [6], there is still a need for consistent and rigorous description of the current methodology and analysis of different implementations of congestion management systems.

The paper attempts to describe the current state of the LMP, It is structured as follows. Describes the mathematical model and derivation of the LMPs briefly discusses the use of the optimal power flow (OPF) as the main tool for economic dispatch and LMP calculation. Next section considers LMP components dedicated to marginal loss pricing and its effect on market clearing results. Some conclusions and specifies directions of new research.

II LMP DEFINITION AND CALCULATION

The LMP at a location is defined as the marginal cost to supply an additional increment of power to the location without violating any system security limits. This price reflects not only the marginal cost of energy production, but also its delivery. Because of the effects of both transmission losses and transmission system congestions, LMP can vary significantly from one location to another.

LMPs are calculated as the result of security constrained economic dispatch (SCED) either in day ahead market (DAM) or real-time market (RTM) honouring operational constraints. The prices are derived from the dual solution of the economic dispatch with commitment statuses of the units fixed. SCED is an OPF program with security transmission constraints and, under the above assumptions, is formulated as follows

$$\min_{P} \boldsymbol{C}^{\mathrm{T}}\boldsymbol{P}$$

$$\text{s.t. } \boldsymbol{e}^{\mathrm{T}}(\boldsymbol{P}-\boldsymbol{D})-\text{Loss}=0, \quad (\lambda>0)$$

$$\boldsymbol{T}(\boldsymbol{P}-\boldsymbol{D})\leq \boldsymbol{F}^{\max}, \quad (\boldsymbol{\mu}\leq 0)$$

$$\boldsymbol{P}^{\min}\leq \boldsymbol{P}\leq \boldsymbol{P}^{\max}, \quad (\boldsymbol{\eta}^{\min}, \boldsymbol{\eta}^{\max}>0)$$

Loss, being a non-linear function of P, is usually replaced by its linear approximation. Different approaches are being used in different markets. The LMP is defined as a change in production cost to optimally deliver an increment of load at the location, while satisfying all the constraints. From this definition, at the optimal point, taking into account complementarity conditions, LMP at bus i, li, can be obtained as the partial derivative of the Lagrangean of

$$|L=\boldsymbol{C}^{\mathrm{T}}\boldsymbol{P}-\lambda(\boldsymbol{e}^{\mathrm{T}}(\boldsymbol{P}-\boldsymbol{D})-\text{Loss})-\boldsymbol{\mu}^{\mathrm{T}}(\boldsymbol{T}(\boldsymbol{P}-\boldsymbol{D})-\boldsymbol{F}^{\max})$$

$$+\boldsymbol{\eta}^{\max}(\boldsymbol{P}-\boldsymbol{P}^{\max})+\boldsymbol{\eta}^{\min}(-\boldsymbol{P}+\boldsymbol{P}^{\min})$$

$$\lambda_i=\frac{\partial L}{\partial D_i}$$

$$\boldsymbol{\lambda}_i=\boldsymbol{\lambda}-\frac{\partial \text{Loss}}{\partial P_i}\boldsymbol{\lambda}+\sum_{1}^{K} T_{ik}\mu_k$$

This is the way LMPs are calculated in most of the implementations.

III LINEAR PROGRAMMING BASED OPTIMAL POWER FLOW

In the vast majority of implementations, this is an linear programming LP-based OPF. It utilises successive LP to find a solution of the non-linear OPF problem. From the practical perspective, LP-based implementation is significantly more robust and faster than non-linear programming method. Successive LP makes use of the decomposition between optimisation and contingency analysis (CA) by generating only violated post-contingent constraints and feeding them into optimisation procedure. This allows one to significantly improve the solution speed and, assuming the convexity of the original problem, solve AC OPF. Despite being a linear problem, together with CA, it produces non-linear optimisation solution.This fact is usually overlooked, and current SCED is often considered being a DC OPF. The DC OPF, in contrast with LP-based or successive OPF, uses DC power flow in CA as well and solves linear approximation of the SCED.Voltage constraints are usually not modelled in the SCED; instead, the units that are required for voltage support are prescheduled ensuring very small deviation of the voltages from the scheduled profile. This proved to be quite an efficient practical way of working with the linear model. Another problem of modelling reactive power/voltage relations in SCED is dealing with the quality of the model and reactive power management.

IV PROPERTIES OF LMPS

If LMPs are calculated as the result of solving linear programming problem, there are several important properties that can be observed. There will always be a subset of units that are marginal; the rest of the units will be either at their minimum or maximum output level. The LMP at each marginal unit location will always be equal to its offer price.

$$\frac{\partial L}{\partial P_i}=0=C_i-\lambda\left(1-\frac{\partial \text{Loss}}{\partial P_i}\right)-\sum_{1}^{K} T_{ik}\mu_k+\eta^{\max}-\eta^{\min}$$

$$\Rightarrow \lambda_i=C_i+\eta^{\max}-\eta^{\min}$$

For the marginal units, both n^{max} and n^{min} equal zero, and λi= Ci . This is true for systems with congestion and losses. From above it is also easy to see the relations between offer prices and LMPs for all infra-marginal units. Every unit dispatched at its maximum output would have its LMP higher than the offer price and the unit dispatched at its minimum output would have the LMP lower than the offer.

V LOCATIONAL MARGINAL PRICING COMPONENTS

The names for the first two components are misleading.The energy component is very often thought of as the price of energy if there were no losses and congestion.

$$\lambda \qquad \qquad - \text{'Energy' component}$$

$$\lambda^{L} = -\frac{\partial \text{Loss}}{\partial P_i}\lambda \quad - \text{Loss component}$$

$$\lambda^{C} = \sum_{i}^{K} T_{ik}u_k \quad - \text{Congestion component}$$

This is not correct: the ‘energy’ component is actually a price of energy. In fact, it will change with the change of the slack location with the dispatch staying the same. The loss component more accurately should be called marginal loss component and it does not reflect the cost of physical losses.

VI MARGINAL LOSS PRICING

Another issue that has been controversial in LMP market design is marginal loss pricing. The importance of marginal loss pricing, especially in the markets with large and very large footprints so most of the LMP markets either implemented or about to implement marginal loss modelling. The major misunderstanding is usually in treating loss components of the LMP as payment for losses, which is wrong. The price of one MWh of physical losses in the LMP-based market is undefined. It is impossible to assign single price to physical losses under LMP mechanism.

Let us consider the energy component

$$\text{EC} = -\sum_{i=1}^{N_d} \lambda_i P_i$$

ISO pays the generator the LMP at their locations

$$\text{EC} = -\sum_{i=1}^{N_d} \lambda_i P_i$$

Overall energy revenue collection by the ISO is as following

$$\text{ER} = \sum_{i=1}^{N_d} \lambda_i D_i - \sum_{i=1}^{N_d} \lambda_i P_i$$

From above equation

$$\text{ER} = \sum_{i=1}^{N_d}\left(\lambda - \frac{\partial \text{Loss}}{\partial P_i}\lambda + \sum_{k=1}^{K} T_{ik}\mu_k\right)D_i - \sum_{i=1}^{N_d}\left(\lambda - \frac{\partial \text{Loss}}{\partial P_i}\lambda + \sum_{k=1}^{K} T_{ik}\mu_k\right)P_i$$

$$\text{ER} = -\lambda\sum_{i=1}^{N}(P_i - D_i) + \lambda\sum_{1}^{N}\frac{\partial \text{Loss}}{\partial P_i}(P_i - D_i) - \sum_{1}^{K}\mu_k T_{ik}(P_i - D_i)$$

$$\textstyle\sum_{i=1}^{N}(P_i - D_i) = \text{Loss}\ \cdot$$

$$\textstyle\sum_{1}^{K} T_{ik}(P_i - D_i) = F^{\max}$$

For the binding constraints and non binding constraints

$$\text{ER} = -\lambda\sum_{i=1}^{N}\text{Loss} + \lambda\sum_{1}^{N}\frac{\partial \text{Loss}}{\partial P_i}(P_i - D_i) - \sum_{1}^{K}\mu_k F^{\max}$$

Now we can see that only the first term contains payments for physical losses. As in the uniform price market, this is the debit because of the imbalance between generation and load. It can only be suggested that the price of MWh of physical losses equals the energy price at the market reference. There is no exact theory under this statement, and any alternative could be considered, but this seems to be the most logical assumption. At the same time, it is important to understand that defined in this way the price of physical losses will be dependent on the location of the market reference.

VII CONCLUSIONS

As LMP market design continues to be widely utilized in different markets, more research is needed in economic, mathematical and engineering foundations of the methodology and efficient implementation approaches.

Although the current methodology is comparatively robust, the issues described in the paper require more scrutiny in order to make congestion management and market auctions more efficient. The following main topics require attention and should be given high priority in research and development:

1. The use of AC-based OPF
2. Rigorous justification and calculation of ex post and ex ante pricing; justification of the prices based on multiperiod optimisation in economic dispatch.

3. Marginal loss pricing and hedging mechanisms against the differences in LMPs and congestion components. Loss revenue allocation mechanism.
4. Rationalisation of the prices while dealing with infeasibilities.
5. Pricing integer decisions both in unit commitment and economic dispatch.

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