

# ADDRESSING ENERGY AND TRANSMISSION PRICING ISSUES IN DEREGULATED ELECTRICITY MARKETS

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INDIAN INSTITUTE OF TECHNOLOGY DELHI  
APRIL 2015

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# ADDRESSING ENERGY AND TRANSMISSION PRICING ISSUES IN DEREGULATED ELECTRICITY MARKETS

by

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Submitted

in fulfilment of the requirements of the degree of

Doctor of Philosophy

to the



INDIAN INSTITUTE OF TECHNOLOGY DELHI  
APRIL 2015

# CERTIFICATE

This is to certify that the thesis titled “**Addressing Energy and Transmission Pricing Issues in Deregulated Electricity Markets**”, submitted by **Mr. Naren Bharatwaj V.** for the award of the degree of **Doctor of Philosophy**, is a record of bonafide research work carried out by him in the Electrical Engineering Department of Indian Institute of Technology Delhi, NewDelhi, India.

**Mr. Naren Bharatwaj V.** has worked under my guidance and supervision and has fulfilled the requirements for the submission of this thesis, which to my knowledge, has reached the requisite standard. The work done as part of this thesis has not been submitted to any other University or Institute for the award of any degree.

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**Date: April 13, 2015**

# ACKNOWLEDGEMENTS

First and foremost, I would like to express my sincere gratitude to my supervisor, Dr. A. R. Abhyankar, for being a constant source of inspiration and the motivating factor behind my decision to pursue a PhD. I sensed a 'wavelength match' a minute after he walked into the classroom to teach a course on Power System Analysis during my Master's degree. Incidentally, it was the first lecture for both of us. I consider it as a privilege to have been associated with him for almost 6 years and thank him for tolerating me for such a long time. I owe my success to his guidance and his perseverance in guiding me through the difficult periods - personal as well as professional - during my tenure at IIT Delhi. I hope I can live up to the expectations of being his student. I could not have imagined a better supervisor and mentor for my PhD.

I would also like to thank Prof. P. R. Bijwe for having been associated with my research during the initial part of my PhD. I've always been in awe of his wide experience and technical expertise. His insistence on detail and thoroughness has and will always influence my thought process.

I'm also grateful to the members of my dissertation committee, Prof. Sukumar Mishra, Dr. B. K. Panigrahi and Prof. T. S. Bhatti for their detailed reviews and suggestions during the progress of my research work. I would like to thank Prof. M. L. Kothari, Prof. Bhim Singh and Dr. N. Senroy for their suggestions and encouragement during my stay at IIT Delhi. I would also like to thank the Electrical Engineering Department at IIT Delhi for accepting my request to convert my M.Tech programme to a PhD programme and the IIT Delhi community as a whole for making my stay a comfortable one.

I wish to express my sincere thanks to my PhD senior, Dr. V. Ravi Kumar Pandi, for having helped me during the initial part of my PhD, and my M.Tech senior Mr. Pradeep Reddy. My stay at IIT Delhi was made memorable by my M.Tech batchmates, M.Tech juniors and the other friends I met here. In particular, I would like to thank

my M.Tech batch mates Rakesh Maurya and Abheejeet Mohapatra for all the technical and non-technical discussions.

I would like to thank all my colleagues from the Power System Simulation Lab - Surender, Chandra Sekhar, Mallesham, Padma Gandha Mishra, Nitin Anand, Sudipta, Gayathri ma'am, Zarina ma'am, Neelakanteshwar, Manohar Singh, Somesh, Stuti Shukla, Mahendra Bhadu, Deep Kiran, Hiren sir and Satish for a healthy work environment during my 6 year stay at IIT Delhi. A special thanks to members of the institute Volleyball team, of which I was a part, and the coach for those memorable moments on and off court.

Lastly, I would like to thank my parents Mrs. Geetha Viswanath and Mr. N. Viswanath for their unconditional love and support throughout my life. Had it not been for their innumerable sacrifices in life, I wouldn't have reached this stage. Without their patience and understanding, this thesis would not have seen the light of day. No amount of thanks can truly reflect the role played by my sister, Anusha Vishwanath, in shaping my career. She was the one who implanted the idea of pursuing a PhD. Her motivational talks from time-to-time helped me get through some of the most difficult times of my life. I would also like to thank my brother-in-law, Rahul Subramaniam and his family for all their blessings and good wishes.

April 2015

Place: New Delhi

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# Abstract

This thesis addresses some pricing issues associated with deregulated electricity markets. Since electricity is treated as a commodity in a restructured environment, its pricing and associated ancillaries becomes vital for the successful operation of an electricity market. Inherent in this statement is the framing and implementation of policies to support the restructured environment. The research work carried out aims at extensively studying pricing practices of energy and transmission markets and suggest improvements.

DCOPF is extensively used in North American electricity markets. Locational Marginal Prices (LMPs) are used to settle the energy markets. Two important issues associated with loss compensated DCOPF models have been tackled in this thesis: appropriate loss distribution and choice of slack bus in reference dependent DCOPF models.

Marginal loss modelling in DCOPF has been used to overcome the drawback of neglecting losses in the lossless DCOPF model. Various models have been proposed in literature that incorporate losses in different ways. However, there has been no unique way of distributing losses across the network. The approaches suggested in literature have some arbitrariness in distributing losses. Since change in loss distribution can lead to different solutions, a clear rationale is required in this regard because it has financial implications. In this thesis, the use of location based schemes is explored, traditionally used for transmission pricing and/or loss allocation, to overcome the arbitrariness in loss distribution for various models proposed in literature. Dif-

ferent performance metrics for comparison with ACOPF have been defined, which provide benchmark results. Better performance indices for line power flows and LMPs is observed when choosing loss distribution using the loss distribution strategy suggested in this thesis.

Though reference independent DCOPF models exist, some reference dependent models that bear certain good virtues pose a research problem of making them reference independent, without touching the original characteristics. For the reference dependent models, changing the reference bus has an effect on the LMP, its components and the resulting objective function. Based on the literature available, marginal loss DCOPF models can be classified into iterative and non-iterative techniques. Losses are estimated using either AC power flow (ACPF) or DC approximation. The iterative techniques are better at estimating losses when compared to non-iterative techniques. All the techniques necessitate the specification of a reference bus and the solution of some techniques depend on this choice. This further has implications on cost of supplying load and losses. This thesis addresses the reference dependency issue of the iterative DC technique, and to overcome this drawback, proposes the use of a two-step iterative technique that eliminates the need to *pre-specify* a reference, thus overcoming this ambiguity. Optimal reference selection *on the fly* leads to least cost solution compared to other reference independent models. Alternatively, a less time consuming distributed slack approach for the iterative DCOPF model is suggested, where the set of participation factors are updated based on solution obtained after every iteration.

The decomposition of LMP obtained from ACOPF is disputable due to its dependency on the choice of energy reference. The dispute arises because the difference of congestion component, on which the FTR payments are made, is not constant and depends on the energy reference. Prior art aimed at obtaining reference independent decomposition. This thesis looks at this dispute as a fairness issue and formulates the decomposition as a fairness problem. The fairness issue is addressed by invoking

max-min fairness criteria which ensures that the FTR Payment (FP) received (made) is not at the expense of other ill-positioned FTR holders. Max-min fairness algorithm is used to arrive at an energy reference choice that aims at maximizing the FP of each FTR. This in turn ensures that revenue received (payment made) is the maximum (minimum) possible under the set of constraints, without adversely affecting the FP of other FTR holders.

The decomposition of Locational Marginal Price (LMP) obtained from ACOPF has been labelled as a 'policy' decision because of its non-unique nature. This has prompted researchers to look into the problem keeping a certain objective, which forms the basis of the policy, in mind. This usually requires the selection of slack to be made a decision variable in an optimization problem, analogous to the max-min fair LMP decomposition suggested in this thesis. This thesis will re-visit the notion and role of slack (reference) in LMP decomposition and enlist the implications of this selection.

Frequency linked Unscheduled Interchange (UI) pricing is one of the characteristic features of Indian power system operation. This peculiar mechanism, associated with power deficit grids, helps in grid discipline. The mechanism, in its original form, has lacuna of losses not being accounted for. In other words, existence of same UI price throughout the grid does not allow this mechanism to be a zero sum settlement. This has further implications in terms of non-parity amongst various types of transactions. This thesis proposes remedy to this shortcoming of the mechanism by providing a locational bias to UI curve. An optimization problem is solved to make it a zero sum settlement. Real time data from the Western Regional Grid of India is employed to obtain the results.

Different transmission fixed cost allocation methods lead to different nodal charges. Development of new transmission pricing scheme is guided by generic principles of transmission pricing. Each method available in the literature and used in practice, conforms to a certain set of principles, if not all. A transmission pricing mechanism

for a system is chosen so that it tries to satisfy most of the country and system specific requirements. The ever conflicting requirements do not allow choice of a single method that satisfies all principles. This thesis proposes a new transmission pricing paradigm based on flexible *mix and match* approach. Aim here is to create a generic flexible toolbox that considers viewpoints and preferences of all stake-holders in terms of principles of transmission pricing, rather than devising a new transmission fixed cost allocation methodology. Thus, the final constitution of nodal transmission charges embeds relative weights given to each principle by each stakeholder. Analytical Hierarchical Process (AHP) is used as a tool for the said approach. Additionally, a quantitative comparison of various transmission pricing methods is performed using Jain's Fairness Index.

The methodologies suggested in this thesis have been extensively studied on test systems and detailed discussions have been provided. The results and discussions provide further insights into the nature of the problem addressed.

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# Acronyms

<b>ABT</b>	Availability Based Tariff
<b>ACOPF</b>	AC Optimal Power Flow
<b>ACPF</b>	AC Power Flow
<b>AHP</b>	Analytic Hierarchy Process
<b>CI</b>	Consistency Index
<b>CR</b>	Consistency Ratio
<b>CS</b>	Congestion Surplus
<b>CERC</b>	Central Electricity Regulatory Commission
<b>DCOPF</b>	DC Optimal Power Flow
<b>EBE</b>	Equivalent Bilateral Exchange
<b>EV</b>	Eigen Vector
<b>FERC</b>	Federal Energy Regulatory Commission
<b>FND</b>	Fictitious Nodal Demand
<b>FTR</b>	Financial Transmission Rights
<b>GGDF</b>	Generalized Generation Distribution Factor

<b>GLDF</b>	Generalized Load Distribution Factor
<b>ISO</b>	Independent System Operator
<b>JFI</b>	Jain's Fairness Index
<b>JM</b>	Judgement Matrix
<b>LHR</b>	Loss Hedging Rights
<b>LMP</b>	Locational Marginal Price
<b>LS</b>	Loss Surplus
<b>MLD</b>	Matrix Loss Distribution
<b>MP</b>	Marginal Participation
<b>NRLF</b>	Newton Raphson Load Flow
<b>NS</b>	Net Surplus
<b>PFT</b>	Power Flow Tracing
<b>PS</b>	Postage Stamp
<b>PSP</b>	Proportionate Sharing Principle
<b>PTDF</b>	Power Transfer Distribution Factor
<b>RHS</b>	Right Hand Side
<b>RTO</b>	Regional Transmission Operator
<b>SFT</b>	Simultaneous Feasibility Test
<b>TSO</b>	Transmission Service Operator
<b>UI</b>	Unscheduled Interchange

**VLD**      Vector Loss Distribution

# Nomenclature

$\%AD^x$	Average difference of $x$
$\%MD^x$	Maximum difference of $x$
$\alpha$	Slack weight vector (AC Model) - dimension $n \times 1$
$\beta$	Slack Distribution Variable (DC Model) - dimension $n \times 1$
$\delta$	Vector of load angles except at angle reference bus - dimension $(n - 1) \times 1$
$\lambda$	LMP vector - dimension $n \times 1$
$P$	Vector of net nodal power injections - dimension $n \times 1$
$V$	Vector of voltage magnitudes - dimension $n \times 1$
$\lambda^c$	Congestion component of LMP vector - dimension $n \times 1$
$\lambda^e$	Energy component of LMP vector - dimension $n \times 1$
$\lambda^l$	Loss component of LMP vector - dimension $n \times 1$
$LF$	Loss Factors vector - dimension $n \times 1$
$\theta$	Vector of load angles of DC model - dimension $n \times 1$
$\mu$	Lagrange multiplier of line power flow constraint vector - dimension $M \times 1$
$\eta_g$	Number of generators

$\eta_{ftr}$	Number of FTRs
$\gamma$	Proportion of loss to be distributed to generator buses
$\lambda_i^c$	$i^{th}$ entry in $\lambda^c$
$\lambda_i^l$	$i^{th}$ entry in $\lambda^l$
$\lambda^{DC}$	Lagrange multiplier of global power balance equation
$\lambda_i$	LMP at bus $i$
$\lambda_{si,i}^c$	Congestion Component of sink node of $i^{th}$ FTR
$\lambda_{so,i}^c$	Congestion Component of source node of $i^{th}$ FTR
<b>D</b>	Loss Distribution Vector - dimension $n \times 1$
<b>FND</b>	Vector of fictitious nodal demands - dimension $n \times 1$
<b>flow<sup>max</sup></b>	Vector of line power flow limits - dimension $M \times 1$
<b>GSF</b>	Generation Shift Factor matrix - dimension $M \times n$
<b>K</b>	Loss distribution matrix - dimension $n \times M$
<b>P<sub>loss</sub><sup>L</sup></b>	Vector of active power loss occurring on each line - dimension $M \times 1$
<b>Pd</b>	Vector of Load Demand - dimension $n \times 1$
<b>Pg</b>	Vector of Power Generation - dimension $n \times 1$
<b>X</b>	Reactance Matrix - dimension $n \times n$
$\mu_l$	Lagrange multiplier of power flow constraint of line $l$
$\rho$	LMP scaling factor
$\tau$	Lagrange multiplier of equality constraint corresponding to $P_{loss}$

$\zeta^k$	Weight associated with transmission pricing method $l$
$\zeta$	Weighing Factor
$a_i$ and $b_i$	Linear curve fitting co-efficients
$C_i(Pg_i)$	Cost function of generator $i$
$flow_l$	Power flow on line $l$
$FP_i$	FTR Payment of $i^{th}$ FTR holder
$GSF_{l-i}$	Entry in GSF matrix corresponding to line $l$ (row) and bus $i$ (column)
$L$	Lagrangian function
$LF_i$	Loss factor at bus $i$
$LF_{si,i}$	Loss sensitivity of sink node of $i^{th}$ FTR
$LF_{so,i}$	Loss sensitivity of source node of $i^{th}$ FTR
$Loss_{mean_{pu}}^{gen}$	Mean of losses attributed to generator bus in per unit
$Loss_{mean_{pu}}^{load}$	Mean of losses attributed to load bus in per unit
$Loss_{pu}^i$	Loss attributed to node $i$ in per unit
$M$	Number of Transmission Lines
$n$	Number of buses
$N_{gen}$	Total number of generators
$N_{load}$	Total number of loads
$P_c^t$	Total power of constituent $c$
$p_c^U$	Unscheduled interchange of constituent $c$

$P_i$	Net nodal power injection at bus $i$
$P_i^{ftr}$	MW amount of $i^{th}$ FTR
$P_{ilm}^{tr}$	Contribution of nodal power injection at bus $i$ on line $lm$ , evaluated from power flow tracing
$P_i^{ac}$	Actual power injection/drawal at node $i$
$P_i^{sc}$	Scheduled power injection/drawal at node $i$
$P_i^U$	Unscheduled Interchange in MW given by $P_i^{ac} - P_i^{sc}$ at node $i$
$P_{lm}^r$	Receiving end power flow on line $lm$
$P_{lm}^s$	Sending end power flow on line $lm$
$P_{loss}$	Total active power loss
$P_{loss}^l$	Power loss occurring on $l^{th}$ line
$Pd_i^{ac}$	Actual value of load at node $i$
$Pd_i^{sc}$	Scheduled value of load at node $i$
$Pd_i$	Load demand at bus $i$
$Pg_i^{ac}$	Actual value of generation at node $i$
$Pg_i^{max}$	Upper limit of generator located at $i^{th}$ bus
$Pg_i^{min}$	Lower limit of generator located at $i^{th}$ bus
$Pg_i^{sc}$	Scheduled value of generation at node $i$
$Pg_i$	Power generation at bus $i$
$PI^x$	Performance Index of $x$
$R_l$	Resistance of line $l$ in p.u.

$T_{l-i}$	Power flow sensitivity of line $l$ with respect to injection at bus $i$
$tp_i$	Nodal transmission charge at bus $i$
$tp_i^b$	Nodal transmission charge at bus $i$ obtained from benchmark method $b$
$tp_i^k$	Nodal transmission charge at bus $i$ obtained from transmission pricing method $k$
$U_{ij}^D$	Utilization of $j^{th}$ line by $i^{th}$ load
$U_{ij}^G$	Utilization of $j^{th}$ line by $i^{th}$ generator
$x_l$	Reactance of line $l$ in p.u.
$z_i^t$	UI rate at bus $i$ during time block $t$
$z_n^t$	Nominal value of UI rate during time block $t$