DEVELOPMENT OF REAL AND REACTIVE POWER ALLOCATION METHODS FOR DEREGULATED POWER SYSTEMS

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A thesis submitted in fulfilment of the
requirements for the award of the degree of
Doctor of Philosophy (Electrical Engineering)

Faculty of Electrical Engineering
Universiti Teknologi Malaysia

JUNE 2007

To my beloved mother and father

ACKNOWLEDGEMENT

First of all, I would like to express my sincere gratitude to my supervisor, Associate Professor Dr. Mohd Wazir Mustafa, for his valuable guidance and support during the period of this research. His expert advice and continued encouragement have been instrumental towards the successful completion of this PhD degree.

Special thanks go to my colleagues at the department. Further to their interesting and helpful comments and suggestions during the technical talks, they have also contributed to create a pleasant and lively atmosphere during my days at the University.

The financial support from the Malaysian Technical Cooperation Program (MTCP) of the Malaysia Government is gratefully acknowledged.

Last but not least, heartfelt gratitude and thanks are due to my family. I feel a deep sense of gratitude for my parents who formed part of my vision and provide a persistent inspiration for my journey in life. I am fortunate to have my wife, Aishath Shama to share this valuable experience with me, and I am very grateful for her love, patience, encouragement and help throughout my research. I would also like to thank my sisters, Dr. Sheena Moosa and Lucia Moosa for their constructive comments and careful proofreading of the thesis manuscript. The unconditional support from my family gave me the strength, courage and confidence to overcome all the difficulties during the course of this work.

ABSTRACT

The aim of deregulation in the electric power industry is to optimize the system welfare, by introducing competitive environment, mainly among the suppliers. Developing fair and equitable real and reactive power allocation method has been an active topic of research, particularly in the new paradigm, with many transactions taking place at any time. This thesis suggests two new methodologies to allocate real and reactive power output of individual generators to system loads and flows. Both allocation procedures presented can be used independently in deregulated power systems. It is based on current operating point of the system, computed through AC load flow program. The proposed reactive power allocation methodology adopts current tracing, instead of power tracing. Based on solved load flow and the network parameters, the method converts power injections and line flows into real and imaginary current injections and flows. These currents are then represented independently as real and imaginary current networks. Since current networks are acyclic lossless networks, proportional sharing principle and graph theory is used to trace the relationship between current sources and current sinks. From this relationship of current components of individual generators, it is possible to find reactive power contribution of each generator. This current tracing method can also be applied for real power allocation, with a few modifications. The second method is mainly applied for real power allocation. The method first clusters the system into small groups of buses. Then an appropriate conventional power flow tracing procedure is adopted to obtain the contribution factors within each cluster of buses. The choice of the chosen algorithm depends on their limitations and suitability. The advantages of the proposed methodologies are demonstrated on commonly used test systems and actual TNB 222 bus system. The proposed methodologies provide better reliability and minimize the limitations of conventional real and reactive power allocation methods.

ABSTRAK

Matlamat penyahaturan industri kuasa elektrik adalah untuk mengoptimumkan kebaikan sistem tersebut, dengan memperkenalkan suasana yang kompetitif, terutamanya kepada para pembekal. Pembangunan kaedah peruntukan kuasa aktif dan reaktif yang adil dan saksama telah menjadi tajuk penyelidikan yang aktif, terutamanya di dalam paradigma baru, dengan banyak transaksi pada sesuatu masa. Tesis ini mencadangkan dua kaedah baru untuk memperuntukkan kuasa keluaran aktif dan reaktif daripada setiap penjana kepada beban dan aliran sistem. Kedua-dua kaedah tersebut boleh digunakan secara berasingan di dalam sistem kuasa ternyahaturan. Ianya berdasarkan kepada titik operasi semasa sistem tersebut yang dikira melalui aturcara aliran beban AU. Kaedah peruntukan kuasa reaktif yang dicadangkan menggunapakai pengesanan arus dan bukannya pengesanan kuasa. Berdasarkan kepada aliran beban yang telah diselesaikan dan parameter rangkaian, kaedah tersebut menukarkan suntikan kuasa dan aliran talian kepada suntikan dan aliran arus. Arus ini kemudiannya diwakili secara berasingan sebagai arus rangkaian sahih dan khayal. Disebabkan rangkaian arus adalah rangkaian bukan kitaran tanpa kehilangan, prinsip perkongsian yang berpatutan dan teori graf digunakan untuk mengesan perkaitan di antara sumber dan destinasi arus. Daripada perkaitan komponen arus bagi setiap penjana tersebut, sumbangan kuasa reaktif daripada setiap penjana boleh didapati. Kaedah pengesanan arus boleh juga digunakan untuk peruntukan kuasa aktif dengan beberapa pengubahsuaian. Kaedah kedua pula khususnya digunakan untuk peruntukan kuasa aktif. Pertamanya kaedah ini merungkaikan sistem tersebut kepada kumpulan-kumpulan bas yang kecil. Kemudian, prosedur pengesanan aliran kuasa konvensional yang sesuai digunapakai untuk memperolehi faktor sumbangan di dalam setiap kumpulan bas. Pilihan sesuatu algoritma bergantung kepada batasan dan kesesuaiannya. Kelebihan kaedah yang dicadangkan ditunjukkan dengan sistem ujian yang biasa digunakan dan sistem TNB 222 bas. Kaedah yang dicadangkan memberikan keboleharapan yang lebih baik dan meminimumkan had kaedah peruntukan kuasa aktif dan reaktif konvensional.

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LIST OF ABBREVIATIONS

AC	-	Alternating current
BILIM	-	Bus inflow line incidence matrix
BOLIM	-	Bus outflow line incidence matrix
CIRCO	-	A Graph layout program
DC	-	Direct current
DOT	-	A Graph layout program
D-var	-	Dynamic VAr
ECNZ	-	Electricity corporation of New Zealand
ESI	-	Electricity supply industry
EST	-	Educational simulation tool
FACTS	-	Flexible AC transmission systems
FERC	-	Federal energy regulatory commission
GGDF	-	Generalized generation distribution factor
GIF	-	Graphics interchange format
GLDF	-	Generalized load distribution factor
GRAPHVIZ	-	Graph visualization software
GSDF	-	Generation shift distribution factor
GUI	-	Graphical user interface
HTS	-	High temperature superconducting
IEEE	-	Institute of electrical and electronics engineers
IGBTs	-	Insulated gate bipolar transistors
IPP	-	Independent power producer
ISDF	-	Injection shift distribution factors
ISO	-	Independent system operator
JPEG	-	Joint photographic experts group
KCL	-	Kirchoff's current law

LUFs - Line utilization factors
M3 - Malaysian managed market
MATLAB - Matrix laboratory software
MatPower - A MATLAB$^{\text{TM}}$ Power System Simulation Package
MVA - Mega volt ampere
NEATO - A Graph layout program
NETA - New electricity trading arrangements
NGC - National grid company
OFFER - Office of energy regulation
OPF - Optimal power flow
PAT - Power analysis toolbox
PNG - Portable network graphics
PSAT - Power system analysis toolbox
PSS/E - Power system simulator for engineering
PST - Power system toolbox
PTDFs - Power transfer distribution factors
PTI - Power technologies incorporated
PTRACK - Power tracing simulator
RPAF - Reactive power adjustment factor
SMD - Standard market design
SPS - SimPowerSystems
STATCOM - Static compensators
SVC - Static VAr compensators
TNB - Tenaga national berhad
VAr - Volt-Ampere reactive
VIU - Vertically integrated utility
VST - Voltage stability toolbox
WSCC - Western systems coordinating council

LIST OF SYMBOLS

$\boldsymbol{A}_L$ - Load extraction factor matrix

$\boldsymbol{A}_l$ - Line extraction factor matrix

$\boldsymbol{A}_u$ - Upstream distribution matrix

$\boldsymbol{B}$ - Contribution factor matrix

B', B'' - Simplified admittance matrix

Cij - Contribution of generator *i* to the load and external flow of Common *j*

F_{ijk} - Share of generator *i* in F_{jk}

F_{jk} - Flow from Common *j* to Common *k*

g - Generator node

I - rms values of current

$I_{i(charge)}$ - Current entered from parallel capacitance of lines connected to bus *i*

I_i^r - Real component associated with I_i

I_i^{im} - Imaginary component associated with I_i

I_{i_sh} - Current flow through y_{i_sh}

I_{ij} ,I_i - Line current flow

I_{inj} , - Current injection

I_k - Internal flow of Common *k*

I_k^i - Complex current of source *k* attributed to sink *i*

$I_k^{i\_r}$ - Real component associated with I_k^i

$I_k^{i\_im}$ - Imaginary component associated with I_k^i

$I_g^{ik\_x}$ - Component of I^{ik_x} due to *g*

I_g^{ik} - Current contributed by generator *g* to each equivalent line section

I^{ik_x} - Line current component between buses *i* and *k*

$I_{ps}^{ik\_x}$ - Component of I^{ik_x} due to *ps*

I_{max} - Maximum value of current

$i(t)$ - Instantaneous current

$\boldsymbol{J}$ - Jacobian matrix

l - Transmission line or branch

n - number

ncg - Number of common generators

ng - number of online generators

nL - Number of loads sinks

nl - Number of lines

ns - Number of network sinks

P - Real power

$\boldsymbol{P}$ - Vector of bus total passing power (real)

$\boldsymbol{P}_G$ - Vector of real power generation

P_{Gk} - Real power generation at bus *k*

P_i - Real power injection at bus *i* or total real power through bus *i*

P_{ic} - Calculated real power injection at bus *i*

P_{ij} - Magnitude of power flow in line between bus *i* and bus *j*

$P_{i\text{-}l}$ - All lines supplied directly from bus *i*

P_{is} - Specified real power injection at bus *i*

$\boldsymbol{P}_l$ - Vector of line power (real)

$\boldsymbol{P}_L$ - Vector of load power (real)

$P_{L\text{-}i}$ - Real power demand at bus *i*

PQ - Load bus

PV - Voltage controlled bus or generator bus

P_g^{ik} - Sending end real power of line between bus *i* and *j* supplied generator *g*

P_g^{kj} - Receiving end real power of line between bus *i* and *j* supplied generator *g*

$(P_{loss})^{ij}$ - Line real power loss between buses *i* and *j*

$\left(P_{loss}\right)_g$ - Contribution from generator g to system real power loss

$\left(P_{load}\right)_{j\_g}$ - Contribution of real power from generator g to load real power at bus j

$p(t)$ - Instantaneous power

ps - Pseudo node

Q - Reactive power

Q_i - Reactive power injection at bus i

Q_{ic} - Calculated reactive power injection at bus i

Q_{is} - Specified reactive power injection at bus i

Q_k^i - Reactive power share of current source k to current sink i

R - Resistance

S_i - Complex power injection at bus i

t - Time instant

V - rms values of voltage

V_i - Bus voltage of bus i

V_{max} - Maximum value of voltage

$v(t)$ - Instantaneous voltage

X - Reactance

Y - Admittance

Y_{ij}, y_{ij} - Element of bus admittance matrix between buses i and j

y_{i_sh} - Equivalent shunt admittance at bus i

Z - Impedance

Z_{line} - Impedance of a power transmission line

$\alpha_i^{(u)}$ - set of upstream buses supplying directly to bus i

β_i - Phase angle associated with I_i

δ_i - Phase angle of bus voltage at bus i

ΔP_i - Mismatch between calculated and specified real power at bus i

ΔQ_i - Mismatch between calculated and specified reactive power at bus i

θ - Phase difference between the voltage and current

π - 3.1416 radians or 180°

φ_{ij} - Phase associated with Y_{ij}

ω - Angular frequency

$k \in \alpha_j$ - Set of lines supplying directly to bus j

$k \in \sigma_j$ - Set of outflow lines from bus j

$l_{j \in i}$ - Set of inflow lines to bus i

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CHAPTER 1

INTRODUCTION

1.1 Motivation

The electricity supply industry (ESI) throughout the world, which has long been regarded as the largest regulated monopoly, is undergoing enormous changes. The ESI is evolving into a distributive and competitive industry, with the aim to improve system efficiency and reduce energy cost, through increased competition among the industry participants.

Technology improvement, market pressure, politics and legislative initiatives are the driving forces that facilitate the modern deregulation and reform in the ESI. The primary steps undertaken in the deregulation process are functional unbundling of generation, transmission and distribution segments. There are, in addition, major developments underway to bring about full competition in many sectors of electricity business, including the implementation of nondiscriminatory transmission open access and unbundling of ancillary services to name a few. The experience gained since last decade and the recent movements unveils the success of the deregulation process. But this success is achieved not without crisis and challenges.

Deregulation and unbundling of major entities and services in the ESI worldwide has given rise to new problems. Many new concepts and terminologies in the field of power systems had to be reevaluated. A major criticism of the early models was that it did not address crucial issues such as the use of system charges and transmission losses on a sound engineering basis. Indeed, at that time of deregulation, the issue was deemed as too complicated to have a viable solution [1].

Since the new regime is still young, many technical and economical issues are yet to be solved. It is the unbundling and transmission open access that provides the motivation for the work of this research.

This thesis focuses on the allocation of unbundled services in the multi transaction power systems. The three services addressed in the thesis are reactive power support service, transmission usage and real power loss. Besides, it also contributes to the development of new tools for analysis of the above mentioned services.

1.2 Power System Deregulation: A Global Perspective

Historically, the electricity industry was a monopoly industry with a vertical structure. In such a structure, when consumers wanted to buy electrical energy, they had no choice. Consumers had to buy it from the utility that held the monopoly for the supply of electricity in the areas where they were located. This means that, the utility that generated the electrical energy, transmitted it from the power plant to the load centers and distributed to the individual customers. Such utility companies could be state owned or private, and they are classified as vertically integrated utility (VIU). The rates of the VIUs were set by the regulatory agencies and were cost-based.

Electric utilities operating under this model made truly remarkable contributions to the economic activity and quality of life. For several decades, the amount of energy delivered by these networks doubled about every eight years and in many parts of the world, an average customer of electricity deprived from the service has been dropped to less than 2 minutes per year [2].

Until last decade, it was almost unimaginable that the ESI could be anything other than a vertical monopoly. The economies of scale of large power plants, the integrated nature of power systems and the fact that electricity, unlike other commodities, could not be stored, all pointed to the logic of having only one vertically integrated service provider to perform all industry functions (other than perhaps local level distribution). A vertical monopoly barred customer choice, the transaction costs of a multiplicity of rival and independent players competing against each other in a market.

In the 1980s, some economists started arguing that the monopoly status of the ESI had run its cause. They said that the monopoly status of the ESI removed the incentive to operate efficiently and encourage unnecessary investments. There are other different forces that have driven the power market towards the deregulation. It include changes in generation technologies, availability of advanced information and communications technologies, improvement of transmission technologies, customer demand for greater reliability and better and more innovative service, and politics [2].

Despite an early attempt by Chile in 1982, the tsunami of ESI deregulation stems from United Kingdom in 1989. Under the Electricity Act of 1989 Central Electricity Generating Board was split into four companies: the National Grid Company (NGC), PowerGen, National Power, and Nuclear Electric. Among these new companies, transmission facilities and functional operation of the grid were transferred to NGC; generation assets were transferred to the other three firms. The Office of Energy Regulation (OFFER) was organized as the UK electricity industry regulator, in April 1990. The operation mode of the new model was a mandatory pool market.

On January 1st, 1999, the roles of OFFER and the Office of Gas Supply merged in the formation of the Office of Gas and Electric Markets. Under the new authority, the New Electricity Trading Arrangements (NETA) was adopted, fundamentally changing the wholesale trading of electricity in England and Wales, to promote competition so that lower prices might prevail. The NETA went live on 27th March 2001 [3].

At the same time, a second country, Norway, restructured its electricity market towards deregulation. The Norwegian Energy Act, which became effective in 1991, introduced third party access to the retail market and competition in electricity production. This act created competition for the sale and purchase of electricity and allowed customers to buy from any generator, trader or the electricity pool. The Swedish deregulation that was decided in October 1995, led to the establishment of a common Norwegian–Swedish Exchange (Nord Pool). This first electricity market completely open to trade across national borders, has been in operation since January 1996. Finland joined the common market in October 1998; Jutland (West Denmark) in July 1999; and in the course of 2000 Zealand (East Denmark) also joined the common Nordic market. The Nordic electricity market is presently the only truly international electricity market. This is a power market, which includes both bilateral and voluntary pool modes [4].

The primary impetus for more fundamental restructuring and competition initiatives in United States can be traced to electricity policy debates that began in California and a few states in the Northeast (Massachusetts, Rhode Island, New York, Pennsylvania, Maine, and New Jersey) in the mid 1990s. This was combined with supporting transmission and wholesale market rules and regulations (e.g. Orders 888 and 889) issued by Federal Energy Regulatory Commission (FERC) at about the same time. The major development is the introduction of independent system operator (ISO) concept and setting up such entities in different regions including California, Pennsylvania- New Jersey-Maryland and New England. However, the power market deregulation has followed different paths in the numerous states which have their own separate markets [5].

Despite the unfortunate California's energy crisis in 2001 due to inconsistent price regulation and insufficiency in local generation, most of the states in the Northeast, some in the Midwest, Texas, and FERC were committed to moving forward with the development of competitive wholesale and retail markets and to making them work well.

The most recent evolution in USA’s ESI is the desire of FERC for the introduction of a standard market design (SMD) by all the deregulated markets [6]. The SMD should result in common transmission rules over all the states, thereby the power trading, by market participants who aim to transport power across different states, will be simplified.

Most Asian countries have introduced some degree of competition in generation by allowing independent power producers (IPP) to sell to established government utilities, most of which have attained the status of state owned corporations. Many are in transition to privatizing their electric utilities and introducing competition in wholesale and retail electricity supply. These include Thailand, Philippines, Indonesia, South Korea, and Malaysia [7].

In Thailand, despite the delay in implementation due to the financial crisis, the government has contracted seven IPP projects and privatized generation subsidiaries of Electricity Generating Authority of Thailand (EGAT). The restructuring of the power industry in the privatization master plan is divided into three stages which led to the introduction of wholesale competition from 2003-2004, privatizing EGAT, and separating generation from transmission [7].

Despite the central controlled economy in China, the power sector has experienced a reform since mid 1980s. In the first phase, private investment in generation has been allowed. In 2002, all the state-owned energy enterprises were transformed in commercial companies. However, there are no eligible consumers yet. The World Bank supports financially the government’s five year plan, from 2001 to 2005, in restructuring the electricity industry [8].

The Indian power sector is presently going through a process of reform and restructuring, as is the trend in many other countries in the region. Independent regulatory commissions are being set up, and vertically integrated utilities are being unbundled into corporate entities. Efforts are also being made to facilitate competition wherever feasible, and the choice of an appropriate power market model assumes significance in this context. India is not yet ready for a major electricity restructuring. The first and main restructuring problem is the gap between demand and generation, irrational and un-remunerative tariff structure and inaccessibility of electricity to households [9].

Meanwhile, Singapore and Japan have introduced limited retail competition by allowing large electricity consumers to choose their own power supplier. In Singapore, from July 2001, electricity customers with power requirements of at least

2 MW can choose their power supplier and can buy electricity in the wholesale market at spot prices. However, retail market liberalization is still in its early stages. Full retail competition has been proposed, and is under implementation in three phases. Phase 2 started in December 2003, targeting non-domestic low-tension consumers with an average monthly consumption of 10,000 kWh or more. The rest of the one million consumers, which use 25% of the total electricity, will become contestable in final phase [10]. In Japan, from April 2005, an estimated amount of over 8000 electricity consumers who use more than 50 kW are able to choose their supplier. Japan's electricity market is served by 10 privately owned vertically integrated utilities and IPPs that have been present since 1995. Full liberalization including residential customers will be proactively discussed beginning in April 2007 [11].

Malaysia opened its electricity market to IPPs in 1994, and 15 licenses were issued. As of 1998, nine of these with a combined capacity of 4.3 GW were in operation. Like most of its neighbors in Southeast Asia, Malaysia expects to introduce wholesale and retail competition in its electricity market. However, especially after the California's debacle, the Malaysian deregulation path was redirected by introducing the Malaysian Managed Market (M3) in 2001. The country has no definite plans or targets towards real deregulation and restructuring [12].

The power sector restructuring in Oceania also has a long history. In 1987, the government of New Zealand began the reform of power sector by setting up the Electricity Corporation of New Zealand (ECNZ). The task of ECNZ was to own and operate the facilities of the Ministry of Energy. In 1988, the system operator, Transpower, was set up by ECNZ. After some years of initial restructuring, a voluntary wholesale electricity market was founded in New Zealand. Its performance to date brings the New Zealand's market among the most successful paradigms of power sector deregulation. The most recent issue is the introduction of the financial transmission rights, as a tool for hedging transmission congestion costs and giving incentives for grid expansion investments [13]. In neighboring Australia, the Industry Commission recommended reforms, in 1990, that included the state owned electricity industry. In 1994, in the state of Victoria, a pool market was established. The same market form was introduced in New South Wales in 1996. These two markets were the founders of National Electricity Market of Australia in 1998. The implementation of a wholesale spot market may be considered as key achievement of Australia's electricity market. The next step of the reform process is the replacement of the present mixed federal and state regulatory structure with a national energy regulator [14].

Africa and the Middle East have lagged behind other regions in implementing reforms to power sectors, except for the concessioning of utility management of private operators (usually a foreign power utility) in some francophone countries. Algeria, Côte d'Ivoire, Egypt, Ghana, Kenya, Morocco, Senegal, and Tanzania have attracted one or more IPPs. Zambia has privatized a generation station and its local transmission grid in the copper-belt area, whereas Togo has privatized its small power utility without restructuring under a 20 year concession. Africa appears to be catching up to other regions, because many more African countries are considering reforms to their power sectors, mainly along the lines of privatization. This approach would be supported by the ongoing developments to form regional power pools in the southern, eastern, and western areas of the continent, which would help compensate for the small size of the national power markets [15].

1.3 Transmission Open Access

The transmission system is the most crucial element that connects the suppliers and loads. It is an integrated network that is shared by all market participants and a medium that generators compete to supply their customers. In the context of deregulated environments, transmission business is taken as a separate service that provides condition for competition. It is treated separately and funded independently irrespective of the ownership of the wires. Transmission system is responsible to provide capacity to transmit power, offer adequate standards of security and quality of supply.

With the present technology, neither the transmission nor the distribution can be classified as a perfect or contestable market. Transmission, because of lumpy investment, environmental constraints and the need for redundancy to meet the security requirements, is recognized as part of the chain where there are economies of scale [16].

It is important to note that the principle technical considerations of the transmission system under open access are same as in the vertical integrated utility environment. The physical characteristic of the electric transmission system remains unchanged under open access. The system must be protected against violations of its physical, operational and technical limits. Therefore in order to provide nondiscriminatory open access, competitive market necessitates an independent operational control of the grid. The control of the grid cannot be guaranteed without establishing the ISO. The ISO administers the transmission price, system security, transmission right, coordinate scheduling etc. The disintegration of the ownership and handing over the operational duties to ISO had gained popularity and it is most widely accepted concept for provision of nondiscriminatory open access.

For both reliability and commerce, bulk power systems require certain services to facilitate the secure and efficient transmission of electricity. These services are called ancillary services. According to FERC, ancillary services are necessary to support the transmission of power from sellers to buyers, given the obligation of control areas and transmission utilities, to maintain a reliable operation of the interconnected transmission system [17]. The FERC rule defined six ancillary services for open access transmission as listed below:

- Scheduling, system control and dispatch,
- Reactive supply and voltage control from generation sources service,
- Regulation and frequency response service,
- Energy imbalance service,
- Operating reserve – spinning reserve service, and
- Operating reserve – supplemental reserve service.

These services are mostly provided by generating sources. A transmission customer must purchase from the transmission provider or self provide these services.

1.4 Objectives and Scope

The active and reactive power transfer and transmission usage allocation are a central issue of the new cosmos of the deregulated electricity markets. The increased requirements for fair and transparent allocation and pricing scheme in the competitive environment, as well as the complexity introduced by unbundling the services, point out why these issues are of great importance and require urgent solutions.

The primary objective of the work reported in the thesis is to develop allocation schemes for unbundled services under transmission open access that are appropriate and provide meaningful results. The main objectives focused in thesis are listed below:

- To develop fair and accurate scheme to allocate reactive power output of individual generators to system loads. It can be done by tracing the path of current flow from generators to loads. The key intension of this scheme is to avoid the limitations of conventional reactive power allocation methods based on power flow tracing.

- To formulate a transmission real power usage allocation method based on current tracing scheme developed for reactive power allocation. In deregulated power system operation it is vital to know the role of each generator to system wires as it may be used for congestion management and transmission pricing.

- To develop an alternative transmission real power usage allocation method by clustering the power systems into manageably small groups. The aim of this methodology is to avoid large matrix calculation and improve the limitations of conversional usage allocation methods based on power flow tracing.

- To identify individual generator contributions to system real power losses and real power transfer to the loads. It can be done by utilizing the developed usage allocation methods.

- To create and compile the associated algorithms and routines into a user friendly simulation tool. Since no free software programs can perform the above mentioned allocation analysis in power system, effort is required to develop such a simulation tool.

A common feature of all the allocation schemes developed in this thesis is that they are use based and implicitly take into account the interaction with the transmission network. However the schemes do not provide economic justification since the developed methodologies are based on electrical engineering concepts, and not on the theories of economics.

The scope of this thesis can be summarized as follows:

- To study and analyze the conventional real and reactive power allocation methods. Many methods are cited in the literature to answer the allocation problems. However, determining accurate allocation could be difficult due to non linear power flow. This fact necessitates using approximate models, sensitivity indices, or tracing algorithms to determine an allocation scheme. In general, since different methods adopt different techniques it is important to acknowledge their pros and cons.

- To investigate the role of generator's real power output. Knowing whether or not, and to what extent, each generator contributes to the usage of a particular system component, requires the deregulated power system to operate economically and efficiently and guarantee of open access to all generators. This analysis will also help to estimate the generator's share to real transmission losses and the amount they need to purchase or self generate to compensate for losses.

- To investigate the role of generator's reactive power output. Since a generator produces both real and reactive power and can operate either as a producer or a consumer of reactive power, it can be speculated that a generator may not always fulfill the reactive power support service.

- To develop and test the proposed methods. The proposed methods should be tested and compared with the traditional methods. Such a study will help to verify the validity and performance of the method for the real life application.

- To discuss the practical consideration and constraints of the proposed methods. Testing the proposed methods on a large power system could reveal the problems in practical use. The limitation of the proposed method will be discussed.

- To demonstrate the capability of the developed program. A considerable portion of this research endeavor was performed on the software created on MATLAB platform. Therefore its performance will be discussed.

1.5 Thesis Outline

The organization of this work is as follows. In Chapter 2, first the nature and characteristics of reactive power in electric power systems is provided. The sources of reactive power are introduced. The importance of reactive power service is shown through the literature review of previous and on going research activities in its kind. Allocation and pricing of reactive power by various researchers are discussed and pros and cons of those approaches are highlighted. In addition, a detailed discussion on an engineering approach for real and reactive power allocation and pricing known as tracing methods are given.

In Chapter 3, a new scheme to allocate reactive power output of individual generators is suggested. The importance of proper system element modelling is highlighted and recommends some system element models to suit tracing procedure proposed in this thesis. Since the method is based on current tracing, a mathematical justification of proportional sharing principle in current flow networks and a proof of acyclic property of current flow networks are presented. Finally, a complete step by step procedure to allocate reactive output of generators is shown with a simple 4 bus system.

In Chapter 4, a review of current methodologies that are developed for allocating real power transmission usage and power transfer allocations is discussed and the general characteristics that must be included in such a scheme is identified. This is followed by two alternative methods for the real power allocation. The first method is an extension of the method that is developed for reactive power allocation in Chapter 3. The second approach is based on concept of network clustering and reducing the system into manageably small systems.

In Chapter 5, the software tools which have been developed for the simulations reported in this thesis are described. The program is suitable to run load flow analysis, transmission usage allocation, real power loss allocation and, real and reactive power transfer allocation analysis. Moreover, the program is also linked to the GRAPHVIZ program [18] to represent power system topology. GRAPHVIZ application to power systems visualization is one of the novelties of the package. Step by step simulation procedure and the capability of the program are finally shown with the WSCC (Western Systems Coordinating Council) 9 bus system.

In Chapter 6, the proposed real and reactive power allocation methods have been tested and analyzed for IEEE 14, IEEE 30, and IEEE 118 and TNB 222 bus systems. For validation, the results of the proposed methods are compared with well known conventional methods and tested on actual large systems such as TNB 222 bus system.

In Chapter 7, the conclusions of this research work can be found. Moreover, some suggestions on the extensions to potential topics for future research are presented. Network data and load flow results for all test cases used in this thesis are reported in Appendices A and B. Publications during the research work of this thesis also given in Appendix C.

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