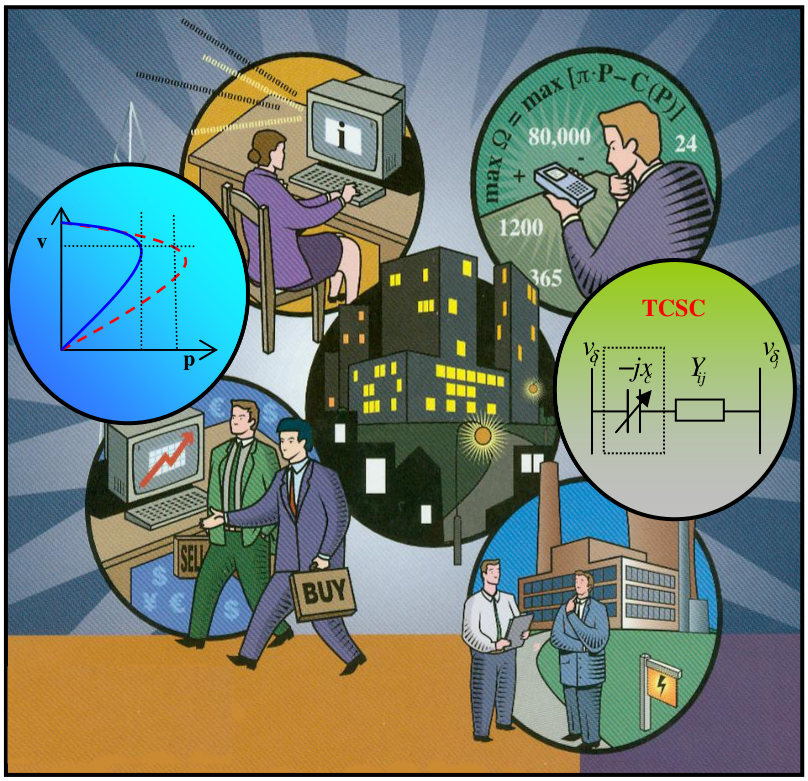

Optimal Market Settlements Incorporating Voltage Stability Considerations and FACTS Devices

Thesis for the Degree of Master of Science

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CHALMERS UNIVERSITY OF TECHNOLOGY
Göteborg, Sweden, 2008

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“Be a dreamer
is the beginning of
our realizations”

To all people I love

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Optimal Market Settlements Incorporating Voltage Stability Considerations and FACTS Devices

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Abstract

In the past decade, many power utilities world-wide have been forced to change their ways of doing business, from vertically integrated functioning to open-market systems. The reasons have been many, and differed, across regions and countries. Reforms were undertaken by introducing commercial incentives in generation, transmission and distribution of electricity, with in many cases, large efficiency gains. Though this may seem fairly straightforward at first glance, there are several complexities involved in restructuring and several new issues have surfaced. Recent large-scale power system blackouts in the USA and Europe have given us a "wake-up" call on the vulnerability of our power systems that they are being operated much closer to the limits than ever before.

This study aims at investigating the changes in power market transaction levels when taking into account the voltage stability consideration and FACTS devices in the market settlement scheme. The study is based on a security constrained optimal power flow (SC-OPF) framework for a combined bilateral-and-pool electricity market. An IEEE 30-bus test system is used in the study in which four separate cases are analyzed, i.e., a base case, a base case with security margin and these two cases with FACTS devices included. It is found that the voltage security constraints could help independent market operators (IMO) to include a sufficient margin for allowable power transactions to ensure the system security while maximizing the social welfare. It is also shown in the study that the use of FACTS devices (e.g., TCSC) can lead to an increase of up to 107% in available load capacity (ALC) for the same total transaction level (TTL) and an increase in TTL by up to about 3.5% when keeping the security loading factor of the system constant. Furthermore, the payment to the IMO is decreased by 4% due to congestion relief effects of FACTS. It can be concluded that power systems will be operating with a larger security margin with the proposed market settlement. It is, however, important to note that the social welfare is compromised with the increased security margin.

Keywords: Deregulated electricity markets, voltage stability, optimal power flow, FACTS devices, congestion management, social welfare.

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Acronyms:

ALC	Available Load Capacity
ATC	Available Transfer Capability
CBM	Capacity Benefit Margin
CPF	Continuation Power Flow
CPF-OPF	Continuation Power Flow Optimal Power Flow
DISCOS	Distribution Companies
ESCOS	Energy Service Companies
ETM	Existing Transmission Commitments
FACTS	Flexible Alternating Current Transmission Systems
GAMS	General Algebraic Modeling System
GENCOS	Generation Companies
IEEE	Institute of Electrical and Electronics Engineers
ISO	Independent System Operator
LIB	Limit-Induced Bifurcation
LMP	Local Marginal Price
MCP	Market Clearing Prices
MLC	Maximum Loading Condition
MO	Market Operator
OPF	Optimal Power Flow
PAY_IMO	Payment to the Independent Market Operator
PCPDIPM	Predictor Corrector Primal Dual Interior Point Algorithm
PDIPM	Primal Dual Interior Point Algorithm
PSAT	Power System Analysis Toolbox
SM-OPF	Security Margin Optimal Power Flow
SNB	Saddle-Node Bifurcation
STATCOM	Static Compensators
SVC	Static Var Compensators
TCPS	Thyristor Controlled Phase Shifter
TCSC	Thyristor Controlled Series Compensation
TRANCOS	Transmission Companies
TRM	Transmission Reliability Margin
TTC	Total Transfer Capability
TTL	Total Transaction Level
UPFC	Universal Power Flow Controllers

Acronyms:

f	Power flow equations
x	Dependent variables
p	Control variables
g	Equality constraints
h	Inequality constraints
$\|v\|$	Bus voltage modules
δ	Bus voltage arguments
r_{ij}	Line resistance
x_{ij}	Line reactance
B_{sh}	Shunt charging
B_{ij}	Line suceptance
G_{ij}	Line conductance
$\|Y\|$	Line admittance modules
ψ	Line admittance arguments
k	Multipliers to designate the rate of load or generation change
P_L	Load active powers
Q_L	Load reactive powers
P_G	Generator active powers
Q_G	Generator reactive powers
P_s	Supply active power bids
P_D	Demand active power bids
P_{ij}	Active power flow
Q_{ij}	Reactive power flow
S_{ij}	Apparent power flow
P_{inj}	Active injection powers
Q_{inj}	Reactive injection powers
ϕ_D	Power factor angle
$V_{\lim}$	Voltage limits
$I_{\lim}$	Current limits
$S_{\lim}$	Apparent power flow limits
C_S	Supply bid prices
C_D	Demand bid prices
λ	Loading parameter

Chapter 1

Introduction

The aim of this chapter is to provide a general description of the process that electricity sector has undergone since the past decades which has resulted in deregulated environments. In addition, the three most common market structures, namely, centralized, pool and hybrid, are described and compared. Moreover, it is explained the reasons why security and economic are causes of great concern, more than ever before, due to the implementation of competence within this industry. Therefore, concepts such as reliability, voltage stability, voltage collapse and so forth are defined. Finally, it is pointed out the organization of this work.

1.1 From regulation to deregulation: A background

In the past decades, the electricity industry has undergone a worldwide restructuring process toward deregulation, which has influenced on several aspects of the market, such as business, service provided and security [1].

Some years ago, most electricity markets all over the world were structured vertically based on monopoly rules. That means, main activities, such as generation, transmission and distribution, were controlled by either a sole or a reduce number of them, see Fig 1.1. The main objective of these downward integrated utilities was to minimize operating cost satisfying all constraints in the system. Governments or central authorities turned out to be pivotal participants in the regulated scenario which decided rates passed on to the consumers in return for the service offered to all of them. The fact is that this settlement worked properly for many years in the electricity framework.

However, discrepancies with those pillars over which philosophy centralised system were relied on started to be articulated by customers triggered mainly due to two events. The first one would be the increase in electricity rates owing to a rise in fuel prices during the seventies. The second fact that acted as catalyst for those who were not satisfied with the monopoly orientation of the sector was the positive results, in terms of prices, quality and efficiency, reported by other industrial fields which had been deregulated previously, such us flight companies. Therefore, the idea of introducing competition in the electricity sector took shape in the late seventies. On the other hand, it seems that not all opinions are in favour of this new trend since it is pointed out that vulnerability to volatility of prices and price spikes because of gaming activities could be much more frequent than in traditional centralised structures.

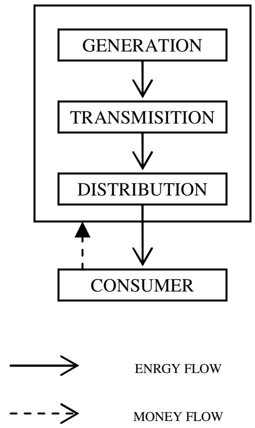


Fig 1.1 Monopoly model of electricity market.

Deregulation in electricity markets [2] can be analysed based on two points of view. First, from the industry side, the introduction of competition has, above all, altered the economics perspective of the sector. Second, from a controller standpoint, besides the latter consideration, security has risen as an issue of great concern, more than ever before, due to the reasons which will be pointed out in section 1.3.

The restructuring process has brought several new entities to the market and has redefined the scope of others inherited from the vertical structure. Thus, it is worth mentioning briefly their main features in order to understand which are the interaction and purpose of them [2] [7]. Therefore, the following participants take part on most of deregulated markets:

- GENCOS (Generation Companies)
- TRANCOS (Transmission Companies)
- DISCOS (Distribution Companies)
- ESCOS (Energy Service Companies)
- Customers
- ISO (Independent System Operator)
- MO (Market Operator)

Generation Companies (GENCOS) are the producers and sellers of electricity, being responsible of the installations and equipments required. *Transmission Companies* (TRANCOS) own and operate the transmission system ensuring the transportation of electricity from generators to customers. This activity is still regulated since it is not profitable built redundant facilities of this nature. *Distribution Companies* (DISCOS) own and operate local distribution companies. They are allowed to buy electricity through either a spot/hybrid market, or directly using contracts with generation companies with the aim of supplying that energy to end-use customers. *Energy Service*

Companies (ESCOS) work as distribution companies in the market but they do not own local distribution companies. They might be large industrial users, pool customers or private companies which objective consists of purchasing power at the least cost. *Customers* are the last users of electricity in the chain. As a result of deregulation, they have at their disposal different ways to buy electricity. *Independent System Operator* (ISO) is responsible for ensuring the reliability and security of the whole system. The role of the ISO depends on the market structure. Therefore, there are two main tasks which can be managed by this entity or be delegated to another. Normally, it provides different services, such as emergency reserves or reactive power. On the other hand, ISO can be involved in the market transaction process (e.g. Ontario). Finally, *Market Operator* (MO) is in charge of market transaction when this activity is not handled by the ISO (e.g. "old" California).

Economically, this new framework could be analysed through the monetary flow established among the latter players [8]. In a vertical structure, generator companies were taker price since they were allowed to fix the electricity rates on account of their dominant position on the market. Thus the cash flow was practically unidirectional, from the final consumer to the producer, being difficult to segregate the cost incurred in intermediate activities, such as generation, transmission and distribution. However, in a horizontal structure, such as the one proposed by deregulation, prices are determined either by bid auction agreements between GENCOS and DISCOS/ESCOS according to specific market rules or directly through contracts between the participants, see

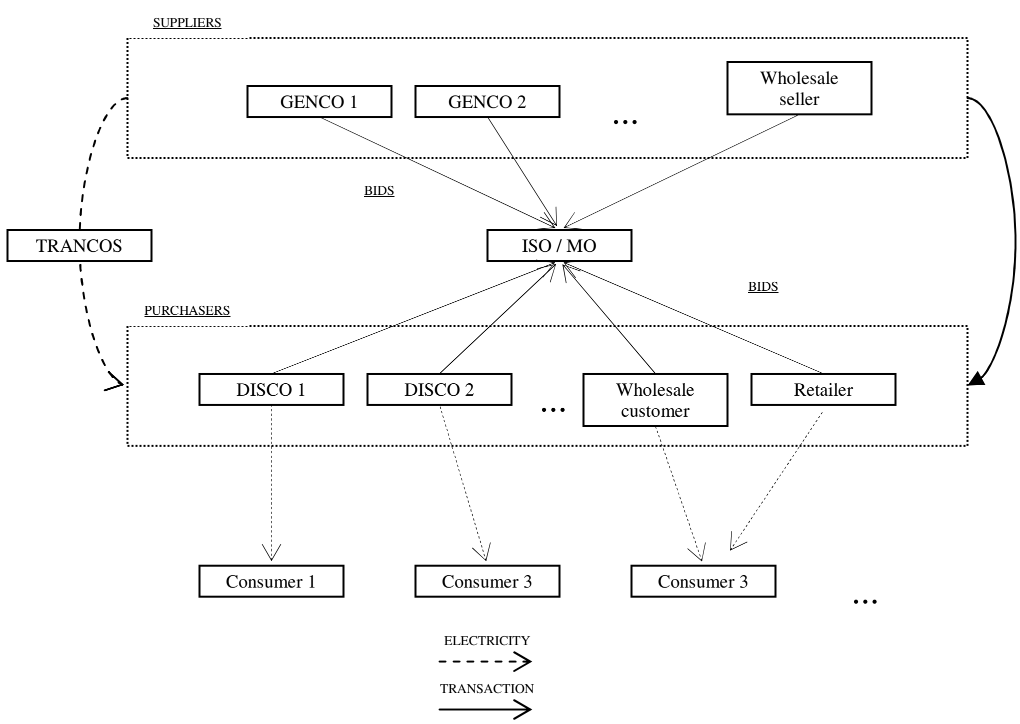


Fig 1.2 A wholesale electricity market.

That means, the revenues for producers are not ensured anymore, depending mainly on the price strategic chosen, instead. For this reason, price indicators are crucial in order to be competitive and profitable [3][4][5][6]. Hence, it is expected that the latter influents positively on customers in terms of reduction of payments and improvement of service quality.

Accordingly to the previous statement, it seems clear that the amount of energy that the system has to deal with have increased to date owing to the objective of producers of maximizing profits and the rapid increase performed by electricity demand during the last years. However, that would be infeasible, if those standards of security used in the regulated framework are not relieved since they were oversized in order to achieve the least level of risk. Therefore, at this point, it has just been introduced one of the main threats accentuated as a result of deregulation, *system reliability*.

1.2 Types of electricity markers

As mentioned before the deregulation process in electricity sector, all over the world, is not uniform, though goals are almost identical. Therefore, grade of implementation and model features can be varied. Thus, market models can be categorized into three main groups, namely, *central markets, decentralised markets and hybrid markets* [9]. Following, some of the most remarkable characteristics of each one are introduced [10]. Centralised markets (e.g. the "old" U.K. market, Chile 1982 [11][12], PJM 1997 [14], New York 1998 [17], New England 1999 [18]) can be considered as unit commitment and Optimal Power Flow (OPF) problems, where central market operation and transmission system operation are monitored by a sole authority. This model is typically implemented on vertical market structures. In decentralized markets (e.g. U.K. 1990 [13], Alberta 1996, Spain 1998 [15], California 1998-2001 [16]), responsibility for operating the system is shared between two entities the two entities introduced previously, Market Operator (MO) and Independent System Operator (ISO), see Fig 1.3. The former determines market schedules and the Market Clearing Prices (MCP) based on those bid submitted by participants using a simple auction mechanism. In this case, a unique price, determined by matching the highest bid demand with the lower supply demand, is used for all transactions, as shown in Fig 1.4.

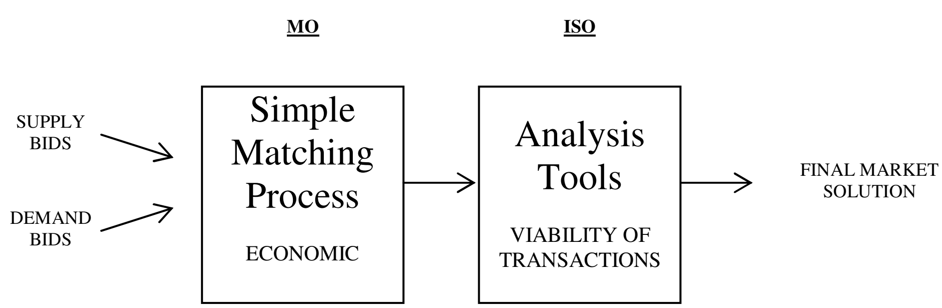


Fig 1.3 General structure of decentralised or simple auction market. Security and economic settlements are decoupled to each other.

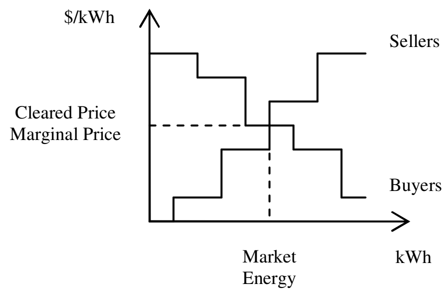


Fig 1.4 Market price matching in simple auction markets.

Finally, hybrid (e.g. Ontario 2002 [19]) markets are based on spot pricing theory and OPF methods. In this case market operation and system operation are not decoupled, Fig 1.5. Furthermore, the price is not uniform, being affected by bid values and several other factors such as congestion and location. Commonly, it is said that decentralized markets seem more "transparent" to all participants though the need of two different operators. However, the rapid development of computer science provides efficient tools that make hybrid models more attractive than time ago. For this reason, during the last year several studies based on this technique have been published with the aim of demonstrating a number of advantages and proposing innovated techniques mainly related to mathematical optimization algorithms and assessment of security issues, such as those listed in section 2.3 (e.g. [9][26][29][53]-[61]).

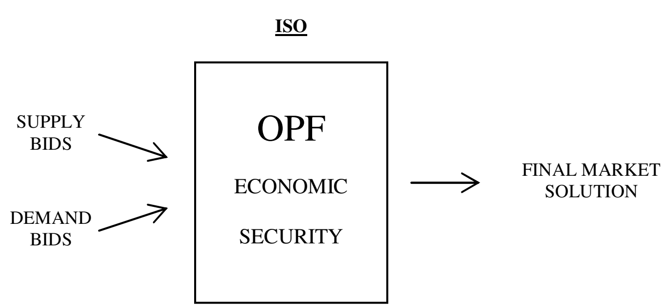


Fig 1.5 General structure of hybrid market. Both security and economic issues are management by a unique entity, the ISO using OPF techniques.

1.3 System Reliability: An important concept

Reliability is a widely used term related to many aspects of system operation. Normally, it is comprised of two concepts: *security* and *adequacy*. On the one hand, adequacy, can be defined as "the ability of electric systems to supply the aggregate electrical demand and energy requirements of their customers at all times, taking into account scheduled and reasonably expected unscheduled outages of system elements".

On the other hand, security "is the ability of the electric systems to withstand sudden disturbances such as short circuits or unanticipated loss of system elements" [10].

Moreover, other important concept related to security is the so called *power system stability* [20][21][22] which can be defined as "the capacity of a system to maintain an operating equilibrium point after being subjected to a disturbance for given initial operating conditions". In addition, some notions have to be taken into account: monitoring certain variables it is possible to determine the nature of the instability, the size of the disturbance has an influence on the tool used to address it and the time framework available to alleviate the problem is other essential. Furthermore, a classical classification of power stabilities extracted from [22] is shown in Fig 1.6

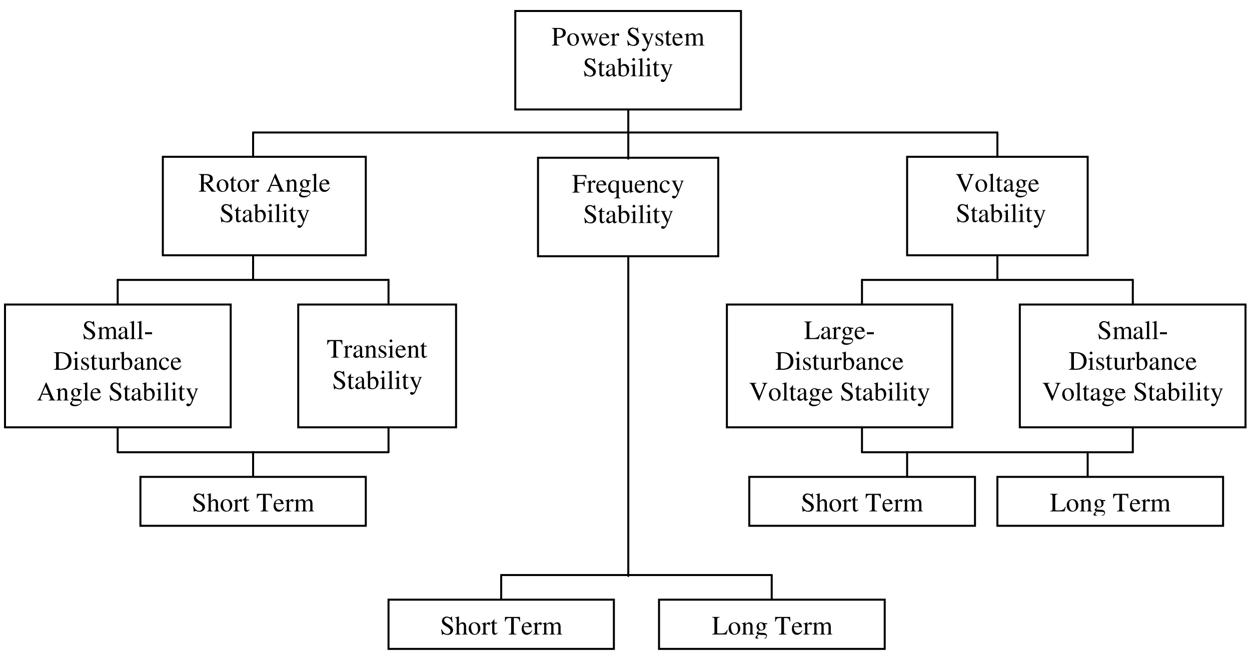


Fig 1.6 Classical classification of power system stability.

Briefly, *small disturbances* can be associated, for example to load changes, while *large disturbances* to fault conditions. Based on time frame, *short-term events* are related mainly with dynamics behaviours but *long-term events* do not demand a so fast reaction. *Angle stability*, is the capacity of synchronous generators to maintain synchronism after being subjected to a disturbance. Thus, it is related to the equilibrium among mechanic and electrical variables. *Frequency stability*, on the other hand, is the ability of the system to maintain a steady frequency, after a significant imbalance between generation and demand power occurs. Finally, *voltage stability* is the capacity of a power system to maintain steady voltages at all buses after a disturbance from an initial operating condition. In this work, the latter is the one analysed and applied.

Moreover, it is important to distinguish three concepts, such as *voltage stability*, *voltage instability* and *voltage collapse*. The first one, voltage stability, is defined in the previous paragraph. However, it is said in [21] that “a system enters a sate of voltage instability when a disturbance, increase in load demand or change in system condition cause a progressive and uncontrollable drop in voltage. Normally, it is related to the inability to meet the demand for reactive power. The heart of the problem is usually the voltage drop that occurs when active power and reactive power flow through the inductive reactance associated to the transmission network”. Finally, “voltage collapse is the process by which the sequence of events accompanying voltage instability leads to a low unacceptable voltage profile in a significant portion of the power system lead to a total or partial blackout” This concept can be analysed from a static or dynamic viewpoint . The static perception is related to load flow problems and maximum power that can be transferred before this problem appear, while the dynamic one requires more detailed, thus complex, models of those elements that constitute power networks, such as loads, generators, lines and so forth.

Furthermore, the difference between *transmission congestion* and *system stab*ility should be pointed out. On the one hand, transmission congestion could occur when the dispatching of transaction or an unexpected power variation due to, for example, a contingency lead to a violation of some transmission security constraints, which are typically thermal limits, voltage limits and stability limits. On the other hand, system stability, as said before, is related to the capacity of the system to withstand sudden disturbances remaining as close as possible to the initial condition that might commit congestion.

The main consequence of congestion is reduction of generation in comparison to that that could be achieved in its absence. Therefore, some amount of power is neither generated not delivered through the network to cover the expected demand. Hence, it leads to cheaper generation but higher cost of energy for the users. In facts, in deregulated markets models, the relief of this problem can produce significant variation in prices depending on each participant and bids. What is more, it has been demonstrated the relation between security and cost, which relevance has risen due to the development of competitive electricity markets. In this work, sensitivity or marginal parameters calculated within an optimization algorithm are used in order to determine the influence of the previous notions on prices providing, at the same time, relevant strategic signals to all market participants. Certainly, the main aim related to this issue is to be able to achieve a fairly distribute security costs among entities involved valuating positively those which do not contribute to network congestion.

It is possible to indicate same real blackouts that have taken place in different networks all around the world which causes can be categorized within the previous discussion [23][24][25]. For example, in 14 August 2003, a loss of voltage stability due to a series of transmission line contingencies and reactive power shortages produced a blackout in eight U.S. states and two Canadian regions. As a result, approximately 50 million people were affected and 11% of the total load served in the Eastern Interconnection of the North America system was interrupted (around 63 GW) which ended up costing $6.4 billion to the U.S. economy. Unfortunately, this has not been the sole case that authorities and market participants have had to cope with recently. Thus, in 23 September 2003, 4 million people were affected in Sweden and Demark. Moreover, five days later, in 28 September 2003, the Italian system lost 6400 MW. Therefore, these figures highlight the importance of taking into account seriously security limits thoroughly and be aware of which they are at different loading conditions.

In short, in competitive electricity markets, the so called zero-risk mandate [26], characteristic in the regulated scenario, is not sustainable any more since customers are not willing to pay high prices for power on account of reducing risk beyond some reasonable limit at any cost. For this reason, it is crucial to monitor and control security issues in nowadays deregulated scenarios without underestimating the importance of the new economic aspects involved. This work proposes a method to determine the most suitable solution after a bid process taking into account different levels of security margin decided by the ISO in hybrid markets. Thus, it will be possible to maximize the social welfare, introduced in Chapter III, and ensure a certain power capacity to withstand other kinds of transaction of unscheduled events in the system.

1.4 Work outline

The present work is organised in the following manner:

Chapter 2 introduces one of the most important concepts related to security issues in nowadays energy management scenario, the so call voltage stability. A loading parameter which provides the possibility to include operational margins within market models is the core of this section. Moreover, Continuation Power Flow (CPF) turns out to be a useful tool to depict PV curves which can be used to demonstrate graphically security criteria. An extensive literature review of most important studies published to date about this topic is presented. Finally, a 14 bus test system is chosen to represent some of its PV curves and determine voltage stability limits using a computer tool called Power System Analysis Toolbox (PSAT).

In Chapter 3, different concepts related to optimal power flow market models are defined. Furthermore, FACTS devices are introduced from different viewpoints, such as typology, usage, characteristics and so forth. Finally, it is developed the mathematical formulation of the four models based on OPF analysed in Chapter 4.

In Chapter 4 the results obtained from those models proposed and developed in the previous chapter are presented and commented. General Algebraic Modeling System (GAMS) is used to carry out the simulations and MATLAB to represent graphically the results using an interface between both programmes.

In Chapter 5, main conclusions from this study are presented. Moreover, different future research directions are provided.

Chapter 2

Voltage Stability and Transfer Capability

Voltage stability, defined in Chapter 1 as the ability of power systems to remain bus voltages within certain acceptable intervals either if it is operated under normal conditions or undergo some contingencies, has to be considered seriously owing to the consequences of voltage stability fails that can lead to blackouts. Therefore, it is essential to understand those basic concepts and tools related to this phenomenon. Thus, it would be possible to use these analyses to enhance the new energy management environment.

2.1 Voltage Stability

2.1.1. Voltage collapse review

A loading parameter, λ, is used in power system analyses in order to apply a general mathematical theory to classify instabilities, namely, *bifurcation theory* [20]. Moreover, this methodology reports quantitative information in the neighbourhood of particular points, such as collapse points and unstable points. Therefore, system equations need to include, besides state variables, a new set of parameters, λ, as follows:

$$f(x,\lambda)=0 \tag{2.1}$$

Several studies have been published based on this theory applied on power system where different formulations using the latter parameter can be outlined [27][28]. Therefore, a classical model could be the following one:

$$P_{L_i} = P_{L_{i0}} + \lambda(k_{L_i} P_{L_i}) \tag{2.2}$$

$$Q_{L_i} = Q_{L_{i0}} + \lambda(k_{L_i} Q_{L_i}) \tag{2.3}$$

$$P_{G_i} = P_{G_{i0}}(1+\lambda k_{G_i}) \tag{2.4}$$

where k_{L_i} k_{G_i} are multipliers to designate the rate of load or generation change at bus *i* as λ changes; $P_{L_{i0}}$ $Q_{L_{i0}}$ $\mathrm{P}_{G_{i0}}$ are the initial load and generation associated to the current operation point; P_{L_i} Q_{L_i} , terms multiplied by the loading factor are called power directions.

However, simplifications of the previous expressions lead to the following two alternatives which can be related to electricity market [29]:

$$P_{G_i} = P_{G_{i0}} + \lambda P_{S_i} \tag{2.5}$$

$$P_{L_i} = P_{L_{0i}} + \lambda P_{D_i} \tag{2.6}$$

$$P_{G_i} = (1+\lambda)(P_{G_{i0}} + P_{S_i}) \tag{2.7}$$

$$P_{L_i} = (1+\lambda)(P_{L_{i0}} + P_{D_i}) \tag{2.8}$$

where λ is the loading parameter; $P_{L_{i0}}$ $P_{G_{i0}}$ are load and generation for the current operating point; P_{S_i} P_{D_i} are power supply and demand at each bus.

In [29] is demonstrated that load directions, powers multiplied by λ, in (2.5)-(2.6) depend only on the market participants, being this formulation appropriated to determine the impact of auction on security and to minimize that effect. Nevertheless, (2.7)-(2.8) optimizes the auction results and the transaction outside the bid process to improve the system security.

According to the mathematical theory introduced previously, it is possible to distinguish two types of singular points associated to the condition of Jacobian matrix, namely, SNB (*Saddle-Node Bifurcation)* and LIB (*Limit-Induced Bifurcation*) [20][28][29]. The latter is related to the disappearance of steady-state solutions when system control limits are reached, for example maximum generator reactive power limits. The former is characterized by two equilibriums, one stable and one unstable, being the maximum power transfer capacity when not other boundaries get active before. Therefore, both of them might lead to voltage collapse and consequently to those problems introduce in Chapter 1. However, it is worth mentioning that voltage stability limit not always is associated to either SNBs or LIBs since bus voltage limits (related to V_{lim}), thermal limits (related to I_{lim}) or maximum transmission limits (related to S_{lim}) can be reached before to the other two bifurcation points. Furthermore, LIBs not have to coincide with SNBs [29].

2.1.2. Continuation Power Flow (CPF)

It is considered that CPF (*Continuation Power Flow*) is an efficient and useful tool to determine the so called *P-V curves* and maximum loading points [20][28][29]. Moreover, information provided by this technique can be used to calculate a series of sensitivity factors of different operating points respect to the loading parameter. Therefore, it is possible to understand how system variables are affected by the latter factor and thus establish which should be varied in order to achieve stability improvement.

Briefly, a general formulation of CPF, consists of an iterative process comprised by two steps, predictor and corrector. First, the predictor step estimates a new solution from an initial point using a tangent vector. Second, the corrector step that can be a local parameterization or a perpendicular intersection is used to locate the exact solution C using a modified power flow to calculate the proper value of λ. Fig 2.1 represents graphically this method.

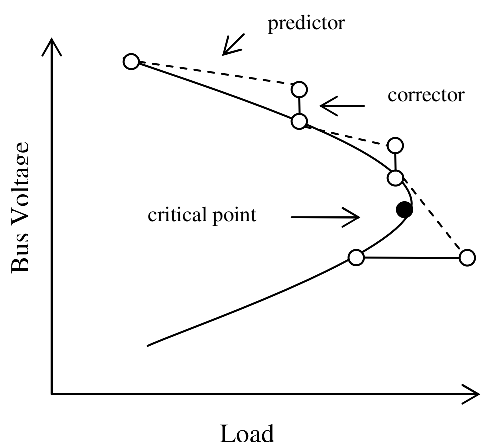


Fig 2.1 Continuation Power Flow scheme.

2.1.3. P-V curves

The so called P-V curves are useful graphical representations that depict the evolution of voltage at different bus in power electrical systems [20][30]. It is possible to demonstrate the concept of these curves using a simple two bus grid, as shows in Fig 2.2.

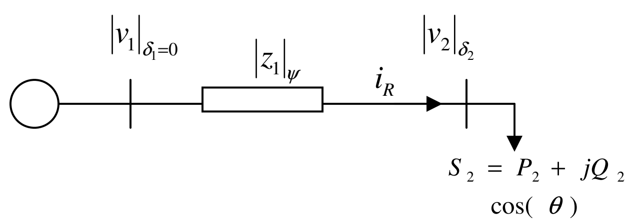


Fig 2.2 Simple two bus grid.

From the two-port equations:

$$P_2 = \frac{|V_1||V_2|}{|Z_1|}\cos(\delta_2 - \psi) - \frac{|V_2|^2}{|Z_1|}\cos(\psi) \tag{2.9}$$

$$Q_2 = \frac{|V_1||V_2|}{|Z_1|}\sin(\delta_2 - \psi) - \frac{|V_2|^2}{|Z_1|}\sin(\psi) \tag{2.10}$$

Using the next trigonometric relation $\cos^2(x) + \sin^2(x) = 1$ with (2.9) and (2.10),

$$(P_2^2 + Q_2^2)Z_1(P_2\cos(\psi) + Q_2\sin(\psi))V_2^2 - V_1^2V_2^2 + V_2^4 = 0 \tag{2.11}$$

From (2.11) assuming constant power factor $Q_2 = P_2\, tg(\cos(\theta))$,

$$V_2 = \sqrt{x} = \sqrt{\frac{-b \pm \sqrt{b^2 - 4ac}}{2a}} \tag{2.12}$$

P-V curves are generated for different values of P_2 keeping constant the power factor in (2.11)-(2.12).

It is possible to observe in Fig 2.3 that for particular values of load active power and power factor, two different voltage levels are determined. The one at the top is said stable since it is associated to higher voltage and lower current than the other. Thus the power system can be operated at this point. When both points coincide, a SNB is reached. Moreover, as the compensation is accentuated both voltage and maximum power transfer limit increase in comparison to a lower or lag compensation. However, for high lead power factors, it is more complicated to determine the different between the feasible and infeasible solution. Indeed, voltage can even rise as the active load active power does as a result of dominant capacitance effect. Furthermore, other type of curves, namely, P-Q curves have been analysed in [30] to determine steady-state voltage stability limit, though further research is needed in order to demonstrate its features in large systems.

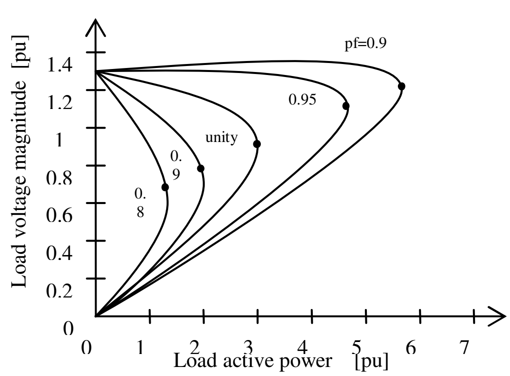


Fig 2.3 P-V curves at different power factors.

2.2. Available Transfer Capability (ATC)

According to [31] "ATC is a measure of the transfer capability remaining in the physical transmission network for further commercial activity over and above already committed uses" This term is defined through the *Total Transfer Capability* (TTC), *Transmission Reliability Margin* (TRM), existing transmission commitments and the *Capacity Benefit Margin* (CBM):

$$ATC = TTC - TRM - ETC \tag{2.13}$$

Where [31][26] ,

> Total Transfer Capability (TTC) "is defined as the amount of electric power that can be transferred over the interconnected transmission network in a reliable manner while meeting all of a specific set of defined pre- and post-contingency system conditions".
>
> $$TTC = \min.\{P_{\max I_{\lim}}, P_{\max V_{\lim}}, P_{\max S_{\lim}}\} \tag{2.14}$$
>
> Transmission Reliability Margin (TRM) "is defined as that amount of transmission transfer capability necessary to ensure that the interconnected transmission network is secure under a reasonable range of uncertainties in system conditions".
>
> Capacity Benefit Margin (CBM) and Existing Transmission Commitments (ETC) "is defined as that amount of transmission transfer capability reserved by load serving entities to ensure access to generation from interconnected systems to meet generation reliability requirements".

In Fig 2.4 the previous concepts are explained graphically using P-V curves of a system power system for different scenarios according to which limit dominates. It is demonstrated that in order to make a thoroughly analysis, it is important to take into account contingencies since the power transfer is remarkable lower than in absence of them. Hence, those measures implemented toward to enhance power system security can cover a wider range of probable situations.

It is possible to simplify (2.13) when no contingencies are taken into account or not intensive detailed analysis is needed, as follows:

$$ALC = MLC - TTL \tag{2.15}$$

where ALC (Available Load Capacity) would be related to ATC, MLC (Maximum loading Condition) would be similar to TTC and TTL (Total Transaction Level) would be associated with TRM.

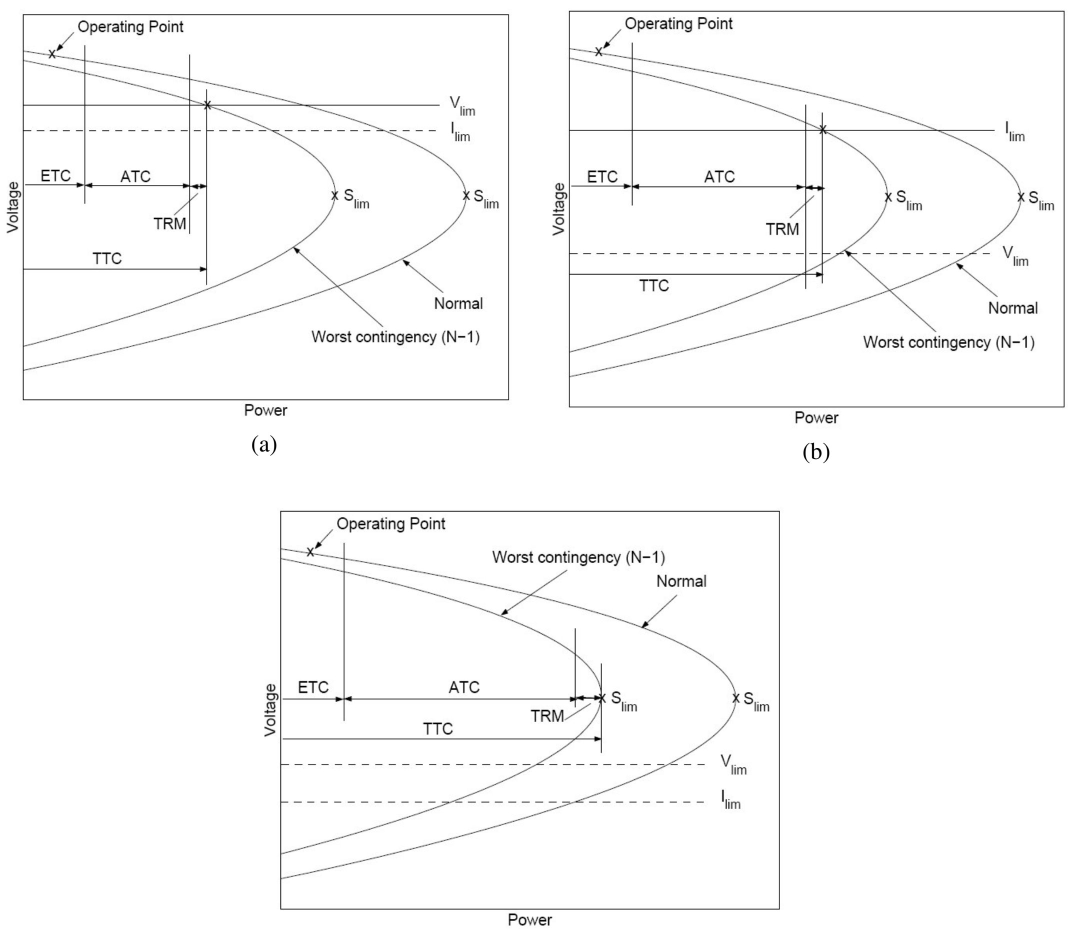
Where the relation with the loading parameter λ is established through the next expressions using the concepts introduced in $ALC = MLC - TTL$ (2.15(2.15).

$$MLC = (1+\lambda_C)\sum P_{Li} \quad (2.16)$$

$$ALC = MLC - \sum P_{Li} = MLC - TTL \quad (2.17)$$

$$TTL = \sum P_{Li} \quad (2.18)$$

$$ALC = \lambda_C \sum P_{Li} = \lambda_C TTL \quad (2.19)$$



(c)

Fig 2.4 Graphical representation of ATC, ETC, TRM and TTC.
(a) Voltage limits dominate. (b) Thermal limits dominate.
(c) Voltage stability limits dominate. (*source [7]*)

2.2.1. A case study

The previous concepts have been demonstrated using PSAT (*Power System Analysis Toolbox*) [32] and a 14 bus test system 0 which details are presented in Appendix A.1. Moreover, a Continuation Power Flow (CPF) technique is performed in order to generate different PV curves in several scenarios.

In Fig 2.1Fig 2.5 it is possible to observe P-V curves associated to three relevant buses of the test system. In this case, no limits have been taken into account. Therefore, the stability limit is defined only by the maximum power transfer that is related to the SNB introduced before. Numeric values are given in Table 2.1.

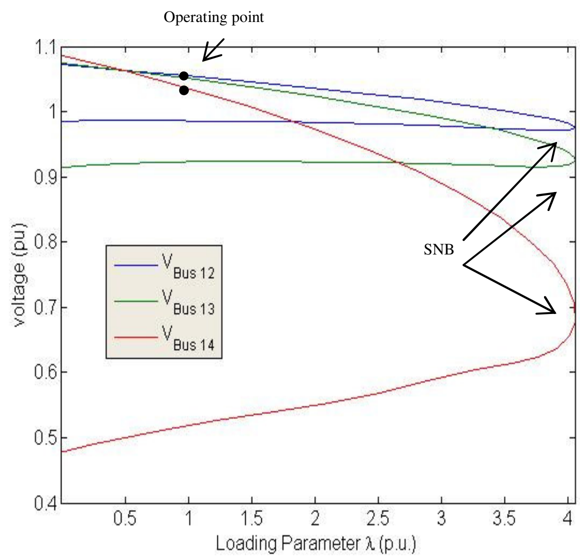


Fig 2.5 P-V curves for some representative buses of the 14 bus test system without considering any of the following limits Vlim, Qglim, Slim

Table 2.1 General results without considering any limit.

base load	259	MW
λ_{max}	4.059	pu
MLC	1310.3	MW
ALC	1051.3	MW

However, when voltage limits are introduced in the algorithm, results differ from the latter simulation. In this case, the maximum loading level before any limit get active is lower than the one calculated without limits (-6.33 %) Thus, the remaining transfer capability is reduced by the same proportion. The first bus which voltage level is equal to one of the limits is bus 14. Therefore, Fig 2.6 depicts the voltage profile of node indicating the definition of ALC and MLC. Table 2.2 contains the numeric values associated to this simulation.

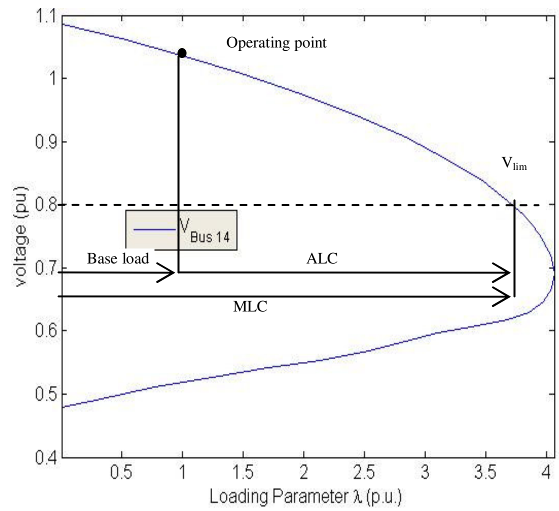


Fig 2.6 P-V curve and representation of MLC, ALC and current operation points for bus 14 when only voltage limits are taken into account

Table 2.2 General results considering voltage limits.

base load [MW]	259
λ_{max} [pu]	3.802
MLC [MW]	1243.8
ALC [MW]	984.8

On the other hand, when only generator reactive power limits are imposed, effects on the system are even more significant, as it is demonstrated in Fig 2. 7 and Table 2.3. The maximum loading parameter reduced by 65.21% in comparison to the simulation without taking into account any limit. Generator 2 is the first unit to reaches its upper limit.

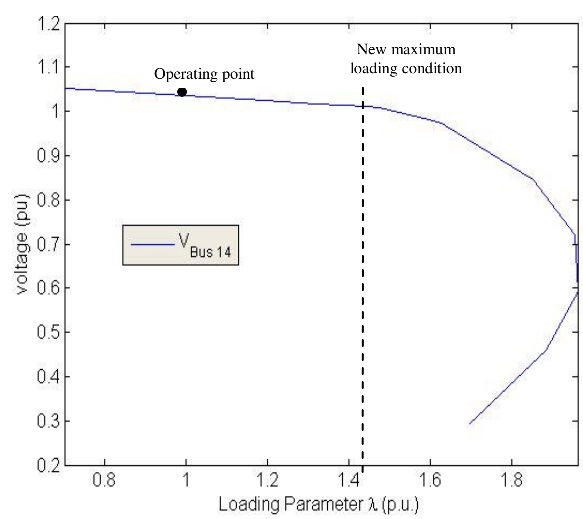


Fig 2. 7 P-V curve for bus 14 when only generator reactive power limits are taken into account

Table 2.3 General results considering generator reactive power limits.

base load [MW]	259
λ_{max} [pu]	1.412
MLC [MW]	624.7
ALC [MW]	365.7

Furthermore, power flow limitation through lines has been also simulated reporting the results represented in Fig 2.8 and listed in Table 2.4. The line from bus 5 to bus 6 is the first one which reaches its limit. In this case the maximum loading parameter suffers a decline by 63.46 which is similar to the effect owing to introduce generator reactive power limits.

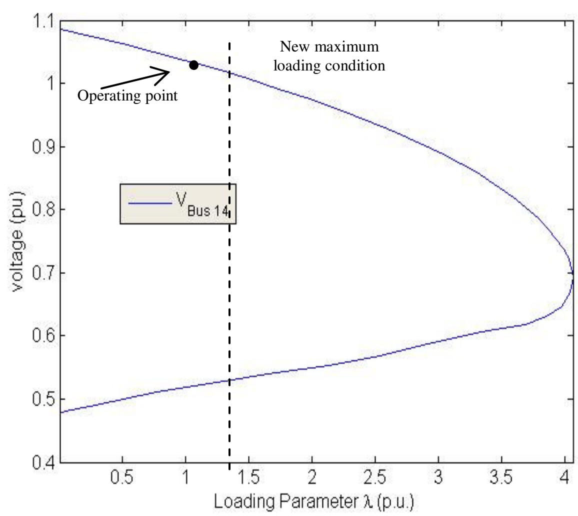


Fig 2.8 P-V curve for bus 14 when only apparent power flow limits through lines are taken into account.

Table 2.4 General results considering power flow limits.

base load [MW]	259
λ_{max} [pu]	1.483
MLC [MW]	643.2
ALC [MW]	384.2

Finally, in Fig 2.9 changes in PV curves owing to some contingencies in terms of line outages are depicted taking into account voltage and power flow boundaries. Therefore, for the outage of line 1-2 the limit is determined by the power flow through line 1-5, while for the outage of branch 2-4 the power flow through line 5-6 limited the maximum loading level. Table 2.5 contains a resume of the main results.

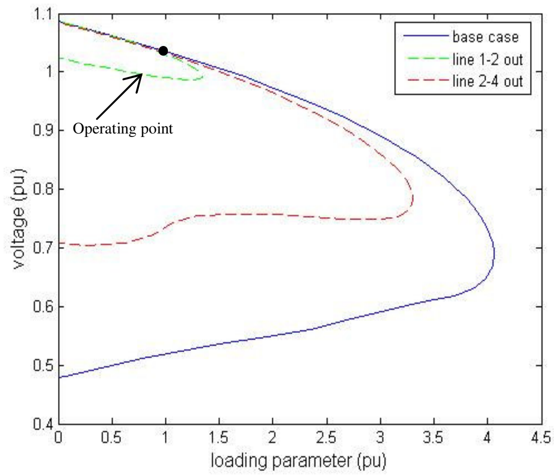


Fig 2.9 P-V curve for bus 14 for different contingencies taking into account voltage and power flow limits.

Table 2.5 General results considering different line outages.

	BASE CASE	LINE 1-2 OUT	LINE 2-4 OUT
base load [MW]	259	259	259
λ_{max} [pu]	1.484	1.152	1.441
MLC [MW]	643.2	557.4	632.2
ALC [MW]	384.2	298.4	373.2

2.3. Voltage Stability analysis: A brief review

2.3.1. Voltage collapse

Since voltage collapse usually leads to blackouts or extremely low voltage in significant areas of power systems, several methods have been proposed to date which can be classified in two different groups, namely, *static* and *dynamic* [27]. Table 2.6 contains the most remarkable features of both categories. Therefore, it seems interesting to review those methodologies published related to this matter [34]**.**

Table 2.6 Classification of voltage collapse approach.

STATIC APPROACH	- Quantification of how close a particular operating point is to the steady state voltage collapse point and estimation of the steady state voltage stability limit for the current operating point. - Requires not high rates of computation time and provides sensitive information. - Provides a closer insight into the system.
DYNAMIC APPROACH	- Analysing how different utilities affect the voltage stability form the viewpoint of dynamic. - Requires a set of differential equation to model excitation elements. - Demands high rates of computation and analysis time.

The static approach of the problem can be divided in two main categories such as, *index* and *optimization methods* [34][35][36]. Table 2.7 summarizes the main characteristics.

Table 2.7 Classification of static methods.

SATATIC	INDEX	- Provides information about the proximity of voltage collapse using different kind of indicators. - Simple and easy programming
	OPTIMIZATION	- Determines optimal control parameters to maximize load margins to voltage collapse. - Wide range of purpose - Accurate results

Index methods can be classified in the following way according to the literature:

- Based on a normal load flow solution (i.e. L-index) [37][38][39][40].
- Based on located power flow solution pairs [41]**.**
- Based on sensitivity analysis (i.e. VQ sensitivities) [39][42]
- Based on Newton-Raphon power flow Jacobian matrix (i.e. singular values, eigenvalues) [43][44]
- Local qualitative indices (i.e. load flow feasibility) [45]

Normally, indexes based on load flow solution are simpler than those which used sensitivity analysis or singular values owing to the straightforward of methods related to load flow equations. Arguably, a disadvantage of using minimum singular values as indexes is the large amount computation time required in performing a singular value factorization for large matrixes. However these problems could be balanced because of the fact that the high sensitivity of minimum singular value near instability limits. In addition, it has been proved that one drawback of simulation methods is the slowly convergence when the collapse region is approached. For this reason, it is complicated to determine the distance between the operating point and the voltage collapse point. Moreover, previous studies are required to determine the step for each iteration. However, the investigation of voltage collapse using load flow feasibility does not rely on load flow or optimal load flow simulations. Therefore, these problems are over come.

On the other hand, it is not possible to make so clear classification of optimization methods owing to the wide range of purpose of this technique [46]. Therefore some of the most important examples gathered in the literature are listed below.

- Optimal shunt and series compensation parameter settings to maximize the distance to a saddle-node bifurcation [47].
- Reactive power margin from the point of view of voltage collapse is determined using interior point methods. A barrier function is used to incorporate limits [48]
- Determine the closest bifurcation to the current operation point on the hyperspace of bifurcation points [49].
- Using the maximum load capability of power system is examined using interior point methods [50].
- Interior point optimization technique is used to determine the optimal PV generator settings to maximize the distance to voltage collapse [51][52].

The dynamic approach [27] to voltage is emerging with new studies. As a matter of fact, the role of reactive power in maintaining proper voltage profile in the system began receiving attention. Likewise, the importance of dynamics of the machines, exciters, tap changers as well as loads was found to effect voltage stability significantly. The major challenge for these methods is to demonstrate sufficient practical applicability in real system management. Thus, it is justified that although the classification shown in Table 2.6, interactions between different kind of stabilities is possible.

2.3.2. Optimal power flow including voltage stability considerations

In this section a review of the most important OPF formulations published to date which include security constraints related to voltage stability are presented. Therefore, Table 2.8 and Table 2.9 show a classification of these methods according to several criteria.

Table 2.8 Classification of OPF with voltage stability criteria according to market type, objective function and type of solution.

	TYPE OF MARKET		OBJECTIVE FUNCTION		MARKET SOLUTION		N-1
	SIMPLE AUCTION MARKET	HYBRID MARKET	SIMPLE	MULTI	PURE	NO PURE	IT IS POSSIBLE
SIMPLE ACTION SYSTEM WITH REDISPATH	X				X		
BASIC OPTIMAL POWER FLOW		X	X		X		
MAXIMUM LOADING DISTANCE		X	X		X		
SECURITY CONSTRAINED OPF-BASED ELECTRICITY MARKET		X	X		X		
VOLTAGE STABILITYCONS TRAINED OPF MARKET MODEL		X	X	X	X	X	X
MIXED CPF-OPF TECHNIQUE		X	X		X		X

According to Table 2.3, it is possible to observe that most studies have focused on hybrid markets [9]. Moreover, objective functions can be classified into different typology, namely, *simple* or *multi*. Simple objective functions usually introduce economic terms such as, generation cost, transmission losses or social benefit, while multiple objective function usually combine economic and security issues. The latter can be formulated in different ways [53], such is shown in Table 2.10**.** It is interesting to observe that voltage stability constrained OPF-market model can use both simple and multiple objective functions. The solution provided by these methods can be either *pure* or *no pure* [29][54]**.** In other words, when the algorithm generates a set of solutions it is said no pure market solution; otherwise the market solution is pure. Generally, multi objective formulations (i.e. linear combination) produce no pure market solutions because the explicitly parameter dependence. For this reason some techniques, such as mixed CPF-OPF, tries to overcome this problem.

Table 2.9 Classification of OPF with voltage stability criteria according to how the voltage stability is managed

	ITERATIVE COMPUTATION OF ATC AND REDISPATCH	BUS VOLTAGE LEVEL	INTRODUCTION OF A SECONDSET OF EQUATIONS	ACTIVE POWER TRANSFER LIMITS	ATC (available trans. capabil.)	MULTIOPJECTIVE FUNCTION	LOADING PARAMETER
SIMPLE ACTION SYSTEM WITH REDISPATH	X						
BASIC OPTIMAL POWER FLOW		X					
MAXIMUM LOADING DISTANCE		X	X		X		X
SECURITY CONSTRAINED OPF-BASED ELECTRICITY MARKET		X		X			
VOLTAGE STABILITYCONS TRAINED OPF MARKET MODEL		X	X		X	X	X
MIXED CPF-OPF TECHNIQUE		X	X		X		X

Table 2.9 demonstrates that each technology of OPF can use more than one mechanism to introduce voltage stability within the model. In all OPF model the bus voltage level is limited using a constraint that fixes upper and lower values. However, that is not enough to ensure voltage security. For this reasons another constraints are used [55][56]. Therefore, some methods introduce a second set of equations which are related to a loading parameter different to the current operating point [9] [53][54][57]. This idea consists on measure and maintains the distance between both operation points. Arguably those algorithms which used active power transfer limits calculated by off-line procedures are easier than others; however they might not reflect accurately the current situation studied. Undoubtedly, the incorporation of ATC (available transfer capability) [58][31][26][58] is the most extended method since improve the performance of the actual power system state. Normally, this magnitude is tight linked to the loading parameter. Finally, the loading parameter can be either fixed before solving the OPF or calculated as a variable. Furthermore, mostly all kind of OPF formulation can be extended to a *multi-period framework* [29]. In that case, time is included to take into account the variation of the parameters in each period.

Table 2.10 Different ways of formulating multi objective functions

FORMULATION OF MULTI OBJECTIVE FUNCTION
Linear combination
Fixed loading margin
Linear combination with a fixed loading margin
Modified goal programming

On the other hand, the introduction of *N-1 contingency* analysis is one of the main goals of the proposed techniques in this field since it can provide more realistic solutions [54][57]. Therefore, two of the methods listed before take into account this criterion. Table 2.11 summarizes these approaches. Normally, it is necessary iterative methods to programming N-1 analysis [59].

Table 2.11 Formulation of N-1 contingency.

SECURITY CONSTRAIN OPF-BASED ELECTRICITY MARKET	ITERATIVE METHOD WITH N-1 CONTINGENCY CRITERIO	- Determining the lowest SACT ("system wide" available transfer capability)
	MULTIPLE VSC-OPF WITH CONTINGENCY RANKING	- Using sensitivity factors.
MIXED CPF-OPF TECHNIQUE	- The security margin is determined using an N-1 contingency criterion.	

Finally, in [21] is demonstrated a tight relation between reactive power, active power and voltage instability phenomena. Therefore, similar models to those indicated previously consider reactive power and voltage stability together [60][61].

Chapter 3

Modelling of Electricity Markets: An Optimal Power Flow Formulation

This chapter describes in details the formulations of the mathematical models of deregulated electricity markets. The models are based on an optimal power flow (OPF) framework. These include base OPF (Optimal Power Flow), base OPF with FACTS (Optimal Power Flow using Flexible Alternating Current Transmission Systems), SM-OPF (Security Margin Optimal Power Flow) and SM-OPF with FACTS (Security Margin Optimal Power Flow using Flexible Alternating Current Transmission Systems). The advantages of using FACTS in power transmission systems are pointed out. Thyristor Controlled Series Compensation (TCSC), has been chosen among others in order to demonstrate the effectiveness of using FACTS devices in power operation and market results.

3.1 Market model based on OPF

As mentioned before three market structures are the most common around the world, namely *centralized or pool markets*, *decentralized or simple auction markets and hybrid or OPF-based markets* [2][8]. The importance of the second and third model has arisen during the last two decades owing to those deregulation processes that electricity sector has undergone. Therefore, it has been decided that this work is going to be focused on one of them, the hybrid or OPF-based market.

3.1.1 Formulation of an Optimal Power Flow framework

The OPF formulation was introduced in the early 1960s by Carpentier and it has turned out to be a useful tool to analyse power systems [62]. It is characterized to be a nonlinear programming problem consisting of one objective function that must be optimized in accordance with a set of associated equality and inequality constraints, as follows:

$$\begin{aligned}
&\textit{Maximize} \quad f(p) && (3.1)\\
&\textit{subject to} \quad g(x,p)=0 && (3.2)\\
&\qquad h_{\min} \le h(x,p) && (3.3)\\
&\qquad h(x,p) \le h_{\max} && (3.4)\\
&\qquad p_{\min} \le p && (3.5)\\
&\qquad p \le p_{\max} && (3.6)
\end{aligned}$$

where f is the objective function, $x \in \Re^n$ are the dependent variables, such as bus voltage phasors and $p \in \Re^m$ are the control variables, i.e., power demand and supply bids P_D and P_S respectively, $g \in \Re^n \to \Re^l$ are the equality constraints and $h \in \Re^n \to \Re^l$ the inequality constraints.

Naturally, computer tools are of utmost importance since obtaining a solution would be unfeasible in another way on account of the huge number of variables and no-linear equations. Nowadays, the most used mathematical method to solved non lineal programming problems in power system is the *interior point method* [63][64]. The main reason of this is their computational advantages when large systems have to be analyzed since include several operational and control limits. Two are the most popular interior point methods, the primal-dual interior point algorithm (PDIPM) and the predictor-corrector primal-dual interior point algorithm (PCPDIPM). The major different between both is the introduction of nonlinear terms into complementary equations by the former. Basically, all of them are based mainly on Lagrandgian formulation and Kuhn Tucker's Conditions [29]. These algorithms reports a series of multipliers that can be defined as marginal indicators associated to those variables that appear on the objective function. Therefore, it is possible to quantify the sensitivity of the objective function to a change in supply-demand market result and to the changes in unit operating limits [54]. The latter information is of great importance for the market participants since the strategies could be relied on that.

The objective function, *f*, used in this work is the *social welfare* defined as:

$$\text{maximize social welfare} \quad f(p) = \sum_i C_{Di} P_{Di} - \sum_i C_{Si} P_{Si} \qquad (3.7)$$

where C_{Si} represents supply price bibs, C_{Di} modelled demand price bids, P_{Si} introduces amount of power supply and P_{Di} corresponds to bulk of power demand.

It represents the maximization of social welfare related to production and consumption within the framework of electricity markets [8]. It is comprised of two terms. The first one, namely consumer surplus, is the sum of accepted demand bids. In other words, power demand cleared times the biding price associated to. The second term, producer surplus, corresponds to the accepted supply bids, defined as it the latter but using cost and power production values instead.

Moreover, the equality constraints, *g*, represent the standard power flow equations to both real and reactive power which are relied on dependent and control variables. On the other hand, *h*, restrict lower and upper limits of different variables such as, voltage, real and reactive power outputs and transmission lines loadings.

3.2 Modelling of transmission lines

The model used to represent transmission lines is the lumped π-equivalent, as is described in the Fig 3.1 [70]:

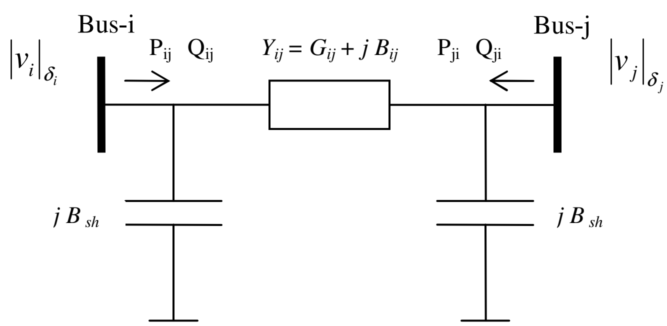


Fig 3.1 Lumped π-equivalent model of a transmission line and power flowing through it

The real and reactive power flow from bus-i to bus-j can be written as follows:

$$P_{ij} = |v_i|^2 G_{ij} - |v_i||v_j|\left[G_{ij}\cos(\delta_i - \delta_j) + B_{ij}\sin(\delta_i - \delta_j)\right] \tag{3.8}$$

$$Q_{ij} = -|v_i|^2 (B_{ij} + B_{sh}) - |v_i||v_j|\left[G_{ij}\sin(\delta_i - \delta_j) - B_{ij}\cos(\delta_i - \delta_j)\right] \tag{3.9}$$

Similarly, the real and reactive power flow from bus-j to bus-i is formulated,

$$P_{ji} = |v_j|^2 G_{ij} - |v_i||v_j|\left[G_{ij}\cos(\delta_i - \delta_j) - B_{ij}\sin(\delta_i - \delta_j)\right] \tag{3.10}$$

$$Q_{ji} = -|v_j|^2 (B_{ij} + B_{sh}) + |v_i||v_j|\left[G_{ij}\sin(\delta_i - \delta_j) + B_{ij}\cos(\delta_i - \delta_j)\right] \tag{3.11}$$

where $G_{ij} = \dfrac{r_{ij}}{r_{ij}^2 + x_{ij}^{\;2}}$ and $B_{ij} = \dfrac{-x_{ij}}{r_{ij}^2 + x_{ij}^{\;2}}$

3.3 Modelling of Flexible Alternating Current Transmission Systems (FACTS)

As mentioned before, one of the most important issues that has to be addressed after deregulation is the fact that power systems are being operated closer to their limits than ever, since all trade participants try to maximize their benefits without having to care about system conditions. Therefore, power transfers have undergone a faster growth than transmission capacity. Thus, operation of power systems has become remarkably more complicated, with a higher probability of suffering unscheduled contingencies and increase in losses. All things considered, systems are more insecure. Consequently, the newcomer Independent System Operator (ISO) might have to face these kinds of problems in real-time operation to facilitate those transactions set ahead following specific market rules. Particularly, one of these problems is congestion in some transmission lines when bulk of power flowing through them exceeds upper limits.

Thereby, ISO, as responsible for power system security has to relieve that congestion to ensure a secure state. Mainly there are two techniques at ISO's disposal to manage this situation which are the following ones [65] :

1. Cost-free measures:
   a. Out-aging of congested lines
   b. Operation of transformer tops phase shifters
   c. Operation of FACTS devices particularly series devices

2. Non-cost free measures:
   a. Re-dispatch of generation in a manner different from the natural setting point of the market. Some generators back down while others increase their output. The effect of this is that generators no longer operate at equal incremental costs.
   b. Curtailment of loads and the exercise of (not-cost-free) load interruption options.

In this work FACTS devices are used to relieve congestion and analyse effects on market results owing to the number of advantages assigned to them compared to the other techniques, such as better utilization of existing transmission system assets, increased transmission system reliability and availability, increased dynamic and transient grid stability and reduction of loop flows, increased quality of supply for sensitive customers and environmental benefits [65][66][67]. For example, FACTS as a cost-free option does not include economical issues related to GENCOS and DISCOS. Moreover, they can be placed in existing transmission systems saving the expenses associated to rebuilding tasks.

FACTS technology can be classified within the power electronic field which performs a rapid improvement day by day. Therefore, nowadays it is a relevant area of study with prosperous applications to power transmission systems among others. Thus, it is possible to list some of the most important advantages of using these devices [66][67]:

- Greater control of power transmitted.
- Secure loading of transmission lines to level nearer to their thermal limits.
- Greater ability of transfer between controlled areas.
- Prevention of cascading outages.
- Damping of power system oscillations.

The latter group of features is relied on the following concept. As is well known, power flowing through an ac line is determined as a function of mainly three variables or parameters, such as phase angle, line end voltage and line impedance. Traditional methods to alleviate congestion and other related events do not perform any direct influent on these variables. Therefore, their efficiency and efficacy in this framework could be limited in comparison to FACTS devices that bring the opportunity to controlling any of the previous variables as demonstrated in Fig 3.2.

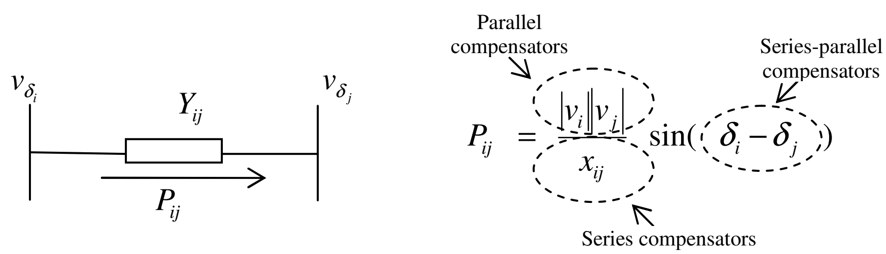


Fig 3.2 Simply FACTS classification based on main effects

It is possible to point out different typologies of FACTS devices [68], such as those included in the next list and in Fig 3.3. Moreover Table 3.1 shows benefits of these components for different applications [67].

- Static Var Compensators (SVC)
- Static Compensators (STATCOM)
- Thyristor Controlled Series Capacitors (TCSC)
- Universal Power Flow Controllers (UPFC)
- Thyristor Controlled Phase Shifter (TCPS)

Table 3.1 Benefits of FACTS devices for different applications.
* → *** better

	Load flow control	Voltage control	Transient stability	Dynamic stability
SVC	*	***	*	**
STATCOM	*	***	**	**
TCSC	**	*	***	**
UPFC	***	***	**	**

(source: Klaus Habur and Donal O'Leary *"For Cost Effective and Reliable Transmission of Electrical Energy"*)

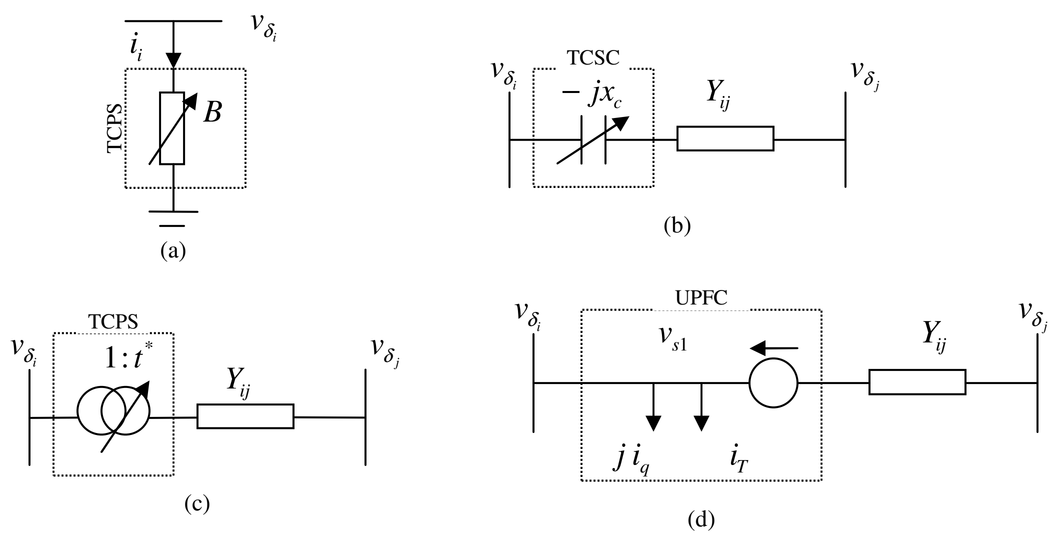


Fig 3.3 Circuit diagram of different FACTS devices. (a) TCPS can be seen as a variable shunt suceptance. (b) TCSC can be seen as a controllable reactance. (c) TCPS can be seen as an equivalent ideal transformer with complex taps. (d) UPFC controls three parameters: magnitude and angle of the inserted voltage, *vs1 φs1* , and the magnitude of the current *iq*

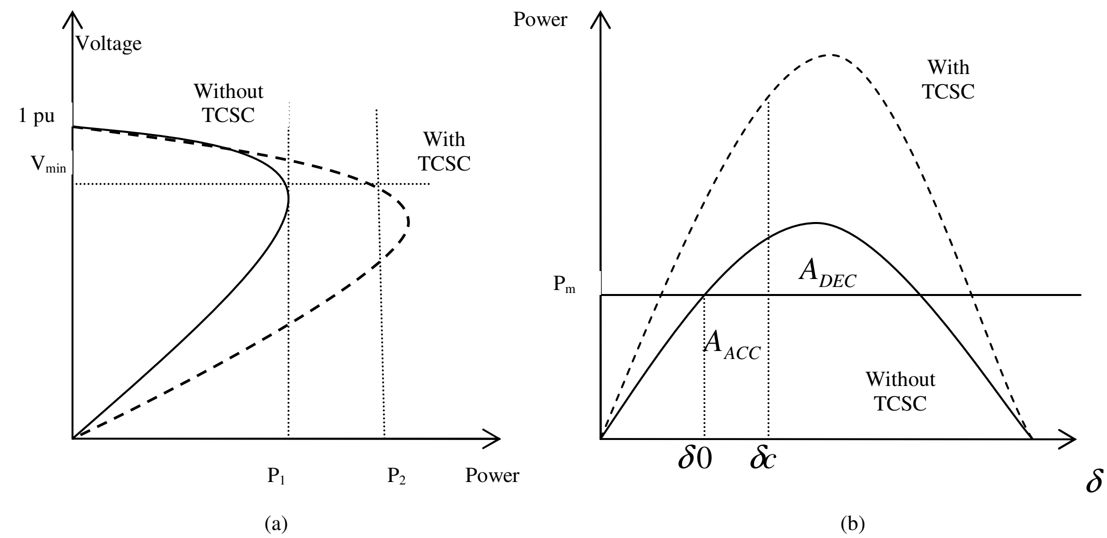
Numerous studies have been published to combine the use of both FACTS devices and OPF. Thus, in [69] a new genetic algorithm/particle swarm optimization searching method (GA/PSO) is developed to search optimal location for FACTS devices and associated optimal system settings using OPF with different objectives function, such as fuel cost minimization, voltage profile improvement and voltage stability enhancement. Moreover, in [65][70][75][77] congestion management in deregulated power system including FACTS devices is treated. In [72] an Interior-Point based OPF is presented when FACTS are introduced in deregulation environment, while in [73] is described an optimization method relied on sequential quadratic programming (SQP). Authors in [74] propose a two step method which consists on a power flow control problem and a conventional OPF problem. Furthermore, in [76] is described how to modify a based OPF formulation in order to include different types of FACTS devices using power model injection.

On the other hand, probably one drawback of FACTS devices is the high investment related to the installation. For this reason, it is necessary to perform different studies in order to find out which is the most efficient location taken into account different factors. Therefore, some sensibility indexes have been performed in order to determine the optimal solution according to the latter point. Thus, in [70][78] are used factors based on reduction of total system reactive power loss and real power flow variation. Finally, [70][71], cost-benefit analyses are proposed to evaluate the economical justification of using FACTS devices for congestion management. Finally, in [68] it is presented an exhaustive review of these devices role in deregulation electric power systems from different viewpoints, such as benefits and technical problems, while in [67] is carried out a comprehensive comparison of different types of FACTS based on several criteria providing real examples of power systems where these components have been implemented, as well as the reported results.

3.3.1 Static model of TCSC

Thyristor Controlled Series Compensation (TCSC) has been chosen, among other types of FACTS, to be implemented in both models OPF and SM-OPF. Basically, TCST in steady state can be defined as a variable capacitance which contributes with reactance $-jx_c$ in series with the line impedance. Therefore, the main contribution of these devices consists on reduce the inductance character of those transmission lines where they are located, and thus influent on [68]: current control, damping oscillation, transient and dynamic stability, voltage stability, fault current limiting. As a result of the influent on voltage stability, this typology has been chosen to be introduced in the models presented in this work. Fig 3.4 demonstrates two effects of introducing TCST devices in power systems.

As a matter of interest, it is possible to trace power systems that have been equipped with TCST devices all over the world yielding positive results [67]. For example, the line that interconnects the North grid and the South grid in Brazil since 1999, which cover more than 95% of the electric power transmission in the country, includes TCST. It has been demonstrated, among others, reduction of losses, stabilization of the line and mitigation of resonance phenomena. Moreover, in the Kayenta Substation, Arizona, Western Area Power Administration (WAPA) system, USA, was installed a TCSC unit in order to overcame a bottleneck limitation in the power system transmission. As a result, the power transfer increase by 33% maintaining reliable system operation and withstand successfully certain contingencies.



P	power	δ0	pre-fault generator angle
V	voltage	δc	angle at fault clearing
δ	generator angle	A_{ACC}	accelerating energy
		A_{DEC}	retarding energy.

Fig 3.4 Two improvements due to TCSC.
(a) Improvement of voltage profile. (b) Improvement of stability margin

There are two methods to include FACTS within the electrical equations. The first one consists of modifying the admittance matrix through the contribution of $-jx_c$. The second alternative, which is used in this work, is based on a power injection model [70][76] which would avoid changing the original power system admittance matrix as is demonstrated below:

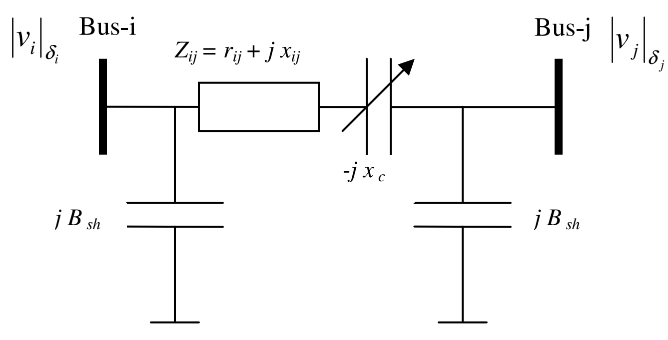


Fig 3.5 Lumped π-equivalent model of a transmission line with TCSC.

The real and reactive power flow from bus-i to bus-j, and from bus-j to bus-i of a transmission line modelled according to the π equivalent circuit having a TCSC connected shown in Fig 3.5, are:

$$P^c{}_{ij} = |v_i|^2 G'_{ij} - |v_i||v_j|\left[G'_{ij}\cos(\delta_i - \delta_j) + B'_{ij}\sin(\delta_i - \delta_j)\right] \quad (3.12)$$

$$Q^c{}_{ij} = -|v_i|^2 (B'_{ij} + B_{sh}) - |v_i||v_j|\left[G'_{ij}\sin(\delta_i - \delta_j) - B'_{ij}\cos(\delta_i - \delta_j)\right] \quad (3.13)$$

$$P^c{}_{ji} = |v_j|^2 G'_{ij} - |v_i||v_j|\left[G'_{ij}\cos(\delta_i - \delta_j) - B'_{ij}\sin(\delta_i - \delta_j)\right] \quad (3.14)$$

$$Q^c{}_{ji} = -|v_j|^2 (B'_{ij} + B_{sh}) + |v_i||v_j|\left[G'_{ij}\sin(\delta_i - \delta_j) + B'_{ij}\cos(\delta_i - \delta_j)\right] \quad (3.15)$$

Furthermore, it is possible to calculate the active and reactive power loss in that line using the following expressions,

$$P_{loss} = P_{ij} + P_{ji} = G'_{ji}(|v_i|^2 + |v_j|^2) - 2|v_i||v_j|G'_{ij}\cos(\delta_i - \delta_j) \quad (3.16)$$

$$Q_{loss} = Q_{ij} + Q_{ji} = -(|v_i|^2 + |v_j|^2)(B'_{ij} + B_{sh}) + 2|v_i||v_j|B'_{ij}\cos(\delta_i - \delta_j) \quad (3.17)$$

where $G'_{ij} = \dfrac{r_{ij}}{r_{ij}^2 + (x_{ij} - x_c)^2}$ and $B'_{ij} = \dfrac{-(x_{ij} - x_c)}{r_{ij}^2 + (x_{ij} - x_c)^2}$

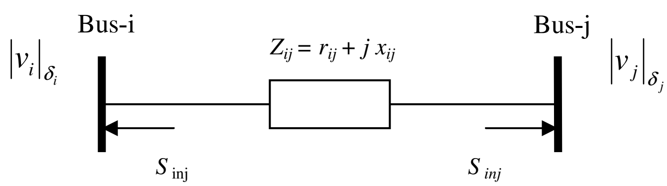


Fig 3.6 Injection model of TCSC

The equivalent model for the line depicted in Fig 3.5 can be represented as a line without series capacitances associated to TCSC and with power injection at the receiving and sending ends of the branch, Fig 3.6. Therefore, the apparent power injected at bus-i and bus-j can be written as,

$$S_{inj\,\mathrm{i}} = P_{inj\,\mathrm{i}} + jQ_{inj\,\mathrm{i}} \quad (3.18)$$

$$S_{inj\,\mathrm{j}} = P_{inj\,\mathrm{j}} + jQ_{inj\,\mathrm{j}} \quad (3.19)$$

The active and reactive power flow injections used in (3.18) and (3.19) are calculated according to the following expressions,

$$P_{inj\,\mathrm{i}} = P_{ij}^c - P_{ij} = |v_i|^2 \Delta G_{ij} - |v_i||v_j|\left[\Delta G_{ij}\cos(\delta_i - \delta_j) + \Delta B_{ij}\sin(\delta_i - \delta_j)\right] \tag{3.20}$$

$$Q_{inj\,\mathrm{i}} = Q_{ij}^c - Q_{ij} = -|v_i|^2 \Delta B_{ij} - |v_i||v_j|\left[\Delta G_{ij}\sin(\delta_i - \delta_j) - \Delta B_{ij}\cos(\delta_i - \delta_j)\right] \tag{3.21}$$

$$P_{inj\,\mathrm{j}} = P_{ji}^c - P_{ji} = |v_j|^2 \Delta G_{ij} - |v_i||v_j|\left[\Delta G_{ij}\cos(\delta_i - \delta_j) - \Delta B_{ij}\sin(\delta_i - \delta_j)\right] \tag{3.22}$$

$$Q_{inj\,\mathrm{j}} = Q_{ji}^c - Q_{ji} = -|v_j|^2 \Delta B_{ij} + |v_i||v_j|\left[\Delta G_{ij}\sin(\delta_i - \delta_j) + \Delta B_{ij}\cos(\delta_i - \delta_j)\right] \tag{3.23}$$

where $\Delta G_{ij} = \dfrac{x_c r_{ij}(x_c - 2x_{ij})}{(r_{ij}^2 + x_{ij}^2)(r_{ij}^2 + (x_{ij} - x_c)^2)}$ and $\Delta B_{ij} = \dfrac{-x_c(r_{ij}^2 - x_{ij}^2 + x_c x_{ij})}{(r_{ij}^2 + x_{ij}^2)(r_{ij}^2 + (x_{ij} - x_c)^2)}$

3.4 Market models considered

3.4.1 Base OPF

The base OPF model used in this work is defined according to the general formulation presented in section 3.1.1 as follows:

a Objective function.

$$Min\ \ Z = -(Cd\ Pd - Cs\ Ps) \tag{3.24}$$

The objective function used is the social welfare described in section 3.1.1. It should be observed that in this case the expression is minimised instead of being maximised. The result is identical since all right hand terms are multiplied by -1. However the sign of marginal values change, though their meanings are the same.

b Power flow equations

$$Ps_i - Pd_i = \sum_{j=1}^{n} |v_i||v_j||Y_{ij}|\cos(\delta_i - \delta_j - \psi_{ij}) \tag{3.25}$$

$$Qg_i - Pd_i tg\phi_i = \sum_{j=1}^{n} |v_i||v_j||Y_{ij}|\sin(\delta_i - \delta_j - \psi_{ij}) \tag{3.26}$$

It is assume that the power factor is constant for each load, $\mathrm{tg}(\phi_\mathrm{i}) = \mathrm{cte}$.

c Apparent power flow limitation

$$S_{ij} = \sqrt{P_{ij}^2 + Q_{ij}^2} \leq S_{ij\,\max} \tag{3.27}$$

$$P_{ij} = |v_i|^2 G_{ij} - |v_i||v_j|\left[G_{ij}\cos(\delta_i - \delta_j) + B_{ij}\sin(\delta_i - \delta_j)\right] \tag{3.28}$$

$$Q_{ij} = -|v_i|^2 (B_{ij} + B_{sh}) - |v_i||v_j|\left[G_{ij}\sin(\delta_i - \delta_j) - B_{ij}\cos(\delta_i - \delta_j)\right] \tag{3.29}$$

Similarly, S_{ji} P_{ji} Q_{ji} are calculated substituting i by j and vice versa in equations (3.27) (3.28) (3.29)

d Supply and demand bids blocks

$$Ps_{\min} \leq Ps \leq Ps_{\max} \tag{3.30}$$
$$Pd_{\min} \leq Pd \leq Pd_{\max} \tag{3.31}$$

e Generation reactive power limits

$$\mathrm{Qg}_{\min} \leq Qg \leq Qg_{\max} \tag{3.32}$$

f Voltage limits

$$V_{\min} \leq v \leq V_{\max} \tag{3.33}$$
$$-\pi/2 \leq \delta \leq \pi/2 \tag{3.34}$$

The need of keeping bus voltages within a certain range is justified to facilitate voltage regulation and enhance security in the operation of transmission systems. Therefore the upper limit is related to avoid insulation failures. However, the lower limit is considerer more arbitrary [8].

In this model the security constraints can be associated to voltages constraints and transmission lines loadings which can be used as a measure of congestion rate at each line. However, it is not possible to quantify directly how much distanced the actual operating point is from the one which defines the commencement of infeasibility region. Therefore, this method is useful to determine, in a proper manner, a current system state but not information about security issues is reported explicitly which is considered a drawback for the market participants since it could be a limitation to determine their strategies.

Finally, a fragment of the code written en GAMS to programme this model is shown in the next frame.

```
EQUATIONS

 SOCIALW     z     objective function for market: social welfare

 PBAL(N)             active power balance in each bus - current state [pu]
 QBAL(N)             reactive power balance in each bus - current state [pu]

 P_flow(N,NC)       Pflow  active power line flow  - current state [pu]
 Q_flow(N,NC)       Qflow  active power line flow  - current state [pu]
 S_flow(N,NC)              apparent power line flow - current state [pu]

;

* OBJECTIVE FUNCTION

SOCIALW..   z=e=(-1)*(sum(N$(BUS(N,'PDMAX') ne
               0),0*BUS(N,'A')*sqr(pbd(N))+BUS(N,'B')*pbd(N)+0*BUS(N,'C'))-
               sum(G$(GDATA(G,'GEN_TYPE') eq
               1),0*GDATA(G,'A')*sqr(pbs(G))+GDATA(G,'B')*pbs(G)+0*GDATA(G,'C')));

* POWER FLOW EQUATIONS

PBAL(N)..   sum(G$(GN(G,N) and (GDATA(G,'GEN_TYPE') eq 1)),((pbs(G)/SB)))-
               ((pbd(N)/SB)$(BUS(N,'PDMAX') ne 0))=e=sum(NC$(CONEX(N,NC) or CONEX(NC,N)
               or (ord(N) eq ord(NC))),MOMATRIX(N,NC)*v(NC)*v(N)*cos(d(N)-d(NC)-
               ARMATRIX(N,NC)));

QBAL(N)..   sum(G$(GN(G,N)),(qg(G)/SB))-
               (((pbd(N)/SB))*(BUS(N,'QL')/BUS(N,'PL')))$(BUS(N,'PL') ne
               0)=e=sum(NC$(CONEX(N,NC) or CONEX(NC,N) or (ord(N) eq
               ord(NC))),MOMATRIX(N,NC)*v(NC)*v(N)*sin(d(N)-d(NC)-ARMATRIX(N,NC)));

* ACTIVE, REACTIVE AND APPARENT POWER THROUGH LINES

P_flow(N,NC)$((CONEX(N,NC) or CONEX(NC,N)))..   Pflow(N,NC)=e=((-
               RMATRIX(N,NC))*(sqr(v(N))-v(N)*v(NC)*cos(d(N)-d(NC)))-(-
               IMATRIX(N,NC))*v(N)*v(NC)*sin(d(N)-d(NC)));

Q_flow(N,NC)$((CONEX(N,NC) or CONEX(NC,N)))..   Qflow(N,NC)=e=(-1*sqr(v(N))*(-
               IMATRIX(N,NC)+LINE(N,NC,'Y')/2+LINE(NC,N,'Y')/2)-v(N)*v(NC)*((-
               RMATRIX(N,NC))*sin(d(N)-d(NC))-(-IMATRIX(N,NC))*cos(d(N)-d(NC))));

S_flow(N,NC)$(CONEX(N,NC) or CONEX(NC,N))..
               sqrt(sqr(Pflow(N,NC))+sqr(Qflow(N,NC)))=l=FS*((LINE(N,NC,'Smax')/(SB))+
               (LINE(NC,N,'Smax')/(SB)));

MODEL opf /
  SOCIALW
  PBAL
  QBAL
  P_flow
  Q_flow
  S_flow
  /;

SOLVE opf USING nlp MINIMIZE z;
```

3.4.2 OPF with FACTS

The OPF model presented before is modified in order to include FACTS devices. As mentioned before Thyristor Controlled Series Compensation (TCSC) has been chosen in order to study the effects on the market results. According to the previous section the OPF including TCSC is defined as follows:

a Objective function: Social welfare

$$Min\ \ Z = -(Cd * Pd - Cs * Ps) \tag{3.35}$$

b Power injection for TCSC

$$P_{inj\,\mathrm{i}} = |v_i|^2 \Delta G_{ij} - |v_i||v_j|\left[\Delta G_{ij}\cos(\delta_i - \delta_j) + \Delta B_{ij}\sin(\delta_i - \delta_j)\right] \tag{3.36}$$

$$Q_{inj\,\mathrm{i}} = -|v_i|^2 \Delta B_{ij} - |v_i||v_j|\left[\Delta G_{ij}\sin(\delta_i - \delta_j) - \Delta B_{ij}\cos(\delta_i - \delta_j)\right] \tag{3.37}$$

where
$$\Delta G_{ij} = \frac{x_{TCSC}\, r_{ij}\,(x_{TCSC} - 2x_{ij})}{(r_{ij}^2 + x_{ij}^2)(r_{ij}^2 + (x_{ij} - x_{TCSC})^2)} \tag{3.38}$$

$$\Delta B_{ij} = \frac{-x_{TCSC}\,(r_{ij}^2 - x_{ij}^2 + x_{TCSC}\, x_{ij})}{(r_{ij}^2 + x_{ij}^2)(r_{ij}^2 + (x_{ij} - x_{TCSC})^2)} \tag{3.39}$$

c Power flow equations

$$Ps_i - Pd_i = \sum_{j=1}^{n} |v_i||v_j||Y_{ij}|\cos(\delta_i - \delta_j - \psi_{ij}) - P_{inj\,\mathrm{i}} \tag{3.40}$$

$$Qg_i - Pd_i tg\phi_i = \sum_{j=1}^{n} |v_i||v_j||Y_{ij}|\sin(\delta_i - \delta_j - \psi_{ij}) - Q_{inj\,\mathrm{i}} \tag{3.41}$$

In this case the power flow equation (3.26) and (3.27) are modified in order to include the charge in the line due to TCSC according to the power injection model presented in section 3.3.1.

d Apparent power flow limitation

$$S_{ij} = \sqrt{P_{ij}^2 + Q_{ij}^2} \leq S_{ij\max} \tag{3.42}$$

$$P_{ij} = |v_i|^2 G_{ij} - |v_i||v_j|\left[G_{ij}\cos(\delta_i - \delta_j) + B_{ij}\sin(\delta_i - \delta_j)\right] - P_{inj\,\mathrm{i}} \tag{3.43}$$

$$Q_{ij} = -|v_i|^2 (B_{ij} + B_{sh}) - |v_i||v_j|\left[G_{ij}\sin(\delta_i - \delta_j) - B_{ij}\cos(\delta_i - \delta_j)\right] - Q_{inj\,\mathrm{i}} \tag{3.44}$$

The latter expressions include the effects of TCSC in terms of power injection.

e Supply and demand bids blocks

$$Ps_{\min} \leq Ps \leq Ps_{\max} \tag{3.45}$$

$$Pd_{\min} \leq Pd \leq Pd_{\max} \tag{3.46}$$

f Generation reactive power limits

$$\mathrm{Qg}_{\min} \leq Qg \leq Qg_{\max} \tag{3.47}$$

g Voltage limits

$$V_{\min} \leq v \leq V_{\max} \tag{3.48}$$

$$-\pi/2 \leq \delta \leq \pi/2 \tag{3.49}$$

h Compensation limits

$$0 \leq x_{TCSC} \leq 0.8\, x_{ij} \tag{3.50}$$

The compensation limit associated to TCSC units is limited to avoid resonance problems with other elements in the system that could produce dramatic operating problems.

Finally, a fragment of the code written en GAMS to programme this model is shown in the next frame.

```
EQUATIONS

 SOCIALW    z    objective function for market: social welfare

 eq1   delta_G  conductance change from i to j owing to FACTS - current state [pu]
 eq2   delta_B  suceptance change from i to j  owing to FACTS - current state [pu]
 eq3   delta_G  conductance change from j to i owing to FACTS - critical state [pu]
 eq4   delta_B  suceptance change from j to i  owing to FACTS - critical state [pu]

 eq5    Pinj      active power injected at bus N for FACT model - current state [pu]
 eq6    Qinj      active power injected at bus N for FACT model - current state [pu]

 PBAL(N)           active power balance in each bus - current state [pu]
 QBAL(N)           reactive power balance in each bus - current state [pu]

 P_flow(N,NC)      Pflow  active power line flow - current state [pu]
 Q_flow(N,NC)      Qflow  active power line flow - current state [pu]
 S_flow(N,NC)             apparent power line flow - current state [pu]
;

* OBJECTIVE FUNCTION

SOCIALW..  z=e=(-1)*(sum(N$(BUS(N,'PDMAX') ne
      0),0*BUS(N,'A')*sqr(pbd(N))+BUS(N,'B')*pbd(N)+0*BUS(N,'C'))-
      sum(G$(GDATA(G,'GEN_TYPE') eq
      1),0*GDATA(G,'A')*sqr(pbs(G))+GDATA(G,'B')*pbs(G)+0*GDATA(G,'C')));
```

```
* POWER INJECTION MODEL TCSC

eq1(N,NC)$(TCSC(N,NC)).. delta_G(N,NC)=e=(-
      1)*MOMATRIX(N,NC)*cos(ARMATRIX(N,NC))*((-1)*(2*LINE(N,NC,'X')-
      xtcsc(N,NC))*xtcsc(N,NC))/(sqr(LINE(N,NC,'R'))+sqr(LINE(N,NC,'X')-
      xtcsc(N,NC)));

eq2(N,NC)$(TCSC(N,NC)).. delta_B(N,NC)=e=-xtcsc(N,NC)*(sqr(LINE(N,NC,'R'))-
      sqr(LINE(N,NC,'X'))+xtcsc(N,NC)*LINE(N,NC,'X'))/((sqr(LINE(N,NC,'R'))+sqr(LINE
      (N,NC,'X')))*(sqr(LINE(N,NC,'R'))+sqr(LINE(N,NC,'X')-xtcsc(N,NC))));

eq3(N,NC)$(TCSC(N,NC)).. delta_G(NC,N)=e=delta_G(N,NC);

eq4(N,NC)$(TCSC(N,NC)).. delta_B(NC,N)=e=delta_B(N,NC);

eq5(N,NC)$(TCSC(N,NC) or TCSC(NC,N)).. Pinj(N,NC)=e=sqr(v(N))*delta_G(N,NC)-
      v(N)*v(NC)*(delta_G(N,NC)*cos(d(N)-d(NC))+delta_B(N,NC)*sin(d(N)-d(NC)));

eq6(N,NC)$(TCSC(N,NC) or TCSC(NC,N)).. Qinj(N,NC)=e=-sqr(v(N))*delta_B(N,NC)-
      v(N)*v(NC)*(delta_G(N,NC)*sin(d(N)-d(NC))-delta_B(N,NC)*cos(d(N)-d(NC)));

* POWER FLOW EQUATIONS

PBAL(N).. sum(G$(GN(G,N) and (GDATA(G,'GEN_TYPE') eq 1)),((pbs(G)/SB)))-
      ((pbd(N)/SB)$(BUS(N,'PDMAX') ne 0))=e=sum(NC$(CONEX(N,NC) or CONEX(NC,N) or
      (ord(N) eq ord(NC))),MOMATRIX(N,NC)*v(NC)*v(N)*cos(d(N)-d(NC)-
      ARMATRIX(N,NC)))-sum(NC$(TCSC(N,NC) or TCSC(NC,N)),Pinj(N,NC));

QBAL(N).. sum(G$(GN(G,N)),(qg(G)/SB))-
      (((pbd(N)/SB))*(BUS(N,'QL')/BUS(N,'PL')))$(BUS(N,'PL') ne
      0)=e=sum(NC$(CONEX(N,NC) or CONEX(NC,N) or (ord(N) eq
      ord(NC))),MOMATRIX(N,NC)*v(NC)*v(N)*sin(d(N)-d(NC)-ARMATRIX(N,NC)))-
      sum(NC$(TCSC(N,NC) or TCSC(NC,N)),Qinj(N,NC));

* ACTIVE, REACTIVE AND APPARENT POWER THROUGH LINES

P_flow(N,NC)$((CONEX(N,NC) or CONEX(NC,N))).. Pflow(N,NC)=e=((-
      RMATRIX(N,NC))*(sqr(v(N))-v(N)*v(NC)*cos(d(N)-d(NC)))-(-
      IMATRIX(N,NC))*v(N)*v(NC)*sin(d(N)-d(NC))-Pinj(N,NC)$(TCSC(N,NC) or
      TCSC(NC,N)));

Q_flow(N,NC)$((CONEX(N,NC) or CONEX(NC,N))).. Qflow(N,NC)=e=(-1*sqr(v(N))*(-
      IMATRIX(N,NC)+LINE(N,NC,'Y')/2+LINE(NC,N,'Y')/2)-v(N)*v(NC)*((-
      RMATRIX(N,NC))*sin(d(N)-d(NC))-(-IMATRIX(N,NC))*cos(d(N)-d(NC)))-
      (Qinj(N,NC)$(TCSC(N,NC) or TCSC(NC,N))));

S_flow(N,NC)$(CONEX(N,NC) or CONEX(NC,N))..
      sqrt(sqr(Pflow(N,NC))+sqr(Qflow(N,NC)))=l=FS*((LINE(N,NC,'Smax')/(SB))+(LINE(N
      C,N,'Smax')/(SB)));

MODEL opf /
  SOCIALW
  PBAL
  QBAL
  eq1
  eq2
  eq3
  eq4
  eq5
  eq6
  P_flow
  Q_flow
  S_flow
  /;

SOLVE opf USING nlp MINIMIZE z;
```

3.4.3 SM-OPF

This is a recent way to incorporate security issues in OPF formulation. It is possible to find through the literature provided in Chapter 2 several ways to address this topic. Therefore, the model used in this work is based on different researches carried out to date.

The main distinction between this model and the base OPF presented before is a new set of equations depended on a loading parameter λ, described in Chapter 2, that drives the system to its maximum loading condition [29]. As a result, it is possible to distinguish two operational states. The first one, namely current operating point, correspond to the actual working point defined by specific values for each variable, while the second one is used to perform security issues. That is, demonstrate how far the system can be settled using predetermine λ ensuring feasibility. Moreover, K_g is used to distribute the active losses associated to the latter state. It is said that the system stops being feasible because it is not possible to fulfil all constraints imposed to the model since some variables reach either a lower or upper limit. It is important to emphasize that there’s no reason for the system to become infeasible when the first limit is achieved by some variable since the capacity of rearranging the others to keep the feasibility though the market results could be not as beneficial as before that situation.

Furthermore, different parameter are defined as a result of the addition of λ, such as Total Transaction Load (TTL), Available Transaction Capacity (ATC) and Maximum Transaction Level (MTL) which are developed below based on the comments pointed out in Chapter 2.

$$P_{Gi} = Ps_i \quad (3.51)$$

$$P_{Li} = Pd_i \quad (3.52)$$

$$P_{G'i} = (1+\lambda+K_{Gc})P_{Gi} \quad (3.53)$$

$$P_{Lci} = (1+\lambda)P_{Li} \quad (3.54)$$

$$MLC = (1+\lambda_C)\sum P_{Li} \quad (3.55)$$

$$ALC = MLC - \sum P_{Li} = MLC - TTL \quad (3.56)$$

$$TTL = \sum P_{Li} \quad (3.57)$$

$$ALC = \lambda_C \sum P_{Li} = \lambda_C TTL \quad (3.58)$$

The ALC index is often used as an indicator of additional power that can be security transferred by the transmission network. It is worth mentioning that since the objective function used is the maximization of social welfare which relies only on variables associated to the current operating point, the loaded state does not ensure that premise. However, the most important thing provided to both operators and market participants through this model is the capacity of analysing consequences of different action regarding to security issues and thus planning decisions.

Normally it is considered that λ has to be within certain boundaries. Therefore, a lower limit is introduced in order to ensure a minimum level of security and the upper one to impose the counterpart. As will be demonstrated the upper boundary is determined either by low local marginal prices (LMP) [29][79] or infeasibility problems, though both of them are fairly related to each other.

Finally, other important concept is the total price paid to the Independent Market Operator (PAY_IMO) which is related to the social welfare and congestion payment. LMP are basically the Lagrangian multipliers of the active power flow equations included in the models. Therefore each bus is characterised by different prices. That is, market participants pay for their consumption or get paid for their productions according to bids as well as congestions cases in the network. The relation between social welfare and market operator payment is explained below:

$$PAY\_IMO = \sum_{\mathrm{i}} LMP_i \;\; P_{inj\,balance\,\mathrm{i}} = \sum_{\mathrm{i}} LMP_i \;\; (P_{Di} - P_{Si}) \tag{3.59}$$

where:

$$LMP_{Si} = \rho_{P_{Si}} = C_{Si} + \mu_{P_{S\max i}} - \mu_{P_{S\min i}} \tag{3.60}$$

$$LMP_{Di} = \rho_{P_{Di}} = C_{Di} + \mu_{P_{D\max i}} - \mu_{P_{D\min i}} - \rho_{Q_{Di}} \tan(\phi_{Di}) \tag{3.61}$$

$$LMP_{Si} = LMP_{Di} \rightarrow LMP_i \tag{3.62}$$

$$P_{inji} = P_{Gi} - P_{Di} \tag{3.63}$$

Moreover,

$$\begin{aligned} PAY\_IMO &= \sum_i LMP_i \; P_{inj\,balance\,i} = \\ &= \sum_i LMP_i \, (P_{Di} - P_{Si}) = \text{Bid part} + \text{Congestion part} \end{aligned} \tag{3.64}$$

where $\text{Bid part} = \mathrm{f}\ (\mathrm{C_{Si}}, \mathrm{C_{Di}})$, $\text{Congestion part} = \mathrm{f}\ (\mu_{P\min}, \mu_{P\max})$ and μ are the multipliers of P_s and P_s in Lagrange formulation.

However the latter formulation for local marginal prices is valid only for a single OPF since the loading parameter λ used in SM-OPF affects them as can see below. Therefore, it could be complicated to compare the payment calculated by OPF and SM-OPF.

$$LMP_{Si} = \rho_{P_{Si}} = C_{Si} + \mu_{P_{S\max i}} - \mu_{P_{S\min i}} - \rho_{cP_{Si}}(1+\lambda+K_g) \tag{3.65}$$

$$LMP_{Di} = \rho_{P_{Di}} = C_{Di} + \mu_{P_{D\max i}} - \mu_{P_{D\max ii}} - \rho_{cP_{Di}}(1+\lambda) - \rho_{cQ_{Di}}(1+\lambda)\tan(\phi_{Di}) \tag{3.66}$$

Therefore, the SM-OPF model is defined as follows:

a Objective function: Social welfare

$$Min\ \ Z = -(Cd * Pd - Cs * Ps) \tag{3.67}$$

b Power flow equations

$$Ps_i - Pd_i = \sum_{j=1}^{n} |v_i||v_j||Y_{ij}|\cos(\delta_i - \delta_j - \psi_{ij}) \tag{3.68}$$

$$Qg_i - Pd_i tg\phi_i = \sum_{j=1}^{n} |v_i||v_j||Y_{ij}|\sin(\delta_i - \delta_j - \psi_{ij}) \tag{3.69}$$

$$(1+\lambda+Kg)Pg_i - (1+\lambda)Pd_i = \sum_{j=1}^{n} |v_{ci}||v_{cj}||Y_{ij}|\cos(\delta_{ci} - \delta_{cj} - \psi_{ij}) \tag{3.70}$$

$$Qg_{ci} - (1+\lambda)Pd_i tg\phi_i = \sum_{j=1}^{n} |v_{ci}||v_{cj}||Y_{ij}|\sin(\delta_{ci} - \delta_{cj} - \psi_{ij}) \tag{3.71}$$

where (3.70) and (3.71) represent the new set of power flow equation described previously in this section which new variables are distinguished by the sub index "c"

c Apparent power flow limitation

$$S_{ij} = \sqrt{P_{ij}^2 + Q_{ij}^2} \le S_{ij\max} \tag{3.72}$$

$$P_{ij} = |v_i|^2 G_{ij} - |v_i||v_j|[G_{ij}\cos(\delta_i - \delta_j) + B_{ij}\sin(\delta_i - \delta_j)] \tag{3.73}$$

$$Q_{ij} = -|v_i|^2 (B_{ij} + B_{sh}) - |v_i||v_j|[G_{ij}\sin(\delta_i - \delta_j) - B_{ij}\cos(\delta_i - \delta_j)] \tag{3.74}$$

$$S_{cij} = \sqrt{P_{cij}^2 + Q_{cij}^2} \le S_{ij\max} \tag{3.75}$$

$$P_{cij} = |v_{ci}|^2 G_{ij} - |v_{ci}||v_{cj}|[G_{ij}\cos(\delta_{ci} - \delta_{cj}) + B_{ij}\sin(\delta_{ci} - \delta_{cj})] \tag{3.76}$$

$$Q_{cij} = -|v_{ci}|^2 (B_{ij} + B_{sh}) - |v_{ci}||v_{cj}|[G_{ij}\sin(\delta_{ci} - \delta_{cj}) - B_{ij}\cos(\delta_{ci} - \delta_{cj})] \tag{3.77}$$

Accordingly, there are limits in apparent power flow associated to the operating point defined by the loading parameter λ.

d Supply and demand bids blocks

$$Ps_{\min} \leq Ps \leq Ps_{\max} \tag{3.78}$$
$$Pd_{\min} \leq Pd \leq Pd_{\max} \tag{3.79}$$

e Generation reactive power limits

$$\mathrm{Qg}_{\min} \leq Qg \leq Qg_{\max} \tag{3.80}$$
$$\mathrm{Qg}_{\min} \leq Qg_c \leq Qg_{\max} \tag{3.81}$$

f Voltage limits

$$V_{\min} \leq v \leq V_{\max} \tag{3.82}$$
$$V_{\min} \leq v_c \leq V_{\max} \tag{3.83}$$
$$-\pi/2 \leq \delta \leq \pi/2 \tag{3.84}$$
$$-\pi/2 \leq \delta_c \leq \pi/2 \tag{3.85}$$

Finally, a fragment of the code written en GAMS to programme this model is shown in the next frame.

```
EQUATIONS

 SOCIALW     z    objective function for market: social welfare

 PBAL(N)           active power balance in each bus - current state [pu]
 QBAL(N)           reactive power balance in each bus - current state [pu]
 PBALC(N)          active power balance in each bus - critical state [pu]
 QBALC(N)          reactive power balance in each bus - critical state [pu]

 P_flow(N,NC)     Pflow  active power line flow - current state [pu]
 Q_flow(N,NC)     Qflow  active power line flow - current state [pu]
 S_flow(N,NC)            apparent power line flow - current state [pu]

 P_flow_c(N,NC)   Pflow_c  active power line flow - critical state [pu]
 Q_flow_c(N,NC)   Qflow_c  active power line flow - critical state [pu]
 S_flow_c(N,NC)            apparent power line flow - critical state [pu]
;

* OBJECTIVE FUNCTION

SOCIALW..   z=e=(-1)*(sum(N$(BUS(N,'PDMAX') ne
        0),0*BUS(N,'A')*sqr(pbd(N))+BUS(N,'B')*pbd(N)+0*BUS(N,'C'))-
        sum(G$(GDATA(G,'GEN_TYPE') eq
        1),0*GDATA(G,'A')*sqr(pbs(G))+GDATA(G,'B')*pbs(G)+0*GDATA(G,'C')));

* POWER FLOW EQUATIONS - ACTUAL OPERATING POINT

PBAL(N)..   sum(G$(GN(G,N) and (GDATA(G,'GEN_TYPE') eq 1)),((pbs(G)/SB)))-
```

```
        ((pbd(N)/SB)$(BUS(N,'PDMAX') ne 0))=e=sum(NC$(CONEX(N,NC) or CONEX(NC,N) or
        (ord(N) eq ord(NC))),MOMATRIX(N,NC)*v(NC)*v(N)*cos(d(N)-d(NC)-ARMATRIX(N,NC)));


QBAL(N)..  sum(G$(GN(G,N)),(qg(G)/SB))-
        (((pbd(N)/SB))*(BUS(N,'QL')/BUS(N,'PL')))$(BUS(N,'PL') ne
        0)=e=sum(NC$(CONEX(N,NC) or CONEX(NC,N) or (ord(N) eq
        ord(NC))),MOMATRIX(N,NC)*v(NC)*v(N)*sin(d(N)-d(NC)-ARMATRIX(N,NC)));

* POWER FLOW EQUATIONS - f(λ)

PBALC(N)..  (1+lamda+kgo)*sum(G$(GN(G,N) and (GDATA(G,'GEN_TYPE') eq 1)),((pbs(G)/SB)))-
        (1+lamda)*( (pbd(N)/SB)$(BUS(N,'PDMAX') ne 0))=e=sum(NC$(CONEX(N,NC) or
        CONEX(NC,N) or (ord(N) eq ord(NC))),MOMATRIX(N,NC)*vc(NC)*vc(N)*cos(dc(N)-
        dc(NC)-ARMATRIX(N,NC)));

QBALC(N)..  sum(G$(GN(G,N)),(qgc(G)/SB))-
        (1+lamda)*(((pbd(N)/SB)*(BUS(N,'QL')/BUS(N,'PL'))))$(BUS(N,'PL') ne
        0)=e=sum(NC$(CONEX(N,NC) or CONEX(NC,N) or (ord(N) eq
        ord(NC))),MOMATRIX(N,NC)*vc(NC)*vc(N)*sin(dc(N)-dc(NC)-ARMATRIX(N,NC)));

* ACTIVE, REACTIVE AND APPARENT POWER THROUGH LINES - ACTUAL OPERATING POINT

P_flow(N,NC)$((CONEX(N,NC) or CONEX(NC,N)))..        Pflow(N,NC)=e=((-
        RMATRIX(N,NC))*(sqr(v(N))-v(N)*v(NC)*cos(d(N)-d(NC)))-(-
        IMATRIX(N,NC))*v(N)*v(NC)*sin(d(N)-d(NC)));

Q_flow(N,NC)$((CONEX(N,NC) or CONEX(NC,N)))..        Qflow(N,NC)=e=(-1*sqr(v(N))*(-
        IMATRIX(N,NC)+LINE(N,NC,'Y')/2+LINE(NC,N,'Y')/2)-v(N)*v(NC)*((-
        RMATRIX(N,NC))*sin(d(N)-d(NC))-(-IMATRIX(N,NC))*cos(d(N)-d(NC))));

S_flow(N,NC)$(CONEX(N,NC) or CONEX(NC,N))..
        sqrt(sqr(Pflow(N,NC))+sqr(Qflow(N,NC)))=l=FS*((LINE(N,NC,'Smax')/(SB))+(LINE(NC,
        N,'Smax')/(SB)));

* ACTIVE, REACTIVE AND APPARENT POWER THROUGH LINES - f(λ)


P_flow_c(N,NC)$(CONEX(N,NC) or CONEX(NC,N))..     Pflow_c(N,NC)=e=((-
        RMATRIX(N,NC))*(sqr(vc(N))-vc(N)*vc(NC)*cos(dc(N)-dc(NC)))-(-
        IMATRIX(N,NC))*vc(N)*vc(NC)*sin(dc(N)-dc(NC)));

Q_flow_c(N,NC)$(CONEX(N,NC) or CONEX(NC,N))..     Qflow_c(N,NC)=e=(-1*sqr(vc(N))*(-
        IMATRIX(N,NC)+LINE(N,NC,'Y')/2+LINE(NC,N,'Y')/2)-vc(N)*vc(NC)*((-
        RMATRIX(N,NC))*sin(dc(N)-dc(NC))-(-IMATRIX(N,NC))*cos(dc(N)-dc(NC))));

S_flow_c(N,NC)$(CONEX(N,NC) or CONEX(NC,N))..
        sqrt(sqr(Pflow_c(N,NC))+sqr(Qflow_c(N,NC)))=l=FS*((LINE(N,NC,'Smax')/(SB))+(LINE
        (NC,N,'Smax')/(SB)));

MODEL opf /
  SOCIALW
  PBAL
  QBAL
  PBALC
  QBALC
  P_flow
  Q_flow
  S_flow
  P_flow_c
  Q_flow_c
  S_flow_c
  /;

SOLVE opf USING nlp MINIMIZE z;
```

3.4.4 SM-OPF with FACTS

At this point, FACTS devices are included in the previous SM-OPF model in order to analyse their influent as it was done in the base OPF case. One more time, the methodology used is the injection power model explain in Section 3.3 Therefore, following the same reasoning proposed when the SM variation was developed, a new set of variables are needed associated to the state defined by the loading parameter λ for FACTS expressions. The following equations defined this model.

a. Objective function: Social welfare

$$Min\ \ Z = -(Cd * Pd - Cs * Ps) \tag{3.86}$$

b. Power injection for TCSC

$$P_{inj\,\mathrm{i}} = |v_i|^2 \Delta G_{ij} - |v_i||v_j|\left[\Delta G_{ij}\cos(\delta_i - \delta_j) + \Delta B_{ij}\sin(\delta_i - \delta_j)\right] \tag{3.87}$$

$$Q_{inj\,\mathrm{i}} = -|v_i|^2 \Delta B_{ij} - |v_i||v_j|\left[G_{ij}\sin(\delta_i - \delta_j) - B_{ij}\cos(\delta_i - \delta_j)\right] \tag{3.88}$$

$$P_{cinj\,\mathrm{i}} = |v_{ci}|^2 \Delta G_{cij} - |v_{ci}||v_{cj}|\left[\Delta G_{cij}\cos(\delta_{ci} - \delta_{cj}) + \Delta B_{cij}\sin(\delta_{ci} - \delta_{cj})\right] \tag{3.89}$$

$$Q_{cinj\,\mathrm{i}} = -|v_{ci}|^2 \Delta B_{cij} - |v_{ci}||v_{cj}|\left[G_{cij}\sin(\delta_{ci} - \delta_{cj}) - B_{ij}\cos(\delta_{ci} - \delta_{cj})\right] \tag{3.90}$$

where

$$\Delta G_{ij} = \frac{x_{TCSC}\, r_{ij}(x_{TCSC} - 2x_{ij})}{(r_{ij}^2 + x_{ij}^2)(r_{ij}^2 + (x_{ij} - x_{TCSC})^2)} \tag{3.91}$$

$$\Delta G_{cij} = \frac{x_{cTCSC}\, r_{ij}(x_{cTCSC} - 2x_{ij})}{(r_{ij}^2 + x_{ij}^2)(r_{ij}^2 + (x_{ij} - x_{cTCSC})^2)} \tag{3.92}$$

$$\Delta B_{ij} = \frac{-x_{TCSC}(r_{ij}^2 - x_{ij}^2 + x_{TCSC}x_{ij})}{(r_{ij}^2 + x_{ij}^2)(r_{ij}^2 + (x_{ij} - x_{TCSC})^2)} \tag{3.93}$$

$$\Delta B_{cij} = \frac{-x_{cTCSC}(r_{ij}^2 - x_{ij}^2 + x_{cTCSC}x_{ij})}{(r_{ij}^2 + x_{ij}^2)(r_{ij}^2 + (x_{ij} - x_{cTCSC})^2)} \tag{3.94}$$

c. Power flow equations

$$Ps_i - Pd_i = \sum_{j=1}^{n} |v_i||v_j||Y_{ij}|\cos(\delta_i - \delta_j - \psi_{ij}) - P_{inj\,\mathrm{i}} \tag{3.95}$$

$$Qg_i - Pd_i tg\phi_i = \sum_{j=1}^{n} |v_i||v_j||Y_{ij}|\sin(\delta_i - \delta_j - \psi_{ij}) - Q_{inj\,\mathrm{i}} \tag{3.96}$$

$$(1 + \lambda_c + Kg)Pg_i - (1 + \lambda_c)Pd_i = \sum_{j=1}^{n} |v_{ci}||v_{cj}||Y_{ij}|\cos(\delta_{ci} - \delta_{cj} - \psi_{ij}) - P_{cinj\,\mathrm{i}} \tag{3.97}$$

$$Qg_{ci} - (1 + \lambda_c)Pd_i tg\phi_i = \sum_{j=1}^{n} |v_{ci}||v_{cj}||Y_{ij}|\sin(\delta_{ci} - \delta_{cj} - \psi_{ij}) - Q_{cinj\,\mathrm{i}} \tag{3.98}$$

d. Apparent power flow limitation

$$S_{ij} = \sqrt{P_{ij}^2 + Q_{ij}^2} \leq S_{ij\max} \tag{3.99}$$

$$P_{ij} = |v_i|^2 G_{ij} - |v_i||v_j|[G_{ij}\cos(\delta_i - \delta_j) + B_{ij}\sin(\delta_i - \delta_j)] - P_{inj\,\mathrm{i}} \tag{3.100}$$

$$Q_{ij} = -|v_i|^2 (B_{ij} + B_{sh}) - |v_i||v_j|[G_{ij}\sin(\delta_i - \delta_j) - B_{ij}\cos(\delta_i - \delta_j)] - Q_{inj\,\mathrm{i}} \tag{3.101}$$

$$S_{cij} = \sqrt{P_{cij}^2 + Q_{cij}^2} \leq S_{ij\max} \tag{3.102}$$

$$P_{cij} = |v_{ci}|^2 G_{ij} - |v_{ci}||v_{cj}|[G_{ij}\cos(\delta_{ci} - \delta_{cj}) + B_{ij}\sin(\delta_{ci} - \delta_{cj})] - P_{c\,inj\,\mathrm{i}} \tag{3.103}$$

$$Q_{cij} = -|v_{ci}|^2 (B_{ij} + B_{sh}) - |v_{ci}||v_{cj}|[G_{ij}\sin(\delta_{ci} - \delta_{cj}) - B_{ij}\cos(\delta_{ci} - \delta_{cj})] - Q_{c\,inj\,\mathrm{i}} \tag{3.104}$$

e. Supply and demand bids blocks

$$Ps_{\min} \leq Ps \leq Ps_{\max} \tag{3.105}$$

$$Pd_{\min} \leq Pd \leq Pd_{\max} \tag{3.106}$$

f. Generation reactive power limits

$$\mathrm{Qg}_{\min} \leq Qg \leq Qg_{\max} \tag{3.107}$$

$$\mathrm{Qg}_{\min} \leq Qg_c \leq Qg_{\max} \tag{3.108}$$

g. Voltage limits

$$V_{\min} \leq v \leq V_{\max} \tag{3.109}$$

$$V_{\min} \leq v_c \leq V_{\max} \tag{3.110}$$

$$-\pi/2 \leq \delta \leq \pi/2 \tag{3.111}$$

$$-\pi/2 \leq \delta_c \leq \pi/2 \tag{3.112}$$

i Compensation limits

$$0 \leq x_{TCSC} \leq 0.8\,x_{ij} \tag{3.113}$$

$$0 \leq x_{cTCSC} \leq 0.8\,x_{ij} \tag{3.114}$$

Finally, a fragment of the code written en GAMS to programme this model is shown in the next frame.

```
EQUATIONS

 SOCIALW     z    objective function for market: social welfare

 eq1    delta_G   conductance change from i to j owing to FACTS - current state [pu]
 eq2    delta_B   suceptance change from i to j  owing to FACTS - current state [pu]
 eq3    delta_G   conductance change from j to i owing to FACTS - critical state [pu]
 eq4    delta_B   suceptance change from j to i  owing to FACTS - critical state [pu]

 eq1_c   delta_Gc  conductance change from i to j owing to FACTS - critical state [pu]
 eq2_c   delta_Bc  suceptance change from i to j owing to FACTS - critical state [pu]
 eq3_c   delta_Gc  conductance change from j to i owing to FACTS - critical state [pu]
 eq4_c   delta_Bc  suceptance change from j to i  owing to FACTS - critical state [pu]

 eq5     Pinj      active power injected at bus N for FACT model - current state [pu]
 eq6     Qinj      active power injected at bus N for FACT model - current state [pu]

 eq5_c   Pinj_c   active power injected at bus N for FACT model - current state [pu]
 eq6_c   Qinj_c   active power injected at bus N for FACT model - current state [pu]

 PBAL(N)            active power balance in each bus - current state [pu]
 QBAL(N)            reactive power balance in each bus - current state [pu]
 PBALC(N)           active power balance in each bus - critical state [pu]
 QBALC(N)           reactive power balance in each bus - critical state [pu]

 P_flow(N,NC)      Pflow  active power line flow - current state [pu]
 Q_flow(N,NC)      Qflow  active power line flow - current state [pu]
 S_flow(N,NC)             apparent power line flow - current state [pu]

 P_flow_c(N,NC)    Pflow_c  active power line flow - critical state [pu]
 Q_flow_c(N,NC)    Qflow_c  active power line flow - critical state [pu]
 S_flow_c(N,NC)             apparent power line flow - critical state [pu]
;

* OBJECTIVE FUNCTION

SOCIALW..  z=e=(-1)*(sum(N$(BUS(N,'PDMAX') ne
       0),0*BUS(N,'A')*sqr(pbd(N))+BUS(N,'B')*pbd(N)+0*BUS(N,'C'))-
       sum(G$(GDATA(G,'GEN_TYPE') eq
       1),0*GDATA(G,'A')*sqr(pbs(G))+GDATA(G,'B')*pbs(G)+0*GDATA(G,'C')));

* POWER INJECTION MODEL TCSC - ACTUAL OPERATING POINT

eq1(N,NC)$(TCSC(N,NC))..  delta_G(N,NC)=e=(-1)*MOMATRIX(N,NC)*cos(ARMATRIX(N,NC))*((-
       1)*(2*LINE(N,NC,'X')-
       xtcsc(N,NC))*xtcsc(N,NC))/(sqr(LINE(N,NC,'R'))+sqr(LINE(N,NC,'X')-xtcsc(N,NC)));

eq2(N,NC)$(TCSC(N,NC))..  delta_B(N,NC)=e=-xtcsc(N,NC)*(sqr(LINE(N,NC,'R'))-
       sqr(LINE(N,NC,'X'))+xtcsc(N,NC)*LINE(N,NC,'X'))/((sqr(LINE(N,NC,'R'))+sqr(LINE(N
       ,NC,'X')))*(sqr(LINE(N,NC,'R'))+sqr(LINE(N,NC,'X')-xtcsc(N,NC))));

eq3(N,NC)$(TCSC(N,NC))..  delta_G(NC,N)=e=delta_G(N,NC);

eq4(N,NC)$(TCSC(N,NC))..  delta_B(NC,N)=e=delta_B(N,NC);

* POWER INJECTION MODEL TCSC - f(λ)

eq1_c(N,NC)$(TCSC(N,NC))..  delta_Gc(N,NC)=e=(-1)*MOMATRIX(N,NC)*cos(ARMATRIX(N,NC))*((-
       1)*(2*LINE(N,NC,'X')-
       xtcsc_c(N,NC))*xtcsc_c(N,NC))/(sqr(LINE(N,NC,'R'))+sqr(LINE(N,NC,'X')-
       xtcsc_c(N,NC)));

eq2_c(N,NC)$(TCSC(N,NC))..  delta_Bc(N,NC)=e=-xtcsc_c(N,NC)*(sqr(LINE(N,NC,'R'))-
       sqr(LINE(N,NC,'X'))+xtcsc_c(N,NC)*LINE(N,NC,'X'))/((sqr(LINE(N,NC,'R'))+sqr(LINE
       (N,NC,'X')))*(sqr(LINE(N,NC,'R'))+sqr(LINE(N,NC,'X')-xtcsc_c(N,NC))));

eq3_c(N,NC)$(TCSC(N,NC))..  delta_Gc(NC,N)=e=delta_Gc(N,NC);

eq4_c(N,NC)$(TCSC(N,NC))..  delta_Bc(NC,N)=e=delta_Bc(N,NC);
```

```
eq5(N,NC)$(TCSC(N,NC) or TCSC(NC,N))..  Pinj(N,NC)=e=sqr(v(N))*delta_G(N,NC)-
        v(N)*v(NC)*(delta_G(N,NC)*cos(d(N)-d(NC))+delta_B(N,NC)*sin(d(N)-d(NC)));

eq6(N,NC)$(TCSC(N,NC) or TCSC(NC,N))..  Qinj(N,NC)=e=-sqr(v(N))*delta_B(N,NC)-
        v(N)*v(NC)*(delta_G(N,NC)*sin(d(N)-d(NC))-delta_B(N,NC)*cos(d(N)-d(NC)));

eq5_c(N,NC)$(TCSC(N,NC) or TCSC(NC,N))..  Pinj_c(N,NC)=e=sqr(vc(N))*delta_Gc(N,NC)-
        vc(N)*vc(NC)*(delta_Gc(N,NC)*cos(dc(N)-dc(NC))+delta_Bc(N,NC)*sin(dc(N)-
        dc(NC)));

eq6_c(N,NC)$(TCSC(N,NC) or TCSC(NC,N))..  Qinj_c(N,NC)=e=-sqr(vc(N))*delta_Bc(N,NC)-
        vc(N)*vc(NC)*(delta_Gc(N,NC)*sin(dc(N)-dc(NC))-delta_Bc(N,NC)*cos(dc(N)-
        dc(NC)));

* POWER FLOW EQUATIONS - ACTUAL OPERATING POINT

PBAL(N)..  sum(G$(GN(G,N) and (GDATA(G,'GEN_TYPE') eq 1)),((pbs(G)/SB)))-
        ((pbd(N)/SB)$(BUS(N,'PDMAX') ne 0))=e=sum(NC$(CONEX(N,NC) or CONEX(NC,N) or
        (ord(N) eq ord(NC))),MOMATRIX(N,NC)*v(NC)*v(N)*cos(d(N)-d(NC)-ARMATRIX(N,NC)))-
        sum(NC$(TCSC(N,NC) or TCSC(NC,N)),Pinj(N,NC));

QBAL(N)..  sum(G$(GN(G,N)),(qg(G)/SB))-
        (((pbd(N)/SB))*(BUS(N,'QL')/BUS(N,'PL')))$(BUS(N,'PL') ne
        0)=e=sum(NC$(CONEX(N,NC) or CONEX(NC,N) or (ord(N) eq
        ord(NC))),MOMATRIX(N,NC)*v(NC)*v(N)*sin(d(N)-d(NC)-ARMATRIX(N,NC)))-
        sum(NC$(TCSC(N,NC) or TCSC(NC,N)),Qinj(N,NC));


* POWER FLOW EQUATIONS - f(λ)

PBALC(N)..  (1+lamda+kgo)*sum(G$(GN(G,N) and (GDATA(G,'GEN_TYPE') eq 1)),((pbs(G)/SB)))-
        (1+lamda)*( (pbd(N)/SB)$(BUS(N,'PDMAX') ne 0))=e=sum(NC$(CONEX(N,NC) or
        CONEX(NC,N) or (ord(N) eq ord(NC))),MOMATRIX(N,NC)*vc(NC)*vc(N)*cos(dc(N)-
        dc(NC)-ARMATRIX(N,NC)))-sum(NC$(TCSC(N,NC) or TCSC(NC,N)),Pinj_c(N,NC));

QBALC(N)..  sum(G$(GN(G,N)),(qgc(G)/SB))-
        (1+lamda)*(((pbd(N)/SB)*(BUS(N,'QL')/BUS(N,'PL'))))$(BUS(N,'PL') ne
        0)=e=sum(NC$(CONEX(N,NC) or CONEX(NC,N) or (ord(N) eq
        ord(NC))),MOMATRIX(N,NC)*vc(NC)*vc(N)*sin(dc(N)-dc(NC)-ARMATRIX(N,NC)))-
        sum(NC$(TCSC(N,NC) or TCSC(NC,N)),Qinj_c(N,NC));

* ACTIVE, REACTIVE AND APPARENT POWER THROUGH LINES - ACTUAL OPERATING POINT

P_flow(N,NC)$((CONEX(N,NC) or CONEX(NC,N)))..  Pflow(N,NC)=e=((-
        RMATRIX(N,NC))*(sqr(v(N))-v(N)*v(NC)*cos(d(N)-d(NC)))-(-
        IMATRIX(N,NC))*v(N)*v(NC)*sin(d(N)-d(NC))-Pinj(N,NC)$(TCSC(N,NC) or
        TCSC(NC,N)));

Q_flow(N,NC)$((CONEX(N,NC) or CONEX(NC,N)))..  Qflow(N,NC)=e=(-1*sqr(v(N))*(-
        IMATRIX(N,NC)+LINE(N,NC,'Y')/2+LINE(NC,N,'Y')/2)-v(N)*v(NC)*((-
        RMATRIX(N,NC))*sin(d(N)-d(NC))-(-IMATRIX(N,NC))*cos(d(N)-d(NC)))-
        (Qinj(N,NC)$(TCSC(N,NC) or TCSC(NC,N))));

S_flow(N,NC)$(CONEX(N,NC) or CONEX(NC,N))..
        sqrt(sqr(Pflow(N,NC))+sqr(Qflow(N,NC)))=l=FS*((LINE(N,NC,'Smax')/(SB))+(LINE(NC,
        N,'Smax')/(SB)));

* ACTIVE, REACTIVE AND APPARENT POWER THROUGH LINES - f(λ)

P_flow_c(N,NC)$(CONEX(N,NC) or CONEX(NC,N))..  Pflow_c(N,NC)=e=((-
        RMATRIX(N,NC))*(sqr(vc(N))-vc(N)*vc(NC)*cos(dc(N)-dc(NC)))-(-
        IMATRIX(N,NC))*vc(N)*vc(NC)*sin(dc(N)-dc(NC))-Pinj_c(N,NC)$(TCSC(N,NC) or
        TCSC(NC,N)));

Q_flow_c(N,NC)$(CONEX(N,NC) or CONEX(NC,N))..  Qflow_c(N,NC)=e=(-1*sqr(vc(N))*(-
        IMATRIX(N,NC)+LINE(N,NC,'Y')/2+LINE(NC,N,'Y')/2)-vc(N)*vc(NC)*((-
        RMATRIX(N,NC))*sin(dc(N)-dc(NC))-(-IMATRIX(N,NC))*cos(dc(N)-dc(NC)))-
        (Qinj_c(N,NC)$(TCSC(N,NC) or TCSC(NC,N))));
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```
S_flow_c(N,NC)$(CONEX(N,NC) or CONEX(NC,N))..
        sqrt(sqr(Pflow_c(N,NC))+sqr(Qflow_c(N,NC)))=l=FS*((LINE(N,NC,'Smax')/(SB))+(LINE
        (NC,N,'Smax')/(SB)));

MODEL opf /
  SOCIALW
  PBAL
  QBAL
  PBALC
  QBALC
  eq1
  eq2
  eq3
  eq4
  eq1_c
  eq2_c
  eq3_c
  eq4_c
  eq5
  eq6
  eq5_c
  eq6_c
  P_flow
  Q_flow
  S_flow
  P_flow_c
  Q_flow_c
  S_flow_c
  /;

SOLVE opf USING nlp MINIMIZE z;
```

3.5 Conclusions

In this section it has been presented a methodology to addressing security threats arose from deregulation markets. Accordingly, different models have been proposed. As a starting point a base OPF has been developed while different improvements have led it to the SM-OPF where it is possible to obtain a direct measurement of a security margin which could turn out to be useful indicator for operators to ensure and monitor the system reliability. Furthermore, it seems that the relevance of hybrid or OPF-base markets can be growth owing to the numerous modifications that are being proposes nowadays. However, the mathematic formulation of the problem can be a drawback since it reduces the simplicity and transparency for market participants.

Chapter 4

Market Settlement with Voltage Stability Considerations and FACTS Devices

In this chapter, the results obtained from the models presented on the previous section are analysed. The analyses focus on behaviour of main power system variables, management of security issues and its effects on market settlements and benefits of FACTS devices installed on some critical lines. A modified IEEE 30-bus test system is used to demonstrate the results. The General Algebraic Modelling System (GAMS/MINOS) is used to model and solve the optimization problems involved and the MATLAB software is used to perform graphical representations through an interface between both programs [82] .

4.1 Test system

A modified IEEE 30-bus test system [33] is used in this work. It is comprised of 30 buses, 41 lines, 3 generators, 3 synchronous condensors, 2 shunt capacitors, 21 loads and 6 transformers. Furthermore, for simplicity, bid prices for power have been considered constant, between 31 \$/MWh and 37 \$/MWh, being fairly close to possible marginal benefit and marginal production cost for participants. In addition, it has been decided to establish boundaries for the minimum amount of power, both generated and consumed, submitted to the market process in order to simulate reasonable loading values according to the apparent power line limits based on those used in [83]. All data are presented in Appendix B.

As mentioned before, in the power system presented there are 3 generators and 21 loads. In order to simulate a competitive market structure, it has been considered the generators as GENCOS and the loads as DISCOS/ESCOS. In all cases, it is assumed that they are individual entities which are operated separately. However, it would not have implicated any loss of generality if some units had been putted into groups belonging either to the same GENCO or DISCO/ESCO according to, for example, geographical or business criteria. A modified single line diagram of the system is shown in Fig 4.1.

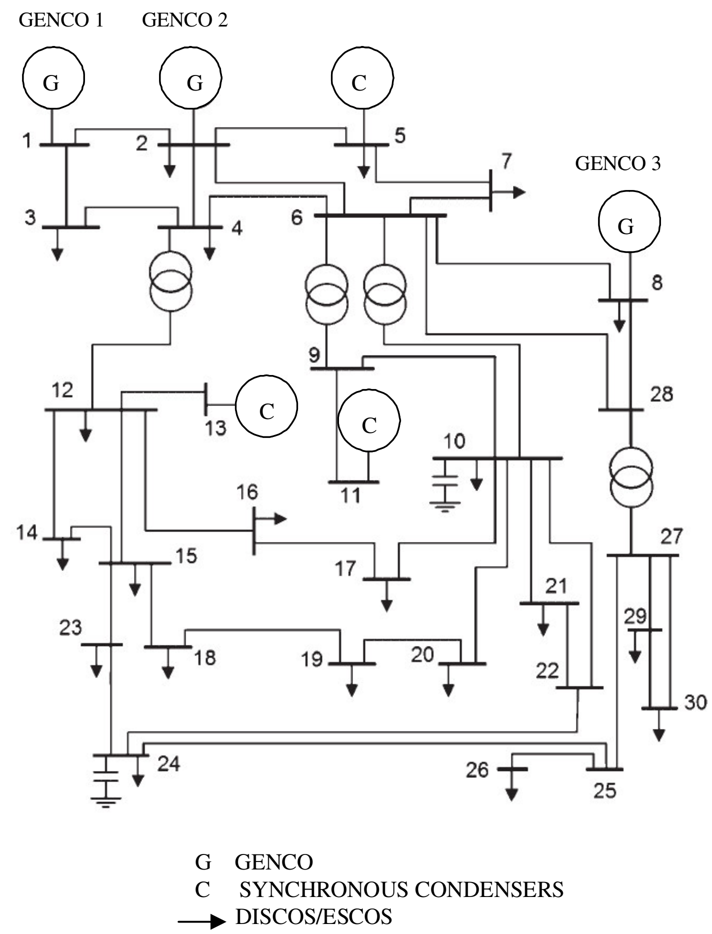


Fig 4.1 Modified IEEE 30 bus test power system.

It is important to mention that the test system represents a transmission grid and not a distribution network. It is necessary to point out this distinction since at this level within the power transaction chain GENCOS, ESCOS and DISCOS are mainly the players allowed to participate in the wholesale market. That means end-customers are not involved directly. However, GENCOS, ESCOS and DISCOS could base their strategies using historic electricity consumption trends of these users. Owing to this, techniques to predict accurately these figures turn out to be complicated [8].

Therefore, in this framework both GENCOS and DISCOS/ESCOS submit to the market operator their requirements which are comprised of different terms. On the one hand, the amount of energy that each participant would be willing to either sells or purchase through this mechanism which is bounded within a minimum and maximum quantity. The lower limit can be determined according to forecast studies of demand based on historic figures, while the upper one can be decided on account of technical constraints or corporative decisions. Moreover, the bid coefficients represent the marginal cost that generation companies incurred to produce electricity and the marginal benefits reported to the customers. In this work, cost functions and benefit functions, formulated through the last two bid parameters, are linear to simplify calculations. Therefore, marginal values for both participants correspond directly to the value *B* indicated in Table A.4 Appendix A. The meaning of these marginal values can be interpreted as follows. From a producer viewpoint it would be the cost of producing the next unit of power, while for a customer it would be the benefit reported for an additional unit purchased.

On the other hand, as explained in section 1.2, in hybrid markets both economical and security issues are management and monitored by only one entity, an independent market operator. Therefore, this authority needs to know which the operating limits of the different units involved in the systems are in order to verify them at the same time that the power transfer is calculated. For this reason, reactive limits are sent to the operator, for instance. Fig 4.2 represents schematically the information required by the operator from the participants where "further information" represents, for example, the availability and location of ancillary services.

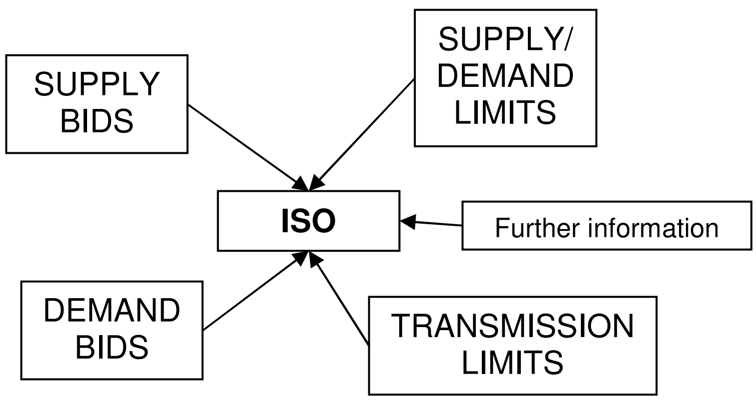


Fig 4.2 Input for ISO in hybrid markets

4.2 Market settlement structures

The four market settlement structures are represented in Fig 4.3 which mathematical formulations were shown through Chapter 3. The first market structure, which was developed in section 3.4.1**,** is a base OPF. Structure II, an extension of the previous one, includes FACTS devices in order to enhance the transmission system according to the notions provided in sections 3.3 and 3.4.2**.** On the other hand, in structure III and structure IV, defined in sections 3.4.3 and 3.4.4 respectively, besides FACTS contributions, its is explored the consequences of introducing a second set of power flow equations to simulate a new operating point associated to security loading margins.

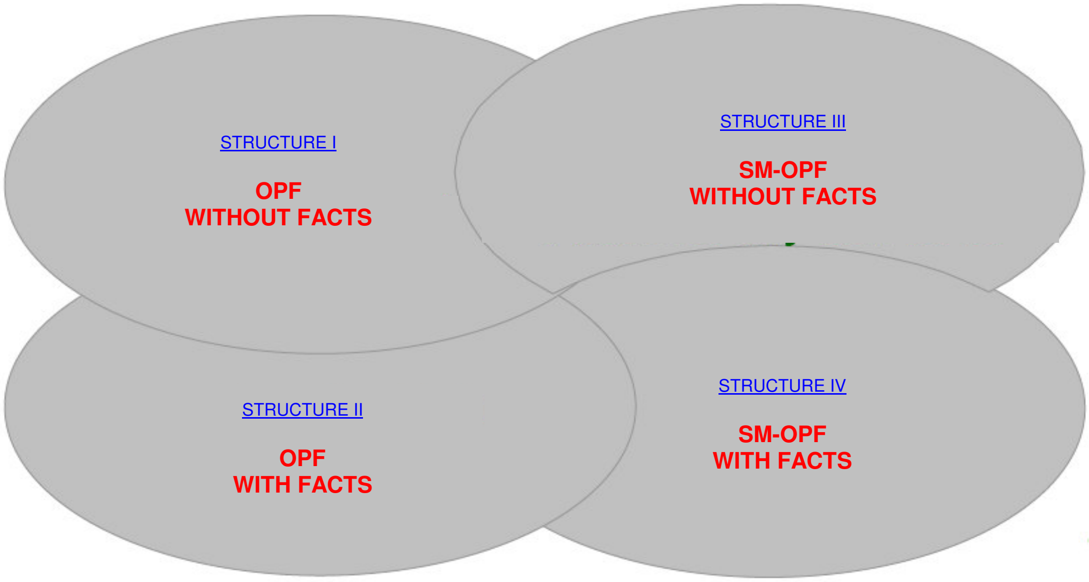


Fig 4.3 Studied market settlement structures

4.3 Market settlement analyses

4.3.1 Base OPF without FACTS devices

Two different cases have been analysed. The first simulation does not consider loading lines limits. That means not upper boundaries are imposed to the apparent power through each line. The second one, that flow is constrained. The former can be associated to that situation when loading line limits for all branches are large enough to not be achieved, while for the latter that limitation is significant and it can influent in the global system operation. Moreover, it is important to be aware that there are other requirements that must be fulfilled in order to ensure a feasible operation of the system, such as voltage range and power submitted levels. Likewise, it is interesting to demonstrate the influent of loading limits in the system since this is one remarkable difference with other kinds of market structures. That is, market settlement and system requirements are defined at the same time instead of perform two steps like in the simple auction model.

In Table 4.1 it is possible to observe the total transaction level (TTL), active losses and payment to the independent market operator (PAY_IMO) for both cases, with and without apparent power limitation. Therefore, without flow upper boundaries, TTL decreases by 2.12%. That entails the system variables are forced to modify their values in order to satisfy those new conditions introduced in the model. Moreover, active losses and PAY_IMO decrease since a lower bulk of power is transmitted in the second case.

Table 4.1 Global results of base OPF

BASE OPF RESULTS					
WTIHOUT S LIMITS			WITH S LIMITS		
TTL	465.91	MW	TTL	456.01	MW
LOSSES	21.40	MW	LOSSES	20.29	MW
PAY_IMO	739.11	$/h	PAY_IMO	733.08	$/h

Table 4.2 Results of base OPF without S limits

BUS	LMP [$/MWh]	V [pu]	Pbs [MW]	Pbd [MW]	PAY [$/h]
1	30.74	1.10	251	0	-7716
2	32.33	1.09	136.31	50	-2790
3	33.55	1.04		2.4	81
4	34.41	1.03		50	1720
5	35.51	1.05		100	3551
6	34.60	1.03		0	0
7	35.52	1.02		50	1776
8	34.15	1.05	100	30	-2390
9	34.77	1.06		0	0
10	34.87	1.03		5.8	202
11	34.77	1.10		0	0
12	34.77	1.05		50	1739
13	34.77	1.10		0	0
14	35.39	1.03		6.2	219
15	35.57	1.03		8.2	292
16	35.02	1.04		3.5	123
17	35.05	1.03		9	315
18	36.10	1.01		3,2	116
19	36.27	1.00		16.9	612
20	35.93	1.01		2.2	79
21	35.81	1.00		50	1791
22	35.70	1.01		0	0
23	35.83	1.02		3.2	115
24	35.88	1.01		8.7	312
25	35.02	1.02		0	0
26	35.67	1.00		3.5	125
27	34.29	1.04		0	0
28	34.69	1.03		0	0
29	35.24	1.02		2.4	85
30	35.90	1.01		10.7	385

Table 4.2 presents values of other variables reported from the solved optimal problem without considering flow limits, such as local marginal prices (LMP), magnitude of bus voltage, supplied and demand power and payment associated to each bus. In addition, Appendix B contains a complete set of tables with results of different simulations. It is possible to observe that the power supplied at bus 1 remains at its lower level while the generator located at bus 8 produces at its upper limit; and finally the one placed at bus 2 changes its value according to the optimal problem. Thus, as could be expected, the model increases generation sorting suppliers according to their bid prices, from the lowest to the highest. Therefore, this can be interpreted as a bidding signal for producers.

Moreover, the different between payments in bus 1 with those associated to other buses is significant. The reason of this behaviour can be explained as follows. The initial power submitted by generation 1 (bus 1) is the highest one, so is the bid price. Likewise, the marginal factor yielded by the algebraic solution of the problem associated to this variable is positive which means that a reduction of this limit would produce a decline in the payment. For this reason the LMP is lower than the bid price. As was indicated in section 3.4.3, market participants pay for their consumptions or get paid for their productions according to bids as well as congestions their cause in the market, while Independent Market Operator used the money generated as a result of the different between these payments to face out operational problems such as congestions. Furthermore, those LMP which are not identical to the bids, demand or supply, means that at this bus power has reached one of its limits, for example the mentioned generator at bus 1 contrary to the one at bus 2.

4.3.2 Base OPF with FACTS devices

Based on the results from the base OPF and presented in Table 4.3 it is observed that the two branches more congested are line 2-4 (from bus 2 to bus 4) and line 10-21 (from bus 10 to bus 21).

Table 4.3 More congested lines and the effect of FACTS on them

MORE CONGESTED LINES		
LINE	WITHOUT FACTS	WITH FACTS
2 4	101 %	90 %
10 21	134 %	134 %

Two Thyristor Controlled Series Compensation (TCSC) units have been placed in line 1-3 and 2-5 respectively, which has turned out to be the most effective location to alleviate that congestion, with the aim of analyse their influence in the market results, see Fig 4.4.

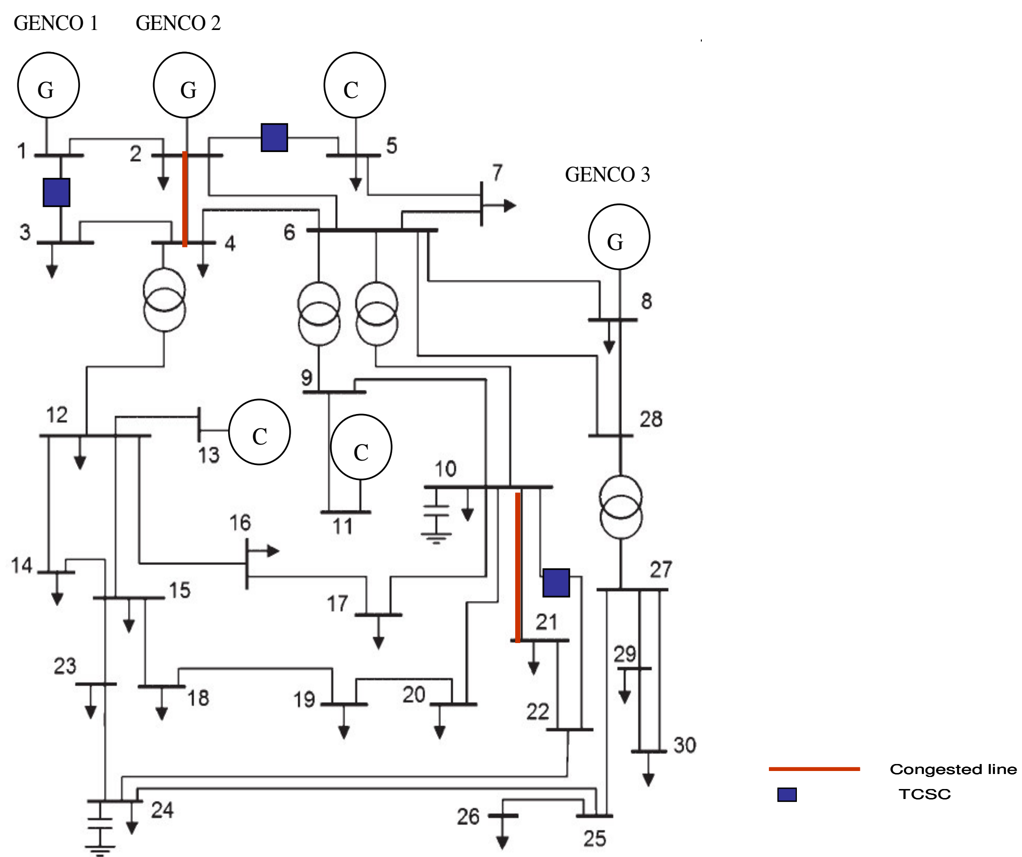


Fig 4.4 Location of most congesting lines and TCSC units

As it was mentioned in the previous chapter, the reactance associated to each device can be varied within 0 and 80% of the line reactance. Therefore, since the optimal function remains the same, that is maximization of social welfare, the compensation level obtained is relied on this rather than relieving congestions problems as much as it could be, Table 4.3.

In Table 4.4 it is possible to observe that the introduction of FACTS (i.e. TCSC units) in the system does not report large changes in the TTL in comparison to those levels reached without these devices, as it is demonstrated graphically in Fig 4.5 (a). For this reason, it is said that the redaction in congestion in this specific case does not increase the power transferred or at least not in a worth rate. However, the influent on PAY_IMO is more significant, Fig 4.5 (b). This reduction is on account of alleviating congestion.

Table 4.4 Comparison between OPF and OPF-FACTS

WITHOUT FACTS					
WTIHOUT S LIMITS			WITH S LIMITS		
TTL	465.91	MW	TTL	456.01	MW
LOSSES	21.40	MW	LOSSES	20.29	MW
PAY_IMO	739.11	$/h	PAY_IMO	733.08	$/h

WITH FACTS IN LINES (1-3) (2-5)					
WTIHOUT S LIMITS			WITH S LIMITS		
TTL	466.82	MW	TTL	456.80	MW
LOSSES	21.23	MW	LOSSES	20.13	MW
PAY_IMO	725.70	$/h	PAY_IMO	722.75	$/h

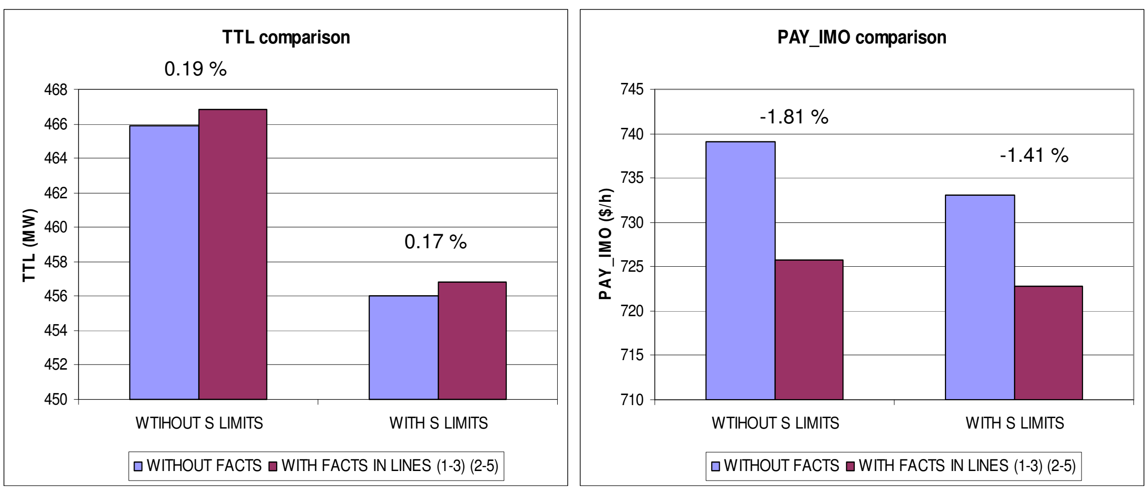


Fig 4.5 Effects of TCSC
(a) variations in TTL (b) variations in PAY_IMO

Therefore, it seems interesting to analyse the behaviour of the system and market in terms of line apparent power limits, demand power bids and compensation level. Thus, Table 4.5 present some results based on the latter statement.

Table 4.5 Comparison between OPF and OPF-FACTS based on congestion and FACTS location (relaxing S limit in line 10-21 to 42.5 MVA)

WITHOUT FACTS					
WTIHOUT S LIMITS			WITH S LIMITS		
TTL	465.91	MW	TTL	463.46	MW
LOSSES	21.40	MW	LOSSES	21.09	MW
PAY_IMO	739.11	$/h	PAY_IMO	770.84	$/h

WITH FACTS IN LINES (1-3) (2-5) (10-22)					
WTIHOUT S LIMITS			WITH S LIMITS		
TTL	466.82	MW	TTL	466.83	MW
LOSSES	21.23	MW	LOSSES	21.24	MW
PAY_IMO	725.70	$/h	PAY_IMO	725.59	$/h

WITH FACTS IN LINES (2-5) (10-22)					
WTIHOUT S LIMITS			WITH S LIMITS		
TTL	466.82	MW	TTL	466.34	MW
LOSSES	21.23	MW	LOSSES	21.27	MW
PAY_IMO	725.70	$/h	PAY_IMO	730.38	$/h

First at all, according to the values reported by the base OPF model the line more congested is 10-21, Table 4.3. Owing to this, the maximum apparent power in that line has been relaxing from 32 MVA to 42.5 MVA. As a result, the TTL with S limits/without FACTS has increased since one of the boundaries that restricted the system before has been reduced (lees coercive). On the other hand, the fact that the TTL is almost identical with and without S limits taking into account FACTS, means that not flow limits are reached when they are included in the model. Hence, in this case the compensation calculated from the OPF problem relieves the congestion problem. Moreover, it should be emphasised the need of measuring and comparing the relative benefits reported by each FACTS unit installed in terms of market results, system operation and inversion associated to. That can be achieved using some of the method mentioned in the literature review of section 3.3 For example, Fig 4.6 based on the results presented in Table 4.5, demonstrates that the different between using two or three FACTS is insignificant in terms of TTL, thus the outlay for the first alternative (two TCSC units) should be significantly smaller than the second one.

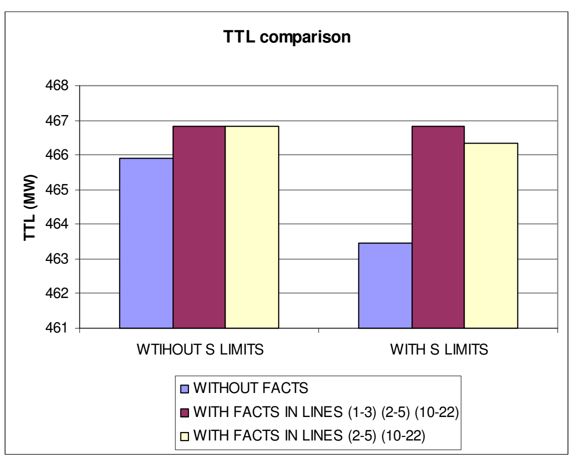


Fig 4.6 Comparison of total transaction level (TTL) in different scenarios.

It is worth mentioning the changes in the payment to the independent market operator observed in Table 4.4. Overall, the payment increases when apparent power flow limits are taken into account since a higher congestion level. According to the general formula of PAY_IMO, explained in section 3.4.3, it is demonstrated that this parameter is influenced by the power imbalance in each bus. Therefore, when no power flow limits are considered that imbalance is lower and thus, is the payment. On the other hand, the introduction of TCSC devices reflects a reduction in this value of 5.8%, from 770.84$/h to 725.59$/h, while higher TTL is achieved.

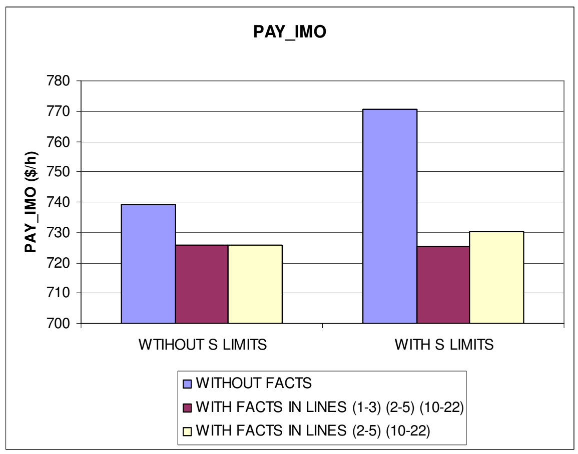


Fig 4.7 Comparison of payment to independent market operator (PAY_IMO) in different scenarios

Fig 4.8 demonstrates how the congestion rate in the two most loaded lines (2-4 and 10-21) varied in function of different initial power demand and compensation levels using the relaxed flow limit indicated previously (42.5 MVA). The first set of lines (slashed) represents the results of the simple OPF model. In this case line 10-21 is overloading in the whole interval while line 2-4 has a range of not congestion below 0.95. Moreover, it is presented graphically the conclusion noted in Table 4.4 about the existence of limits violated. The second set of lines (-.-) is associated with the OPF-FACTS model using FACTS in lines 2-5 and 10-22. As a result, the congestion problem is displaced toward higher loading levels what proves the efficiency of these kinds of devices. The last pair of strokes (solid) performs the evolution of the apparent power through both lines with a fixed compensation level higher than that obtained from the OPF-FACTS model, 50% for line 2-5 and 60% for line 10-22. In this case, clearly the congestion problem has been eradicated within the study range.

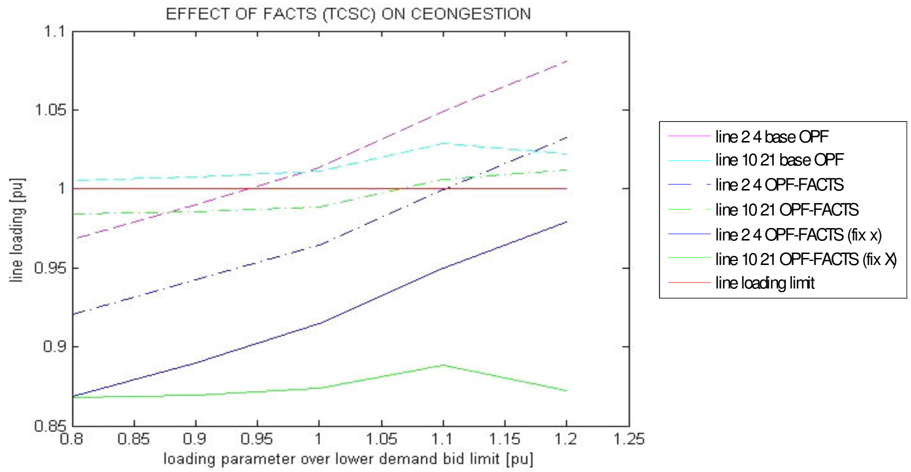


Fig 4.8 Congestion ratios of lines 2-4 and 10-21 for different initial demand bids and compensation levels

The reason of why the OPF-FACTS settlement did not report higher compensation levels if that had led to lower congestion rates is because the social welfare in this case would have been lower than the one obtained using the compensation level reported by the model, as depicted in Fig 4.9. Therefore, the social welfare obtained using OPF-FACTS lied on the other two curves within the whole range. However, the differences in TTL are not significant, Fig 4.10. In short, to relieve congestion more than the level obtained from the OPF-FACTS settlement, the compensation level has to be risen.

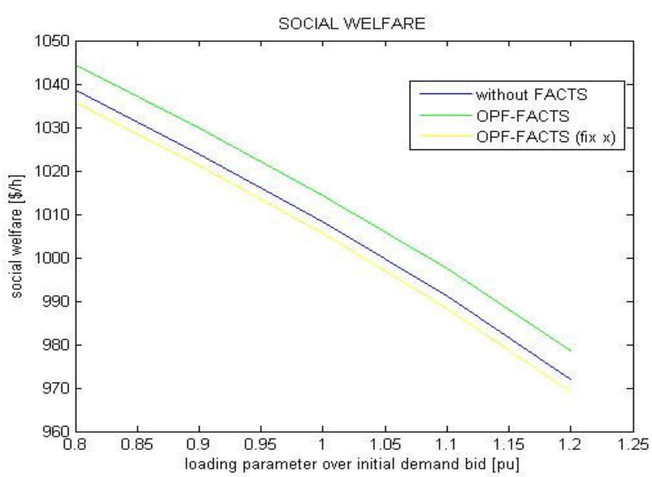


Fig 4.9 Social Welfare and TTL for different compensation levels

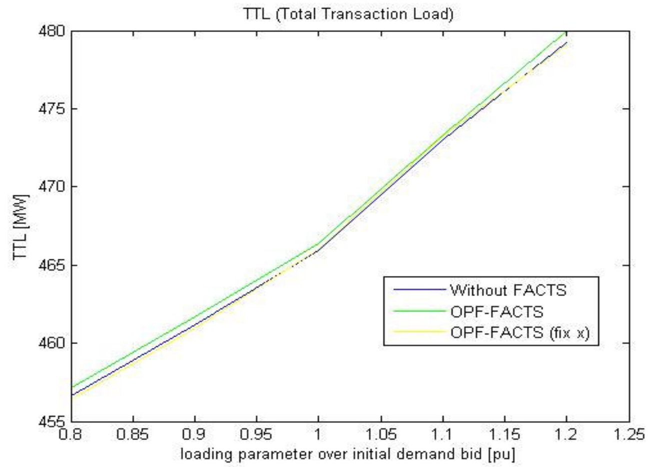
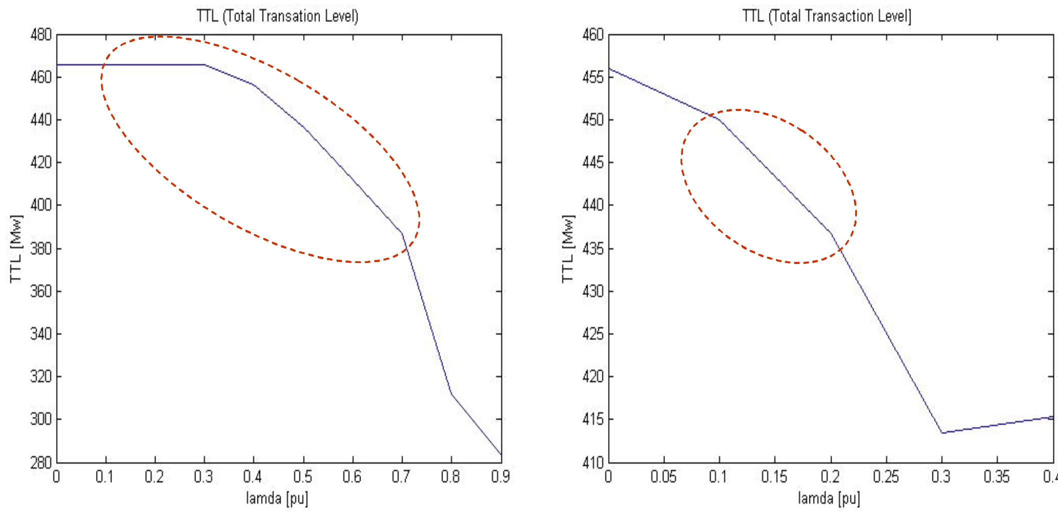


Fig 4.10 Social Welfare and TTL for different compensation levels

4.3.3 SM-OPF without FACTS devices

In this model, as explained in Chapter 3 and section 3.4.3, a loading parameter λ has been used in order to include a security margin in the previous base OPF model. The methodology consists of assigning values to the latter coefficient within a range determined by feasibility of the system and LMP values. Thus, using the definition of available load capability (ALC) (3.58) it is possible to quantify how much power transaction can be increased remaining the system operation feasible. In other words, it is provided a measure of the severity of changes that the power system is able to withstand overall.

In Fig 4.11 it possible to observe how TTL changes in function of both loading parameter λ and apparent power limits. Arguably, there are three regions that are worth mentioning in the case where not flow constraints are imposed. The first one, λ between 0 and 0.3, TTL does not change its value which is 465 MW approximately. The second one, lasted for over a period of 0.4, presents a steady downward trend until λ is equal to 0.7. Finally, the last stretch performs a sharper fall before the feasible limit is reached. Therefore, as more limits are reached, TTL decreases its value since the system is not able to withstand the requirements and converge at the same time. Consequently, the red ellipse frames the most probable area of operation for this particular case since it contains states with rational levels of security. On the other hand, when power limitation through the lines is taken into account, the downward trend is fairly significant from the beginning of the studied period. Moreover, the length of that interval is smaller than the one appears in the unbounded situation. As a result, it is possible to conclude that the effect of congestion is evident since when the upper apparent power limits are introduced within the model the variables are modified compared to the previous case reducing TTL. Furthermore, as was expected, the interval for a reasonable operation is marked smaller.



WTHOUT S LIMITS WTH S LIMITS

Fig 4.11 Total transaction level (TTL) for different loading conditions

Local marginal price (LMP) is other way to establish the range of operation for the system. It is considered that it is not sense for the market operator to state such region where the highest LMP is lower than the highest bid price among market participants according to the formula presented in section 3.4.3. Fig 4.12 shows the trend of LMP for both cases, with and without apparent power limits though the lines. Therefore, it is possible to observe that LMP start a steep decline fairly close to the end of the feasible interval. Thus, it is justified the relevance of determining such a properly bounded area to run the system from an economic point of view as well.

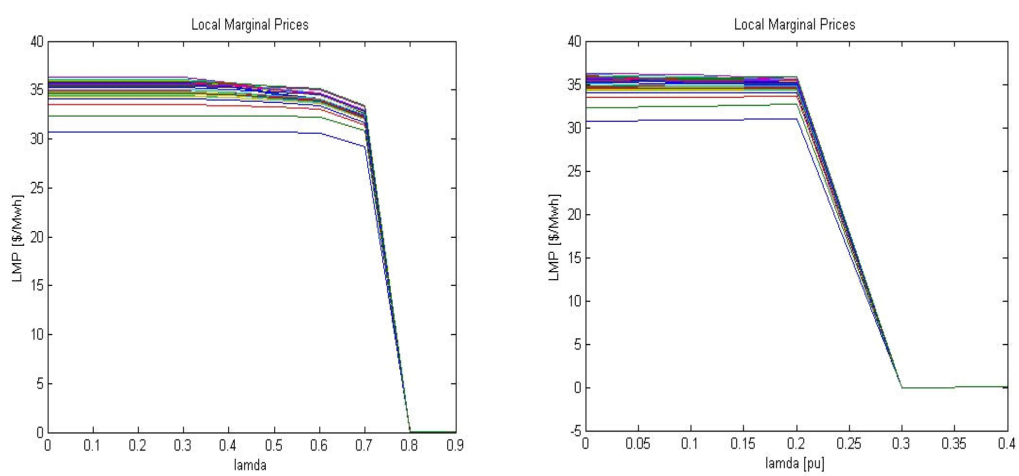


Fig 4.12 LMP for different loading conditions

It is said that loads used are elastic because they can fluctuate according to the market settlement in order to maximize the social welfare. This behaviour is depicted together with the active power supplied in Fig 4.13. It is possible to establish a parallelism between these figures and those related to TTL and LMP since the same significant areas can be underlined. On the other hand, a pure inelastic demand is characterized to not vary according to the price.

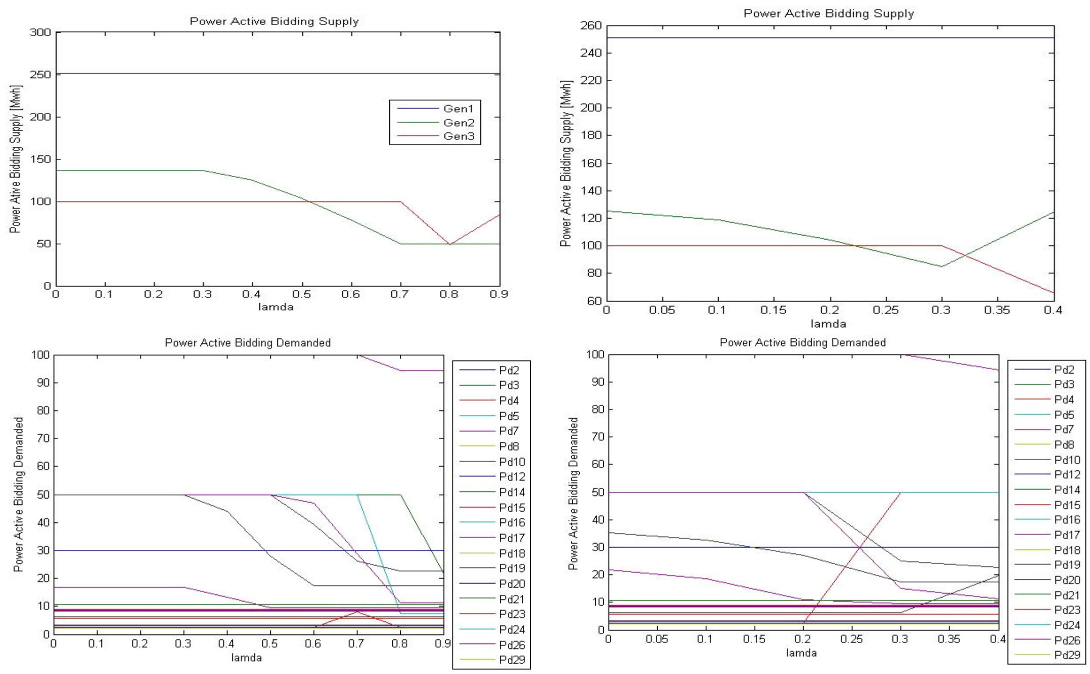


Fig 4.13 Power demanded and Power supplied

Table 4.6 resumes the main results for two different conditions. The first one, the security margin introduced is zero while, in the second case it is assigned the maximum value to the loading parameter before the operation turns out to be infeasible. It can be observed that the TTL is significant lower using the highest λ, however the ALC reaches its maximum. One important point is to be aware that the fact of not having explicitly a security margin does not mean that when λ is equal to zero the system is just in the limits of its capacity, but simply the model reports the optimal solution according to the maximization of social welfare. Therefore, ALC is not related directly to social welfare but to system limits since TTL plus ALC for the maximum margin rate is not equal to the TTL for λ equal to zero. Thus, the current operation point provided by the model SM-OPF ensures the maximization of social welfare, whereas the state associated to the loading parameter does not fulfil this premise. Predictably, it seems reasonable since the security statement is related with anomalous events that are not desired and the most important thing is to be able to withstand them regardless other considerations. Finally, active losses decrease as the security margin increase since less bulk of power is transmitted; and PAY_IMO falls because there is less congestion, the marginal prices are lower and the power injected at each node has declined. Therefore, this methodology proposed different scenarios to markets participants and operators in order to manage economically and reliably the power system and planning strategies.

Table 4.6 Main results for null and maximum security margin

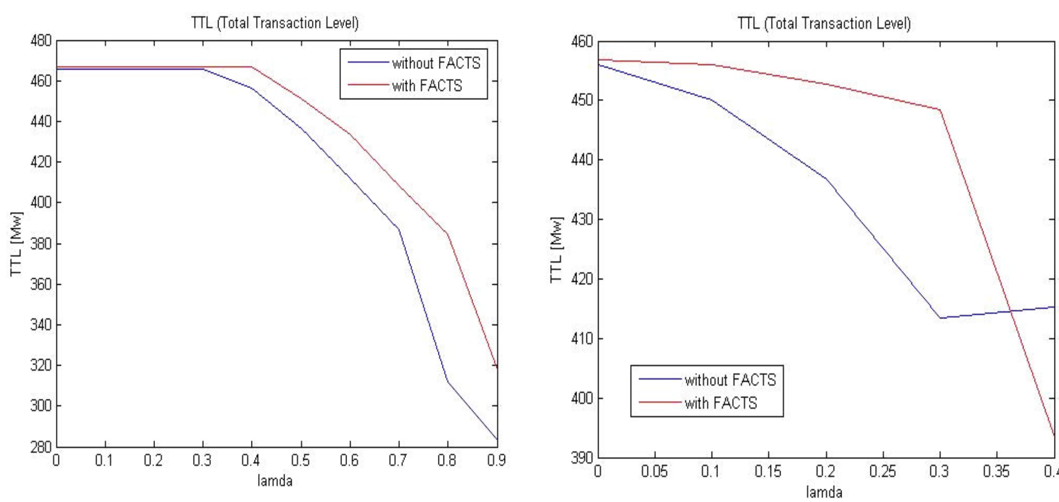
NO SECURITY MARGIN $\lambda = 0$					
WTIHOUT S LIMITS			WITH S LIMITS		
TTL	465.91	MW	TTL	456.00	MW
LOSSES	21.40	MW	LOSSES	20.29	MW
PAY_IMO	739.11	\$/h	PAY_IMO	733.08	\$/h

WITH MAXIMUM SECURITY MARGIN					
WTIHOUT S LIMITS $\lambda_{max} = 0.730$ pu			WITH S LIMITS $\lambda_{max} = 0.234$ pu		
TTL	386.81	MW	TTL	430.40	MW
ALC	282.37	MW	ALC	100.72	MW
LOSSES	14.18	MW	LOSSES	17.77	MW
PAY_IMO	428.38	\$/h	PAY_IMO	576.21	\$/h

In Appendix B all results for different simulation are gathered.

4.3.4 SM-OPF with FACTS devices

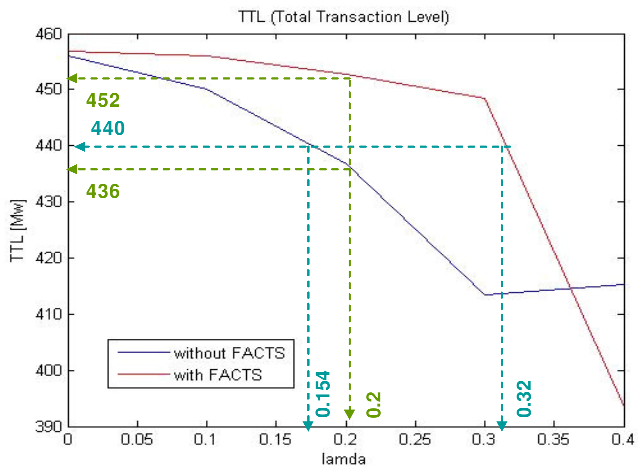
In Fig 4.14 it is shown a comparison of TTL before and after the introduction of TCSC in lines 1-3 and 2-5. The effects on this parameter are significant, above all in the case where apparent power limits are included in the model.



WTHOUT S LIMITS WTH S LIMITS

Fig 4.14 TTL comparison before and after using FACTS devices

Therefore, the used of these devices can increase the amount of power transferred keeping the same security margin or even increasing it, as demonstrated in Fig 4.15 for the case when S limits are taken into account in the model. It is possible to conclude that for the same TTL value a higher maximum security margin is achieved using FACTS, while for a common loading value the TTL is increased as well, Table 4.7.



WTH S LIMITS

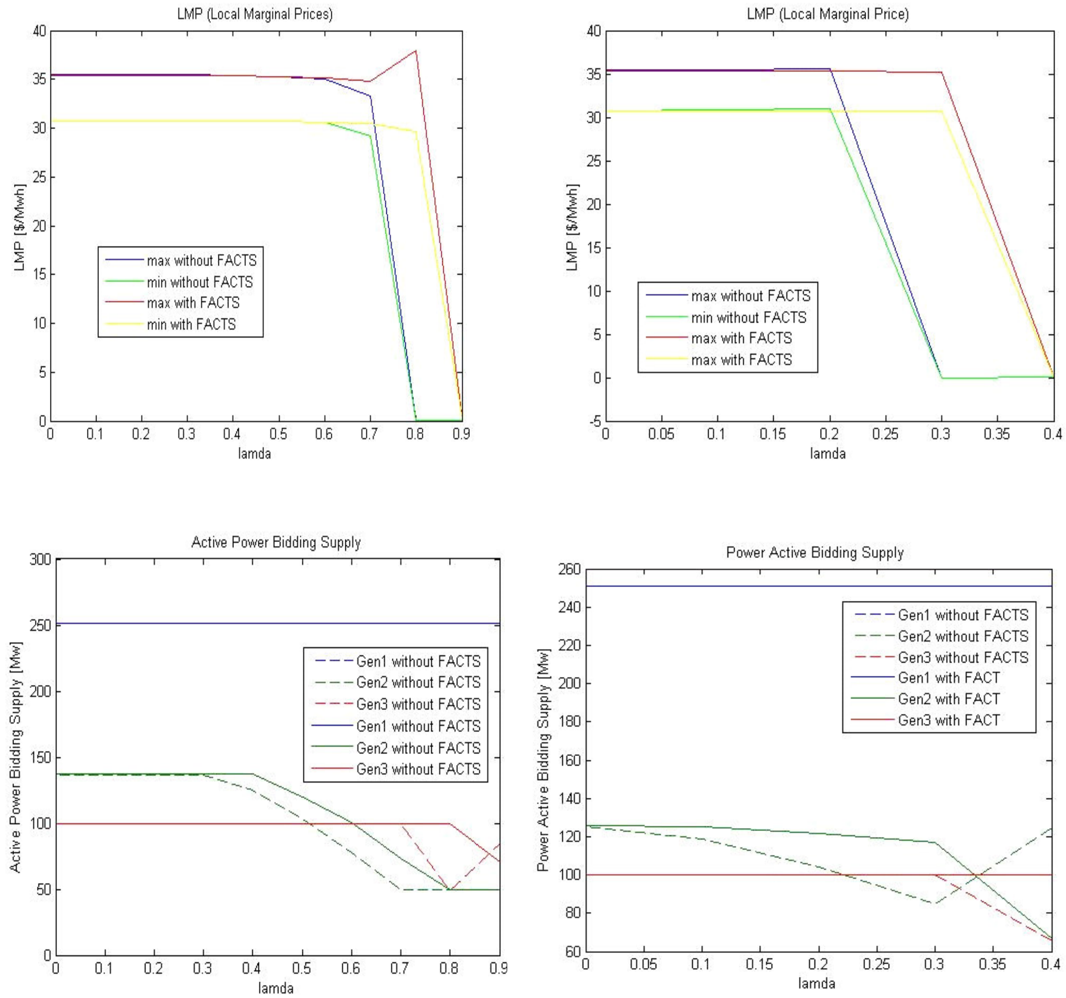
Fig 4.15 Effects of using FACTS devices

Table 4.7 Effects shown in Fig 4.15 of using FACTS devices

TTL = 440 MW			
	WITHOUT FACTS	WITH FACTS	CHANGE
λ ALC [MW]	0.154 67.76	0.32 140.80	108 %

λ = 0.2 pu			
	WITHOUT FACTS	WITH FACTS	CHANGE
TTL ALC [MW]	436 87.2	452 90.4	3.68 %

Fig 4.16 shows the effects of FACTS on other parameters, such as upper-lower LMP boundaries and power supplied. It is observed that the range where LMP are higher than the minimum bid price has increased. This behaviour is more significant when apparent power limits are included in the model. It is important to notice the anomalous peak that appears when no power flow constraints are taken into account owing to the proximity of the infeasible region. For this reason it is necessary to avoid working close to the zone where LMP start a steep decline. It is also observed that all generators are able to keep higher production ratios using FACTS than without them.



WTHOUT S LIMITS WTH S LIMITS

Fig 4.16 Effect of FACTS devices on LMP and power supply

In Table 4.8 different parameters are listed for each case study using both models SM-OPF and SM-OPF with FACTS. As was mentioned before, the maximum value of λ increases when FACTS are included, so does ALC. On the other hand, it is not clear how to depict the trend flowed by the PAY_IMO. According to the definition of this parameter, it is necessary to take into account different facts such as, power injection, local marginal prices at each bus and the contribution of the loading parameter. However, the common trend consists of a reduction in PAY_IMO as the system is less loading.

Table 4.8 Comparison between SM-OPF without FACTS and SM-OPF with FACTS

WITHOUT FACTS					
WTIHOUT S LIMITS			WITH S LIMITS		
$\lambda = 0$ pu			$\lambda = 0$ pu		
TTL	465.91	MW	TTL	456.00	MW
LOSSES	21.40	MW	LOSSES	20.29	MW
PAY_IMO	739.10	\$/h	PAY_IMO	733.08	\$/h
$\lambda_{max} = 0.73$ pu			$\lambda_{max} = 0.234$ pu		
TTL	386.81	MW	TTL	430.40	MW
ALC	282.37	MW	ALC	100.72	MW
LOSSES	14.18	MW	LOSSES	17.77	MW
PAY_IMO	428.38	\$/h	PAY_IMO	576.21	\$/h

WITH FACTS					
WTIHOUT S LIMITS			WITH S LIMITS		
$\lambda = 0$ pu			$\lambda = 0$ pu		
TTL	466.82	MW	TTL	456.80	MW
LOSSES	21.24	MW	LOSSES	20.13	MW
PAY_IMO	725.70	\$/h	PAY_IMO	722.75	\$/h
$\lambda_{max} = 0.77$ pu			$\lambda_{max} = 0.358$ pu		
TTL	386.48	MW	TTL	444.36	MW
ALC	297.59	MW	ALC	159.08	MW
LOSSES	14.69	MW	LOSSES	18.60	MW
PAY_IMO	481.93	\$/h	PAY_IMO	548.92	\$/h

Table 4.9 quantifies in relative terms the previous results. As can be seen, the most significant variations take place when it is decided to included FACTS devices considering apparent power limits.

Table 4.9 Relative variation owing to FACTS

RELATIVE CHANGES OWING TO INSTAL FACTS			
WTIHOUT S LIMITS		WITH S LIMITS	
$\lambda = 0$ pu		$\lambda = 0$ pu	
TTL	0.19	TTL	0.18
LOSSES	-0.75	LOSSES	-0.79
PAY_IMO	-1.80	PAY_IMO	-1.41
λ_{max}		λ_{max}	
TTL	-0.08	TTL	3.24
ALC	5.39	ALC	57.94
λ	5.48	λ	52.99
PAY_IMO	12.50	PAY_IMO	-4.74
LOSSES	3.56	LOSSES	4.67

Fig 4.17 and Fig 4.18 represent graphically the variation on TTL and PAY_IMO respectively.

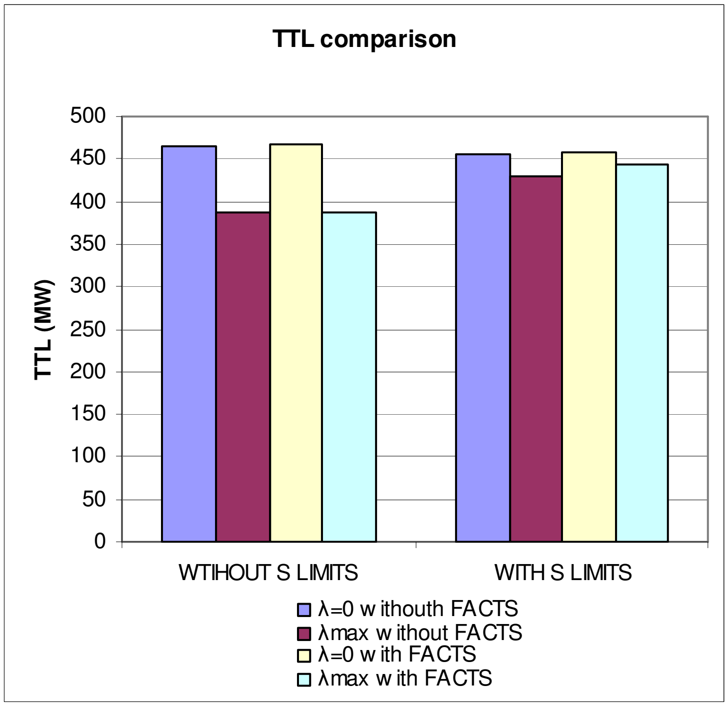


Fig 4.17 TTL comparison between SM-OPF with and without including FACTS devices

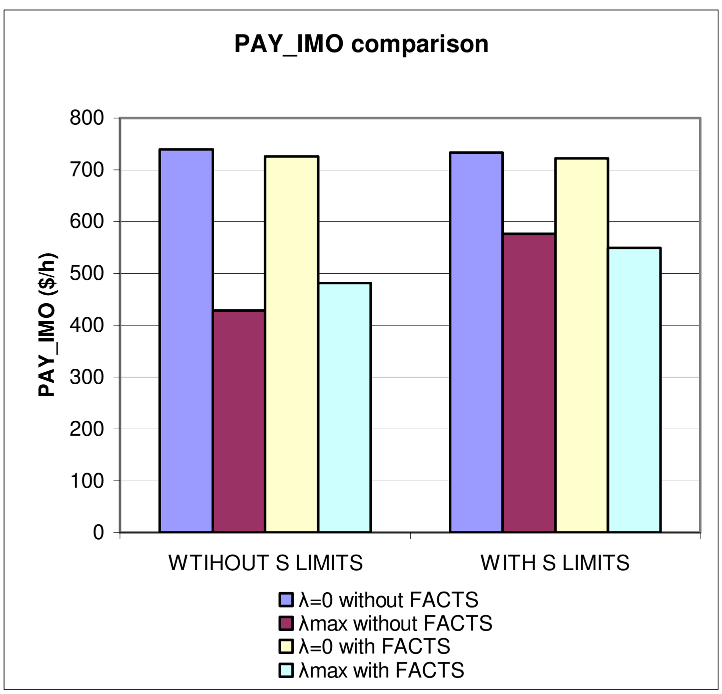


Fig 4.18 PAY_IMO comparison between SM-OPF with and without including FACTS devices

It is worth analysing the differences between maximising the security margin and the social welfare separately. That involves modifying the objective function in the market settlement. Therefore, the following general formulation can be used when the aim consists of determining the highest feasible security margin [53] (see review in section 2.3).

$$
\begin{aligned}
\textit{Objective function} \quad & \max \quad \lambda \\
s.t. \quad & g(x,p) = 0 \\
& h_{\min} \le h(x,p) \le h_{\max} \\
& p_{\min} \le p \le p_{\max}
\end{aligned}
$$

where λ represents the difference in load between the current operating point and the one associated to this parameter, x are the dependent variables, such as bus voltage phasors and p are the control variables, i.e., power demand and supply bids P_D and P_S respectively, g are the equality constraints and h the inequality constraints.

Table 4.10 contains the results of the previous two models. Overall, it can be said that the maximization of security margin leads to a lower TTL, higher active losses and obviously higher relative loading margin, while the maximization of social welfare reports higher TTL, lower active losses and lower relative loading margin. On the other hand, compensation levels obtained in both cases are significantly different. In the first formulation, maximization of security margin, the compensation rate is determined by the upper boundary. However, in the second case these values are lower.

Table 4.10 Results of two models: security loading margin maximization and social welfare maximization

MAXIMIZATION OF SECURITY MARGIN (λ)					
WTIHOUT S LIMITS			WITH S LIMITS		
TTL	359.3	MW	TTL	294.1	MW
LOSSES	24.14	MW	LOSSES	27.91	MW
λ_{max}	0.856	pu	λ_{max}	0.422	pu
compensation			compensation		
1 3	80	%	1 3	80	%
2 5	80	%	2 5	80	%

MAXIMIZATION OF SOCIAL WELFARE					
WTIHOUT S LIMITS			WITH S LIMITS		
TTL	386.48	MW	TTL	444.36	MW
LOSSES	14.69	MW	LOSSES	18.6	MW
λ_{max}	0.77	pu	λ_{max}	0.358	pu
compensation			compensation		
1 3	18.23	%	1 3	19.97	%
2 5	30.51	%	2 5	29.72	%

In Appendix B all the variables are listed with their values for the cases analysed in this section.

Chapter 5

Conclusions

5.1 Conclusions

This work has reviewed how electricity markets have evolved from regulation to deregulation structures during the last years due to a series of causes, such as increase in production prices, prosperous results reported by other sectors liberalized earlier and a general social dissatisfaction. Therefore, it is possible to say that most electricity markets all over the world have implemented decentralized politics in this area. Thus, it seems that a new scenario for energy management has arisen with the aim of being more fair and beneficial than the former vertical structure to market players.

On the one hand, it has been argued that it is not possible to operate power systems remaining the same configuration inherit from the centralized scenario for different reasons. First, security standards were very intensive because it was desired to reduce risk of transmission problems as much as possible regardless the associated cost since rates submitted to customers where determined only by one or a reduce number of authorities. Second, infrastructures, such as transmission lines, power stations and equipment, were not designed to support the expected significant increase in power transaction due to the introduction of competence in the sector. Third, the way of calculating prices of services provided to different participants does not seem fair since it was fixed only by one part and it was difficult to account the cost of different activities evolved in the transaction process. Four, there were not other alternative to purchase electricity at one's disposal. Fifth, it is reasonable to think that new independent participants could be needed to supervise both power transaction and security issues.

As a result of the comments pointed in the previous paragraph, it is worth mentioning that control and monitoring reliability are possible two of the most important responsibilities of independent system operator nowadays since the need of reducing those security criteria imposed in regulated scenario in order to be able to transmit higher bulk of power. Therefore, it is necessary to investigate which the main security aspects are and how they could be modelled to be introduced in market models. Indeed, voltage stability is one of the most popular constraints. Arguably, the literature review provided in this work remarks the amount of studies published about this topic to date.

Hybrid market seems to be more favourable to include security criteria than simple action models for different reasons. First, it has been demonstrated that OPF is a reliable method to determined market settlement. Moreover, owing to the rapid development of computer tools (e.g. GAMS [80]) and mathematical algorithms, it is possible to solve more complex no-lineal optimization problems including both power transaction and security issues. Secondly, new price and sensitivity index, such as Location Marginal Price (LMP), can be calculated through this methodology providing useful referents to market participants to plan their strategies.

On the other hand, the use a loading parameter, and thus the possibility of simulating two different operation points within the same OPF lead to the introduction of a security margin while the goal determined by the objective function is ensured. Therefore, the independent market operator is able to forecast market settlement for different security margins and to have the ability of keeping some transmission capacity to withstand unscheduled contingencies or other transaction.

Finally, FACTS devices have been introduced in this work. It has been demonstrated that nowadays these units are an important solution to address congestion problems and increase transmission capacity in power systems. Therefore, several studies have been carried out in this field focus on establishing different criteria to optimize the allocation of these equipments and emphasise their benefits. A particular typology of FACTS, namely, TCSC, has been implemented in both models simulated in this work in order to study its influent. Furthermore, the injection representation of these devices has turn out to be an easy mode to include them within the classical power flow equations. Undoubtedly, security and transfer capacity are improved while the objective function ensures the desire goal.

5.2 Future research directions

It is possible to say that most of the authors who have written about this topic agree with a series of facts that future research directions should be focused on. For example, implementing more detailed model of those units used in power transmission systems, such generators, load and so forth, would lead to more realistically simulation and hence more accurate results. Moreover, it is necessary to propose a global model which could include the management of different electricity power sources such as, thermal, hydro and nuclear plants; a comprehensive range of security constraints; useful economic referents to all market participants; reservoirs and ancillary services and the capability of being extended easily.

On the other hand, it is necessary to improve the perception that participants in the sector have of OPF in hybrid markets. Normally, it is said that the mechanism used in the latter model is not as transparent as the simple auction method is. This lack of simplicity has to be overcome in order to increase the implementation ratio of OPF in the actual framework.

Appendix A

Market and Transmission System Data

A Market and transmission system data

A.1 14 bus test system

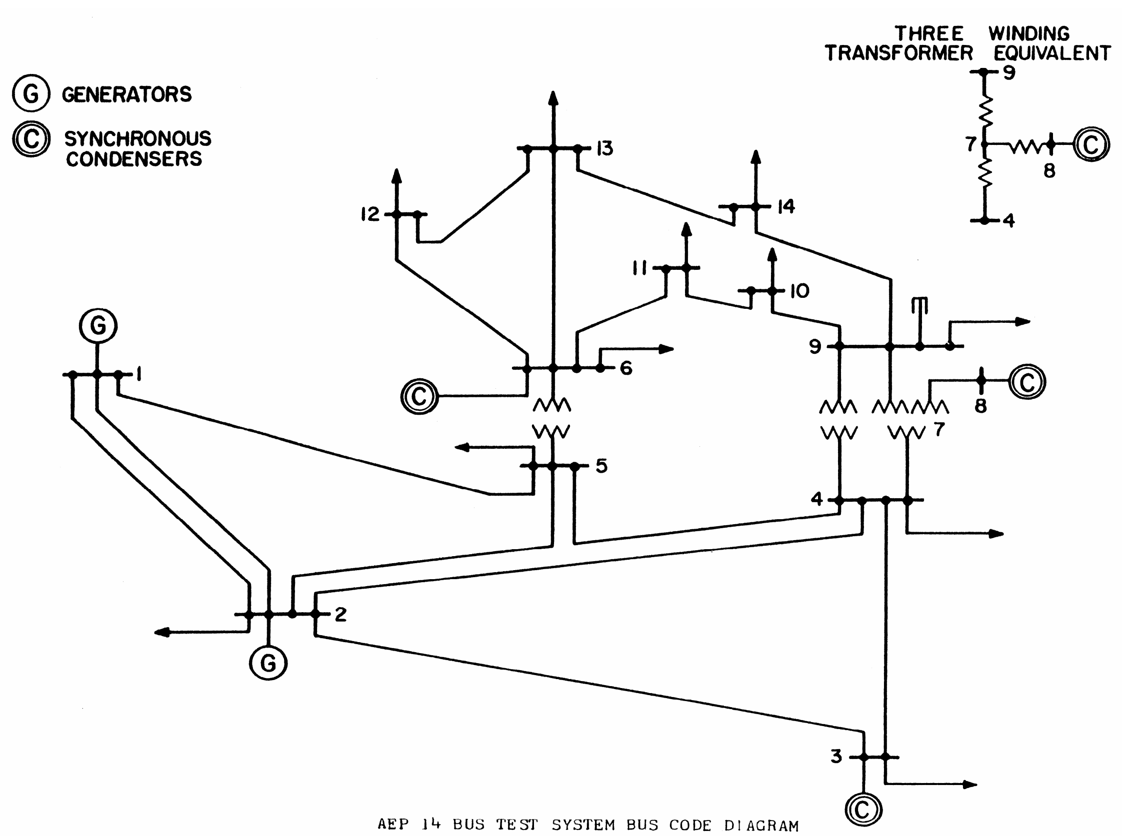


Fig A.1 14 bust test system

Table A.1 Line data 14 bus test system.

LINE DATA							
LINE BUSES		LINE PARAMETERS			ACTIVE TRANSFORMERS		LINE POWER LIMITATION
		r_{ij}	x_{ij}	$b_{sh\ total}$	x	n	S_{max}
FROM	T0	[pu]	[pu]	[pu]	[pu]	[pu]	[MVAR]
1	2	0.01938	0.05917	0.0528			292.41
1	5	0.05403	0.22304	0.0492			292.41
2	3	0.04699	0.19797	0.0438			292.41
2	4	0.05811	0.17632	0.0340			292.41
2	5	0.05695	0.17388	0.0346			292.41
3	4	0.06701	0.17103	0.0128			292.41
4	5	0.01335	0.04211	0.0			292.41
4	7	0.0	0.0	0.0	0.20912	0.978	42.25
4	9	0.0	0.0	0.0	0.55618	0.969	16.00
5	6	0.0	0.0	0.0	0.25202	0.932	42.25
6	11	0.09498	0.19890	0.0			25.00
6	12	0.12291	0.25581	0.0			25.00
6	13	0.06615	0.13027	0.0			25.00
7	8	0.0	0.17615	0.0			25.00
7	9	0.0	0.11001	0.0			42.25
9	10	0.03181	0.08450	0.0			25.00
9	14	0.12711	0.27038	0.0			25.00
10	11	0.08205	0.19207	0.0			25.00
12	13	0.22092	0.19988	0.0			25.00
13	14	0.17093	0.34802	0.0			25.00

Table A.2 Bus and Load data 14 bus test system.

BUS	VOLTAGE			LOAD		SHUNT	GENERATION LIMITS	
	V_{MIN} [pu]	V_{MAX} [pu]	V_{BASE} [KV]	P [MW]	Q [MVAr]	X_{SC} [pu]	Q_{MIN} [MVAr]	Q_{MAX} [MVAr]
1	1.060	1.060	69.0	0.0	0.0		-100	100
2	1.045	1.045	69.0	21.7	12.7		-40	80
3	1.010	1.010	69.0	94.2	19.0		0	60
4	0.8	1.200	69.0	47.8	-3.9			
5	0.8	1.200	69.0	7.6	1.6			
6	1.070	1.070	13.8	11.2	7.5		-6	40
7	0.8	1.200	13.8	0.0	0.0			
8	1.090	1.090	18.0	0.0	0.0		-6	24
9	0.8	1.200	13.8	29.5	16.6	0.19		
10	0.8	1.200	13.8	9.0	5.8			
11	0.8	1.200	13.8	3.5	1.8			
12	0.8	1.200	13.8	6.1	1.6			
13	0.8	1.200	13.8	13.5	5.8			
14	0.8	1.200	13.8	14.9	5.0			

POWER FLOW REPORT

P S A T 1.3.4

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website: http://thunderbox.uwaterloo.ca/~fmilano

Date: 12-May-2008 22:45:57

NETWORK STATISTICS

Buses:	14
Lines:	16
Transformers:	4
Generators:	5
Loads:	11

SOLUTION STATISTICS

Number of Iterations:	4
Maximum P mismatch [p.u.]	0
Maximum Q mismatch [p.u.]	0
Power rate [MVA]	100

POWER FLOW RESULTS

Bus	V [p.u.]	phase [rad]	P gen [p.u.]	Q gen [p.u.]	P load [p.u.]	Q load [p.u.]
Bus 01	1.06	0	2.3239	-0.169	0	0
Bus 02	1.045	-0.08693	0.4	0.42358	0.217	0.127
Bus 03	1.01	-0.22197	0	0.23369	0.942	0.19
Bus 04	1.0187	-0.1802	0	0	0.478	-0.04
Bus 05	1.0203	-0.15329	0	0	0.076	0.016
Bus 06	1.07	-0.24823	0	0.12223	0.112	0.075
Bus 07	1.062	-0.23333	0	0	0	0
Bus 08	1.09	-0.23333	0	0.17345	0	0
Bus 09	1.0564	-0.26087	0	0	0.295	0.166
Bus 10	1.0513	-0.26363	0	0	0.09	0.058
Bus 11	1.0571	-0.25823	0	0	0.035	0.018
Bus 12	1.0552	-0.26315	0	0	0.061	0.016
Bus 13	1.0505	-0.26458	0	0	0.135	0.058
Bus 14	1.0358	-0.27994	0	0	0.149	0.05

LINE FLOWS

From Bus	To Bus	Line	P Flow [p.u.]	Q Flow [p.u.]	P Loss [p.u.]	Q Loss [p.u.]
Bus 02	Bus 05	1	0.41512	0.00748	0.00902	-0.00871
Bus 06	Bus 12	2	0.07782	0.02492	0.00072	0.00149
Bus 12	Bus 13	3	0.0161	0.00743	6e-005	6e-005
Bus 06	Bus 13	4	0.1774	0.07169	0.00212	0.00417
Bus 06	Bus 11	5	0.07341	0.03468	0.00055	0.00115
Bus 11	Bus 10	6	0.03786	0.01554	0.00012	0.00029
Bus 09	Bus 10	7	0.05239	-0.16892	0.00013	-0.21167
Bus 09	Bus 14	8	0.09438	-0.17534	0.00117	-0.20954
Bus 14	Bus 13	9	-0.05578	-0.0158	0.00054	0.00109
Bus 07	Bus 09	10	0.28087	0.05798	0	-0.204
Bus 01	Bus 02	11	1.5683	-0.20392	0.04295	0.07263
Bus 03	Bus 02	12	-0.70866	0.01584	0.0232	0.05149
Bus 03	Bus 04	13	-0.23334	0.02786	0.00371	-0.02612
Bus 01	Bus 05	14	0.75554	0.03492	0.02764	0.06084
Bus 05	Bus 04	15	0.61738	-0.15408	0.00517	0.00299
Bus 02	Bus 04	16	0.56139	-0.02311	0.01677	0.01106
Bus 05	Bus 06	17	0.44062	0.12836	0	0.04429

Bus 04	Bus 09	18	0.1609	-0.00317	0	-0.19899
Bus 04	Bus 07	19	0.28087	-0.0941	0	0.01691
Bus 08	Bus 07	20	0	0.17345	0	0.00446

LINE FLOWS

From Bus	To Bus	Line	P Flow [p.u.]	Q Flow [p.u.]	P Loss [p.u.]	Q Loss [p.u.]
Bus 05	Bus 02	1	-0.4061	-0.0162	0.00902	-0.00871
Bus 12	Bus 06	2	-0.0771	-0.02343	0.00072	0.00149
Bus 13	Bus 12	3	-0.01604	-0.00737	6e-005	6e-005
Bus 13	Bus 06	4	-0.17528	-0.06752	0.00212	0.00417
Bus 11	Bus 06	5	-0.07286	-0.03354	0.00055	0.00115
Bus 10	Bus 11	6	-0.03774	-0.01525	0.00012	0.00029
Bus 10	Bus 09	7	-0.05226	-0.04275	0.00013	-0.21167
Bus 14	Bus 09	8	-0.09322	-0.0342	0.00117	-0.20954
Bus 13	Bus 14	9	0.05632	0.01689	0.00054	0.00109
Bus 09	Bus 07	10	-0.28087	-0.26198	0	-0.204
Bus 02	Bus 01	11	-1.5254	0.27656	0.04295	0.07263
Bus 02	Bus 03	12	0.73186	0.03565	0.0232	0.05149
Bus 04	Bus 03	13	0.23705	-0.05398	0.00371	-0.02612
Bus 05	Bus 01	14	-0.7279	0.02592	0.02764	0.06084
Bus 04	Bus 05	15	-0.61221	0.15708	0.00517	0.00299
Bus 04	Bus 02	16	-0.54462	0.03417	0.01677	0.01106
Bus 06	Bus 05	17	-0.44062	-0.08406	0	0.04429
Bus 09	Bus 04	18	-0.1609	-0.19582	0	-0.19899
Bus 07	Bus 04	19	-0.28087	0.11101	0	0.01691
Bus 07	Bus 08	20	0	-0.16899	0	0.00446

GLOBAL SUMMARY REPORT

TOTAL GENERATION

REAL POWER [p.u.] 2.7239
REACTIVE POWER [p.u.] 0.78395

TOTAL LOAD

REAL POWER [p.u.] 2.59
REACTIVE POWER [p.u.] 0.734

TOTAL SHUNT

REAL POWER [p.u.] 0
REACTIVE POWER (IND) [p.u.] 0
REACTIVE POWER (CAP) [p.u.] 0.21202

TOTAL LOSSES

REAL POWER [p.u.] 0.13386
REACTIVE POWER [p.u.] -0.58611

LIMIT VIOLATION STATISTICS
ALL VOLTAGES WITHIN LIMITS.
ALL REACTIVE POWER WITHIN LIMITS.
ALL CURRENT FLOWS WITHIN LIMITS.
ALL REAL POWER FLOWS WITHIN LIMITS.
ALL APPARENT POWER FLOWS WITHIN LIMITS.

A.2 30 bus test system

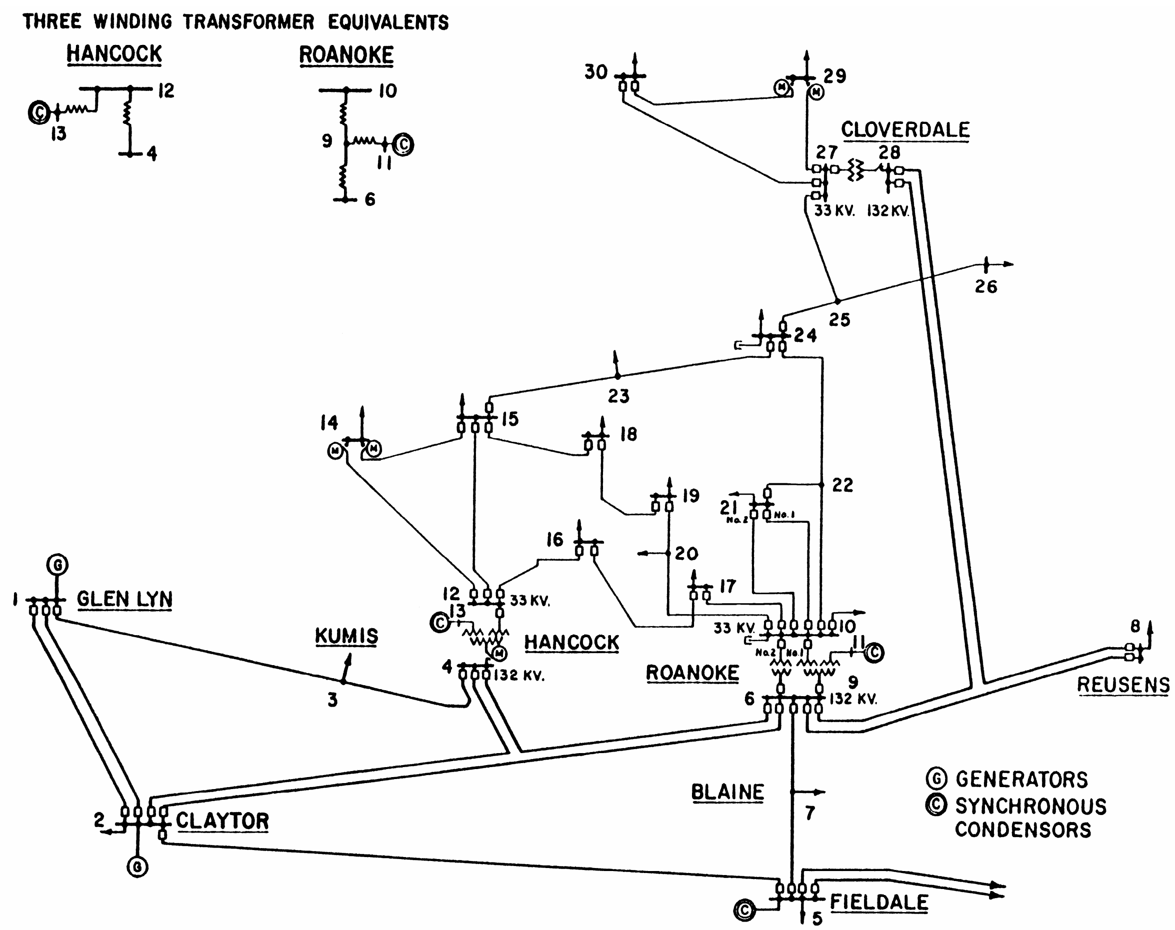

Fig A.2 30 bust test system

Table A.3 Line data 30 bus test system.

LINE DATA							
LINE BUSES		LINE PARAMETERS			ACTIVE TRANSFORMERS		LINE POWER LIMITATION
		r_{ij}	x_{ij}	$b_{sh\ total}$	x	n	S_{max}
FROM	T0	[pu]	[pu]	[pu]	[pu]	[pu]	[MVAR]
1	2	0.0192	0.0575	0.0528			200
1	3	0.0452	0.1652	0.0408			130
2	4	0.0570	0.1737	0.0368			66
3	4	0.0132	0.0379	0.0084			130
2	5	0.0472	0.1983	0.0418			130
2	6	0.0581	0.1763	0.0374			90
4	6	0.0119	0.0414	0.0090			90
5	7	0.0460	0.1160	0.0204			70
6	7	0.0267	0.0820	0.0170			130
6	8	0.0120	0.0420	0.0090			137
6	9	0	0	0	0.2080	0.978	90
6	10	0	0	0	0.5560	0.969	48
9	11	0	0.2080	0			65
9	10	0	0.1100	0			89
4	12	0	0	0	0.2560	0.932	109
12	13	0	0.1400	0			65
12	14	0.1231	0.2559	0			32
12	15	0.0662	0.1304	0			48
12	16	0.0945	0.1987	0			32
14	15	0.2210	0.1997	0			16
16	17	0.0524	0.1923	0			16
15	18	0.1073	0.2185	0			18
18	19	0.0639	0.1292	0			16
19	20	0.0340	0.0680	0			32
10	20	0.0936	0.2090	0			37
10	17	0.0324	0.0845	0			35
10	21	0.0348	0.0749	0			32
10	22	0.0727	0.1499	0			32
21	22	0.0116	0.0236	0			32
15	23	0.1000	0.2020	0			16
22	24	0.1150	0.1790	0			21
23	24	0.1320	0.2700	0			16
24	25	0.1885	0.3292	0			16
25	26	0.2544	0.3800	0			16
25	27	0.1093	0.2087	0			19
27	28	0	0	0	0.3960	1.033	65
27	29	0.2198	0.4153	0			21
27	30	0.3202	0.6027	0			16
29	30	0.2399	0.4533	0			16
8	28	0.0636	0.2000	0.0428			36
6	28	0.0169	0.0599	0.0130			32

Table A.4 Generators and Synchronous condensers data 30 bus test system.

GENERATORS AND SYNCHRONOUS CONDENSORS DATA								
GENER.	BUS	BID LIMITS		REACTIVE LIMITS		BID COEFFICIENTS A*p^2+B*p+C		
		PBMIN [MW]	PBMAX [MW]	QMIN [MVAr]	QMAX [MVAr]	A [$/MWh^2]	B [$/MWh]	C [$]
G1	1	251	300	-100	100	0	32.66	0
G2	2	50	250	-100	80	0	32.33	0
G3	8	10	100	-100	50	0	31.83	0
G4	5	SYNCHRONOUS CONDENSORS		-100	100	SYNCHRONOUS CONDENSORS		
G5	11			-100	100			
G6	13			-100	100			

Table A.5 Bus and Demand data 30 bus test system.

BUS AND DEMAND DATA									
BUS	VOLTAGE			BID LIMITS		SHUNT	BID COEFFICIENTS A*p^2+B*p+C		
	V_{MIN} [pu]	V_{MAX} [pu]	V_{BASE} [KV]	PBMIN [MW]	PBMAX [MW]	X_{SC} [pu]	A [$/MWh^2]	B [$/MWh]	C [$]
1	0.9	1.1	132	0.0	0		0	33.18	0
2	0.9	1.1	132	21.7	50		0	36.62	0
3	0.9	1.1	132	2.4	50		0	33.54	0
4	0.9	1.1	132	7.6	50		0	36.92	0
5	0.9	1.1	132	94.2	100		0	36.67	0
6	0.9	1.1	132	0.0	0		0	33.51	0
7	0.9	1.1	132	22.8	50		0	36.62	0
8	0.9	1.1	132	30.0	50		0	33.07	0
9	0.9	1.1	1	0.0	0		0	33.42	0
10	0.9	1.1	33	5.8	50	0.19	0	33.53	0
11	0.9	1.1	11	0.0	0		0	33.08	0
12	0.9	1.1	33	11.2	50		0	36.22	0
13	0.9	1.1	11	0.0	0		0	33.74	0
14	0.9	1.1	33	6.2	50		0	33.41	0
15	0.9	1.1	33	8.2	50		0	33.54	0
16	0.9	1.1	33	3.5	50		0	33.57	0
17	0.9	1.1	33	9.0	50		0	33.88	0
18	0.9	1.1	33	3.2	50		0	33.17	0
19	0.9	1.1	33	9.5	50		0	36.66	0
20	0.9	1.1	33	2.2	50		0	33.19	0
21	0.9	1.1	33	17.5	50		0	36.90	0
22	0.9	1.1	33	0.0	0		0	33.39	0
23	0.9	1.1	33	3.2	50		0	36.27	0
24	0.9	1.1	33	8.7	50	0.043	0	33.95	0
25	0.9	1.1	33	0.0	0		0	33.82	0
26	0.9	1.1	33	3.5	50		0	33.20	0
27	0.9	1.1	33	0.0	0		0	33.65	0
28	0.9	1.1	132	0.0	0		0	36.68	0
29	0.9	1.1	33	2.4	50		0	33.49	0
30	0.9	1.1	33	10.6	50		0	36.10	0

Appendix B

Simulation Results

B Simulation results

Table B.1 Results for OPF-FACTS model without apparent power flow limitation

BUS	LMP [$/MWh]	V [pu]	Pbs [MW]	Pbd [MW]	PAY [$/h]
1	30.75	1.10	251	0	-7718
2	32.33	1.09	137.1	50	-2815
3	33.52	1.04		2.4	80
4	34.38	1.03		50	1719
5	35.38	1.05		100	3538
6	34.58	1.04		0	0
7	35.47	1.02		50	1773
8	34.13	1.05	100	30	-2389
9	34.74	1.06		0	0
10	34.83	1.03		5.8	202
11	34.74	1.10		0	0
12	34.74	1.05		50	1737
13	34.74	1.10		0	0
14	35.36	1.03		6.2	219
15	35.54	103		8.2	291
16	34.99	1.04		3.5	122
17	35.02	1.03		9	315
18	36.09	1.01		3.2	115
19	36.27	1.00		17.5	636
20	35.92	1.01		2.2	79
21	35.77	1.01		50	1789
22	35.66	1.01		0	0
23	35.80	1.02		3.2	115
24	35.85	1.01		8.7	312
25	34.99	1.02		0	0
26	35.64	1.01		3.5	125
27	34.26	1.04		0	0
28	34.67	1.03		0	0
29	35.23	1.02		2.4	85
30	35.91	1.01		11	395

TTL	466.82	MW
LOSSES	21.23	MW
PAY_IMO	725.7	$/h

COMPENSATION		
1 3	21.09	%
2 5	30.44	%

Table B.2 Results for OPF-FACTS model with apparent power flow limitation

BUS	LMP [$/MWh]	V [pu]	Pbs [MW]	Pbd [MW]	PAY [$/h]
1	30.74	1.10	251	0	-7715
2	32.33	1.09	125.9	50	-2455
3	33.43	1.05		2.4	80
4	34.26	1.03		50	1713
5	35.31	1.05		100	3531
6	34.42	1.04		0	0
7	35.33	1.03		50	1767
8	33.98	1.06	100	30	-2379
9	34.45	1.06		0	0
10	34.46	1.05		5.8	200
11	34.45	1.10		0	0
12	34.68	1.05		50	1734
13	34.68	1.10		0	0
14	35.31	1.04		6.2	219
15	35.51	1.03		8.2	291
16	34.76	1.05		3.5	122
17	34.70	1.04		9	312
18	36.08	1.02		3.2	115
19	36.29	1.01		22.5	816
20	35.82	1.02		2.2	79
21	36.02	1.03		35.1	1265
22	35.82	1.03		0	0
23	35.82	1.03		3.2	115
24	35.94	1.02		8.7	313
25	35.04	1.03		0	0
26	35.68	1.02		3.5	125
27	34.29	1.05		0	0
28	34.52	1.04		0	0
29	35.23	1.03		2.4	85
30	35.89	1.02		10.9	391

TTL	456.8	MW
LOSSES	20.13	MW
PAY_IMO	722.75	$/h

COMPENSATION		
1 3	20.52	%
2 5	29.98	%

Table B.3 Results for SM-OPF model without apparent power flow limitation and λ=0.

BUS	LMP [$/MWh]	V [pu]	Pbs [MW]	Pbd [MW]	PAY [$/h]
1	30.74	1.10	251	0	-7716
2	32.33	1.09	136.3	50	-2790
3	33.55	1.04		2.4	81
4	34.40	1.03		50	1720
5	35.50	1.05		100	3551
6	34.60	1.03		0	0
7	35.51	1.02		50	1776
8	34.14	1.05	100	30	-2390
9	34.76	1.06		0	0
10	34.86	1.03		5.8	202
11	34.76	1.10		0	0
12	34.73	1.05		50	1739
13	34.73	1.10		0	0
14	35.38	1.03		6.2	219
15	35.56	1.03		8.2	292
16	35.01	1.04		3.5	123
17	35.05	1.03		9	315
18	36.09	1.01		3.2	116
19	36.26	1.00		16.9	612
20	35.92	1.01		2.2	79
21	35.81	1.00		50	1791
22	35.69	1.01		0	0
23	35.83	1.02		3.2	115
24	35.87	1.01		8.7	312
25	35.01	1.02		0	0
26	35.67	1.00		3.5	125
27	34.29	1.04		0	0
28	34.69	1.03		0	0
29	35.24	1.02		2.4	85
30	35.90	1.01		10.7	385

TTL	465.91	MW
LOSSES	21.4	MW
PAY_IMO	739.1	$/h

$$\lambda = 0$$

Table B.4 Results for SM-OPF model without apparent power flow limitation and λmax.

BUS	LMP [$/MWh]	V [pu]	Pbs [MW]	Pbd [MW]	PAY [$/h]
1	28.14	1.10	251	0	-7062
2	29.68	1.08	50	50	0
3	30.30	1.05		25.8	782
4	30.76	1.05		50	1538
5	31.96	1.05		100	3196
6	30.80	1.06		0	0
7	31.43	1.05		22.8	717
8	30.43	1.08	100	30	-2130
9	30.84	1.09		0	0
10	30.86	1.09		5.8	179
11	30.84	1.10		0	0
12	30.79	1.09		14.7	453
13	30.79	1.10		0	0
14	31.24	1.08		6.2	194
15	31.33	1.07		8.2	257
16	30.99	1.08		3.5	108
17	31.00	1.08		9	279
18	31.57	1.07		3.2	101
19	31.59	1.07		9.5	300
20	31.43	1.07		2.2	69
21	31.16	1.07		17.5	545
22	31.15	1.08		0	0
23	31.51	1.07		3.2	101
24	31.53	1.06		8.7	274
25	31.22	1.07		0	0
26	31.75	1.05		3.5	111
27	30.83	1.07		0	0
28	30.87	1.06		0	0
29	31.61	1.06		2.4	76
30	32.14	1.04		10.6	341

TTL	386.81	MW
ALC	282.37	MW
LOSSES	14.18	MW
PAY_IMO	428.38	$/h

$$\lambda = 0.73$$

Table B.5 Results for SM-OPF model with apparent power flow limitation and λ=0.

BUS	LMP [$/MWh]	V [pu]	Pbs [MW]	Pbd [MW]	PAY [$/h]
1	30.73	1.10	251	0	-7713
2	32.33	1.09	125.3	50	-2435
3	33.45	1.05		2.4	80
4	34.28	1.03		50	1714
5	35.42	1.05		100	3542
6	34.44	1.04		0	0
7	35.37	1.03		50	1769
8	34.00	1.06	100	30	-2380
9	34.48	1.06		0	0
10	34.50	1.05		5.8	200
11	34.48	1.10		0	0
12	34.71	1.05		50	1735
13	34.71	1.10		0	0
14	35.34	1.04		6.2	219
15	35.53	1.03		8.2	291
16	34.79	1.05		3.5	122
17	34.73	1.04		9	313
18	36.09	1.02		3.2	115
19	36.28	1.01		21.9	794
20	35.83	1.02		2.2	79
21	36.02	1.03		35.1	1266
22	35.82	1.03		0	0
23	35.84	1.03		3.2	115
24	35.95	1.02		8.7	313
25	35.06	1.03		0	0
26	35.70	1.02		3.5	125
27	34.31	1.05		0	0
28	34.54	1.04		0	0
29	35.24	1.03		2.4	85
30	35.89	1.02		10.7	384

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TTL	456	MW
LOSSES	20.29	MW
PAY_IMO	733.08	$/h

$$\lambda = 0$$

Table B.6 Results for SM-OPF model with apparent power flow limitation and λmax.

BUS	LMP [$/MWh]	V [pu]	Pbs [MW]	Pbd [MW]	PAY [$/h]
1	29.61	1.10	251	0	-7431
2	31.20	1.09	97.2	50	-1473
3	32.03	1.05		2.4	77
4	32.76	1.04		50	1638
5	34.02	1.05		100	3402
6	32.89	1.05		0	0
7	33.84	1.03		50	1692
8	32.48	1.07	100	30	-2274
9	32.89	1.08		0	0
10	32.89	1.07		5.8	191
11	32.89	1.10		0	0
12	33.09	1.07		46.1	1525
13	33.09	1.10		0	0
14	33.60	1.05		6.2	208
15	33.62	1.05		8.2	276
16	33.16	1.06		3.5	116
17	33.10	1.06		9	298
18	33.81	1.05		3.2	108
19	33.79	1.04		9.5	321
20	33.58	1.05		2.2	74
21	33.35	1.05		26	866
22	33.32	1.05		0	0
23	33.78	1.04		3.2	108
24	33.73	1.04		8.7	293
25	33.24	1.05		0	0
26	33.82	1.03		3.5	118
27	32.73	1.06		0	0
28	32.96	1.05		0	0
29	33.58	1.04		2.4	81
30	34.17	1.03		10.6	362

TTL	430.4	MW
ALC	100.72	MW
LOSSES	17.77	MW
PAY_IMO	576.21	$/h

$$\lambda = 0.234$$

Table B.7 Results for SM-OPF-FACTS model without apparent power flow limitation and λ=0

BUS	LMP [$/MWh]	V [pu]	Pbs [MW]	Pbd [MW]	PAY [$/h]
1	30.75	1.10	251	0	-7718
2	32.33	1.09	137.1	50	-2815
3	33.52	1.04		2.4	80
4	34.38	1.03		50	1719
5	35.38	1.05		100	3538
6	34.58	1.04		0	0
7	35.47	1.02		50	1773
8	34.13	1.05	100	30	-2389
9	34.74	1.06		0	0
10	34.83	1.03		5.8	202
11	34.74	110		0	0
12	34.74	1.05		50	1737
13	34.74	1.10		0	0
14	35.36	1.03		6.2	219
15	35.54	1.03		8.2	291
16	34.99	1.04		3.5	122
17	35.02	1.03		9	315
18	36.09	1.01		3.2	115
19	36.27	1.00		17.5	636
20	35.92	1.01		2.2	79
21	35.77	1.01		0	1789
22	35.66	1.01		0	0
23	35.80	1.02		3.2	115
24	35.85	1.01		8.7	312
25	34.99	1.02		0	0
26	35.64	1.01		3.5	125
27	34.26	1.04		0	0
28	34.67	1.03		0	0
29	35.23	1.02		2.4	85
30	35.91	1.01		11	395

TTL	466.82	MW
LOSSES	21.24	MW
PAY_IMO	725.7	$/h

COMPENSATION		
1 3	21.09	%
2 5	30.44	%

$$\lambda = 0$$

Table B.8 Results for SM-OPF model without apparent power flow limitation and λmax

BUS	LMP [$/MWh]	V [pu]	Pbs [MW]	Pbd [MW]	PAY [$/h]
1	30.37	1.10	251	0	-7622
2	32.07	1.08	50.2	50	-5
3	32.55	1.06		2.4	78
4	33.21	1.05		50	1660
5	34.55	1.05		100	3455
6	33.31	1.06		0	0
7	34.13	1.04		34.1	1164
8	32.91	1.07	100	30	-2304
9	33.31	1.09		0	0
10	33.31	1.08		5.8	193
11	33.31	1.10		0	0
12	33.36	1.08		26.5	883
13	33.36	1.10		0	0
14	33.85	1.07		6.2	210
15	33.91	1.07		8.2	278
16	33.51	1.08		3.5	117
17	33.49	1.08		9	301
18	34.14	1.06		3.2	109
19	34.15	1.06		9.5	324
20	33.95	1.07		2.2	75
21	33.64	1.07		17.5	589
22	33.63	1.07		0	0
23	34.09	1.06		3.2	109
24	34.07	1.06		8.7	296
25	33.71	1.06		0	0
26	34.28	1.05		3.5	120
27	33.28	1.07		0	0
28	33.38	1.06		0	0
29	34.12	1.05		2.4	82
30	34.69	1.04		10.6	368

TTL	386.48	MW
ALC	297.59	MW
LOSSES	14.69	MW
PAY_IMO	481.93	$/h

COMPENSATION		
1 3	18.23	%
2 5	30.51	%

$$\lambda = 0.77$$

Table B.9 Results for SM-OPF model with apparent power flow limitation and λ=0

BUS	LMP [$/MWh]	V [pu]	Pbs [MW]	Pbd [MW]	PAY [$/h]
1	30.74	1.10	251	0	-7715
2	32.33	1.09	125.9	50	-2455
3	33.43	1.05		2.4	80
4	34.26	1.03		50	1713
5	35.31	1.05		100	3531
6	34.42	1.04		0	0
7	35.33	1.03		50	1767
8	33.98	1.06	100	30	-2379
9	34.45	1.06		0	0
10	34.46	1.05		5.8	200
11	34.45	1.10		0	0
12	34.68	1.05		50	1734
13	34.68	1.10		0	0
14	35.31	1.04		6.2	219
15	35.51	1.03		8.2	291
16	34.76	1.05		3.5	122
17	34.70	1.04		9	312
18	36.08	1.02		3.2	115
19	36.29	1.01		22.5	816
20	35.82	1.02		2.2	79
21	36.02	1.03		35.1	1265
22	35.82	1.03		0	0
23	35.82	1.03		3.2	115
24	35.94	1.02		8.7	313
25	35.04	1.03		0	0
26	35.68	1.02		3.5	125
27	34.29	1.05		0	0
28	34.52	1.04			0
29	35.23	1.03		2.4	85
30	35.89	1.02		10.9	391

TTL	456.8	MW
LOSSES	20.13	MW
PAY_IMO	722.75	$/h

COMPENSATION		
1 3	20.52	%
2 5	29.98	%

$\lambda = 0$

Table B.10 Results for SM-OPF model with apparent power flow limitation and λmax

BUS	LMP [$/MWh]	V [pu]	Pbs [MW]	Pbd [MW]	PAY [$/h]
1	26.92	1.10	251	0	-6757
2	28.33	1.09	111.9	50	-1755
3	29.21	1.05		6.7	196
4	29.88	1.04		50	1494
5	30.86	1.05		100	3086
6	29.98	1.05		0	0
7	30.81	1.03		50	1540
8	29.61	1.06	100	30	-2073
9	29.98	1.07		0	0
10	29.98	1.06		5.8	174
11	29.98	1.10		0	0
12	30.24	1.06		50	1512
13	30.24	1.10		0	0
14	30.73	1.05		6.2	191
15	30.80	1.04		8.2	253
16	30.26	1.06		3.5	106
17	30.19	1.06		9	272
18	31.18	1.03		3.2	100
19	31.28	1.03		18.4	576
20	30.96	1.04		2.2	68
21	30.37	1.05		22.7	691
22	30.35	1.05		0	0
23	30.89	1.04		3.2	99
24	30.76	1.04		8.7	268
25	30.28	1.05		0	0
26	30.81	1.03		3.5	108
27	29.79	1.06		0	0
28	30.05	1.05		0	0
29	30.57	1.04		2.4	73
30	31.10	1.03		10.6	330

TTL	444.36	MW
ALC	159.08	MW
LOSSES	18.6	MW
PAY_IMO	548.92	$/h

COMPENSATION		
1 3	19.97	%
2 5	29.72	%

$$\lambda = 0.358$$

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