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Valuating Controllable Devices in Congested Networks

Christian Schaffner, Göran Andersson
Swiss Federal Institute of Technology
Zürich, Switzerland

Introduction

The electric transmission networks are pushed more and more towards their limits. Even in highly meshed networks like in Europe this leads to congestions which in turn can produce significant price differences between the areas around these congestions. Another – maybe more visible – problem with congested networks are security concerns. Recent events, e.g. the italian blackout on September 28^{th} 2004, brought this issue into evidence again. Eliminating these congestions by means of installing new transmission lines is normally difficult, if not impossible. It often takes decades from evaluating a new line to the time it is installed. Political and environmental regulations further add to the difficulties in improving the physical network.

This paper will present different methods to relieve congestions in general – including short-term and long-term methods and bidding systems for transmission services – and with controllable devices such as Flexible AC Transmission Systems (FACTS) in particular. We will discuss the complexity of these methods, by looking at the pros and contras of detailed simulations versus simplified solutions.

One possibility to relieve congestion is to increase the available transfer capacity over a congested link by installing a controllable device. We will show a methodology to determine the value of such an installation. Using a simplified network model we use optimization techniques to determine the electricity price in different areas. This data is used as input for the economical evaluation methodology to assess the value of such an installation. A special legal entity is proposed that makes it possible for power producers to invest in this technology.

We will compare two methods to calculate the price differences in a congested network. The *first method* uses an optimal power flow calculation to model the underlying networks and the FACTS devices in detail. The *second method* uses a simplified network model with aggregated generation and load in each area. The transmission network is reduced to fixed constraints between the areas.

Relieving Transmission Constraints

There are different methods to relieve congestions in a electric power transmission network. The aim is to remove or reduce the physical limitations of free trade, which cause network zones with significantly different prices. These price differences and the generation patterns give an indication on how much an area is isolated from another area by reduced transfer capabilities.

The methods are categorized into *short-term* methods, which try to relieve overloaded lines with available network infrastructure, *long-term* methods, which involve reinforcement of the physical network, and a third category that proposes the creation of a special *bidding system* for services to help reduce congestions.

Short-Term Methods

Traditionally vertically integrated network operators have tried to avoid network congestions by planning their generator dispatch accordingly. If a congestion was likely during a certain period of time, the operators scheduled their production units differently by transferring production to a unit not affected by the congestion. This technique does not alleviate the problem of market splitting. It is only used to prevent outages of overloaded lines.

The redispatching of the production can be organized centrally by an independent system operator. Another possibility is to trade the surplus of production leading to the congestion in a separate bidding round where producers enter newly calculated price curves (see [1]).

Installed controllable devices (e.g. FACTS) can also contribute to relieving congestions by controlling the load flow with special control setting during critical overload situations.

Short-term methods only provide emergency services in situations where lines could become overloaded.

Long-Term Methods

Long-term methods are instruments or incentives that try to influence the expansion and enhancement of the network topology over time.

One possibility is to use optimization techniques that include the capacity limits into the objective function. The lines' capacity therefore needs to be included into the optimization tool. An extra term is added to the social welfare function which is the sum of all transmission line capacities multiplied by the per unit cost factor for the extension of the respective lines. The expansion of the transmission network is integrated into the global optimization of the network operation. It is possible to give incentives not only to changes in production patterns but also to new investments in the transmission system. Ref. [2] proposes such a method.

Another possibility is to give incentives to producers and consumers via special transmission pricing. The differences of the incremental nodal prices can be used to influence new investments by power consumers and producers. New production is more likely to be installed at places with high nodal prices, whereas new consumers would choose areas with lower prices. This method should then optimize the geographical distribution of loads and generators to reduce network congestions. It will not, however, give any incentives on new or optimized transmission assets. Ref. [3] describes two different methods implementing this idea.

Bidding Systems for Transmission Services

The third category includes methods that are based on bidding systems. The well-known bidding phase between power producers and consumers is supplemented with a second bidding phase. This additional bidding is held between the power producers and consumers on one side and the transmission system operators on the other side. Both sides bid their incremental cost curves for transmission capacity. The negotiation needs to be carried out for every transmission line. All participants are then offered to alter their original bids again. Ref. [4] describes such a method.

Valuating a Controllable Device

In a liberalized electricity market, the transmission capability of an electrical network – which usually is regarded as a natural monopoly – is of economic value to the network operator. Due to various constraints such as security considerations and network topology, transmission lines often can only be utilized significantly below their physical limits. To improve customer benefit one possibility is to raise the economic value of the transmission lines by increasing the power transfer capability of these lines. Additionally, there will be a gain in overall market efficiency since more energy trading can take place between competing regions with different price structures. Instead of installing new transmission lines, FACTS devices can also increase the overall utilization of an electrical power network by directly controlling the power flow.

The biggest issue before investing in such a project is often the limited knowledge of its efficiency and, related to that, the financial benefits it can generate over its lifetime. Therefore appropriate valuation tools are needed.

Two different methods to determine the area prices are presented in this paper. The first uses an optimal power flow calculation modeling a TCSC device and the transmission lines in detail. The other method reduces this complexity by using aggregated loads and generators in different areas, where the network is only modeled as the limited transfer capacities between these areas.

The results of both models can be used as input to a financial analysis tool. We will compare these results in a three area example.

Detailed Model of Underlying Network

In this section we describe the first method to determine the effect of a controllable device on price differences between regions. It uses a detailed model of the underlying network and of the controllable device. The electric network is modelled by a linearized (DC) load flow, that is extended by the calculation of power losses.

For the FACTS device we use a *Thyristor Controlled Series Capacitor* (TCSC) that is modelled by its relation between the firing angle and the resulting serial impedance (see Fig. 1). The susceptance B ($= X^{-1}$) is calculated as:

$$B(\alpha) = B_L \frac{\pi - 2\alpha - \sin 2\alpha}{\pi} + B_C. \tag{1}$$

where B_L is the susceptance of the impedance of the TCSC and B_C the susceptance of the capacitance. The resonance angle α_{res} (indicated as a dotted vertical line in Fig. 1) has to be avoided by a security margin of $+/-10°$. Details about the modelling of FACTS devices can be found in e.g. [5].

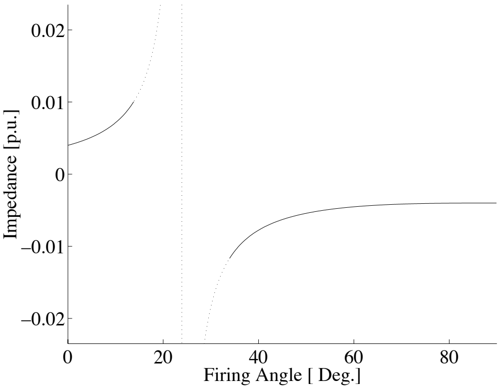

Fig. 1. Operating Range (bold lines) of a TCSC

Additionally the available transmission capacity (ATC) of the lines in the network are modelled as constraints: for each line a different ATC value can be set that will not be violated. Only this allows us to study the effect of congestions on electricity prices.

An optimal power flow (OPF) algorithm is then used to optimize the so-called social welfare, subject to transmission constraints, generation limits, and TCSC limits. The mathematical setup is done in the form of

$$\begin{array}{lll} \text{minimize} & f(x) & x \in \mathbf{R^n} \\ \text{subject to} & Ax - b = 0 & \\ & Cx - d \leq 0 & \\ & g_i(x) = 0 & \\ & h_j(x) \leq 0. & \end{array} \tag{2}$$

where $f(x)$ is the objective function, $Ax - b$ the linear equality constraints, $Cx - d$ the linear inequality constraints, $g_i(x)$ the non-linear equality constraints, and $h_j(x)$ the non-linear inequality constraints.

Objective function. As the objective function we use the so-called social welfare which is defined as:

$$SW = \underbrace{\sum W_i(l_i) - \lambda \cdot P_\lambda}_{CS} + \underbrace{\lambda \cdot P_\lambda - \sum C_j(g_j)}_{GS}, \qquad (3)$$

where $\sum C_j(g_j)$ is the sum of all generators' costs and $\sum W_i(l_i)$ the sum of what the consumers are willing to pay. The generators surplus is the term GS and the consumer surplus the term CS and P_λ is the power at the intersection of the consumer's and producer's aggregated incremental cost curves.

The consumer surplus is defined as the difference between the value the consumer is prepared to pay and what he actually pays. It is assumed that the consumers behave rationally, in that they do not purchase any good that has a higher price on the market than the benefit he would derive from it.

Linear inequality constraints. The linear inequality constraints are defined by the upper and lower production limits of the generators and the upper and lower consumption limits of the loads. Also the impedance of the FACTS device is kept in the limits as described in Eq. 1 and shown in Fig. 1

Nonlinear equality constraints. The nonlinear equality constraints are defined by the power balance in each node in the network. For node m the nonlinear equation is defined as:

$$\sum_j g_{m_i} - \sum_i l_{m_i} \\ - \sum_{n_{con}} \frac{\theta_m - \theta_n}{X_{mn}} - \frac{1}{2} \sum_{n_{con}} R_{mn} \left(\frac{\theta_m - \theta_n}{X_{mn}} \right)^2 = 0 \qquad (4)$$

where

- g_{m_i}: power produced by generator j at node m
- l_{m_i}: power consumed by load i at node m
- $\sum_{n_{con}}$: sum over all nodes n connected to node m
- θ_m: voltage angle at node m
- $\frac{\theta_m - \theta_n}{X_{mn}}$: power flow from node m to node n
- R_{mn}: resistance of the line between nodes m and n
- $X_{mn} = X_{mn}^{line} + X_{mn}^{facts}$: If a TCSC is built into the line between node m and node n the impedance between these two nodes is composed of a fixed part X_{mn}^{line} and a flexible part X_{mn}^{facts}, which is determined during optimization.

The factor $\frac{1}{2}$ in the last term of Equation 4 is caused by the fact that half of the total power loss is associated with the emitting and half of it with the receiving node.

Nonlinear inequality constraints. The nonlinear inequality constraints are given by the transmission capacity of the transmission lines and by the physical limits of the TCSCs.

For each transmission line the nonlinear inequalities are defined by

$$\pm \frac{\theta_m - \theta_n}{X_{mn}} - \bar{P}_{line}^{mn} \leq 0 \qquad (5)$$

For the TCSC the feasible region of the impedance as shown in Fig. 1 are taken as inequality constraints.

The generators are modeled with upper production limits and quadratic cost curves, the flexible loads have minimum and maximum consumption limits and a linear price per unit curve. For typical values see e.g. Fig. 4 and Fig. 3.

The algorithm adjusts the dispatching of the generators, the flexible loads and the settings of the TCSC in order to maximize social welfare. The objective function is therefore equal to the social welfare, which is composed of the producer surplus (the profit of the producers) and the consumer surplus. The consumer surplus is set to be the difference between what the consumer is willing to pay and what he actually had to pay.

Assumptions. The following assumptions are made in the detailed model:

- *Small voltage angle differences*: Assuming that the voltages are close to their nominal values and the angle differences are small the load flow in a line is approximated with:

$$P_{mn} = \frac{\theta_m - \theta_n}{X_{mn}}.$$

- *Generator constraints*: The generators are limited by a minimum and maximum output capacity modeled with additional inequality constraints.

Outputs of the optimization. The results of the optimization tool are the power generation of the generators, the consumed power of the loads, the load flow in the network and the voltage angles at each node, the firing angle of the TCSC.

The incremental prices at each node are gained from the Lagrangian multipliers. They also indicate which inequality constraints are limiting, thus showing e.g. which line is at the ATC limit.

This model is partly based on the work in [6].

"Copperplate Model" of Underlying Network

The idea behind this model is that an algorithm using optimal ac power flow as presented above is often unnecessarily complex for the purpose of valuating investments for controllable devices. An exact model that includes calculated power flows depends on exact network data, which is normally hard to forecast. Therefore a simplified market model is developed where the transmission system is divided into regions that are connected via limited capacity transfer paths. The detailed networks inside the regions are not included in the model. This simplification is also known as "copperplate model" or "super node model" (see Fig. 10).

The generators and loads are modeled as aggregated players in each region with their respective limits similar to what is shown in e.g. Fig. 3. We assume no transmission costs, no losses, and we neglect line impedances (they are replaced by zonal constraints).

The improvement due to the controllable devices is simply modeled as a proportional increase of the inter-area constraints. The typical output of this model is the electricity prices in function of the variation of a congested link. This model is described in more detail in [7].

The objective function for the optimization is – as in the detailed model – the social welfare. The definition is here:

$$\text{Maximize } SW = \sum_i W_i(l_i) - \sum_j C_j(g_j) \qquad (6)$$

Where:

- SW is the Social Welfare
- W_i is maximum price the consumer i is prepared to pay
- l_i is the quantity of power consumed by load i
- C_j is the generator j's cost of production
- g_j is the quantity of power produced by generator j

Assumptions. The following assumptions are made in the "copperplate" model:

- *No transmission costs*: Usually transmission costs are added ex post as overhead costs, based on a number of factors such as delivery zones and transmission volume. The model could however be amended to take into account the specific costs of using certain power transmission links. Each transmission link would then have a cost function associated with it.
- *Line impedances*: Line impedances are neglected and replaced by zonal constraints
- *No losses*: Losses are a function of the transmitted power and can be billed as part of transmission costs via ancillary services. They are not included in this model.
- *Generator constraints*: The generators are limited by a minimum and maximum output capacity modeled with additional inequality constraints.

Calculation Results

Detailed Model

For the demonstration of the detailed model we chose the network shown in Fig. 2.

It consists of three regions: Region A, which is a low price, high production area, region B that has expensive generators and high loads and Region C, which is mainly transmitting power from region A to B. This will result in a power flow mainly from region A to B via region C and leads to high prices in region B in comparison to the other regions. Critical congested lines are line number 3 and line number 6. Line number 2 has a high capacity and is normally not fully loaded. The TCSC in region A will be used to be able to transport more energy into the high price area.

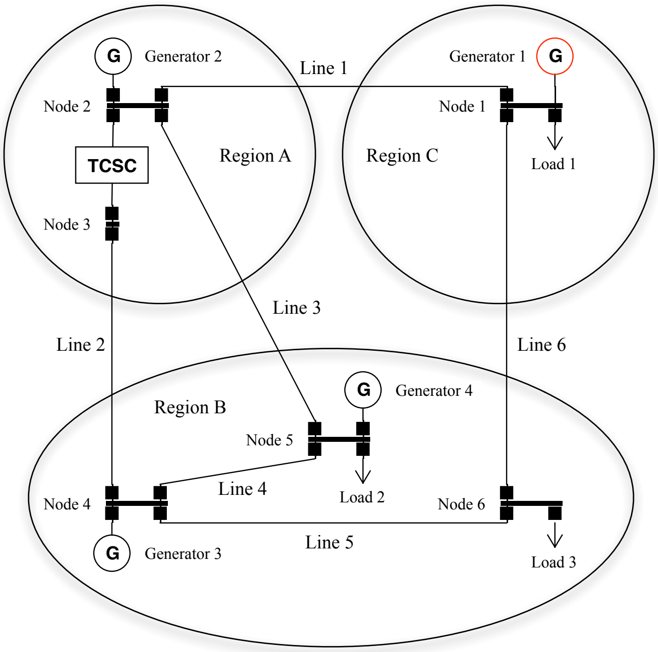

Fig. 2. Network used in the calculations of the detailed model.

Below we will present the results of three different simulation setups: *First,* without TCSC, *second,* with the TCSC enabled, and *third,* with a bigger TCSC, that allows for equal prices in all three areas. For all three cases the generator limits and incremental cost curves are set up as shown in Fig. 3 and the load limits and the prices the consumers are willing to pay are set up as shown in Fig. 4.

Results without TCSC. Fig. 5 shows the flows through the different lines without TCSC. Line 3 is fully loaded and line 6 is almost at its limit. In Fig. 3 we see how the different generators are dispatched. The stars indicate the operating points. Generator 2 in region A is the cheapest generator and therefore produces the most. But due to the congested network also the more expensive generators in Region B and C have to contribute. Fig. 4 shows how much power the different loads consume – indicated by the stars. The biggest load (Load 3) sits in region B.

Comparing the incremental prices at each nodes as indicated in the second column ("without TCSC") in Table I it is obvious that the market is split between region B and the other two regions. In region B the prices are around 3.0 Euro cents/kW, whereas in the other two regions the prices are around 2.4 Euro cents/kW.

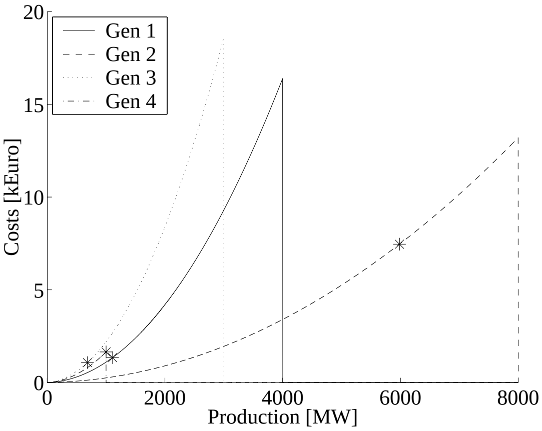

Fig. 3. Generator limits and operating points without TCSC

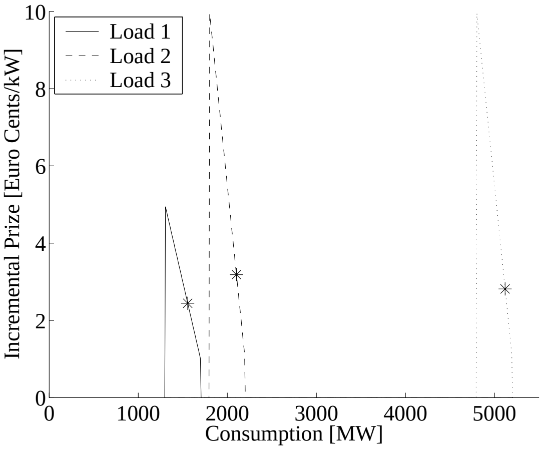

Fig. 4. Load limits and operating points without TCSC

Results with TCSC. For the *second* simulation the TCSC with $X_L = 0.001$ p.u. and $X_C = 0.002$ p.u. is enabled in line 2. Fig. 7 shows the new load flows through the different lines. Lines 3 and 6 are still very highly loaded, but line 2 now carries considerably more. This allows the generator in region A to produce more than can be seen in Fig. 6. This change influences in turn the different nodal prices, as indicated in the third column ("TCSC Rating 1") in Table I. While the prices in region A and C have increased, the prices in region B have gone down by a considerable amount.

Results with a bigger TCSC. If we double the size of the TCSC to $X_L = 0.002$ p.u. and $X_C = 0.004$ p.u. the congestion in line 3 is completely removed as can be seen in Fig. 9. The cheap generator in region A can produce even more so that e.g. generator 4 is forced to reduce its production below its upper limit (see Fig. 8). The removed congestions in the network lead to equal nodal prices in the whole network (see second fourth column ("TCSC Rating 2") in Table I).

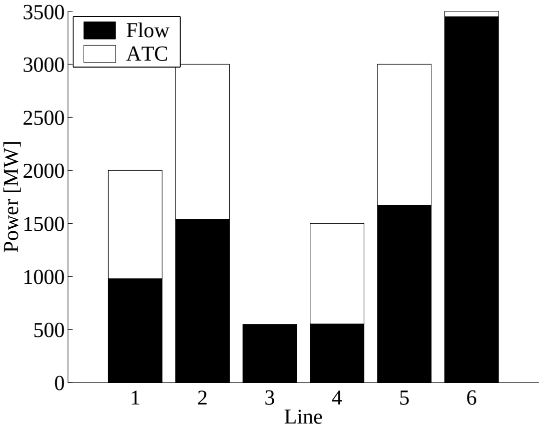

Fig. 5. Load flows through lines without TCSC

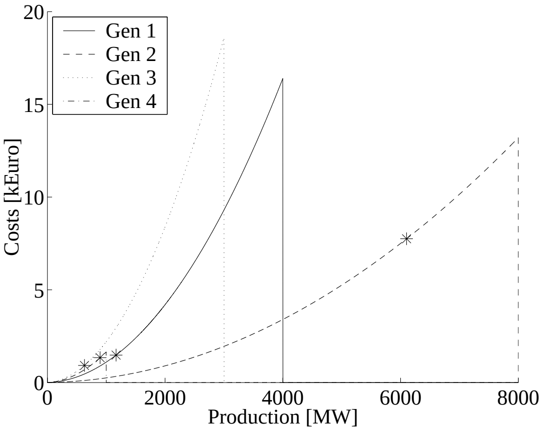

Fig. 6. Generator limits and operating points with TCSC Rating 1

TABLE I
Incremental prices (in Euro cents) at each node.

Node	w/o TCSC	TCSC Rating 1	TCSC Rating 2
1	2.44	2.49	2.54
2	2.32	2.43	2.54
4	2.94	2.72	2.54
5	3.18	2.84	2.54
6	2.81	2.66	2.54

These results show how a TCSC can improve the social welfare and reduce nodal prices in high price areas by increasing the transfer capacity between congested areas.

"Copperplate Model"

Since results of this model were already presented in [7] we will not show detailed results here. The simulation setup for the "Copperplate Model' ' is a lot less complex as for the detailed model. We only set the cost structure of aggre-

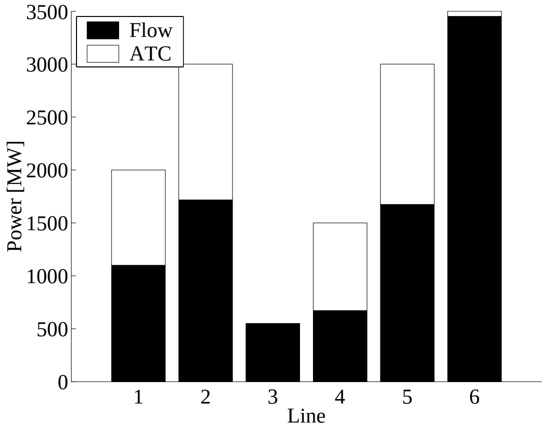

Fig. 7. Load flows through lines with TCSC Rating 1

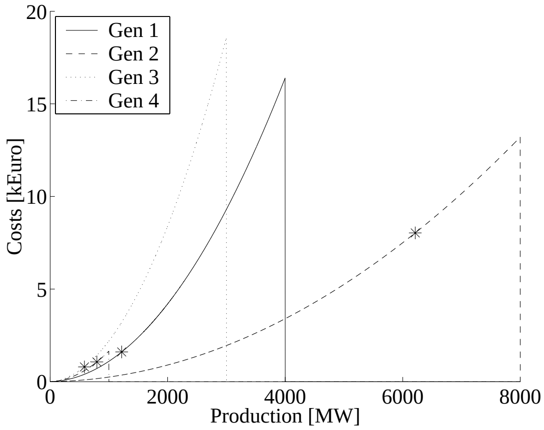

Fig. 8. Generator limits and operating points with TCSC Rating 2

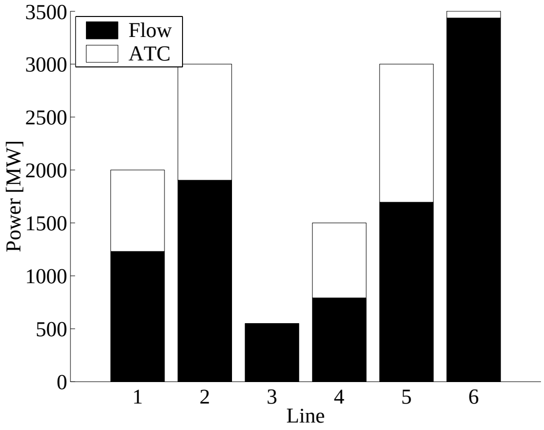

Fig. 9. Load flows through lines with TCSC Rating 2

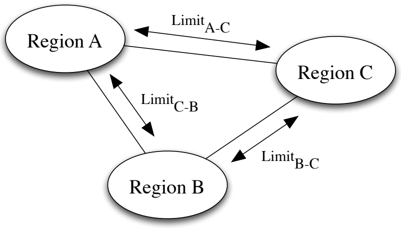

Fig. 10. Example for a "Copperplate Model" or "Super Node Model" with three regions

gated generators and the flexible loads in each area. The transmission constraints are modelled with limits between each region. Fig. 10 shows this setup.

Fig. 11 shows how the electricity prices in the three areas converge to the same price if the congested link is increased to a capacity of 15 MW.

The final results are similar to what we get from the detailed model, even if the number of input variables is significantly reduced.

Valuating a Controllable Device

Valuation Method

To perform the actual valuation of the FACTS device one needs to find a framework suitable for this special kind of project. As a framework for this study, a so-called Special Purpose Vehicle company (SPV) is used. This company is a separate legal entity from the power producer but is fully owned by the power producer. This is necessary to comply with the regulation that generating companies need to be financially separated from companies working in the field of electricity transmission. The SPV borrows the full amount it needs to fund the project from the power producer. It then buys electric energy in the low price zone and re-sells it in the high price zone. The cash flow is in the opposite direction. It gets paid from the consumers in the high price zone and gives back the profit to the power producer company (see Fig. 12).

This setup suits the typical issues to relieve congestions in existing networks very well. The power producers are interested in being able to trade more energy through congested links. But at the same time are not allowed to invest directly in the network. A separate legal entity, the SPV, however allows them to invest in such a project.

The method used to carry out the economic valuation is known as the Discounted Cash Flow (DCF) model. It values a company's capital as the operating value, deducted by the value of debt [8]. This method is suitable for this specific project because the financial market will not influence the valuation results directly in our case of a debt only financed company.

In [7] all necessary input parameters for the valuation are detailed. The most important are:

- *Generation costs projections*: The projected cost of the energy production in the different areas for the time of the valuation need to be estimated.

- *Installed production capacity* in the different regions.

- *Transmission capacity enhancement* by the FACTS device.

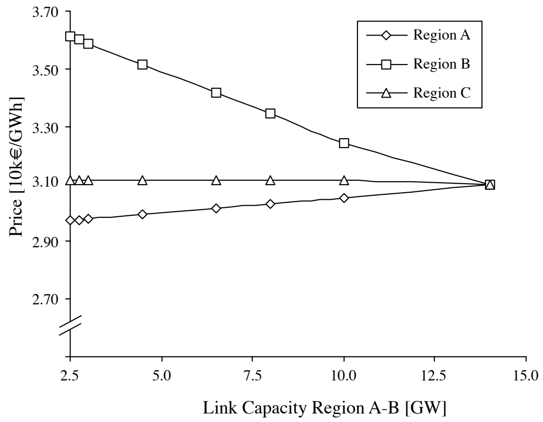

Fig. 11. Electricity prices in three regions with different generation patterns in function of the link capacity between region A and B.

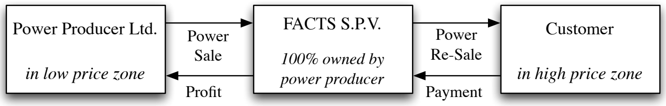

Fig. 12. A Special Purpose Vehicle (SPV) is used as business model

- *Project lifetime*
- *Project utilization*
- *Risk free interest rate*
- *Cost of borrowing money*
- *Cost of running the FACTS device*
- *Initial investment*

The FACTS device can increase the transfer capacity from a low price area to a high price area and thus allows the owning party to make profit on the price difference. This value can be determined by the detailed model or by the simplified "copperplate model".

As output from the valuation we can determine the free cash flows of the SPV projected for the lifetime of the FACTS device. We gain also insights on the Return on Capital numbers.

Comparison of Valuation Methods

By comparing the two different methods for calculating the changes in price differences it is obvious that the number of needed input variables differ widely. The "Copperplate Model" only needs information about the production and load setup as well as the improved transmission capacity between the separated areas. For the detailed model a lot more input parameters are needed: Detailed physical parameters about the involved lines and FACTS devices are needed.

But the influence of these detailed parameters are only very limited on the final result of the DCF valuation. A lot more important are the knowledge about the financial circumstances of the company, the assumed changes in the underlying network, etc.

Therefore we propose the following approach: The detailed model should be used as a first step to determine the possibility of setting up a FACTS device at different locations in a network and its influences on load flow changes and price differences.

For the actual valuation the "Copperplate Model" is better suited and uses a less complex setup.

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Christian Schaffner received his diploma (M.S.) in electrical engineering from the Swiss Federal Institute of Technology (ETH), Zurich in Switzerland in 1997. He is PhD student and research assistant at the Power Systems Group headed by Prof. Dr. Göran Andersson at ETHZ. His research interests are economic evaluation of controllable devices (for example FACTS) for congestion management in liberalized electric energy markets and Internet-based interactive education software for the use in power engineering education.

Göran Andersson was born in Malmö, Sweden. He obtained his M.S. and Ph.D. degree from the University of Lund in 1975 and 1980, respectively. In 1980 he joined ASEA, now ABB, HVDC division in Ludvika, Sweden, and in 1986 he was appointed full professor in electric power systems at the Royal Institute of Technology (KTH), Stockholm, Sweden. Since 2000 he is full professor in electric power systems at the Swiss Federal Institute of Technology (ETH), Zürich, where he heads the powers systems laboratory. His research interests are in power system analysis and control, in particular power systems dynamics and issues involving HVDC and other power electronics based equipment. He is a member of the Royal Swedish Academy of Engineering Sciences and Royal Swedish Academy of Sciences and a Fellow of IEEE.