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Reactive Power Valuation

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Contents

1. Introduction

With deregulation of electricity sector each electric power service should be economically valued and the fair rules for evaluation and compensation should be established.

Reactive power service is one of the key ancillary services and the trading in it is becoming a reality for deregulated electricity markets. This has resulted in a need to quantify the value and to compensate the service of reactive power support. The main question is how much reactive power is worth economically. The first step in this investigation is to determine the technical value of the reactive power, which later could be transferred into money-based value.

In this work we'll try to determine some problems with reactive power based on the Swedish energy company Sydkraft experience. For the investigation a simplified test system will be build. Some methods for evaluating the reactive power will be established and checked on the test system. A special case concerning trading the reactive power between Sydkraft company and Swedish transmission company Svenska Kraftnät will be examined. Appropriate conclusions will be made.

1.1 Problems with reactive power

We'll try to determine some most interesting problems with reactive power using the experience and data of Sydkraft company, the second biggest company in the electricity sector in Sweden, which owns generation assets and a regional network in the South and generation in the North of Sweden.

1.1.1 Reactive power exchange between Sydkraft and Svenska Kraftnät

Svenska Kraftnät is the Transmission System Operator in Sweden, and also the owner of the transmission grid.

Reactive power is exchanged at many levels and points in the power system between Sydkraft and Svenska Kraftnät. Both parties involved usually benefit from this exchange, but a fair compensation must be defined based on the value of reactive power. This must be done in such a way that the economical incentives support issues like system security and voltage quality.

According to the data from Sydkraft during heavy load conditions this company extracts about 458 MVar of reactive power in the interconnection points of the 400 kV grid. During the low load conditions, on the other hand, Sydkraft supplies 72 MVar of reactive power into the transmission network.

Until now during the daily operations Sydkraft had to keep the reactive flow through the system transformers to zero only if Svenska Kraftnät especially required that. Enforcing this required to have enough reactive capacity on both sides. Since both parties want to avoid additional investments, a better solution should be sought for.

So there are several possible perspectives in this situation:

- The zero exchange in system transformers is enforced and each organization covers its own costs for this;
- A value of reactive power extracted or supplied to the transmission grid depending on load conditions, interconnection points location, strength of the network and etc is defined, so that the reactive power is traded between Svenska Kraftnät and Sydkraft.

In this work using our test system we'll try to answer the question is reactive power flow in system transformer crucial to the system security and losses in the area. What investments would be required from both sides for that purpose?

1.1.2 Reactive power exchange between distributed generation and the network. Wind power stations

Reactive power problems usually occur at the interconnection points of different systems or now in the deregulated market between different owners of transmission or distribution networks, reactive power generators and consumers. As reactive power is a local product its value to system security and voltage control very much depends on the location in the system.

The existence of embedded generation can release capacity in a distribution or other network to which it is connected. And any generation embedded on that network reduces the likelihood of overloading and loss of supply, so improving the reliability of the network.

Wind power stations is a common example of embedded generation. A specific character of those power stations is that while generating the active power they consume the reactive one. Combined with the generation level that varies with the weather conditions, this causes voltage problems at the interconnection points and the installment of compensation devices is required

So the questions could be how much the wind power station owner should compensate the network for reactive power consumption? What about the positive factors wind power station introduces to the network – load relieve and reliability?

Reactive power evaluation methods, established in this work, could be used in defining the value of reactive power extracted by wind power stations too.

1.2 Questions to answer

Besides the problems with reactive power described above in this work we’ll try to find the answers to the following questions:

- *Which reactive power source is the most important to the system? What are the criteria?*
- *How much MVar from other sources does this corresponds to?*
- *What does this MVar from one or other source do to system losses?*
- *What does this MVar mean to transfer capacity?*
- *How much does this MVar cost to install and to produce?*

2. Reactive power service

What is the place of reactive power service between the ancillary services in power system? What is the aim of it? How is reactive power being produced and how much does it cost? These are the questions we'll try to answer in the following chapter.

2.1 Ancillary services

Basic system services cannot be delivered without ancillary services. The ancillary services that support basic system services are shown in the Table 1 (CIGRE report, 1999):

Table 1. Overview of ancillary services providing basic system services

Basic system service / Ancillary service	Frequency	Voltage	System Restor.	Back-up Supply	Stability	armonics
Power reserve	+		+	+	+	
Exchange reserve	+		+	+		
Load reduction	+	+		+		
Distribution tap changing		+	+	+		
Generator tap changing		+				
Static compensation		+				
Rotating compensation		+			+	
Black start			+			
Filter behavior of generation						+
Protection operation speed					+	
Frequency / voltage domains	+	+				
House load operation			+			
Synchronization			+			
Generator harmonics						+
Resistance to faults, phase unbalance, harmonic and voltage fluctuations	+	+	+		+	

Load reduction, distribution tap changing, static compensation, rotating compensation with voltage regulator, generator tap changing, generator frequency / voltage domains, generator resistance to faults, phase unbalance, harmonic and voltage fluctuations are services, which contribute to the voltage (including voltage stability) support, that is closely related to reactive power and are the theme of interest in this work.

2.2 Reactive Power/Voltage control service

Reactive power/Voltage control service should satisfy System requirements listed below (CIGRE report, 1999):

- Satisfy overall system and customer requirements for reactive energy on a continuous basis;
- Maintain system voltages within acceptable limits;
- Provide a reserve to cover changed reactive requirements caused by contingencies, against which the system is normally secured, and satisfy certain quality criteria in relation to speed of response;
- Optimize system losses.

In reactive power and voltage control a distinction between three levels of voltage control could be made (UCTE report, 1999):

Primary control is implemented by the voltage regulators of generating units, which will initiate a rapid variation in the excitation of generators when they detect a variation in voltage across their terminals. Other controllable devices, such as static var compensators (SVCs) may also be involved in primary regulation.

Secondary control co-ordinates the action of voltage and reactive power control devices within a given zone of the network in order to maintain the requisite voltage level at a certain node point in the system.

Tertiary control involves a process of optimization, using calculations based upon real time measurements, in order to adjust the settings of devices, which influence the distribution of reactive power (generating unit controllers, tap transformer controllers and compensating devices, like reactors and capacitors).

Where the system load is high, the operator must be certain that, in case of a loss of generation, the remaining facilities will be able to deliver enough reactive power to keep the voltage within the required range. The same applies to the converse situation, where the system load is low and reactive power needs to be absorbed.

2.3 Reactive Power Sources

Reactive power is produced or absorbed by all major components of a power system (M. Erche, 1987; Miller):

- Generators;
- Power transfer components;
- Loads;
- Reactive power compensation devices.

2.3.1 Generators

Electric power generators are installed to supply active power. Additionally a generator is supporting the voltage, producing reactive power when over-excited and absorbing reactive power when under-excited. Reactive power is continuously controllable. The ability of a generator to provide reactive support depends on its real-power production. Figure 1 shows the combined limits on real and reactive production for a typical generator (B. Kirby, 1997).

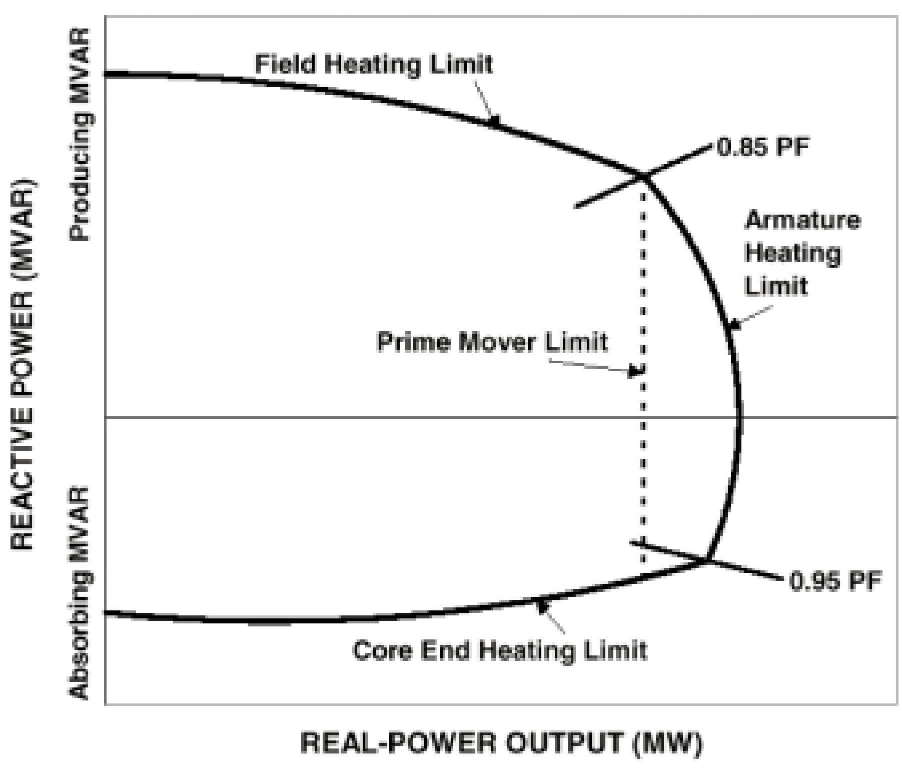

Figure 1. Reactive power capability dependence on real power production for a synchronous generator

Like most electric equipment, generators are limited by their current-carrying capability. Reactive power production is depended on the field heating limit and absorption on the core end-heating limit of the generator. Active power output limit is limited by armature heating.

Control over the reactive output and the terminal voltage of the generator is provided by adjusting the DC current in the generator's rotating field. Control can be automatic, continuous, and fast. The inherent characteristics of the generator help maintain system voltage. At any given field setting, the generator has a specific terminal voltage it is attempting to hold. If the system voltage declines, the generator will inject reactive power into the power system, tending to raise system voltage. If the system voltage rises, the reactive output of the generator will drop, and ultimately reactive power will flow into the generator, tending to lower system voltage. The voltage regulator will accentuate this behavior by driving the field current in the appropriate direction to obtain the desired system voltage.

2.3.2 Power transfer components

The major power transfer components are transformers, overhead lines and underground cables. HVDC converter stations can also be treated as power transfer components.

Transformers

Transformers provide the capability to raise alternating-current generation voltages to levels that make long-distance power transfers practical and then lowering voltages back to levels that can be distributed and used. The ratio of the number of turns in the primary to the number of turns in the secondary coil determines the ratio of the primary voltage to the secondary voltage. By tapping the primary or secondary coil at various points, the ratio between the primary and secondary voltage can be adjusted. Transformer taps can be either fixed or adjustable under load through the use of a load-tap changer (LTC). Tap capability is selected for each application during transformer design. Fixed or variable taps often provide ±10% voltage selection, with fixed taps typically in 5 steps and variable taps in 32 steps.

Transformer-tap changers can be used for voltage control, but the control differs from that provided by reactive sources. Transformer taps can force voltage up (or down) on one side of a transformer, but it is at the expense of reducing (or raising) the voltage on the other side. The reactive power required to raise (or lower) voltage on a bus is forced to flow through the transformer from the bus on the other side. The reactive power consumption of a transformer at rated current is within the range 0.05 to 0.2 p.u. based on the transformer ratings.

Fixed taps are useful when compensating for load growth and other long-term shifts in system use. LTCs are used for more-rapid adjustments, such as compensating for the voltage fluctuations associated with the daily load cycle. While LTCs could potentially provide rapid voltage control, their performance is normally intentionally degraded. With an LTC, tap changing is accomplished by opening and closing contacts within the transformer's tap-changing mechanism.

Transmission lines and cables

Transmission lines and cables generate and consume reactive power at the same time. Reactive power production is equal:

$$Q_{Gen} = V^2 B \ ;$$

B – shunt susceptance.

$$Q_{Con} = I^2 X \ ;$$

X – line or cable impedance.

As we see from the expressions above reactive power generation is almost constant, because the voltage of the line is usually constant, and the line's reactive power consumption depends on the current or load connected to the line that is variable. So at the heavy load conditions transmission lines consume reactive power, decreasing the line voltage, and in the low load conditions – generate, increasing line voltage. The case when line's reactive power production is equal to consumption is called natural loading.

HVDC converters

Thyristor-based HVDC converters always consume reactive power when in operation. The reactive power consumption of the HVDC converter/inverter is 50-60 % of the active power converted. The reactive power requirements of the converter and system have to be met by providing appropriate reactive power in the station. For that reason reactive power compensations devices are used together with reactive power control from the ac side.

2.3.3 Loads

Voltage stability is closely related to load characteristics. The reactive power consumption of the load has a great impact on voltage profile at the bus. The response of loads to voltage changes occurring over many minutes can affect voltage stability. For transient voltage stability the dynamic characteristics of loads such as induction motors are critical.

Some typical reactive power consuming loads examples are given below.

Induction motors

About 60 % of electricity consumption goes to power motors and induction motors take nearly 90 % of total motor energy depending on industry and other factors. The steady-state active power drawn by motors is fairly independent of voltage until the point of stalling. The reactive power of the motor is more sensitive to voltage levels. As voltage drops the reactive power will decrease first, but then increase as the voltage drops further.

Induction generators

Induction generators as reactive power load became actual with the wind power station expansion into electricity sector. Wind plants are equipped with induction generators, which require a significant amount of reactive power. Part of the requirement is usually supplied by local power factor correction capacitors, connected at the terminal of each turbine. The rest is supplied from the network, which can lead to low voltages and increased losses.

Discharged lightning

About one-third of commercial load is lightning – largely fluorescent. Fluorescent and other discharged lightning has a voltage sensitivity *Pv* in the range 1-1.3 and *Qv* in the range 3-4.5. At voltages between 65-80 % of nominal they will extinguish, but restart when voltage recovers.

Constant energy loads

Loads such as space heating, water heating, industrial process heating and air conditioning are controlled by thermostats, causing the loads to be constant energy in the time scale of minutes. Heating loads are especially important during wintertime, when system load is large and any supply voltage drop causes an increase in load current, that makes situation even worse.

Arc furnaces

Arc furnaces are a unique representation of problems with voltage stability, power factor correction and harmonic filtering. Rapid, large and erratic variations in furnace current cause voltage disturbances for supply utility and nuisance to neighboring customers. So the problem of voltage stabilization and reactive power control is usually solved by connecting the furnace to a higher network voltage, installing synchronous condensers and other fast responding reactive power generating units.

2.3.4 Reactive Power compensation devices

Synchronous condensers

Every synchronous machine (motor or generator) has the reactive power capabilities the same as synchronous generators. Synchronous machines that are designed exclusively to provide reactive support are called synchronous condensers. Synchronous condensers have all of the response speed and controllability advantages of generators without the need to construct the rest of the power plant (e.g., fuel-handling equipment and boilers). Because they are rotating machines with moving parts and auxiliary systems, they require significantly more maintenance than static compensators. They also consume real power equal to about 3% of the machine's reactive-power rating.

Synchronous condensers are used in transmission systems: at the receiving end of long transmissions, in important substations and in conjunction with HVDC converter stations.

Small synchronous condensers have also been used in high-power industrial networks to increase the short circuit power.

The reactive power output is continuously controllable. The response time with closed-loop voltage control is from a few seconds and up, depending on different factors.

In recent years the synchronous condensers have been practically ruled out by the thyristor controlled static VAR compensators, because those are much more cheaper and have regulating characteristics similar to synchronous condensers.

Static VAR compensators

An SVC combines conventional capacitors and inductors with fast switching capability. Switching takes place in the sub cycle timeframe (i.e., in less than 1/50 of a second), providing a continuous range of control. The range can be designed to span from absorbing to generating reactive power. Advantages include fast, precise regulation of voltage and unrestricted, largely transient-free, capacitor bank switching. Voltage is regulated according to a slope (droop) characteristic.

Static VAR compensator could be made up from:

TCR (thyristor controlled reactor);

TSC (thyristor switched capacitor);

TSR (thyristor switched reactor);

FC (fixed capacitor);

Harmonic filter.

Because SVCs use capacitors they suffer from the same degradation in reactive capability as voltage drops. They also do not have the short-term overload capability of generators and synchronous condensers. SVC applications usually require harmonic filters to reduce the amount of harmonics injected into the power system by the thyristor switching.

SVCs provide direct control of voltage (C.W. Taylor, 1994); this is very valuable when there is little generation in the load area. The remaining capacitive capability of an SVC is a good indication of proximity to voltage instability. SVCs provide rapid control of temporary overvoltages.

But on the other hand SVCs have limited overload capability, because SVC is a capacitor bank at its boost limit. The critical or collapse voltage becomes the SVC regulated voltage and instability usually occurs once an SVC reaches its boost limit. SVCs are expensive; shunt capacitor banks should first be used to allow unity power factor operation of nearby generators.

Static synchronous compensator (STATCOM)

The STATCOM is a solid-state shunt device that generates or absorbs reactive power and is one member of a family of devices known as flexible AC transmission system (FACTS) devices. The STATCOM is similar to the SVC in response speed, control capabilities, and the use of power electronics. Rather than using conventional capacitors and inductors combined with thyristors, the STATCOM uses self-commutated power electronics to synthesize the reactive power output. Consequently, output capability is generally symmetric, providing as much capability for production as absorption. The solid-state nature of the STATCOM means that, similar to the SVC, the controls can be designed to provide very fast and effective voltage control (B. Kirby, 1997).

While not having the short-term overload capability of generators and synchronous condensers, STATCOM capacity does not suffer as seriously as SVCs and capacitors do from degraded voltage. STATCOMs are current limited so their MVAR capability responds linearly to voltage as opposed to the voltage-squared relationship of SVCs and capacitors. This attribute greatly increases the usefulness of STATCOMs in preventing voltage collapse.

Series capacitors and reactors

Series capacitors compensation is usually applied for long transmission lines and transient stability improvement. Series compensation reduces net transmission line inductive reactance. The reactive generation I^2X_C compensates for the reactive consumption I^2X of the transmission line. Series capacitor reactive generation increases with the current squared, thus generating reactive power when it is most needed. This is a self-regulating nature of series capacitors. At light loads series capacitors have little effect.

Shunt capacitors

The primary purposes of transmission system shunt compensation near load areas are voltage control and load stabilization. Mechanically switched shunt capacitor banks are installed at major substations in load areas for producing reactive power and keeping voltage within required limits. For voltage stability shunt capacitor banks are very useful in allowing nearby generators to operate near unity power factor. This maximizes fast acting reactive reserve. Compared to SVCs, mechanically switched capacitor banks have the advantage of much lower cost. Switching speeds can be quite fast. Current limiting reactors are used to minimize switching transients.

There are several disadvantages to mechanically switched capacitors. For voltage emergencies the shortcoming of shunt capacitor banks is that the reactive power output drops with the voltage squared. For transient voltage instability the switching may not be fast enough to prevent induction motor stalling. Precise and rapid control of voltage is not possible. Like inductors, capacitor banks are discrete devices, but they are often configured with several steps to provide a limited amount of variable control. If voltage collapse results in a system, the stable parts of the system may experience damaging overvoltages immediately following separation.

Shunt reactors

Shunt reactors are mainly used to keep the voltage down, by absorbing the reactive power, in the case of light load and load rejection, and to compensate the capacitive load of the line.

Other

Other equipment can be involved in the provision of reactive power and energy, such as:

- Unified Power Flow Controllers (UPFC) and other advanced FACTS (flexible ac transmission system) devices;
- Tap staggering of transformers connected in parallel;
- Disconnection of transmission lines;
- Load shedding;

2.3.5 Investments in reactive compensation

This section will try to answer the question: *How much does 1 MVar cost to install and to produce?* The table below from (B. Kirby, 1997) gives some numbers. These are, of course, approximate and may vary according to equipment producer and type.

Table 2. Capital and operating costs of reactive power compensation equipment

Equipment type	Capital costs ($/kVar)	Operating costs
Generator	Difficult to separate	High
Synchronous condenser	30-35	High
Capacitor, reactor	8-10	Very low
Static VAR compensator	45-50	Moderate
STATCOM	50-55	Moderate

3. Test system

In order to analyze different methods, a test system has been designed. The intention is to mimic characteristics of the Sydkraft 130 kV subtransmission system and the connection to the 400 kV system of Svenska Kraftnät.

3.1 Scheme

The test system scheme was designed according to particularities of Swedish electric power system: main power generation in the North and high consumption in the South of the country. Sydkraft area (130 kV grid) is being represented more precisely, because it is the main object of investigation. It includes four load buses with comparatively higher power consumption than generators in that area can provide. So most power have to be supplied from the North or Svenska Kraftnät area, which is represented as several parallel long 400 kV lines.

The scheme of the test system is shown in the figure below. The names used in the scheme have the following meanings:

G1, G2 – Sydkraft area generators;

Gs1, Gs2 - Svenska Kraftnät area generators;

D1, D2, D3 – 130 kV transmission lines;

Ds1, Ds2, Ds3, Ds4 – 400 kV transmission lines;

L1, L2, L3, L4 – Sydkraft area loads;

Ts1, Ts2 – 400/130 kV system transformers.

The parameters are given in the Appendix.

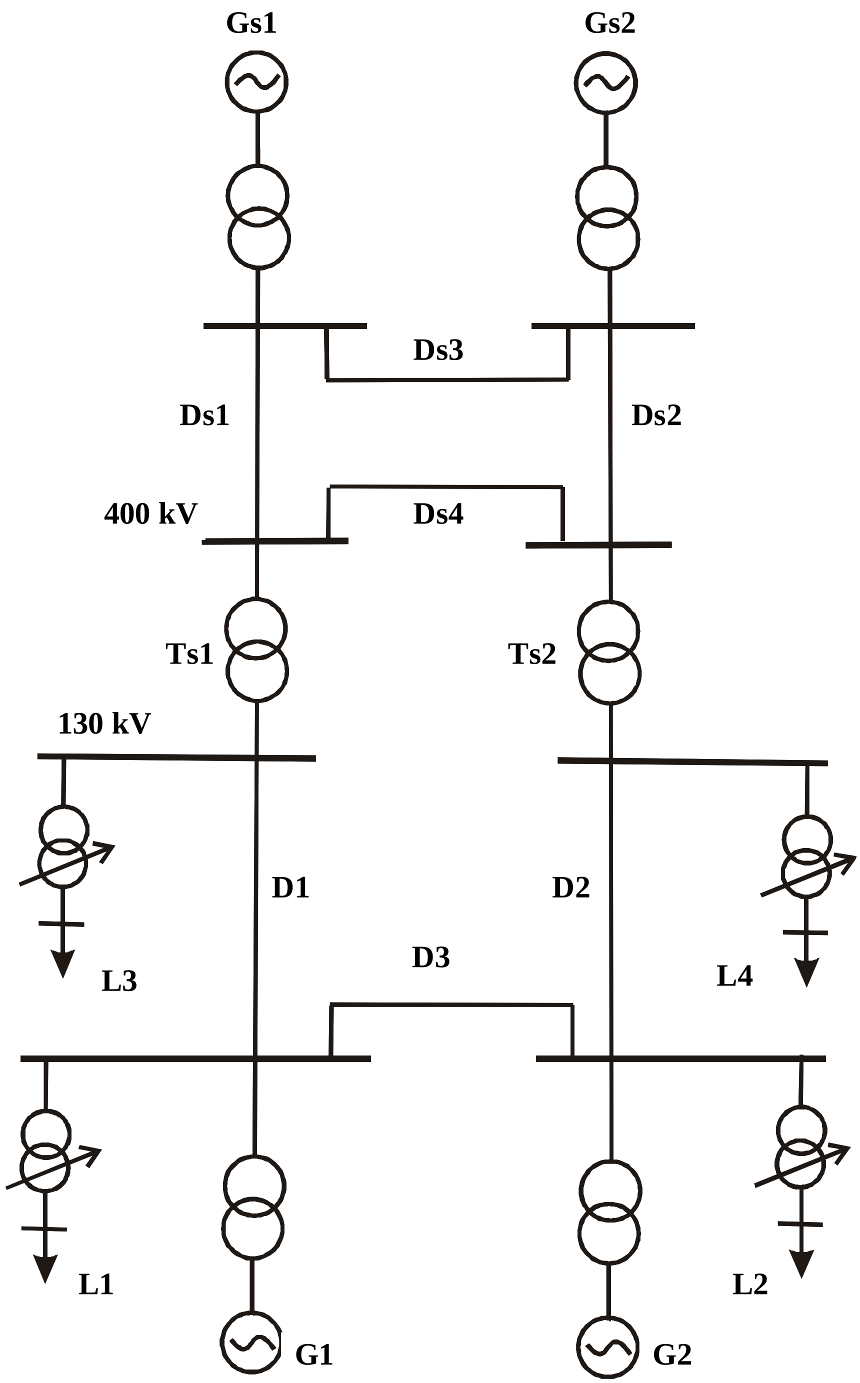

Figure 2. Test system model scheme

3.2 Software

For the test system investigation we will use PowerWorld Simulator Version 7.0. This power system simulation educational package capable to solve the system of 12 buses is available for free from www.powerworld.com. Licensed product can get the power flow solution for the system of up to 60,000 buses.

Simulator allows visualizing the system through the use of full-color animated diagrams and all the power flows, voltages at the buses, losses and many other system parameters could be monitored online. Transmission lines may be switched in or out of service interactively, new transmission or generation may be added and system response or problems can be monitored and solved online. In addition to these features, Simulator boasts integrated economic dispatch, area transaction economic analysis, power transfer distribution factor (PTDF) computation, short circuit analysis and contingency analysis, optimal power flow (OPF); load, generation, and interchange schedule variations over time may be prescribed.

The most interesting for our investigation is the voltage adequacy and stability tool (VAST), which lets to solve multiple power flow solutions in order to generate a PV curve for a particular transfer or a QV curve at a given bus. The simulation results can be shown graphically. The VAST module uses the Simulator built-in Newton Raphson power flow algorithm.

3.3 PowerWorld test system model

PowerWorld test system model is shown in the figure. In this educational version we can use only 12 buses, so in some cases (from generators Gs1, Gs2 and at load L4 bus) we don't use transformers to escape from adding additional bus to the test system.

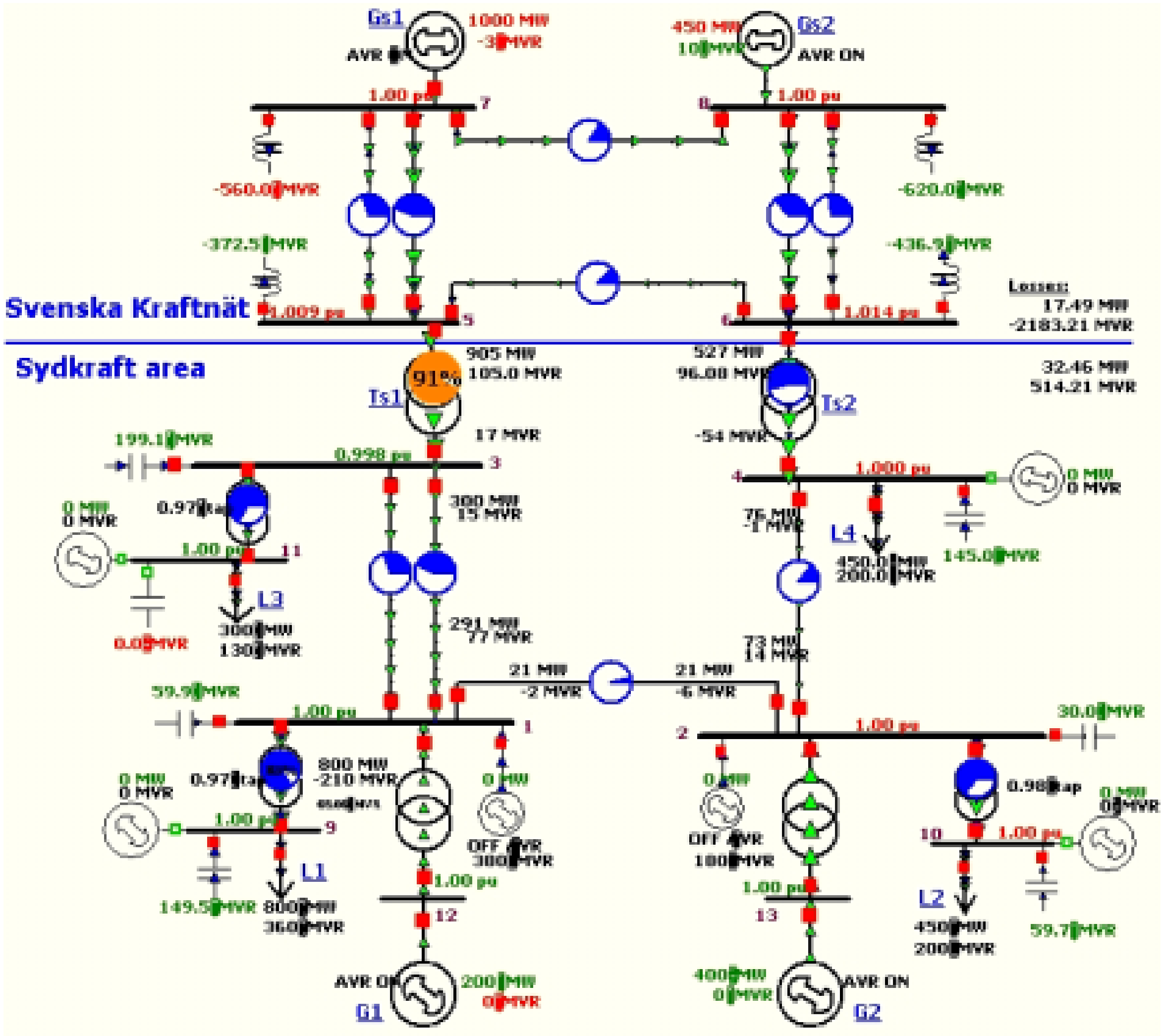

Figure 3. PowerWorld test system model

At the buses 1 and 2 we use additional generators only for reactive power supply for keeping the voltage at appropriate limits. The same aim could be achieved by increasing the size of capacitor banks, installed in the earlier mentioned buses 1 and 2, but as capacitor banks are getting very large voltage variations become high and additional reactive power supply from generators G1 and G2 decrease the voltage at buses 1 and 2. Using additional generators or synchronous condensers bus voltage increases with every additional MVar supplied to the bus.

The limited number of buses and other simplifications made to built up the test system model should not have much influence on the results of the simulations. On the other hand only the proposed methods and the calculation algorithms have value and numbers will be used only for the comparison of the results.

4. Reactive power valuation

Which reactive power source is the most important to the system? What is the criterion in defining that?

For evaluation of source's reactive power to system security and voltage stability many methods can be used. In our investigation we'll try the most promising candidates. Those are Voltage Sensitivity (VS), PV curves, Back-up generation and Equivalent Reactive Compensation (ERC) methods. For testing the methods we used PowerWorld software and its built in capabilities. The high load case was tested.

4.1 Voltage Sensitivity (VS) based Method

Besides of ranking the system sources according to reactive power supply capabilities, this method also answers the question: *What does 1 MVar from one or other source do to system losses?*

We will try to set the value for the reactive power of all test system generators in one case and for Sydkraft area reactive power sources in the other. That will be two generators G1, G2 and reactive power input from the system transformers Ts1 and Ts2. For this investigation we'll use PowerWorld software, which lets to find different sensitivity values.

Table 3. Sensitivity values of generators and loads

	L1 $VS_{L1,Gi}$, MVar	**L2 $VS_{L2,Gi}$, MVar**	**L3 $VS_{L3,Gi}$, MVar**	**L4 $VS_{L4,Gi}$, MVar**	**Sum, ΣVS_{Gi}, MVar**
G1 $VS_{G1,Li}$, MVar	1.045	0.061	0.603	0.2	1.911
G2 $VS_{G2,Li}$, MVar	0.064	1.036	0.069	0.116	1.285
Gs1 $VS_{Gs1,Li}$, MVar	0.269	0.039	0.823	0.419	1.55
Gs2 $VS_{Gs2,Li}$, MVar	0.133	0.051	0.396	0.908	1.488
Sum, ΣVS_{Li}; MVar	1.511	1.187	1.891	1.643	
QLS_{Li}, MW	0.011	0.003	0.023	0.01	
PLS_{Li}, MW	0.104	0.083	0.025	0.009	

Voltages Sensitivities (VS) show the effect an additional injection of real or reactive power at a bus has on real, reactive, or complex power flow on a particular line or interface. Mathematically it is

$$\frac{dQ_G}{dS_L} = \left(\frac{\sum dQ_{Gi}}{dV}\right) \cdot \left(\frac{dS_L}{dV}\right)^{-1}$$

and the numbers could be obtained from the Jacobian matrix.

So for example an additional marginal load increase in 1 MVA at load bus L1 requires generators capabilities of 1.511 MVar, as shown on the first column, to keep the voltage constant. Generator G1 has the greatest influence in this case, because it is the closest to the load L1.

Sum ΣVS_{Li} represents the sensitivity of each load to all generators MVar output.

Sum ΣVS_{Gi} represents the sensitivity of each generator in MVar to the marginal change of all loads.

As we see from the Sum ΣVS_{Gi} generator G1 is the most valuable in regulating the voltage in the system and reacting to the load variation. And the marginal increase of load L3, as we see from Sum ΣVS_{Li}, requires more system reactive power resources than other loads.

In the last two rows the Bus Marginal Loss Sensitivities QLS and PLS are shown. They are used to calculate the sensitivity of a real power loss function, P losses, to bus real and reactive power injections. Stated mathematically, it calculates dP_{losses}/dP_L and dP_{losses}/dQ_L, where P_L and Q_L are the real and reactive power injections at the load bus. It indicates how losses would change if one more MW or MVar of power were injected at the load bus.

So in the table 4 we set the reactive power value of each generator according to the data from the table 3.

Table 4. VS method voltage and losses sensitivities of the sources

	VS_{Gi}	QLS_{Gi}, MW	PLS_{Gi}, MW
G1	1.911	0.016	0.085
G2	1.285	0.0048	0.078
Gs1	1.55	0.014	0.034
Gs2	1.488	0.011	0.023

Q and P losses sensitivities QLS_{Gi} and PLS_{Gi} of the generators have been calculated as follows:

$$QLS_{Gi} = \sum_{L1}^{n} \frac{VS_{Gi}}{\sum VS_{Li}} \cdot QLS_{Li};$$

$$PLS_{Gi} = \sum_{L1}^{n} \frac{VS_{Gi}}{\sum VS_{Li}} \cdot PLS_{Li}.$$

This means that we find the sum how each generator contributes to the losses sensitivities at load buses.

For example QLS_{G1} has been calculated as follows:

$$QLS_{G1} = \frac{1.045}{1.511} \cdot 0.011 + \frac{0.061}{1.187} \cdot 0.003 + \frac{0.603}{1.891} \cdot 0.023 + \frac{0.2}{1.643} \cdot 0.01 = 0.016 \ MW.$$

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So generators G1 and G2 produce the highest marginal losses. It depends on the network configuration and location of the source in the system.

Using the data from the table 4 we can find the cost based marginal reactive power value (RPV) of every source in the system (J.B. Gil, 2000).

$$RPV_{Gi} = \left[VS_{Gi} \cdot f(C_{QGi}) + QLS_{Gi} + PLS_{Gi} \right] \cdot SP;$$

$f(C_{QGi})$ – generator's active power losses as a function of produced reactive power, MW/MVar;

VS_{Gi} – generator's voltage sensitivity, MVar;

QLS_{Gi}, PLS_{Gi} – Q and P losses sensitivities, MW;

SP – active power spot price (available at www.nordpool.com), SEK/MW.

Generator's active power losses as a function of produced reactive power $f(C_{QGi})$, can be found from the figures similar to the one below. The losses curve depends on the type and characteristics of generator.

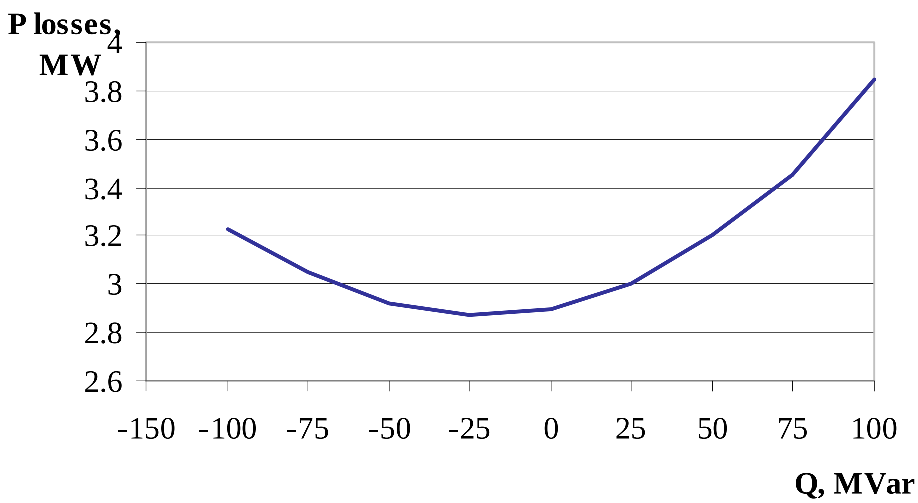

Figure 4. The example of generator's active power losses as a function of produced reactive power at rated MW output

This means that reactive power value of each generator is the sum of active power losses, due to the marginal load change and generator respond to it, multiplied by active power spot price in the system at that moment.

The same calculations can be done using the reactive power sources only in a certain area, as in our test system only Sydkraft area with generators G1, G2 and power flows in system transformers Ts1 and Ts2. This enables us know the value of reactive power not only from the generators but also from one area to other.

So in our example Sydkraft company can get the value of reactive power injected from Svenska Kraftnät at the exchange point, system transformer, not taking care about the source it is produced at. It also could be understood, that Svenska Kraftnät area is replaced by fictitious generators, which supplies the reactive power and reacts to the load changes at the areas' interconnection points.

Table 5. Sensitivity values of sources and loads

	L1 $VS_{L1,Gi}$, MVar	**L2 $VS_{L2,Gi}$, MVar**	**L3 $VS_{L3,Gi}$, MVar**	**L4 $VS_{L4,Gi}$, MVar**	**Sum, ΣVS_{Gi}, MVar**
G1 $VS_{G1,Li}$, MVar	1.045	0.061	0.603	0.2	1.909
G2 $VS_{G2,Li}$, MVar	0.064	1.036	0.070	0.116	1.286
Ts1 $VS_{Gs1,Li}$, MVar	0.272	0.015	0.884	-0.04	1.131
Ts2 $VS_{Gs2,Li}$, MVar	0.015	0.052	0.036	1.096	1.199
Sum, ΣVS_{Li}; MVar	1.396	1.164	1.593	1.372	
QLS_{Li}, MW	0.011	0.003	0.023	0.01	
PLS_{Li}, MW	0.104	0.083	0.025	0.0089	

Table 6. VS method voltage and losses sensitivities of the sources

	VS_{Gi}	**QLS_{Gi}, MW**	**PLS_{Gi}, MW**
G1	1.909	0.018	0.093
G2	1.286	0.0052	0.08
Ts1	1.131	0.014	0.035
Ts2	1.199	0.0087	0.012

4.2 PV curves Method

Reactive power valuation by PV curve method can be done using voltage adequacy and stability tool (VAST) of the PowerWorld software. It is performed by increasing the load at the selected buses of the system and getting the response of the sources until the system reaches the limits and crashes.

So the answer to: *What does 1 MVar mean to transfer capacity?* can be found.

The procedure of this method is as follows:

1. Select the load or the group of loads in the area or whole system you want to vary. In our test system it will be loads L1-L4. It is possible to increase only the active load or keep the power factor constant. In our case power factor was kept constant.
2. Select the generator or the group of generators to cover the system demand. Only generators with AGC (generators responding to load level) could be varied, while others are used for reactive power supply. We select generators G1-G2 (without AGC) and Gs1-Gs2 (with AGC).
3. Determine the step size of the transfer. In our case the initial step size is 1MW.
4. Pick up the quantities you want to monitor. Voltage, power flows of generators', loads' buses, transmission lines and other quantities can be selected.
5. Perform the simulation until system reaches the limits and collapse margin is obtained. Variation of the selected quantities can be viewed graphically.

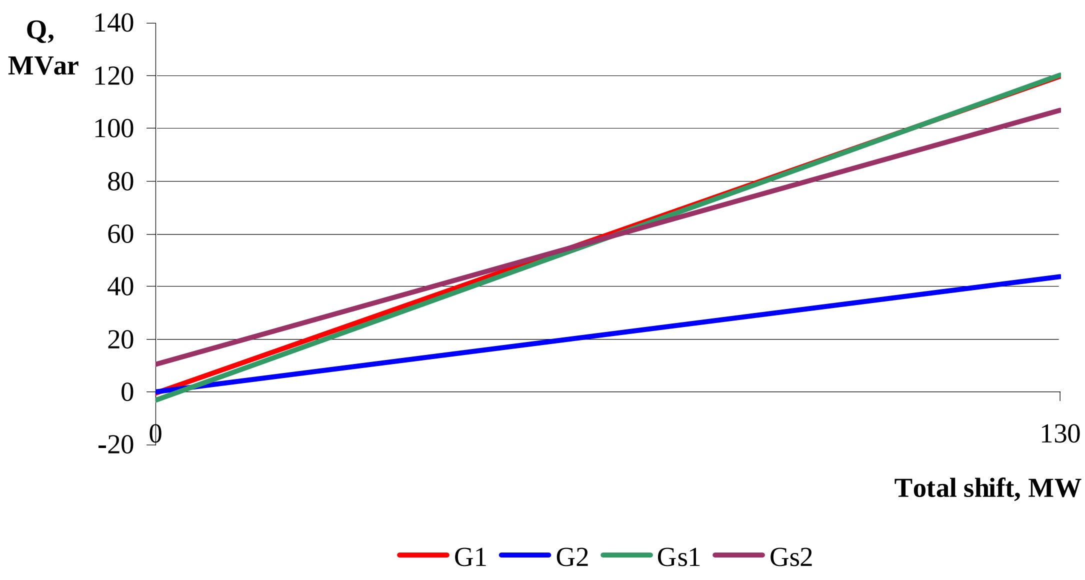

Figure 5. Generators' reactive power output versus total load shift

Collapse margin in this case is 130 MW, because generator G1 reaches reactive power output limits of 120 MVar and becomes unable to support the reactive power demand of the loads and voltage in the system.

6. Sensitivity coefficients of the curves for all generators could be established. It was made using Curve Expert software to linearize the curves and get sensitivity coefficients in the range from zero to 120 MW of generators total active power output.

Table 7. PV curve method sensitivities of the generators

Generator	Sensitivity
G1	0.923
G2	0.336
Gs1	0.948
Gs2	0.743

4.3 Equivalent Reactive Compensation (ERC) Method

According to the authors of this method (W. Xu, 2000) the basic form of the idea is as follows: if a Var source changes its output, the network voltage profile and stability levels will change. To maintain a same degree of network security, Var compensations can be added (at all load buses). The total amount of fictitious compensation added is a direct measure of the value of the missing Var output from the source. The fictitious injected reactive power is termed as Equivalent Reactive Compensation.

The procedure of this method used for our test system model is like this:

1. Add fictitious synchronous condensers $Q_{S,i}$ (generators with zero active power output) to each load bus L1-L4. There are no reactive power limits for the condensers.

   In further research the fictitious condensers can be placed in a given zone or area of a system, instead of all over the system. Reactive output limits could be added to the fictitious condensers. The Var limits could be set in proportion to the size of bus MVA load.

2. The reactive power output of generators is kept at the base case level, that is almost zero, and AVR is turned off. So generators are represented as PQ buses.

3. For the dynamic reactive power source to be studied we increase its reactive power output $Q_{G,i}$ from the Q_{Gmin} to Q_{Gmax}. Q_{ERCs} are calculated in the process as reactive power output of all fictitious condensers:

$$Q_{ERC} = \sum_{i=L} Q_{S,i};$$

4. Q_{ERC} as a function of $Q_{G,i}$, the output of the study source, can be plotted.

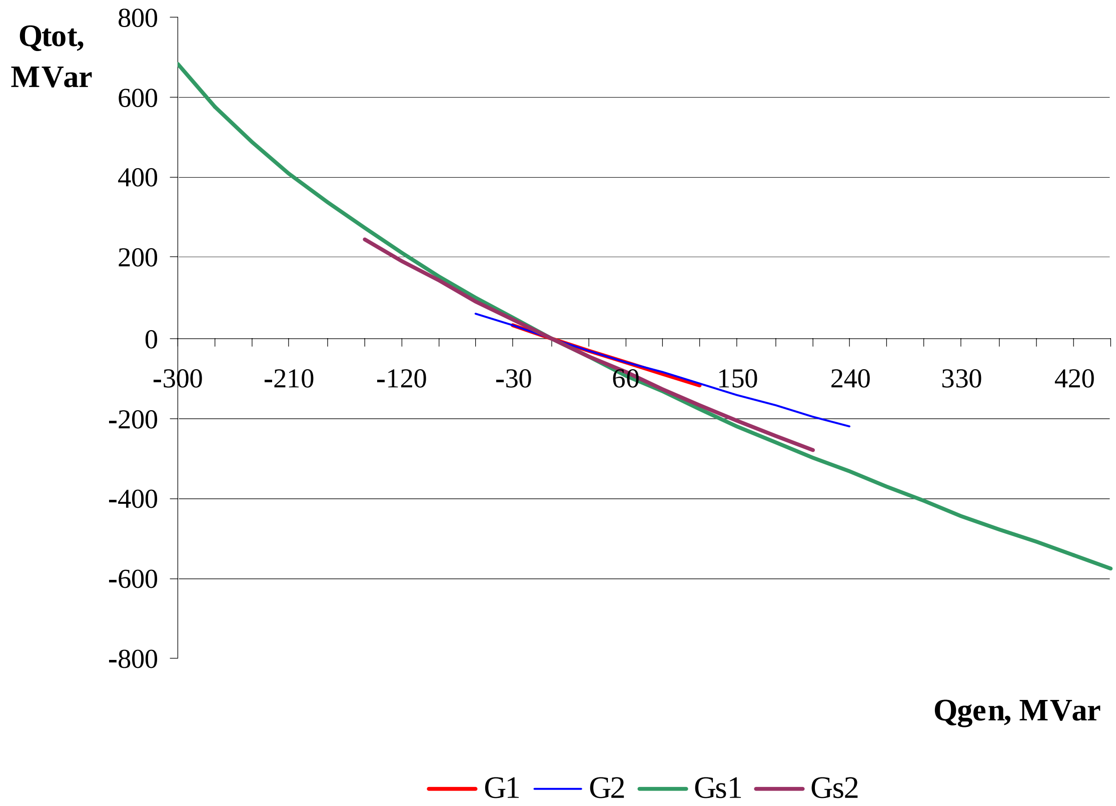

Figure 6. Q_{ERC} as a function of $Q_{G,i}$,

5. Q_{ERC} curves for each reactive power source can be transformed into the value curves.

$$V(Q_{G,i}) = Q_{ERC,i}(Q_{G\min,i}) - Q_{ERC,i}(Q_{G,i});$$

$Q_{ERC,i}(.)$ – the compensation curve for the reactive power source;

$Q_{Gmin,i}$ – the lowest permissible reactive power output of the source or Q_{ERC} at the zero reactive power output of the generator.

The value curve represents the system-wide reactive power savings one can achieve if the output of any dynamic Var source is increased. More savings a generator can give to the system implies more efficient it is to support system security.

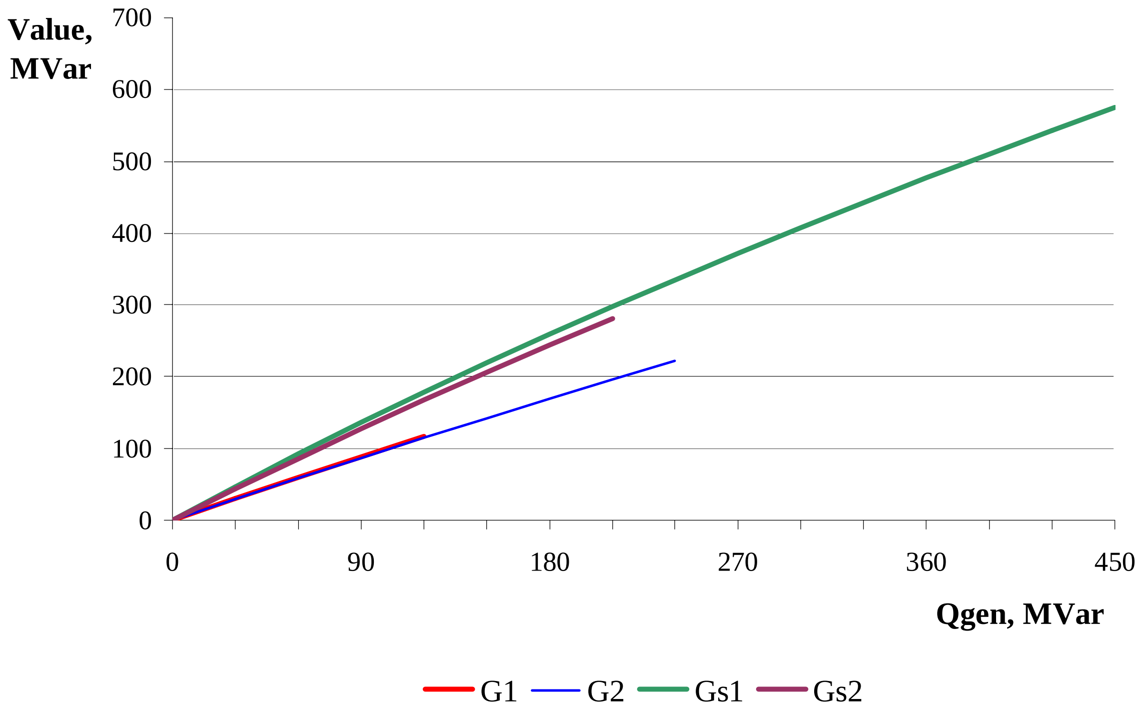

Figure 7. Value curves

So the reactive power output from G1 and G2 is less expensive to the system – so those generators are the most efficient to our test system in supporting system security.

6. Sensitivity coefficients of the value curves for all generators could be established. Curve Expert software was used to linearize the curves and get sensitivity coefficients in the range from zero to 120 MVar of generators reactive power output.

Table 8. ERC method sensitivities of the generators

Generator	Sensitivity
G1	0.98
G2	0.96
Gs1	1.47
Gs2	1.40

Generator with lowest sensitivity value is the most efficient to the system security and dynamic reactive power supply. So according to this method, generators G1 and G2 are the most efficient to our test system.

4.4 Back-up generation Method

In this case we'll try to answer the question: *How much MVar from other sources would be needed to replace Q from the selected source?*

To evaluate generators' reactive power support capabilities we'll decrease marginally the output of reactive power of one generator and track the response to this from the others. So the decrease by 1 MVar gives the following results:

Table 9. Back-up method sensitivities of the generators

Generator	Sensitivity
G1	8.1
G2	7.8
Gs1	1.76
Gs2	1.55

This means that the shortage of 1 MVar from G1 requires 8.1 MVar from other reactive power sources to keep the system at the same voltage and security level.

4.5 Comparison of the methods

For the comparison of the methods we'll use sensitivity values and percentage ratios.

Table 10. Comparison of the methods

	V Sens.	%	PV	%	ERC	%	Back-up	%
G1	1.91	***100***	0.923	***97***	0.98	***98***	8.1	***100***
G2	1.29	***67***	0.336	***35***	0.96	***100***	7.8	***96***
Gs1	1.55	***81***	0.948	***100***	1.47	***65***	1.76	***22***
Gs2	1.49	***78***	0.743	***78***	1.40	***69***	1.55	***19***

Decreasing number in the percentage column represents less importance of the generator to system reactive power support. So as we see different methods give different results. But the results from Voltage Sensitivity and PV curves methods are close; ERC and Back-up generation are similar too. Both two groups are different in their nature, because in the first group generators are responding to the load change and in the second – system responds to the changing output of reactive power from one or other generator.

We get that generators G1 and Gs1 are the most important in tracking load changes in the system; G1 and G2 are the most efficient in substituting other generators from the view of system security.

Graphical comparison of the results is shown in the figures below.

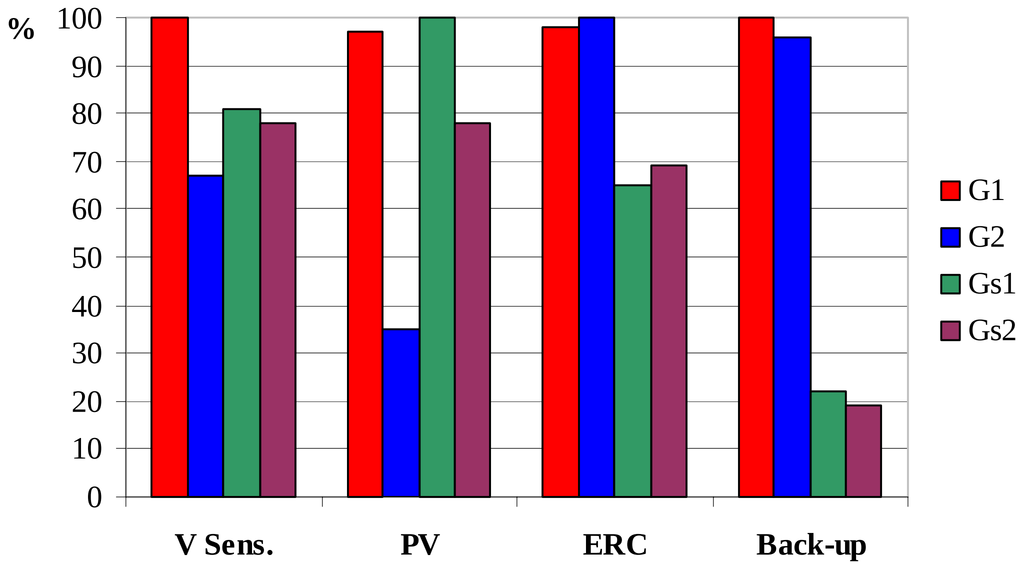

Figure 8. Comparison “Method=f(Generator)”

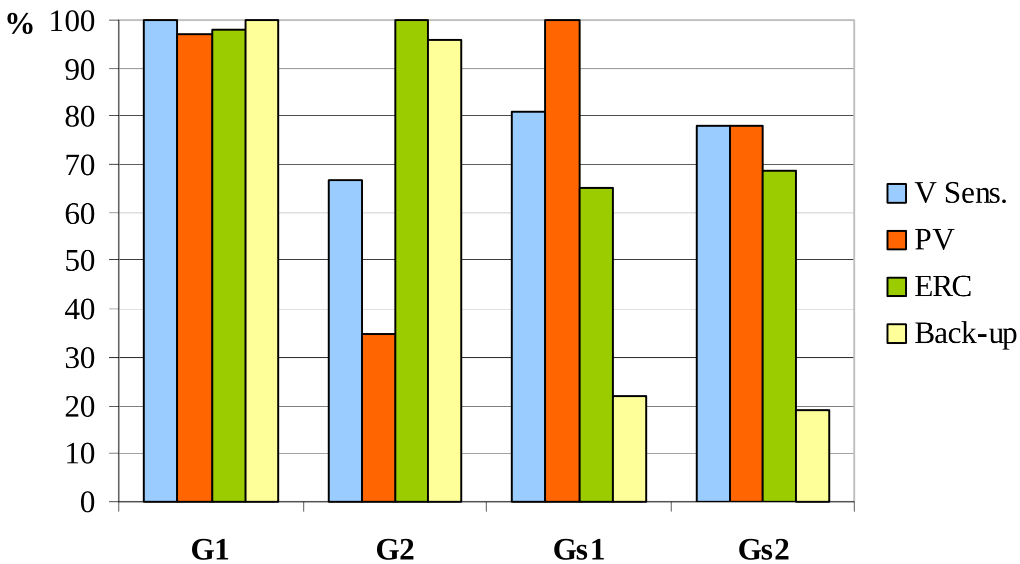

Figure 9. Comparison “Generator=f(Method)”

To answer the question why one or other generator is more important than the other, we have to look at its location and the configuration of the network. Reactive power source distance to the load is a crucial quantity. Other important quantities are the sizes of the generator and load. So in most cases of our simulations G1 is the most important and this is because it is located close to the biggest load in the area. The output of G1 is 200 MW and it is close to the load L1 (800+j360), so the bigger part of energy is supplied from the distance generators that implies additional losses in the system and makes G1 more attractive and important then others.

The following conclusions about the methods of reactive power valuation can be made:

- Using PowerWorld built-in capabilities in Voltage Sensitivity (VS) method we don't need to switch off the generators AVR to vary the reactive power output. So the real conditions and the state of the system are represented better. But on the other hand we get only marginal value of reactive power and don't know how system responds to greater load changes if their impact is not linear. With this method we can also find out how losses are changing in the system with every additional MVar injected.
- PV curve method gives the response of the generators reactive power output to the load shift in the system. It also contains information about the system transfer limit. But it is not very clear because usually system collapses when one of the generators reaches the limits of reactive power output.
- ERC method provides information about system response to the changing reactive power output of the source. For the simulation we have to insert some additional fictitious condensers into the system and that is interrupting the real conditions.
- Back-up generation method is very intuitive and it shows how much of additional reactive power we have to supply to cover the Q shortage from one or other reactive power source to keep bus voltages (at PV buses) at the predetermined values.
- VS and PV curve methods show how generators react with their reactive power output to the changing load in the system. ERC and Back-up generation methods help to realize the importance of the reactive power reserve of the sources. So those two groups of methods show different value of reactive power.
- The importance of the source to the system reactive power support depends on the network configuration, source location and the state of the system.

5. Zero flow case investigation

5.1 Investments in reactive compensation

The reactive power exchange between Sydkraft and Svenska Kraftnät depends on the load conditions and vary from one interconnection point to the other. According to the data from the Sydkraft company reactive power exchange during high and low load conditions is shown in the table 11.

Table 11. Reactive power exchange between Sydkraft and Svenska Kraftnät on the 400 kV sides of the system transformers

Interconnection points	**High load conditions (99-01-29. 8.30) (MVar)**	**Low load conditions (00-07-25. 5.30) (MVar)**
Bornholm	2	-13
AIE	-19	1
SEE	95	-19
BBK	-9	9
DK 130 kV	-33	-5
SÅN	130	-59
BED	69	-17
VMON	4	16
Norr 130 kV	57	70
AVA	22	-81
NSÖ	19	-2
SVP	45	64
NBO	40	-23
HEÖ	36	-13
Extraction	519	160
Supply	-61	-232
Total exchange	**458**	**-72**

"-" – reactive power supplied to 400 kV network;

"+" – reactive power extracted from 400 kV network.

According to the table we can divide the Sydkraft area into the Western and Eastern part with corresponding intersection points with 400 kV Svenska Kraftnät network. So the Western part is being represented by the substations from Bornholm to BED, and the Eastern - from VMON to HEÖ. Those aggregated intersection points are represented as system transformers Ts1 and Ts2 in our test system model (table 12).

Table 12. Reactive power exchange representation in the test system model

	Test system		High load conditions, MVar	Low load conditions, MVar
West Bornholm, AIE, SEE, BBK, DK, SÅN, BED	**Ts1**	Real	235	-103
		Model	105	-45
East VMON, Norr, AVA, NSÖ, SVP, NBO, HEÖ	**Ts2**	Real	223	31
		Model	95	15

The numbers for real and test system (Model) case are picked according to the Sydkraft area active load fraction for real and test systems.

To have a zero reactive power flow in the system transformers Ts1 and Ts2 we need to have or install some additional reactive power compensation devices. On the 400 kV side we need reactors and on the 130 kV – capacitors. According to the calculations used on our investigation model during high load conditions for the certain reactive power flow in the system transformers we need to have compensation devices as shown in the pictures below:

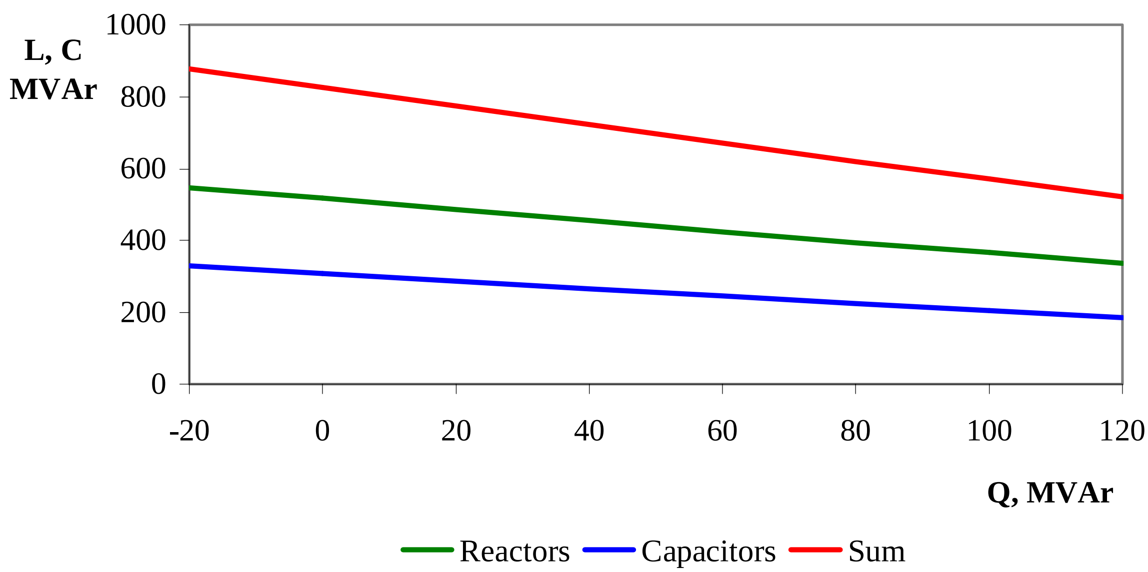

Figure 10. Reactive power compensation installment for the certain Q flow at Ts1

Voltage profile at both sides of the transformer looks like shown in the figure. We tried to keep the voltage on 130 kV side constant V=1.0 p.u. and looked how 400 kV side voltage changed at different reactive power flow levels in the transformer.

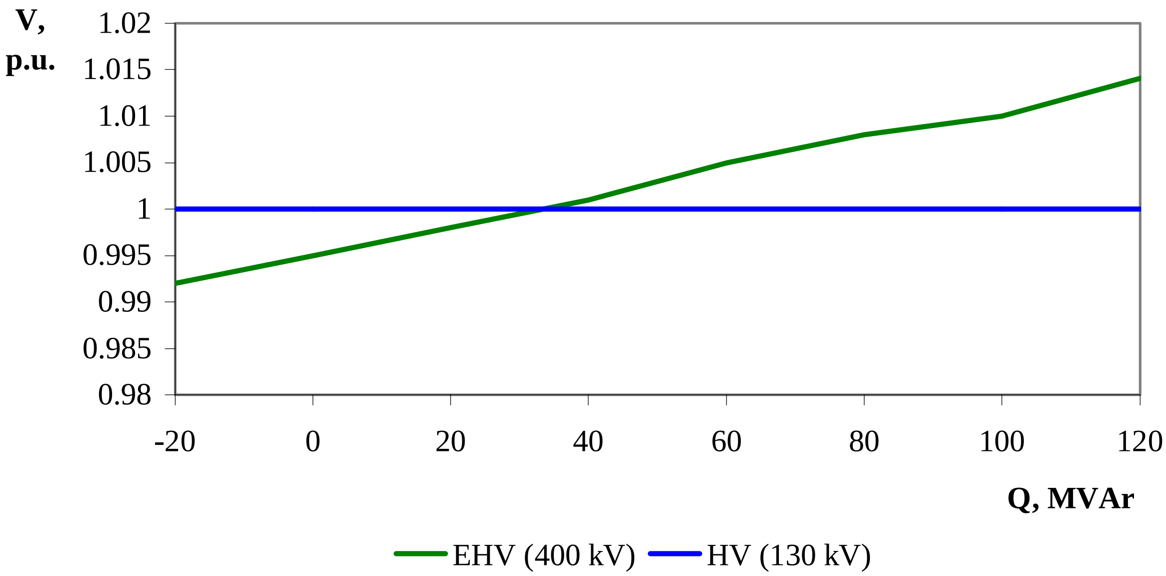

Figure 11. Voltage profile at Ts1 400 kV and 130 kV sides

For the certain level of reactive power flow in the system transformer Ts2 we need additional reactive compensation as shown in the figure below.

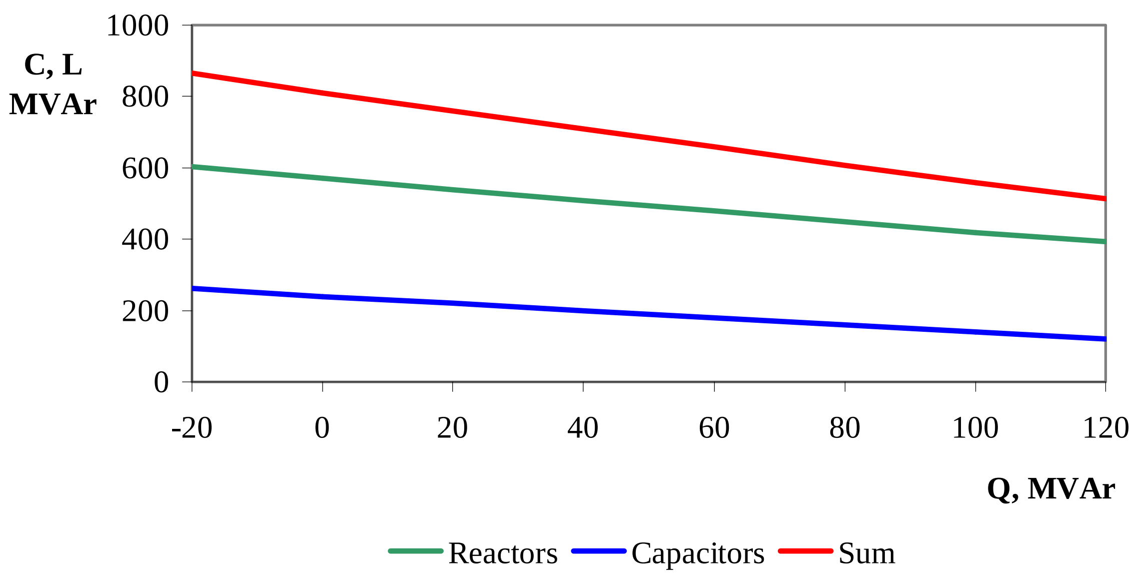

Figure 12. Reactive power compensation installment for the certain Q flow at Ts2

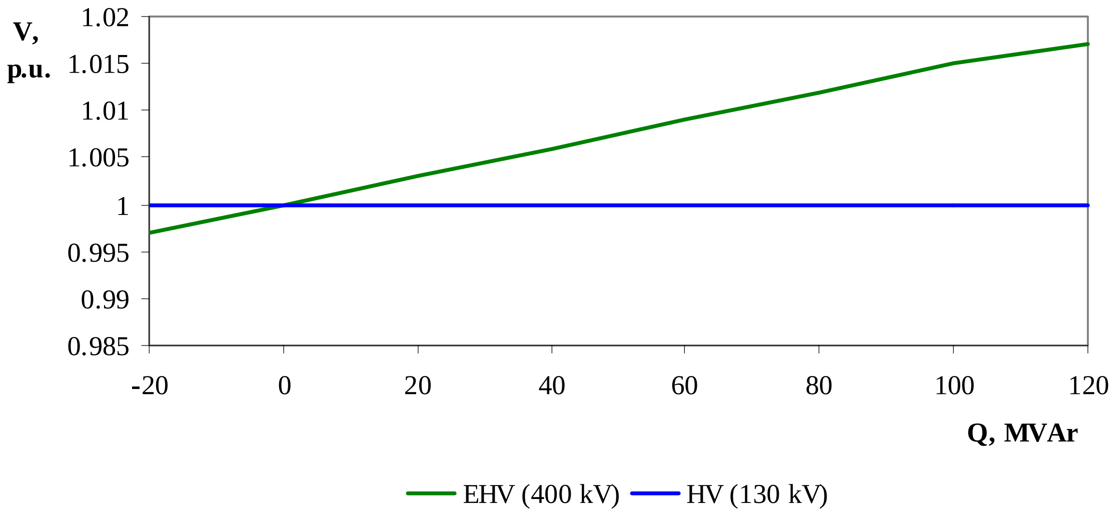

Figure 13. Voltage profile at Ts2

Using CurveExpert software for the data interpolation we get that for every extra MVar towards the zero reactive power flow in the system transformers we need to install the amount of reactive power compensation devices as shown in the table.

Table 13. Installments for ΔQ=1 MVar

	Ts1	Ts2
Reactors, MVar	-1.52	-1.48
Capacitors, MVar	-1.02	-0.98
Sum, MVar	-2.54	-2.46

So the average values of coefficients could be like this:

$\mathbf{K_C=1.0;}$

$\mathbf{K_L=1.5;}$

$\mathbf{K_{sum}=2.5.}$

For every 1 MVar driven flow of reactive power in systems transformers towards zero we'll need 1 MVar of capacitors on the 130 kV side and 1.5 MVar of reactors on 400 kV side.

For the low load case the situation is very similar. The only difference that in some transformers we have an opposite reactive power flow than in the high load conditions – the flow is from Sydkraft area to the Svenska Kraftnät network. In this case we have decrease reactive power consumption on 400 kV network and decrease reactive power generation or increase consumption (install reactors) on 130 kV side.

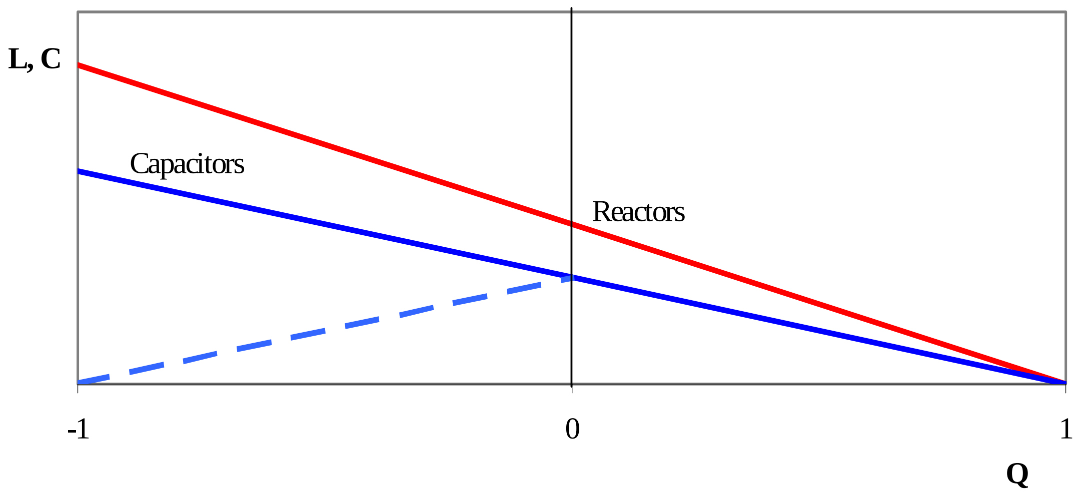

Figure 14. Investments in reactive compensation

So for the Sydkraft situation during high load conditions with maximum reactive power consumption from the 400 kV network we'll need something about 519 MVar (table 11) of reactive power exchange with Svenska Kraftnät to drive to zero. This would require additional reactive power compensation capacity from both sides equal to:

519 MVar*2.5 = 1300 MVar

Or from Sydkraft company:

519 MVar*1.0 = 519 MVar.

At the current situation Sydkraft has 975 MVar of capacitor banks installed on 130 kV network. So additional 519 MVar looks great enough.

Of course all numbers calculated in this paragraph are based on our test system and should be checked for the real network.

5.2 Normal and zero flow case comparison

For the normal and zero case comparison we will use the tables below. The first table represents high load situation with four different conditions: normal, zero flow, and normal, zero flow case with the disturbances. To simulate the disturbances in the system we disconnect one of three Ds1 parallel lines.

The second table is made during the low load conditions in the system and it has the same quantities as the table for the high load conditions.

Table 14. High load situation

	Normal	Zero flow	Normal case with disturbances	Zero flow case with disturbances
P losses SK, MW	32.46	32.45	37.12	36.40
P losses SvK, MW	17.49	17.63	21.34	21.47
Q losses SK, MVar	514.2	515.1	588.5	581.1
Q losses SvK, MVar	-2183.2	-2143.3	-1455.4	-1431.1
Reactors at Ts1 400 kV	366	504		
Capacitors at Ts1 130 kV	200	310		
Reactors at Ts2 400 kV	425	554		
Capacitors at Ts2 130 kV	145	240		
Transfer limit, MW	130.6	128.8	18.5	15.8
V Sensitivity method				
G1	1.91	1.93	2.56	2.63
G2	1.29	1.29	1.48	1.49
Gs1	1.55	1.56	4.24	4.37
Gs2	1.49	1.50	0*	0
PV curve method				
G1	0.92	0.94	1.37	1.41
G2	0.34	0.34	0.29	0.47
Gs1	0.95	0.97	2.65	2.74
Gs2	0.74	0.76	0	0
ERC method				
G1	0.98	0.98	0.97	0.97
G2	0.96	0.96	0.96	0.96
Gs1	1.49	1.50	1.51	1.52
Gs2	1.39	1.41	1.25	1.26
Back-up method				
G1	8.10	9.96	7.4	-11.88
G2	7.80	7.17	9.3	9.26
Gs1	1.76	1.80	-1.18	-1.22
Gs2	1.55	0.09	1.56	1.6

* - The response from the generator Gs2 is zero because after disconnecting one line from Ds2 the output of reactive power from Gs2 reaches the limits and Q shortage in the system has to be compensated from the other sources.

Table 15. Low load situation

	Normal	Zero flow	Normal case with disturbances	Zero flow case with disturbances
P losses SK, MW	9.57	9.55	10.04	9.91
P losses SvK, MW	2.97	2.95	3.54	3.54
Q losses SK, MVar	134.2	134.1	142.4	140.9
Q losses SvK, MVar	-2475.6	-2480.7	-1971.4	-1977.6
Reactors at Ts1 400 kV	696	616		
Capacitors at Ts1 130 kV	138	42		
Reactors at Ts2 400 kV	596	634		
Capacitors at Ts2 130 kV	110	124		
Transfer limit, MW	302.6 (278)*	302.6 (278)	196.4	196.4
V Sensitivity method				
G1	1.52	1.52	1.62	1.62
G2	1.19	1.19	1.26	1.26
Gs1	0.95	0.96	1.80	1.80
Gs2	1.04	1.04	0	0
PV curve method				
G1	0.46	0.46	0.48	0.48
G2	0.14	0.14	0.14	0.14
Gs1	0.29	0.29	0.39	0.39
Gs2	0.06	0.06	0	0
ERC method				
G1	0.99	0.99	0.99	0.99
G2	0.98	0.98	0.98	0.98
Gs1	1.03	1.03	0.94	0.94
Gs2	1.02	1.02	0.96	0.96
Back-up method				
G1	2.46	2.44	2.42	2.33
G2	3.39	3.53	3.40	3.39
Gs1	1.15	1.06	1.17	1.24
Gs2	1.08	1.14	0.99	0.99

* - The first number represents system collapse margin or transfer limit, and the number in brackets – Inadequate voltage margin, that is smaller then the transfer limit.

So from the performed simulations and data above we can make the following conclusions:

- To get the zero flow on 400 kV side of the system transformer requires additional reactive power compensation from both sides: Sydkraft and Svenska Kraftnät. And according to our calculations for every extra MVar towards the zero reactive power flow in the system transformers we need to install 2.5 MVar of reactive power compensation devices.
- Active power losses in both normal and zero flow case are almost equal. In Sydkraft area the reduction of losses in zero flow is 0.07 % and it depends on the initial state of both cases.
- The difference between normal and zero flow cases in the terms of generators' response to reactive power demand according to the proposed methods is greater with higher load. In low load conditions the parameters are almost the same.
- The system transfer limit or the collapse margin is a little greater (1 %) in normal than in zero flow, but it also depends on the initial state of generators.

6. Conclusions

In this work we tried to define the value of reactive power using four different valuation methods: Voltage Sensitivity, PV curve, Equivalent Reactive Compensation and Back-up generation. A simple test system model was build and tested with PowerWorld software. Preliminary results showed different nature of reactive power from the sources.

For the same test system model we have tried to find out the advantages and disadvantages of having zero reactive power flow in the system transformers. So the results showed that for every extra MVar towards the zero reactive power flow in the system transformers we need to install 2.5 MVar of reactive power compensation devices. Having zero flow system losses and transfer capacity changes very little.

In the introduction part we defined some questions we wanted to answer in this work. So the answers and the final conclusions are like this:

- *Which reactive power source is the most important to the system? What are the criteria?*

We tried to answer this question with the help of all four proposed methods of reactive power valuation. They give different results, but at the same time showed different nature of reactive power. Voltage Sensitivity and PV curve methods show how generators react with their reactive power output to the changing load in the system. ERC and Back-up generation methods help to realize the importance of the reactive power reserve of the sources. Generator closest to the relatively high load is the most important to the system.

- *How much MVar from other sources would be needed to replace Q from the selected source?*

Back-up generation method is the answer to this. It describes the importance of the source to system reactive power reserve and shows how much of additional reactive power we have to supply to cover the Q shortage from one or other reactive power source to keep bus voltages (at PV buses) at the predetermined values.

- *What does 1 MVar from one or other source do to system losses?*

Active and reactive power losses sensitivities to additional MVar injected into the system can be obtained using Voltage Sensitivity method. Marginal losses produced by the source depend on the network configuration and location of the source in the system.

- *What does this 1 MVar mean to transfer capacity?*

With PV curve method we were able to see what influence each generator in our test system had on the transfer limit. During high load condition the transfer limit was obtained when one of the sources reached the limits of reactive power output. So the source closest to the loads and with relatively low reactive power output limits is crucial to the system.

- *How much does this MVar cost to install and to produce?*

Reactive power sources and sinks were analyzed in the section 2.3 and in table 2 approximate numbers about the installation and production costs of reactive power equipment were given. The most expensive, but the best sources of reactive power support are machinery equipment – generators, synchronous condensers.

For further investigation in this area, the results should be checked on the real electric power system to find out if the proposed methods are suitable.

7. References

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Appendix: Test system model parameters

All the parameters used in the test system are listed in the tables below.

Table 16. Per unit base quantities

V_{base}, kV	138	415
S_{base}, MW	100	100
Z_{base}, Ω	190.44	1722.25

Table 17. Lines' parameters

	D1	D2	D3	Ds1	Ds2	Ds3	Ds4
, km	50	200	200	600	600	200	300
x, Ω/km	0.4	0.4	0.4	0.3	0.3	0.3	0.3
/r	10	10	10	15	15	15	15
arallel lines	2	1	1	3	3	1	1
, pu	0.0525	0.4201	0.4201	0.0348	0.0348	0.0348	0.0523
, pu	0.0052	0.04201	0.04201	0.00077	0.00077	0.00232	0.00348
, pu	0.054	0.107	0.107	11.160	11.160	1.240	1.860

Table 18. Transformers' parameters

	Ts1	Ts2	T1	T2	T3	T4
S, MVA	1000	1000	1000	750	500	750
X, pu (S_b)	0.15	0.15	0.1	0.1	0.1	0.1
X, pu(100 MVA)	0.015	0.015	0.01	0.013	0.02	0.013
R, pu(100 MVA)	0.00050	0.00050	0.00033	0.00044	0.00067	0.00044

x/r=30

Table 19. Generators' parameters

	G1	G2	Gs1	Gs2
P, MW	200	400	1000	500 (slack bus)
Qmin, MVar	-30	-60	-300	-150
Qmax, MVar	120	240	450	210

Table 20. Loads' parameters

	L1	L2	L3	L4
P_{high}, MW	800	450	300	450
Q_{high}, MVar	360	200	130	200
P_{low}, MW	450	250	170	250
Q_{low}, MVar	200	110	80	110

cosφ=0.9