Reactive power support for the power system

Review of incentives for reactive power support in the power system

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Reactive power for voltage support

The power system consists of several different voltage levels, from the 400 kV transmission system to the 400 V local grid with a distribution system in between, which for example is described in [1]. For changing voltage levels, transformers are used. However, since there are voltage drops over components in the power system caused by the power flow, there must be measures to control the voltage to stay within the given limits of typically ±3 to 10 % during varying operating conditions.

There are two different ways to control the voltage in the power system:

- Transformers with tap changers. Having tap changers on a transformer can change the ratio of the transformer in several steps. If the voltage at the low voltage side is too low, the ratio of the transformer is decreased resulting in a higher voltage at the low voltage side. In the same way, if the voltage is too high the ratio of the transformer is increased. The response time of a tap changer is typically 30-60 s and the voltage can for example be changed in steps of 1.67 % with ± 8 steps available.
- Voltage control from reactive power. The grid components at higher voltage levels, such as lines and transformers, are mainly inductive and therefore the voltage is heavily dependent on the reactive power flow. The voltage can therefore be changed by producing or consuming reactive power. Producing reactive power increases the voltage and consuming reactive power decreases the voltage. At lower voltage levels the grid is more resistive and then the voltage is also dependent on the active power flow. In almost purely resistive grids, i.e. at many houses connected at 400 V, the voltage is almost solely dependent on the active power flow.

Historically, the use of inductive loads led to higher demand for reactive power, which was commonly compensated using capacitor banks. Today, shunt compensation is more commonly used together with technologies such as STATCOMs, SVCs and converter based generation, needed also at lower voltage levels since the generation is more distributed. The increasing amount of distributed generation has also created a larger need for reactive power support at lower voltage levels. As a result, reactive power is no longer only needed to be produced, but also consumed.

Since there are several different ways to control the voltage, it is important with a coordination between voltage control supplied by components such as generation and energy storage and the operation of the tap changers.

Since the tap changers are part of the existing infrastructure and owned by the grid owner, there are no specific economic incentives for providing voltage control with tap changers, instead possible economic incentives for providing reactive power are considered in this document.

Existing economic incentives for reactive power support

While the market for active power support is relatively mature it has until now not been a general market for reactive power support. This can partly be explained by the local nature of reactive power and voltage control. There are requirements in the grid codes on capability for reactive power as well as control modes for reactive power, voltage and power factor [2]. However, the economic incentive up until now has been a cost for actors that exceeded their maximum allowed reactive power in the connection point.

Proposed economic incentives for reactive power by Svenska kraftnät

During spring 2026, Svenska kraftnät (Svk) proposed new incentives for reactive power support in Sweden [3], which will take effect on 1 January 2027. As part of this framework, the tariff component "Effektkomponent för spänningsreglering" (hereafter referred to as the Voltage Regulation Component) is intended to cover future costs related to the need for voltage regulation.

The Voltage Regulation Component will be divided into two parts: a charge component, intended to cover future costs related to customer use of the grid, and a compensation component, intended to compensate customers whose provision of voltage regulation reduce these costs. The compensation component is voluntary.

When determining the compensation component, the response from the actor for each 15-minute settlement period is divided into voltage regulating (Type 1) reactive power exchange and non-voltage regulating (Type 2) reactive power exchange. For an exchange to be considered voltage regulating (Type 1), it shall, when voltage at the connection point increases, decrease injection or increase consumption of reactive power. Likewise, when the voltage at the connection point decreases, it shall increase injection or decrease consumption of reactive power.

The measurements of voltage and reactive power are collected every 3 seconds over a 2-hour regression window. The regression analysis uses the most recent 2 hours of measurement data. Every 15 minutes settlement period, the dataset is updated by removing the oldest 15 minutes of data and adding the latest 15 minutes of data. The 2-hour data is then plotted, and linear regression is fitted and updated every 15 minutes. The slope of the regression line represents dQ/dU and the voltage regulating (Type 1) reactive power exchange is defined by

$$\frac{dQ}{dU} < -X\ Mvar/kV$$

where the derivative of Q with respect to U should result in a sufficiently negative slope for it to be considered voltage regulating. Svk proposes X to be 1 Mvar/kV. In contrast, the non-voltage regulating (Type 2) is defined by

$$\frac{dQ}{dU} \geq -X\ Mvar/kV$$

where the slope of the regression line is greater than or equal to $-X$, meaning that the change of reactive power is not sufficiently negative to be considered voltage regulating. Every exchange that is not considered to be voltage regulating (Type 1) should be classified as non-voltage regulating (Type 2).

For each 15-minute settlement period, the average values of voltage and reactive power at the point of connection are calculated. These average values are then used to determine the operating point in a QU-diagram, which in turn determines whether the settlement period results in compensation, a charge or neither. The total monthly average reactive power from settlement resulting in compensation is offset against the total monthly average reactive power from settlement periods resulting in a charge. The resulting net reactive power is then multiplied by the compensation rate of 31 500 SEK/Mvar to determine the monthly payment.

Literature review of proposed economic incentives for reactive power

The proposed economic incentives for voltage control given by Svenska kraftnät is at the connection point to the transmission grid and the DSOs do not yet have general economic incentives for their customers in place. Looking at proposed methods in literature, several studies have examined economic incentives for small-scale distributed energy resource (DER) owners to participate in voltage regulation. The article presented in [4] studies a 400 V distribution grid with 50 % photovoltaic (PV) penetration. Using real time PV generation and load data and an optimization framework with data based on German local household load profiles and PV compensation rates the authors evaluate the potential of inverter-based reactive power provision. They emphasize that supplying reactive power may shorten inverter lifetime and reduce revenues due to active power curtailment and therefore argue that these costs should be reflected in the incentive scheme. Their results show that reactive power provision improved voltage quality while also providing small financial benefit to DER owners. Average compensation increased from 2.37 EUR per day without reactive power provision to 2.48 EUR with provision, resulting in an additional earning of 40 EUR per year. However, the study does not discuss the extent to which this level of compensation is sufficient to motivate DER owner to willingly participate with voltage regulation.

Building on these findings, the study presented in [5] further examines how PV and energy storage system (ESS) owners can be encouraged to provide reactive power support. Similar to [4], the authors state that using PV and ESS for reactive power can impact inverter lifetime, accelerate battery degradation and revenue loss due to active power curtailment. However, rather than only estimating the economic impact, they investigate compensation levels that would lead DER owners to willingly supply reactive power. The study uses a leader-follower framework in which the Distribution System Operator (DSO) acts as the leader by setting incentive prices and the DER owners act as followers who respond by optimizing their DER operation to maximize their own economic benefit. Simulations at 12.66 kV level showed that proper incentives significantly improved voltage quality, reducing daily voltage deviations by 61.5 % compared to a case where only traditional reactive power compensation devices were used. Furthermore, the results also show that DER owners participation is highly sensitive to compensation levels.

Study case – Reactive power support at different voltage levels

Reactive power has a direct influence on voltage and is therefore used to control the voltage. Active power, on the other hand, is not used to control voltage but affects the voltage level when power is transferred. The impact on the voltage by a change in active and reactive power depends on the voltage level at which the active or reactive power is supplied. Therefore, the study case is used to show how active and reactive power affects the voltage at different voltage levels and to investigate to what extent reactive power can be provided from lower voltage levels.

A simplified network model has been developed to investigate the reactive power performance at the point of common coupling (PCC) through a load flow analysis. As illustrated in Figure 1, the network consists of three voltage levels: 400 V, 20 kV and the PCC at 130 kV. The voltage levels are connected through transformers T1 and T2 and cables are represented at 400 V and 20 kV levels. The data for the transformers are provided in Table 1 and the cable data is presented in Table 2. The external grid is represented by a short-circuit power of 2000 MVA with an impedance angle of 83°, corresponding to an X/R ratio of 8.14 i.e., a predominantly inductive network.

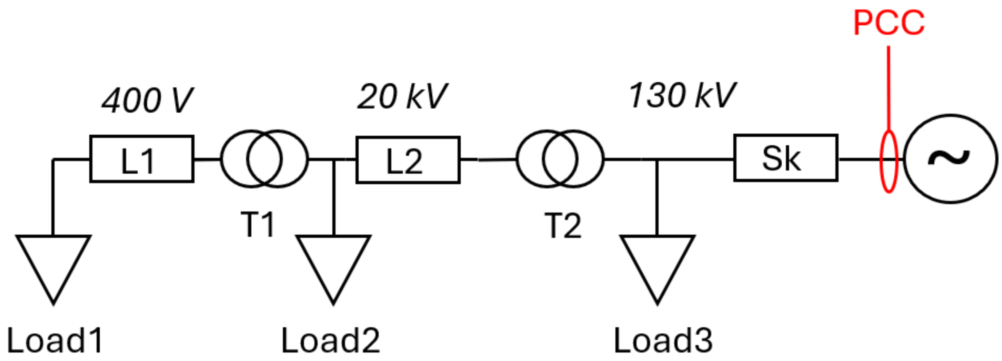


Figure 1. Illustration of the studied simplified network.

Table 1. Transformer data for T1 and T2.

Transformer	**T1**	**T2**
Rated voltage, V_2/V_1	0.4/20 kV	20/130 kV
Rated power, S_T	1 MVA	50 MVA
Short circuit voltage, u_k	5 %	10 %
X/R ratio	6	40

Table 2. Cable data for L1 and L2.

Cable	**L1**	**L2**
Rated voltage, V	400 V	20 kV
Rated power, S_L	1 MVA	50 MVA
Resistance, R_L	0.205 Ω/km	0.125 Ω/km
Reactance, X_L	0.08 Ω/km	0.1 Ω/km
Cable length, L	0.08 km alt. 1 km	5 km

Ability for voltage control

To control the voltage at a point, injection of reactive power gives a change in the voltage. When calculating the ability for voltage control, the short circuit impedance at that point is used as illustrated in Figure 2.

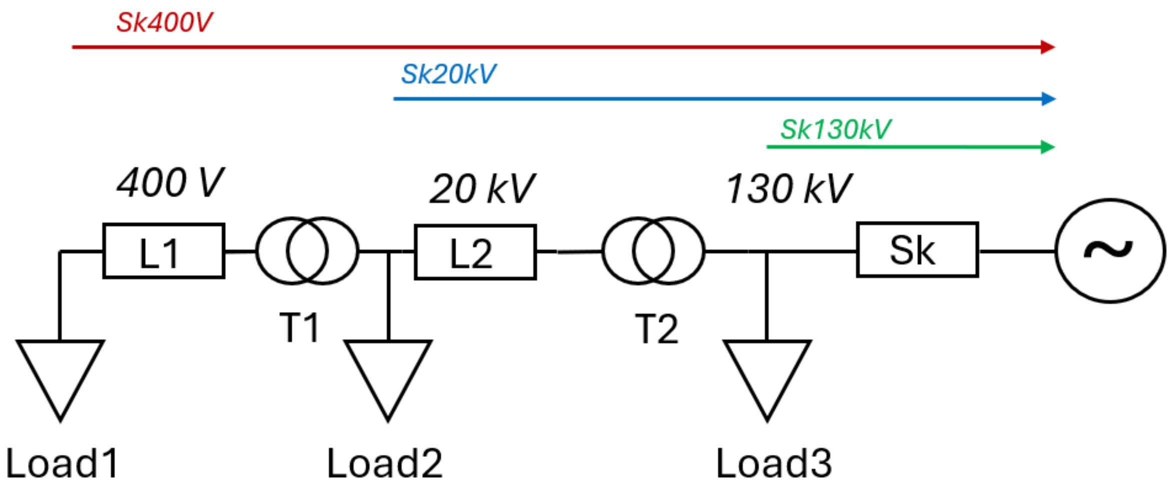


Figure 2 Short circuit impedance for the different connection points.

The voltage at the connection point is then the voltage at the strong grid plus the voltage drop across the short circuit impedance caused by the current. When obtaining the short circuit impedance for a connection point it is generally the closest component that gives the largest contribution. As an example, seen from the connection at 400 V, L1 and T1 has the higher impedance since both L2 and T2 are designed for considerable higher power and therefore have lower impedance.

The ability to control the voltage is illustrated in Table 3. It shows how much voltage drop that is achieved if 0.5 pu active or reactive power is injected from load 1, 2 and 3, respectively. Assume that the load has the same rated power as the nearest transformer, i.e. 1 MVA for Load 1 and 50 MVA for load 2. For Load 3, 100 MVA is assumed. The production of active and reactive power are studied separately to investigate how the production affects the grid at different voltage levels.

Table 3 Resulting voltage drop when injecting active or reactive power.

	Voltage control with P		**Voltage control with Q**	
Voltage level	**P_{inj}**	**Delta V**	**Q_{inj}**	**Delta V**
130 kV	100 MW	0.61 %	100 MVAr	5.0 %
20 kV	25 MW	1.06 %	25 MVAr	6.7 %
400 V, strong grid	0.5 MW	1.17 %	0.5 MVAr	2.9 %
400 V, weak grid	0.5 MW	9.6 %	0.5 MVAr	6.2 %

From the results it can be seen that at higher voltage levels, i.e. when the grid is more inductive, active power gives only about 10 % impact on the voltage compared to reactive power. For the weak grid scenario at 400 V, the voltage is more affected by active power injection, as the cable is mainly resistive. In the strong grid scenario, the cable is shorter and the total short circuit impedance is therefore less resistive, making the voltage more affected by reactive power.

Transfer of reactive power

Further, if reactive power should be supplied at lower voltage levels to support the voltage at higher voltage levels, it is important to consider reactive power losses in the components. Therefore, the same model is used, with the cases illustrated in Figure 3.

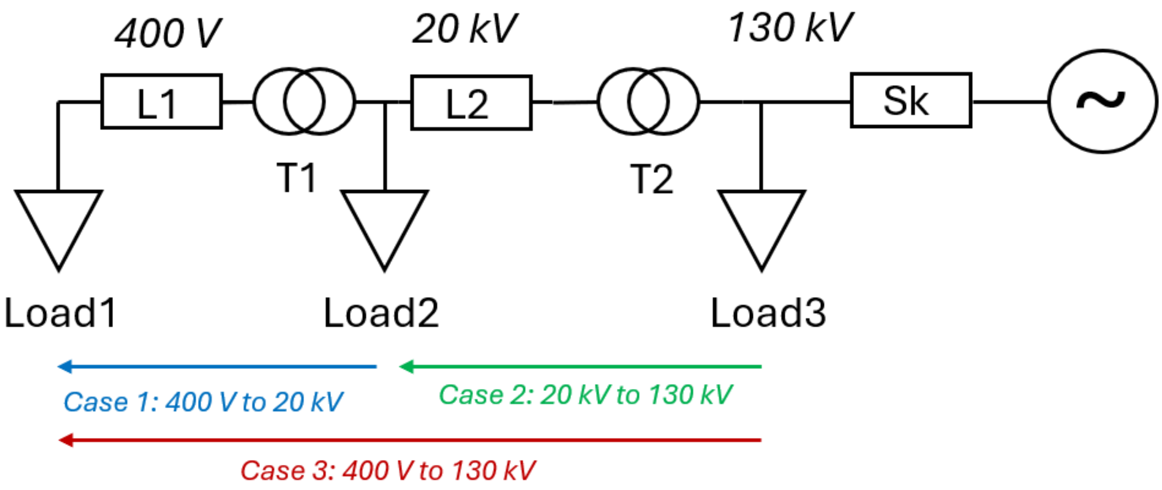
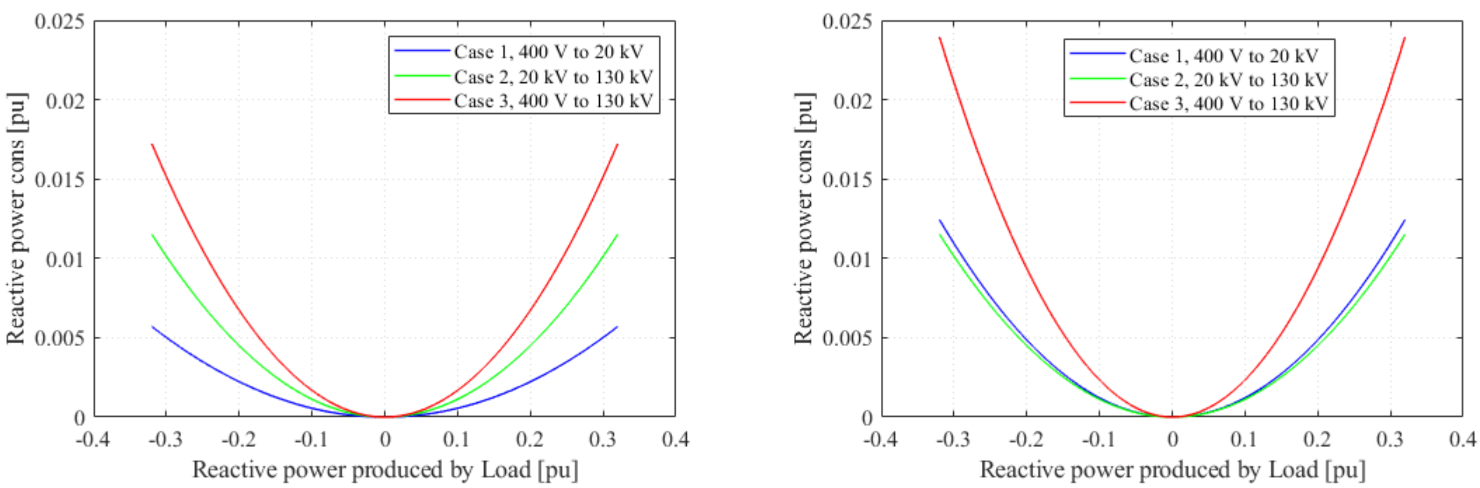


Figure 3. Study cases for reactive power losses.

Three cases are considered:

- ***Case 1*** where the resulting reactive power at 20 kV from the reactive power in Load 1 is considered. The reactive power losses in L1 and T1 are considered.
- ***Case 2*** where the resulting reactive power at 130 kV from the reactive power in Load 2 is considered. The reactive power losses in L2 and T2 are considered.
- ***Case 3*** where the resulting reactive power at 130 kV from the reactive power in Load 1 is considered. The reactive power losses in L1, L2, T1 and T2 are considered.

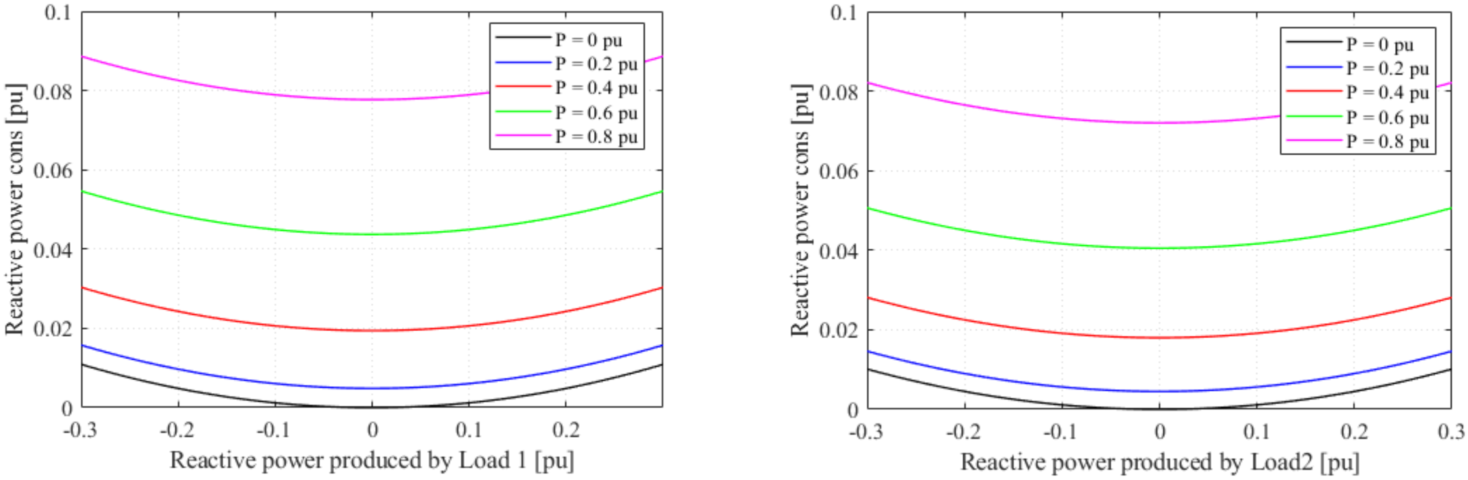
For the above mentioned study cases, the resulting reactive power losses between the load and the point where the reactive power is supplied is shown in Figure 4. Note that there are two different connection points at 400 V, one weak grid and one strong grid, represented by 1 km and 80 m cable lengths, respectively.



(a) Strong grid at 400 V *(b) Weak grid at 400 V*

Figure 4. Consumed reactive power in the transformers and cables as a function of reactive power consumed by the load. In this case P=0 and the values are given in pu of the transformer rating. Values are shown for (a) strong grid and (b) weak grid at 400 V.

Adding active power, the corresponding losses can be seen in Figure 5.

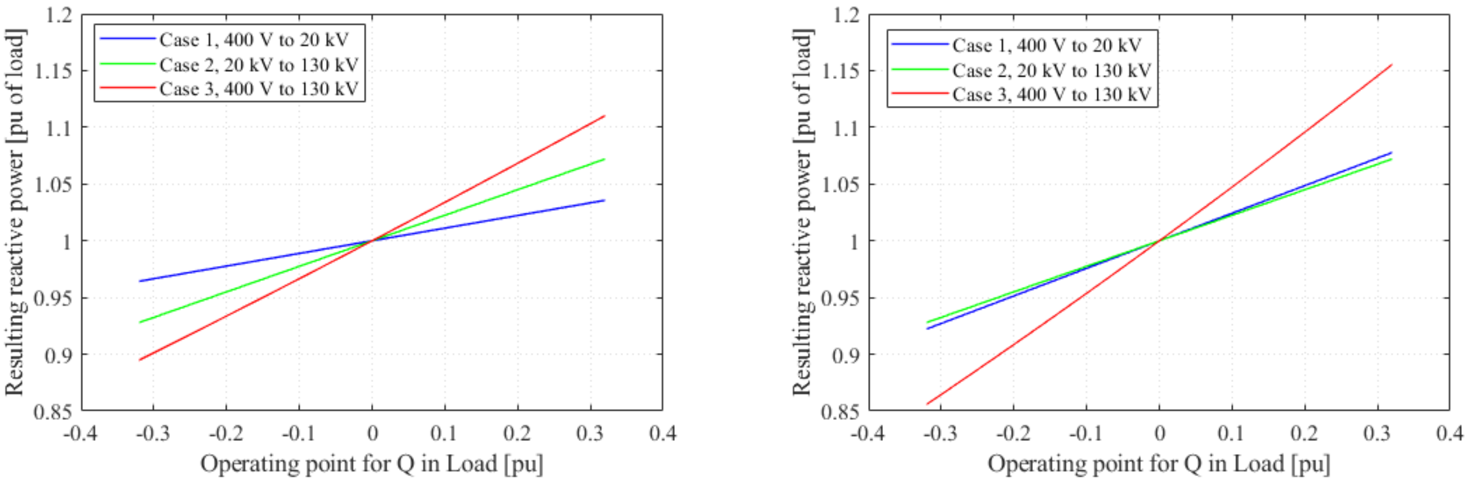


(a) Case 1 *(b) Case 2*

Figure 5. Consumed reactive power in the transformers and cables as a function of reactive power consumed by the load. The values are given in pu of the transformer rating. Values are shown for the weak grid for (a) case 1 (b) case 2.

When adding active power, the reactive power losses are increasing showing that the reactive power losses depend on the current related to the reactive power component. However, active power gives a constant offset in reactive power losses and the addition of reactive power losses when adding more reactive power can be studied independently of the active power.

To see how the capability to provide reactive power depends on the operating point, the resulting added reactive power in the connection point compared to the added reactive power in the load is shown in Figure 6. It can be seen as the derivative of the results shown in Figure 4. As an example, for case 1, the plot shows the fraction between the reactive power increase at 20 kV and the added reactive power at the 400 V load. Note that for case 3 it has been assumed to have the same load conditions at both T1 and T2.



(a) Strong grid at 400 V *(b) Weak grid at 400 V*

Figure 6. Resulting reactive power related to the reactive power consumed/produced by the load.

As seen in the figures, for low load conditions the resulting added reactive power at the higher voltage level is similar to the added reactive power at the load, i.e there are only small reactive power losses in the cable and transformer. However, for higher production/consumption of reactive power an increase in the reactive power results in a larger increase in the reactive power loss in the reactance in the transformer and cables. Consequently, the fraction of the added reactive power that is transferred to a higher power level depends on the operation point.

Theoretical explanation

When a generator controls the generator terminal voltage with a reactive droop of 0 %, it will result in a reactive droop, seen from the high voltage side of transformer T1 in Figure 7, equal to the short-circuit reactance of the transformer. This results in a voltage drop across the transformer. Sub-transmission lines in distribution networks are typically inductive and therefore add further reactance, increasing the reactive droop seen from the transmission system. Similarly, transformer T2, which connects the transmission and sub-transmission systems, adds further reactance and consequently increases the reactive droop seen from the transmission system.

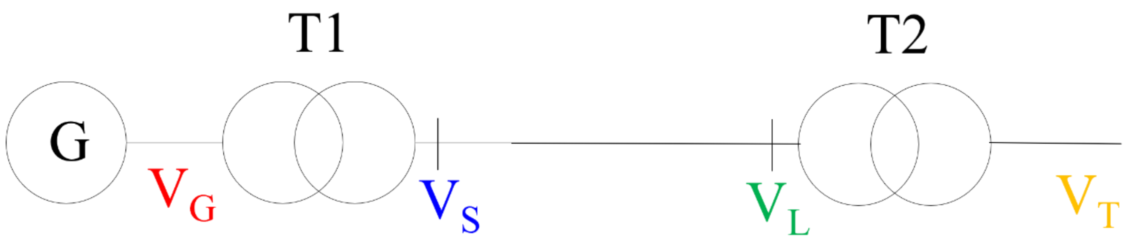


Figure 7. Line diagram of a simplified power system.

The reactive droop therefore shows how the voltage changes with the reactive power output of the generator, Q_G. As seen in Figure 11, the generator terminal voltage V_G, remains constant due to the 0 % droop, while the voltage measured further up in the system decreases with increasing reactive power due to the reactance of the transformer and the lines.

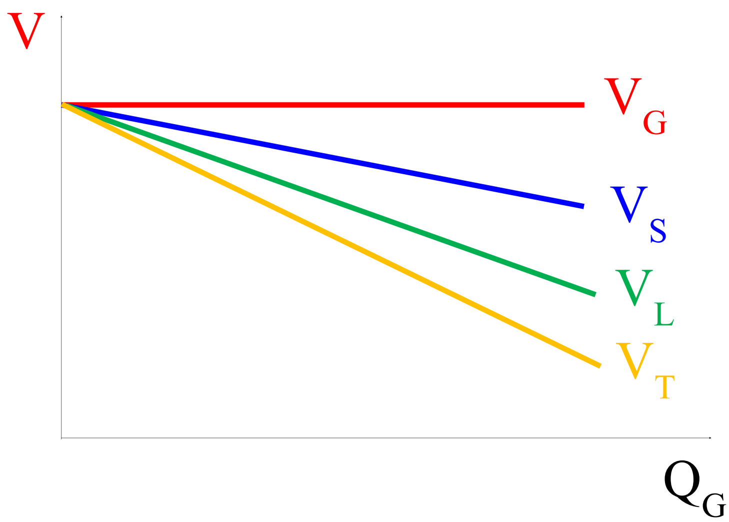


Figure 8. Relationship between voltage and reactive power output of the generator.

As shown in the result of the study case, reactive power has a significantley smaller impact at lower voltage levels and in weak grid conditions where the grid is mainly resisitve. In contrast, it has a higher impact on the grid at higher voltage levels where the grid is mainly inductive. To illustrate why active and reactive power depend on either resistance or reactance, we can derive an expression from a line diagram of a transmission line, shown in Figure 9. U_2 is the reference voltage, the load at the end of the line is inductive and the line is assumed to be lossless. The voltage drop over the reactance is therefore $\Delta U = jXI_2$.

Figure 9. Line diagram of a transmission line.

The magnitude and phase of the voltages and current shown in the above figure can be illustrated in a phasor diagram as shown in Figure 10. The current through the line can be derived as

$$\boldsymbol{I_2} = \frac{\boldsymbol{S_2^*}}{U_2} = \frac{(P_2 + jQ_2)^*}{U_2} = \frac{P_2 - jQ_2}{U_2}$$

This gives a and b as

$$a = \Delta U * sin\varphi = jX * I_2 sin\varphi = \ jX * \frac{-jQ_2}{U_2} \ = X * \frac{Q_2}{U_2}$$

$$b = \Delta U * cos\,\varphi = jX * I_2 cos\varphi = jX * \frac{\mathrm{P}_2}{\mathrm{U}_2}$$

To determine U_1, it is possible to use Phytagoras theorem and since $U_2 + a \gg b$, b can be considered negligable, which results in

$$U_1 = \sqrt{(U_2 + a)^2 + b^2} \approx U_2 + a = U_2 + X^* \frac{Q_2}{U_2}$$

This means that the voltage only depends on reactive power and the active power has a negligable impact on the voltage.

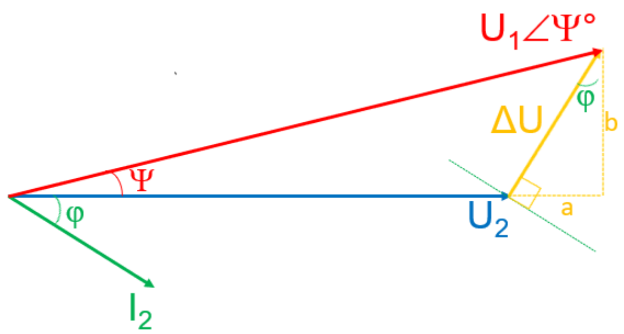


Figure 10. Phasor diagram of voltage drop over a transmission line.

The opposite conclusion can be made for lines at lower voltage levels, where the lines are almost purely resistive. The phasor diagram of this scenario is presented in Figure 11, where U_2 is the reference voltage, the load at the end of the line is inductive and the line is assumed to be resistive. The voltage drop over the line is $\Delta U = RI_2$ and by deriving it similarly to the transmission scenario above, U_1 is determined to only depend on the active power and the reactive power has a negligible impact on the voltage.

$$U_1 = \sqrt{(U_2 + a)^2 + b^2} \approx U_2 + a = U_2 + R^* \frac{P_2}{U_2}$$

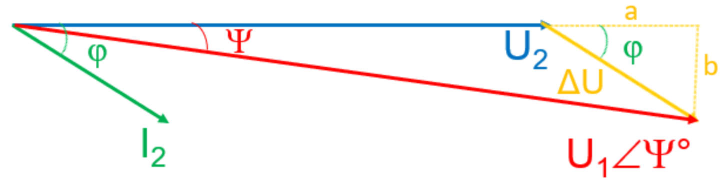


Figure 11. Phasor diagram of voltage drop over a line at lower voltage level.

Conclusions

The results from the study case can be related to the economic incentives introduced by Svenska kraftnät. Economic incentives create a value for reactive power provision based on its contribution to voltage regulation at the relevant connection point. However, the ability to provide reactive power from a lower voltage level is not independent of the characteristics of the network through which the reactive power is transferred. For providing reactive power at a higher voltage level, the reactive losses in the components between the actor providing reactive power at the point where the reactive power should be provided can be seen in Figure 6. If consuming reactive power (positive value in Figure 6), the reactive power losses will give higher reactive power at the point where the reactive power should be supplied. The other way around, when producing reactive power, the reactive power losses result in that just a part of the reactive power reaches the point where it should be supplied. Also, the reactive power losses in the components depend on the operating point and therefore it is hard to provide a specified reactive power at a higher voltage level.

The economic incentives for reactive power provision can create an opportunity to utilize reactive power capabilities that are already available in the system, such as converter based generation. By oversizing the converters, it is possible to provide both active power while also contribute with reactive power regulation.

For example, since the relationship between active, reactive and apparent power is given by $S^2 = P^2 + Q^2$, increasing the converter rating from 1.00 pu to 1.01 pu while maintaining an active power of 1.00 pu gives

$$Q_{max} = \sqrt{1.01^2 - 1^2} \approx 0.14$$

Thus, a 1 % increase in converter rating can provide a reactive power capability corresponding to approximately 14 % of the original converter rating. Or by oversizing the converter by 10 %, the reactive power capability increases to approximately 46 % of the original converter rating while still producing 1 pu active power. This illustrates why slightly oversizing converters can be an economically attractive way of obtaining additional reactive power capability, especially when the converter is already being installed for other purposes.

However, the economic value of the reactive power depends not only on the cost of making the capacity available, but also on how effective it contributes to voltage control higher up in the system. While a converter based resource may have considerable reactive power capability, its actual contribution to voltage control at higher voltage levels may be limited since converter connected generation often is connected at lower voltage levels.

References

[1] Vattenfall AB, "Elnätets uppbyggnad," 2026. [Online]. Available: https://www.vattenfalleldistribution.se/var-verksamhet/om-elnatet/elnatets-uppbyggnad/. [Accessed 2026-06-30].

[2] Commission Regulation (EU) 2016/631 of 14 April 2016 establishing a network code on requirements for grid connection of generators".

[3] Svenska kraftnät, "Bilaga 4 - Effektkomponent för spänningsreglering," 2025-08-29.

[4] P. L. Tränkner, S. Eichhorn and C. Goebel, "Economic Dispatch of Reactive Power Provided by PV Inverters in Low Voltage Grids," in *2025 IEEE Kiel PowerTech*, Kiel, Germany, 2025.

[5] H. Bai, G. Li, R. Yao, S. Liu, S. Jiang and Z. Zhong, "Reactive Voltage Regulation and Economic Incentive Mechanism for Flexible Interaction of PV and ESS Resources in Distribution Networks," *IEEE Access,* vol. 14, pp. 70337-70350, 2026.