MANAGING REACTIVE POWER IN MV DISTRIBUTION GRIDS CONTAINING DISTRIBUTED GENERATION

Pieter VERMEYEN
Eandis – Belgium
pieter.vermeyen@eandis.be

Piet LAUWERS
Eandis – Belgium
piet.lauwers@eandis.be

ABSTRACT

With the increasing number of generators in LV and MV distribution grids in Belgium, the flows of active power in the MV grids have become more variable. The flows of reactive power are less influenced. As a result, considerable fines due to poor power factors are paid to the TSO. These fines could be reduced by adapting the tariff system or by implementing compensation of reactive power in the MV grid. Voltage control in primary substations is affected by large amounts of reactive power. The increase of distributed generation is an opportunity to influence reactive power flows by using these generators. The simplest way is to provide generators with a fixed reactive operating curve.

INTRODUCTION

Eandis is a DSO (distribution system operator) in Belgium, distributing electricity and/or natural gas in 234 municipalities. The MV grid of Eandis consists of about 190 primary substations (HV to MV), 15000 MV customers and 30000 MV/LV substations. The total length of the MV cables is about 34000 km.

Since 2006 there has been a strong increase in the amount of distributed generation (DG) in the Eandis network: from about 0.1 GW in 2006 to 2.7 GW in 2014. The installed generation capacity in 2014 consisted of about 1 GW in LV and 1.7 GW in MV. For comparison: the order of magnitude of the maximum consumption in the Eandis network is about 6 GW. As a result of the DG, there is two-way exchange of active power with the HV network in multiple primary substations.

The growth of DG has increased the ratio of reactive power to active power in the Eandis network. As a result, reactive power is becoming an important topic when interacting with the TSO (transmission system operator) and with MV customers. In the first section of this paper, the interaction between DSO and TSO is discussed. Reactive power has financial and technical implications. Next, the interaction between the DSO and the generator owners is discussed. Eandis requires MV customers with newly installed DG to implement a reactive operating curve in the generator, in accordance with national regulation C10/11 [1].

INTERACTION BETWEEN DSO AND TSO

Elia is the TSO in Belgium. In the primary substations, the MV network of Eandis is connected to Elia's HV network, at a voltage of 36, 70 or 150 kV.

Reactive power of MV networks

A key factor in managing reactive power in a MV network is the reactive power of the network itself. This component of the reactive power is fixed and continuously present, while the reactive power of loads and generators varies in time.

The MV network of Eandis consists of underground cables. As a result, the network represents an important capacitive reactive power. The main rated voltages used by Eandis are 10.5, 11.4, 12.4 and 15.6 kV. As the reactive power of a capacitor is proportional to the square of the voltage, the reactive power of a 15.6 kV cable is about twice the reactive power of a 10.5 kV cable of equal length.

Different cable types have a different capacitance. For the Eandis network, overall average values of the reactive power of the networks of primary substations were calculated in the following way. For 29 substations the resulting reactive power was calculated by means of a load flow calculation in NEPLAN, with all loads and generators switched off in the calculation. Next, the reactive powers of the substations with the same rated voltage were added. The corresponding cable lengths were added as well. Finally, for each rated voltage, the total reactive power was divided by the total cable length. The results are shown in Table 1.

Table 1: Calculated values of the average reactive power (in kvar/km) of MV cable networks, for four rated voltages

U_{rated}	[kV]	10.5	11.4	12.4	15.6
Q_{cables}	[kvar/km]	-10.1	-11.7	-12.0	-22.6

With these values, the reactive power of a cable network can be estimated if the total length is known, e.g. a 12.4 kV network with a total length of 250 km corresponds to a reactive power of about -3 Mvar.

TSO's tariff for exchange of reactive power

The Belgian TSO aims to limit the exchange of reactive power with the DSOs by means of a tariff system: a DSO pays monthly fines for surplus of reactive power. The motivation for this system is voltage control. As a first aspect, in [2] it is reported that voltage control in HV networks has become more difficult, as the TSO's sources of reactive power are decreasing in number, due to the shift from centralized generation to distributed generation. A second, related aspect is the high voltage drop across HV/MV transformers when the reactive power flowing through the transformer reaches high levels. Due to this voltage drop, the full range of a transformer's taps may not be available for voltage control.

The TSO's tariff system is based on two areas in the plane of active power P and reactive power Q, which should be avoided. These areas are outlined in Figure 1; in yellow and green. The yellow and green area for Q > 0 represents inductive surplus. The yellow and green area for Q < 0 represents capacitive surplus. These areas are described by the following expressions:

- P > 0,
- |Q| > 3.3 % of P_{max} for 0 < P ≤ 10 % of P_{max},
- |Q| > 33 % of P for P > 10 % of P_{max}, i.e. PF < 0.95.

P_{max} is the maximum value of P for each month (100 % in Figure 1). This value is specific for each primary substation and it is different each month, depending on consumption and production. For P < 0, i.e. export of active power to the HV network, there is no limit for Q.

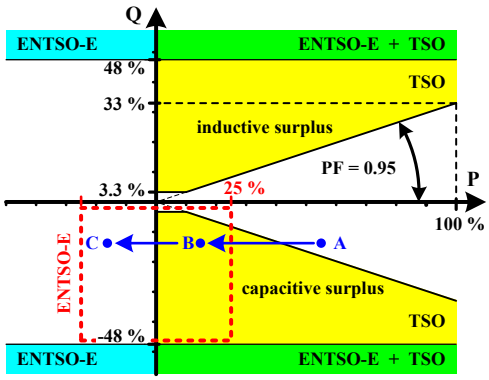

Figure 1: Diagram for active power P and reactive power Q, showing the Belgian TSO's tariff areas for reactive power and the range limits of ENTSO-E

Figure 1 also shows the range limits as outlined in the ENTSO-E Network Code on Demand Connection [3], i.e. the blue and green areas. These limits are situated at |Q| = 48 %. TSO's should specify their tariff areas within ENTSO-E's range limits. ENTSO-E's Network Code also specifies an additional area, i.e. the red rectangle in Figure 1: the DSO should have means for reactive compensation in order to avoid this area: |P| < 25 % and Q < 0, i.e. avoid capacitive operation when active power flow is low.

For each 15-minute interval with a surplus of reactive power (i.e. operating point within the inductive or capacitive surplus area) the TSO charges a cost to the DSO: EUR 3.75, 6.5 or 7.5 per Mvarh of reactive surplus, depending on the point in time. In 2013, the total cost of additional reactive power was EUR 715000: EUR 505000 for capacitive and EUR 210000 for inductive reactive power.

An increase of DG shifts the operating points of a primary substation towards lower consumption of active power, e.g. from A to B, or from B to C in Figure 1. With a shift from A to B, the amount of reactive power stays the same. However, it generates a cost.

Examples of power profiles of MV grids

In this paragraph, selected examples of profiles of active and reactive power of primary substations (HV/MV) are shown. These profiles are heat maps. The red areas represent combinations of P and Q with a high occurrence rate. The blue areas are combinations with a low occurrence rate. The two dashed lines represent a power factor (PF) of 0.95, i.e. the TSO's boundaries for reactive power. As P_{max} varies each month, the Q interval between -3.3 % and 3.3 % varies in Mvar, which is why it is omitted in the following heat maps.

Figure 2 shows the power profile of a 10.5 kV primary substation with a cable network of -4.9 Mvar. The amount of DG connected to the MV network is 25 MW. This profile is almost entirely inductive (Q > 0). There is no transfer of active power to the HV grid. The TSO's inductive limit is occasionally crossed with a small surplus, resulting in an average fine of EUR 95 / month.

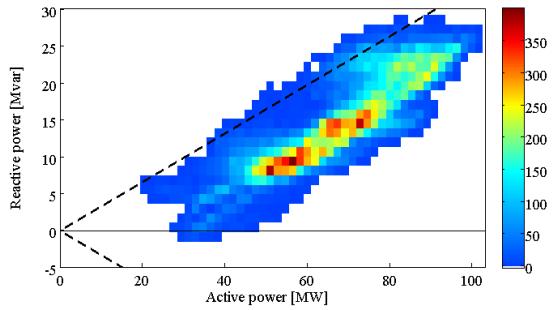

Figure 2: P and Q of PS58652 (Nov 2013 – Oct 2014)

Figure 3 shows the profile of a 10.5 kV primary substation with a cable network of -1.2 Mvar and with 39 MW of DG. Many operating points are situated in the inductive surplus area, resulting in a relatively high average cost of EUR 5270 / month. For Eandis, this is the primary substation with the highest cost for inductive reactive power. There is regular export of active power to the HV network. The active power P of the operating points ranges between -20 and 35 MW. This is due to the varying activity of a large industrial customer with a 33 MW generator.

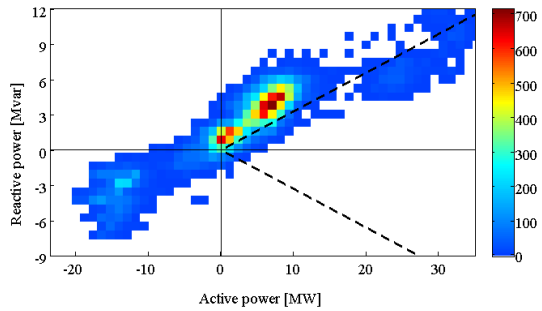

Figure 3: P and Q of PS57954 (Jul 2013 – Feb 2014)

Figure 4 shows the profile of a 15.6 kV primary substation with a cable network of -7.4 Mvar and with 12 MW of DG. This profile is entirely capacitive (Q < 0). This is mainly due to the capacitance of the cable network. This profile is situated well inside the capacitive surplus area, resulting in the highest average cost for capacitive reactive power: EUR 11205 / month. There is occasional export of active power to the HV network.

Figure 5 shows the profile of a 15.6 kV primary substation with a cable network of -2.7 Mvar and with 34 MW of DG. This profile contains points in both surplus areas, resulting in an average fine of EUR 232 / month for capacitive reactive power and an average fine of EUR

628 / month for inductive reactive power. This results in a total cost of EUR 860 / month. There is occasional export of active power to the HV network.

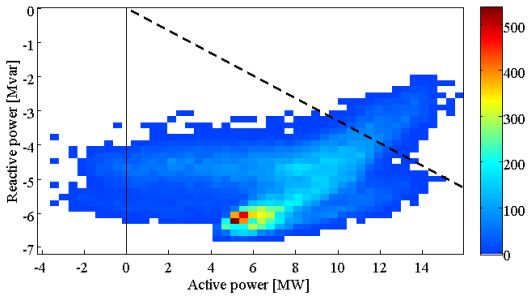

Figure 4: P and Q of PS87984 (Nov 2013 – Oct 2014)

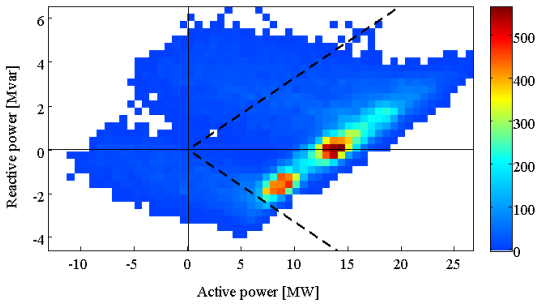

Figure 5: P and Q of PS64397 (Nov 2013 – Oct 2014)

Figure 6 shows the profile of a 15.6 kV primary substation with a cable network of -13.8 Mvar and with 82 MW of DG. This profile is mostly capacitive (Q < 0) and there is regular export of active power to the HV network. The average fine is EUR 9965 / month.

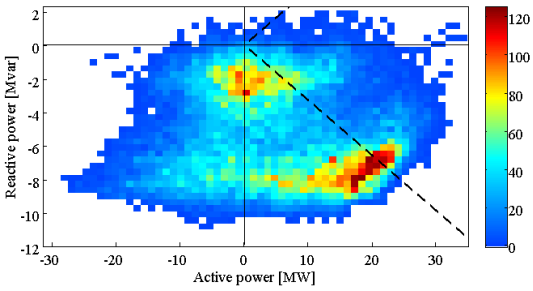

Figure 6: P and Q of PS39690 (Nov 2013 – Oct 2014)

These examples illustrate that primary substations have very different power profiles. The profiles are determined by the customers (with and without generators) and by the cable network. The effect of the cables is clearly present in the profiles of Figures 4 and 6.

Example of compensation of reactive power

As a first step in reducing the cost for reactive power surplus, the primary substation with the highest cost for inductive reactive power was selected for reactive compensation by means of LV capacitor banks. Figure 3 shows the power profile of this primary substation before it was compensated. The average fine was EUR 5270 / month or EUR 63240 / year. Figure 7 shows the centre of Figure 3 in more detail. The areas with high occurrence rates are situated above the upper dashed line with PF = 0.95.

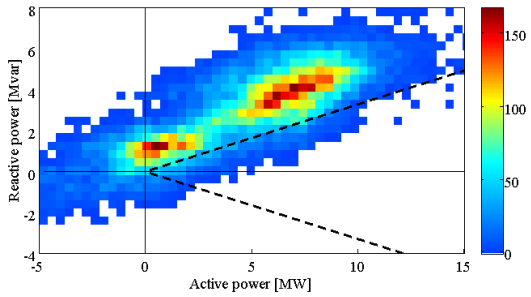

Figure 7: View of the center of the profile in Figure 3.

In March and April of 2014, thirty low-voltage capacitor banks of 50 kvar each were installed in secondary substations (MV/LV), resulting in -1.5 Mvar of installed reactive power. The total cost of one capacitor bank is about EUR 1400 (equipment and working hours), so the investment cost of thirty units is EUR 42000.

Figure 8 shows the power profile of the same primary substation since the capacitor banks have been installed. A considerable number of operating points have now been moved out of the inductive surplus region. The red dashed line is the result of shifting the upper black dashed line downward by 1.5 Mvar; it is the relative position of the TSO's inductive boundary if the capacitor banks had not been installed.

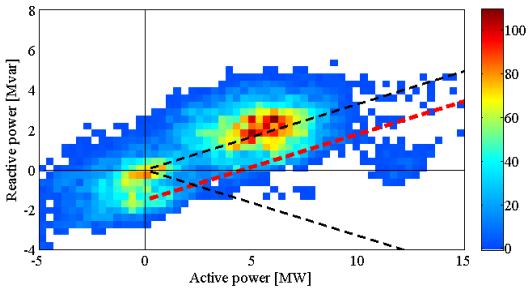

Figure 8: P and Q of PS57954 with compensation installed (May 2014 – Oct 2014).

Since the installation, the average fine has decreased: it is now about 1680 €/month or 20160 €/year, based on 7 months of data: from May to November of 2014. As the power profile has become less inductive, there is now a capacitive component of the average fine: EUR 264 / month. The average fine for inductive reactive power is EUR 1416 / month.

With these LV capacitors, a cost reduction of EUR 43080 per year has been achieved. Comparison with the investment cost of EUR 42000 shows that the payback period of the capacitor banks is about one year. This payback period is quite short. This is because the majority of the 15-minute intervals were situated in the inductive surplus area before the capacitor banks were installed. Therefore the DSO benefits from this investment most of the time. For a primary substation with less operating points in the inductive surplus area, the payback period will be longer than one year.

Tap range of HV/MV transformers

The tap range of the TSO's HV/MV transformers appears to have been designed for voltage control in circumstances of heavy load and high inductive reactive power. Nowadays the MV network is expanding, resulting in a steady growth of capacitive reactive power of the network. Active power consumption is reduced or reversed by DG. As a result, in certain primary substations the full tap range can no longer be used for voltage control; the operating interval is shifted to the edge of the tap range. Therefore, when installing a new HV/MV transformer, it should have a tap range more suitable for the present power profiles.

Reactive compensation and adaptation of tariff

The Belgian TSO's surplus areas (Figure 1) are based on a PF of 0.95. For a constant reactive power and a varying active power, the fine for reactive power increases with decreasing active power consumption. However, the voltage drop across a transformer is determined mainly by the reactive power flowing through the transformer. The effect of active power is much smaller. Therefore the problem of increased voltage drop would be better reflected in the fines with a fixed reactive power limit instead of a PF limit.

If the DSO applies reactive compensation of a primary substation by means of fixed capacitors or fixed reactors, the optimal amount of compensation is determined by the points of the power profile that are shifted out of one surplus area (resulting in cost decrease) and the points that are shifted into the opposite surplus are (resulting in cost increase). With the narrow interval between the surplus zones, reactive compensation aimed at minimizing the monthly fines would not be the optimal technical solution for the TSO's problems. A wider interval would allow for a more problem oriented solution. The interval could be asymmetrical, e.g. to allow more inductive power than capacitive power.

These proposed changes to the tariff system, i.e. a constant, wider interval between the surplus areas, are possible within the range limits |Q| = 48 % of ENTSO-E (Figure 1). With these adaptations, the tariff system for reactive power would correspond better to the TSO's technical problems.

However, the ENTSO-E area represented by the red rectangle in Figure 1 is problematic. Complying with this requirement would require large investments in reactors or other technologies (FACTS), e.g. for the profiles in Figures 4, 5 and 6. A certain amount of capacitive reactive power should be allowed. Keeping the operating points of a primary substation within strict limits has become more difficult than in the past. Before implementing reactive compensation, the necessity of these limits should be investigated thoroughly. Consultation between all stakeholders is needed to establish good, cost effective guidelines and solutions.

INTERACTION BETWEEN DSO AND DG

Generators are controllable devices. Reactive power of generators can be controlled in such a way as to benefit the network operators (DSO and TSO) as well as the customers with DG. When a contract is made for the connection of a new generator to the distribution network, the DSO can request that the generator is provided with a reactive operating curve, in accordance with national technical regulations [1]. Until 2012, Eandis did not make use of this possibility, leaving the choice of reactive operation up to the customer.

DSO's tariff for exchange of reactive power

In general, a MV customer pays a monthly fine to the DSO if the total reactive energy exchanged during one month exceeds 49 % (33 % for the largest customers) of the total amount of consumed active energy. Reactive energy exchanged during injection of active power is not taken into account. Customers with a generator that is smaller than their average consumption can experience an increase of this fine, due to the reduced consumption.

Example of reactive operation of wind turbines

In 2012 a wind turbine project (2 x 2.5 MVA) was connected to the MV network. It was decided to connect the turbines to the nearest existing cable, instead of laying a new MV cable to connect the wind turbines to the network. Calculations showed that using this existing cable, the local voltage could become too high, so it was decided that the turbines should have an inductive operating curve, so as to counteract the voltage increase during power injection. The proposed curve is represented by the dashed line in Figure 9 and is described by the following expressions:

- $Q = 0$ for $0 < P \leq 70$ % of P_{rated} (PF = 1),
- $Q = 29$ % of P for $P \geq 80$ % of P_{rated} (PF = 0.96),
- A gradual change of Q for 70 % < P < 80 %

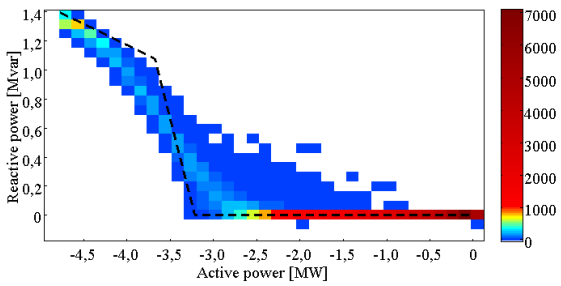

Figure 9: Measured active and reactive power of wind turbines (2 x 2.5 MVA) (Dec 2012 – Aug 2014). The dashed line is the proposed operating curve.

Figure 9 also contains a heat map showing the measured power profile (active and reactive power) of the wind turbines. Compared to the previous heat maps (Figures 2 to 8), the colour scheme has been adapted in order to focus on the points with a low occurrence rate. The measured power profile does not follow the proposed curve exactly (cf. dashed line), but there is a good match at maximum power.

Figure 10 shows the voltage measured at the wind turbines' point of connection, as a percentage of the voltage measured in the primary substation. The voltage is shown as a function of the injected active power. The solid line is the calculated voltage with reactive operation. The dashed line shows the calculated voltage without reactive operation. The heat map shows quite a large variation along the vertical axis. This is partly due

to consumption and injection by other customers, and partly due to the uncertainty introduced by dividing one measured data series by another measured data series. The calculated curve is situated within the central area of the heat map.

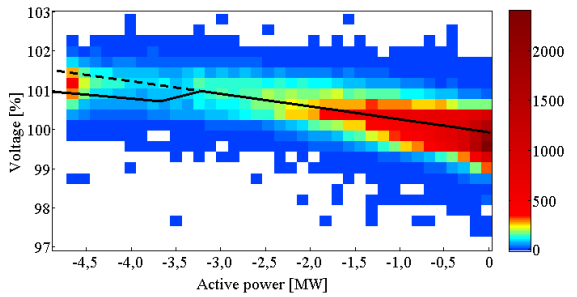

Figure 10: Measured voltage near wind turbines, as a function of injected active power (Dec 2012 – Aug 2014). The solid line is the calculated voltage.

On the left side in Figure 10, at maximum power injection, a red square is visible, indicating a local peak in occurrence rate. This peak is situated between both calculated curves: with and without reactive operation. The solid line and the heat map illustrate that by applying a PF decreasing from 1 to 0.96 starting at about 70 % of rated power, the voltage level can be kept more or less equal between 70 % and 100 % of rated power.

Reactive operating curves for generators

Since 2013, Eandis requires newly installed generators with a rated power higher than 400 kVA to have a reactive operating curve. The reactive settings depend on the rated power, the generator technology and the rated voltage of the grid.

The standard case is moderate inductive operation, with Q = 5 % of P (PF = 0.999), as represented by the red line in Figure 11. The resulting inductive power counteracts the voltage increase near the generators, it also compensates the reactive power of the cable connecting the customer to the network, and it makes the primary substations more inductive or less capacitive, which is useful because the greater part of the costs for reactive power is caused by capacitive reactive power.

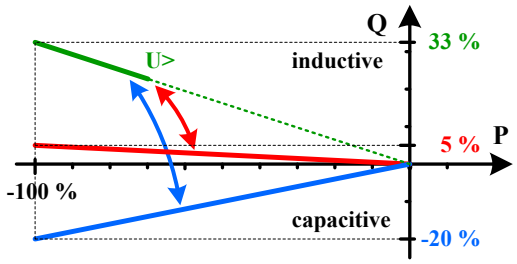

Figure 11: Possible curves for reactive operation for DG > 400 kVA, as requested by Eandis

A different reactive operating curve can be requested by the DSO for large projects (larger than about 3 MVA) in networks at 10.5, 11.4 or 12.4 kV: capacitive operation with Q = 20 % of P (PF = 0.98), as represented by the blue line in Figure 11. Primary substations at 10.5, 11.4 or 12.4 kV are typically inductive, so this operating curve can be used to compensate a part of the inductive power. In case the voltage increase due to the capacitive reactive power would be too large, the next operating curve should be implemented as well.

An additional reactive operating curve is requested for generators larger than 1 MVA that may cause high voltage levels when operating near nominal power or for generators larger than 4 MVA: inductive operation with Q = 33 % of P (PF = 0.95), as represented by the green line in Figure 12. This additional operating curve should be activated when the locally measured voltage crosses a certain threshold. As a result, the voltage will be reduced.

Both inductive operating curves in Figure 11 counteract the voltage increase of DG. This makes it possible to connect more DG to the grid, compared to previous, more conservative design rules.

It is difficult to ask customers with existing DG to implement these reactive operating curves, although a fixed operating curve with Q = 5 % of P should be possible for most generators.

A future development could be voltage control by DG, by continuously adapting reactive power depending on measured voltage, instead of applying one or two discrete reactive operating curves as shown in Figure 10.

CONCLUSION

In Belgium the flow of active power from the HV network to MV networks has been reduced or reversed by the increase of DG, while reactive power has not been reduced. Consequently, the TSO is experiencing increased voltage levels in the HV network and voltage control of HV/MV transformers is more difficult. For certain primary substations, DSO Eandis pays considerable fines for reactive power surplus. Adaptations to the TSO's tariff system for reactive power are desirable, in order to make the tariff correspond to the technical problems. Investments in reactive compensation of primary substations should be carried out if the pay-pack period is acceptable and if the TSO and the DSO are in agreement about the technical necessity of the limits.

Since 2013 Eandis has been using the possibility to specify reactive operating curves for newly installed DG in the MV network, in accordance with national technical regulations. This should help reducing reactive power exchange in primary substations. Applying inductive reactive operating curves for DG is also a way to increase customers' chances of connecting new DG to the MV network.

REFERENCES

[1] Synergrid, 2012, *C10/11 - Specifieke technische voorschriften voor decentrale productie-installaties die in parallel werken met het distributienet*, 9, available at www.synergrid.be.

[2] ENTSO-E, 2012, *Network code for requirements for demand connection, explanatory note,* 12-13, available at www.entsoe.eu.

[3] ENTSO-E, 2012, *Network code on demand connection,* article 16: Reactive power requirements, available at www.entsoe.eu.