REACTIVE POWER MANAGEMENT AT T – D INTERFACE

ENTSO-E guidance document for national implementation for network codes on grid connection

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DESCRIPTION

Code(s) & Article(s)	NC DCC Article 15, Reactive power requirements.
Introduction	Different system operators for the networks (e.g. distribution or transmission network), network topologies (degree of network meshing), localisation of the connection point at the distribution-transmission interface and load and embedded generation characteristics, lead to the need for different ranges of reactive power. For this reason, the exchange of reactive power at each interface between the two networks strongly depends on the above mentioned local needs. For instance, heavily loaded meshed grids or radial or remote grids typically need more injection of reactive power (production), whereas the same meshed grid in light loading conditions need more reactive power consumption in order to keep the network voltage within the permitted range. This IGD is clarifying the impacting aspects to be considered for the definition of the reactive power and voltage requirement at the T-D interface, including influence from the reactive power and voltage control capabilities of grid equipment, demand users and generating units.
NC frame	The NC DCC prescribes the boundaries within which the Relevant TSO can set design limitations on reactive power exchanges of transmission-connected demand facilities and transmission-connected distribution systems. As this is a connection code, no link is directly made for the utilisation of the capability. However, utilisation of the capabilities will be implemented in operational network codes / guidelines and national regulations. In general it is more cost effective at system level to generate reactive power at the location where it is needed to avoid higher losses and large voltage deviations. Furthermore, the transport of reactive power is possible only over limited distances. In addition, reactive power is traditionally provided by generating units thanks to the limited marginal investment compared to the delivery of active power only. As in the future, a larger share of the total generation installed capacity will be connected to distribution grids, the provision of reactive power at transmission level and distribution level shall be coordinated. Therefore, for the benefit of the system and pursuing local reactive compensation, it is essential that transmission-connected demand facilities and transmission-connected distribution systems are capable to maintain their operation at their Connection Point within a pre-established and limited reactive range. It is then also expected that by the future transition of generation to the distribution grids and related requirement at the Transmission System Operator – Distribution System Operator (T-D) interface, reactive or voltage related requirements for distributed connected users will need to be reviewed nationally. A core principle that should underpin all TSO & DSOs interactions with regard to reactive power is that each system operator is responsible for ensuring voltage requirements on its network.

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Further info	[1] Frequently asked questions, Network code on demand connection, December 2012 [2] Demand Connection Code, Call for stakeholder input, April 2012 [3] Future System Challenges in Europe. Contributions to Solutions from Connection Network Codes. 2016 CIGRÉ USNC International Colloquium Evolution of Power System Planning to Support Connection of Generation, Distributed Resources and Alternative Technologies The latest NCs and the Guideline documents are available at the ENTSO-E website.

INTERDEPENDENCIES

Between the CNCs	Reactive power management at Transmission – Distribution (T – D) Interface is not impacting the implementation of other connection codes. On the other hand the reactive power management is impacted by the requirements for reactive power capabilities and voltage control capabilities of demand users and generating units defined by the national implementation of the NCs RfG, DCC and HVDC as well as by the national requirements which are not directly covered by the NCs. For example, the capabilities of a DSO to fulfil the requirement for reactive power exchange at its interface with the transmission system (as defined in the NC DCC) is impacted by the capabilities of the generating units connected within the distribution grid and the strength of the need for such a requirement is impacted by the capabilities of the generating units connected within the transmission grid. The capabilities of the generating units are defined by NC RfG and by the choices made for the MW thresholds between types A/B/C/D following national implementation of NC RfG.
With other NCs	It must be highlighted that connection requirements will be complemented by operational requirements defined by the national implementation of the Guidelines on system operation and by local operational requirements as this is currently a common practice (see Annex 1). Connection capabilities will therefore be used in operation.
System characteristics	The consequences of greater contribution from Renewable Energy Sources (RES) in context of system voltage and availability of reactive power capability has to be considered. With the highest level of RES penetration many synchronous generators will be displaced at the times of high RES production (e.g. windy/sunny). This removes a key source of reactive power. In many countries during such conditions the generation (mainly from RES) is located away from the system/load centres to coastal areas (e.g. large wind) and also embedded (e.g. solar photovoltaic (PV) and smaller wind) [3]. Moreover, the development of underground cables in the distribution grid and even the transmission grid and the development of embedded generation in the distribution networks (including closed distribution networks) have an increasing impact on the reactive power flows at the interface between transmission and distribution networks. The above leaves the transmission systems with less reactive resources to: - Be able to compensate the reactive demand of the DSO networks, and - Cope with its own transmission related reactive demand. Furthermore, per unit cost of static reactive compensation equipment (reactors or capacitor banks) is typically increasing with the voltage level at which it is

	connected. Nonetheless, it should also be noted that the size of the compensation equipment could also influence the per unit cost of static reactive compensation equipment. This economy of scale should however not impact the primary objective of voltage management of every bus bar and of transmission losses minimisation. Consequently, ENTSO-E believes that the voltage stability of the system should be supported by all the stakeholders (including the TSOs). This view was generally supported by stakeholders. Some requirements already exist in some countries, for generators, customers and/or distribution system operators, but they need to be reviewed in order to cope with the new European challenges. In Annex I, the results of a survey on the currently applied requirements on reactive power exchange on the T– D /T - Demand facilities interface are shown for different countries / TSOs. Overall system performance is improved, either technically or economically, if appropriate measures are taken concerning reactive power management for transmission connected distribution networks or demand facilities at the connection point. Reactive power delivered where needed is more cost effective, allowing also for loss reduction, higher active power loading, less need for system reinforcements and lower capital cost of lower voltage installation. Voltage stability is also recognized as an important basis for system security. The Cost Benefit Analyses (CBA) provided in the “Call for Stakeholder Input” for NC DCC and supplemented by additional synchronous areas analysis (see FAQ 22 in [1]) have shown that from a socio-economic viewpoint the total cost to meet the DSO system need for reactive power is lower if the reactive compensation is undertaken lower down in the system (closer to the demand) than if invested at the higher voltage level. The results of this CBA are shown in Annex II. A possible process for the definition of the reactive power and voltage requirement at the T-D interface, including influence from the reactive power and voltage control capabilities of demand and generating units is proposed in Annex III.
Technology characteristics	-
COLLABORATION	
TSO – TSO	Limited TSO-TSO collaboration is expected for the implementation of such requirements. However, ENTSO-E is requested in NC DCC to monitor the network code implementation (Article 57) in particular identifying the divergences in the National Implementation.
TSO – DSO	TSO & DSOs (including Closed Distribution System Operators, CDSO) collaboration is of prior importance. Several specific aspects are defined in the NC. - The requirements 15.1(a) and 15.1(b) of NC DCC are non-exhaustive requirements and a maximum acceptable reactive power exchange has to be specified the relevant TSO for both importing and exporting reactive power. The TSO shall require not less than a maximum range of 48 percent (i.e. 0.9 power factor) of the larger of the maximum import

capability or maximum export capability unless the exception clause (see next bullet point) is considered;

- Authorization to deviate from the maximum acceptable reactive power range of the 15.1.(a) and 15.1.(b) of the NC are foreseen “where either technical or financial system benefits are proved by the relevant TSO and the transmission-connected distribution system operator through joint analysis”;
- For both above bullet points, the scope of the analysis shall be agreed between the relevant TSO and the transmission-connected distribution system operator. This scope shall take into consideration the specific system characteristics, variable structure of power exchange, bidirectional flows and the reactive power capabilities in the distribution system.

It needs to be recalled that connection codes focus on connection requirements related to capabilities. Some important aspects are therefore out of the direct scope of the Connection Code implementation and of this Implementation Guidance Document (IGD) such as:

- Reactive power management in operational planning;
- Use of the Distributed Energy Resources reactive power capabilities;
- Requirements in the Guidelines on system operation.

In the context of the joint analysis several steps will expected to be needed such as, but not limited to, definition of planning points as expected realistic operation points (different load and generation conditions as defined in article 43.1 on compliance simulations with regard to the reactive power capability), methods for compliance simulation and necessary equipment, or equivalent arrangements, to measure the active and reactive power as defined in article 46 on compliance monitoring.

Where either technical or financial system benefits are proved by the relevant TSO and the transmission-connected distribution system operator through joint analysis, the optimal solution for reactive power exchange between their systems can be determined. The scope of this joint analysis should be defined at national level to make sure that the particular local situation is sufficiently taken into account. This scope should consider at least:

- T-D interface voltage level, because it will determine the kind of technical solution that can be used at the interface, see also survey in Annex I;
- Interaction with power quality parameters;
- Strive for a global technical optimum at minimum cost;
- Avoiding cost shifts from one party to the other unless it is proven that this shift would contribute to the global techno-economical optimum;
- Overall cost of the chosen solution should be minimal for the system (distribution/ transmission/users);

As an additional approach towards the reactive power requirements TSOs and DSOs see, in certain situations, added value in considering the aggregation of connection points (between TSO and DSO) and regroup the connection points in a number of zones (especially in case of a meshed distribution network).

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	The reactive power requirements can then be set for those zones as a whole and not separately.
RNO – Grid User	As above-mentioned, it is expected that the reactive power management at T – D Interface will be influenced by the future transition of generation to the distribution grids, interaction between distributed connected users (both generation and load) and DSO or CDSO. This is only partly addressed by the NCs but it could be a driver to modify/update/confirm national connection requirements.
Example(s)	-

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ANNEX I Survey on reactive power boundaries on T-D/T-Demand Facility interface

One of the aspects that needs to be taken into account to understand the span of requirements currently applied at the T-D interface or the expected span resulting from the NC implementation is the diversity of the interface between TSO & DSOs.

In every European country surveyed, the T-D interface consists of a substation with several transformers in parallel. The lower voltage side of the transformation substation ranges from 150kV to MV. This large difference is not only observed between countries but also from location to location within some countries;

The size of the transformers used at the T-D interface and the number of these transformers range from 350MVA to 16MVA and from 2 to 4 transformers in parallel.

In every country, transformers towards distribution grids have on load tap changer. However, the ownership of the transformers as well as the controllability of their taps differs from country to country or from location to location within some countries. In addition, in every European country surveyed, the capacitor or inductor banks are in the majority located at the lower voltage side of the transformation substation (or on a tertiary winding of the transformer) and the operator of these banks differs from country to country (TSO or DSO).

<u>T–-D reactive power exchange boundaries in different countries (Survey from April 2016):</u>

Country / TSO	**Power factor requirements**				**Active control of exchange of reactive power (automatic)**	**Reactive power flow limited at low active flow**
	Connection		*Operation*			
	DSO	*Demand facility*	*DSO*	*Demand facility*		
Spain / REE	a) Peak Period: cos φ ≥ 0.95 inductive b) Off Peak Period: no reactive power to TSO ≥ 1 inductive c) Intermediate Period: 1 ≥ cos φ ≥ 0.95 inductive	a) Peak Period: cos φ ≥ 0.95 inductive b) Off Peak Period: no reactive power to TSO c) Intermediate Period: 1 ≥ cos φ ≥ 0.95 inductive	a) Peak Period: cos φ ≥ 0.95 inductive b) Off Peak Period: no reactive power to TSO c) Intermediate Period: 1 ≥ cos φ ≥ 0.95 inductive	a) Peak Period: cos φ ≥ 095 inductive b) Off Peak Period: no reactive power to TSO c) Intermediate Period: 1 ≥ cos φ ≥ 0.95 inductive penalties in place	no	no
Slovenia / ELES	cos φ ≥ 0.9	cos φ ≥ 0.9	-	cos φ ≥ 0,95 penalties in place	no	no
Netherlands / TenneT	cos φ = 1	1 ≥ cos φ ≥ 0.85 inductive	-	1 ≥ cos φ ≥ 0.85 inductive	no	no
Italy / Terna	only voltage requirements	specified by contract	only voltage requirements	specified by contract	no	no
Slovak Republic / SEPS	1 ≥ cos φ ≥ 0.95 inductive	1 ≥ cos φ ≥ 0.95 inductive	1 ≥ cos φ ≥ 0.95 inductive penalties in place	1 ≥ cos φ ≥ 0.95 inductive penalties in place	no	no
Austria / APG	No specific requirements but low exchange of reactive power	cos φ ≥ 0.9	No limits	cos φ ≥ 0.9 penalties are possible	no	no
Bosnia and Herzegovina / NOS BiH	cos φ ≥ 0.9	cos φ ≥ 0.9	No limits	cos φ ≥ 0.9	no	no
Belgium / Elia	no requirements	no requirements	cos φ ≥ 0.95 minimum range of 3,29% x Pmax penalties in place	V ≥ 30 kV: cos φ ≥ 0.95 minimum range of 3.29% x Pmax V < 30 kV: cos φ ≥ 09 minimum range of 4.84% x Pmax penalties in place	-	-
Norway / Statnett	cos φ = 1	cos φ = 1	cos φ = 1 tariff as penalty	cos φ = 1 tariff as penalty	no	no
Croatia / HOPS	no requirements	1 ≥ cos φ ≥ 0.95 inductive	-	1 ≥ cos φ ≥ 0.95 inductive penalties in place	no	no
Greece / IPTO	no requirements	no requirements	no requirements	cos φ ≥ 0.95 – 0.9 specified by contract penalties in place	no	no
Czech Republic / CEPS	1 ≥ cos φ ≥ 0.95 inductive	1 ≥ cos φ ≥ 0.95 inductive	1 ≥ cos φ ≥ 0.95 inductive penalties at DSO level	1 ≥ cos φ ≥ 0.95 inductive penalties at DSO level	no	no
Serbia / EMS	1 ≥ cos φ ≥ 0.95 inductive	1 ≥ cos φ ≥ 0.95 inductive	1 ≥ cos φ ≥ 0.95 inductive penalties in place	1 ≥ cos φ ≥ 0.95 inductive penalties in place	no	no

France / RTE	no requirements	1 ≥ cos φ ≥ 0.928 inductive tariff incentive	1 ≥ cos φ ≥0,995- 0.928 specified by contract tariff incentive	1 ≥ cos φ ≥ 0.928 inductive tariff incentive	no	no
Poland / PSE S.A.	1 ≥ cos φ ≥ 0.928	1 ≥ cos φ ≥ 0.928 special cases: 1 ≥ cos φ ≥ 0.98	1 ≥ cos φ ≥ 0.928 penalties in place	1 ≥ cos φ ≥ 0.928 special cases: 1 ≥ cos φ ≥ 0.98 penalties in place	no	no
Germany / 50Herz	bilateral agreements between TSO and DSO	bilateral agreements between TSO and Demand facility	bilateral agreements between TSO and DSO	bilateral agreements between TSO and Demand facility	Under development	no

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ANNEX II CBA on reactive power equipment connected on different voltage levels

Introduction
Different connection points with different characteristics are selected. Generally an urban location and a rural location are of interest. The rationale for this is that introduction of a new transmission connected load in the urban location is likely to be less pronounced as the increase in Vars is proportionally much smaller and the system independence from generation to use will be lower.
At each location the study has examined the introduction of a new load (50MW at 0.85PF, 500MW at 0.85PF), and examined the needs for additional reactive power from either generation or passive components for reactive power support.
The study considered two options:

1. Reactive power support provided by the user at the next voltage level down from their connection point
2. Reactive power support provided by the TSO – optimum location to be determined by TSO performing study.

For each study the network is at least N-1 compliant, and compliant with the TSO planning standards.
Option 1: Reactive power support by user

For this option costs of reactive power support are typical costs for reactive power support.
Type of reactive power support (caps, reactors, SVC, etc.) are estimated by TSO to meet their existing planning criteria. The studies examine peak and trough in load demand in 2015 and 2020.
Full compensation (PF1.0) by the user to HV side of transformer is the target.

Option 2: Reactive power support by TSO

For this option costs of reactive support are by nationally typical costs for reactive power support.

Irish Test Case
Utilising the generic scope as described above, the study test cases selected were:

1. 50MW with 0.85PF demand connection at Binbane 110/38kV station at 38kV
2. 500MW with 0.85PF demand connection at Flagford 220/110kV station at 110kV
3. 50MW with 0.85PF demand connection at Finglas 110/38kV station at 38kV
4. 100MW with 0.85PF demand connection at Ryebrook 110/38kV station at 38kV

The results from these studies which provided viable network solutions are shown below in Table 1. Each of the test cases has been tested to be complaint with network planning standards.
Test Case 1 and 3 were examined looking at solutions at the connecting stations at 38kV and 110kV, and trying to centralise the reactive compensation requirements to provide widespread support.
The centralised solution is included to confirm whether the transmission solution can be optimised to be a solution for a wider area which might be cheaper than equivalent multiple 38kV reactive compensation devices. In either case either this solution does not work as it is too remote from the location where the reactive power is needed.

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Table 1. Results of test cases in Ireland

Test Case 1 – 50MW in Binbane 110kV station		
Scheme	Assumption	Total cost in kEuros
110kV connected	Assume 30 + 22 MVAr capacitor blocks	2136
110kV centralised connected	Does not work	-
38kV connected	Assume 30 + 17 MVAr capacitor blocks	719
Test Case 2 – 500MW in Flagford 220kV station		
Scheme	Assumption	Total cost in kEuros
220kV Connected	Assume 6 * 60 + 20 MVAr capacitor blocks	9340
110kV Connected	Assume 6 * 60 + 20 MVAr capacitor blocks	9340
Test Case 3 – 50MW in Finglas 220/110kV station		
Scheme	Assumption	Total cost in kEuros
110kV Connected	Assume 33 MVAr reactor block	862
38kV Connected	Assume 35 MVAr reactor block	150
Test Case 4 – 100MW in Ryebrook 110kV station		
110kV Connected	Assume 30 MVAr capacitor block	1095
110kV Centralised at Finglas	Assume 30 MVAr capacitor block	1095
38kV Connected	Assume 30 MVAr capacitor block	419

Conclusion of the cost benefit analysis of reactive power requirements

It has been found that reactive power is in general most cost-effectively provided beyond the connection point in the DSO network or its demand users.

Therefore the reactive power requirements should restrict the steady-state range of reactive power that is imported and exported over the T-D interface to a minimum as reactive power support can be best generated were it is needed. On the other hand ranges should be so wide that they do not restrict the use of the capabilities of embedded generation and Demand Response (DR).

ANNEX III Possible process for the definition of the reactive power and voltage requirement at the T-D interface, including influence from the reactive power and voltage control capabilities of grid equipments, demand users and generating units

Introduction

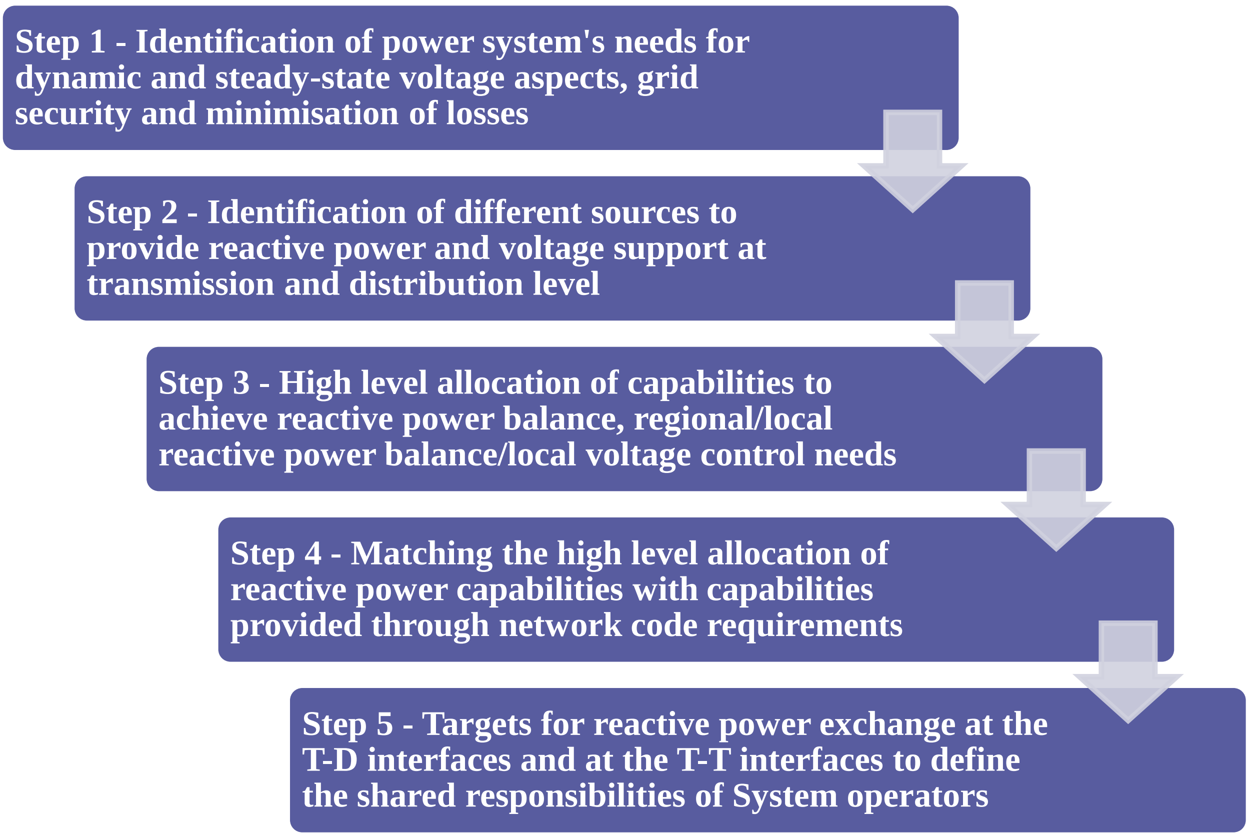
The objective of this process is to support a general approach for the design of reactive power and voltage requirements at the T-D interface. The objective is not to prescribe the approach to be followed at national level and ENTSO-E recognises that they are other possible processes that can be used to reach the same objective.

One of the major aspects of the recommended approach for the problem of voltage control and reactive power is that this aspect should be considered from the point of view of the global system benefits and not from individual owner/operator interest. The proposed approach aims at re-affirming the use of the principle stated in the Art. 6.3 (c) of DCC NC “*apply the principle of optimisation between highest overall efficiency and lowest total costs for all parties involved”* applying the Regulation at National Level. Therefore, the definition of the individual owner/operator requirements should come at a later stage once an expected global optimum has been reached taking into account uncertainties of the future system conditions.

It is also very important to clarify that requirements at the T-D interfaces (and T-T interfaces) should be designed to make every network operator aware of his responsibilities to keep the system close to an expected global system optimum. This covers the need to take the best possible decisions concerning their own assets but also the connection of users to their own grid in order not to deviate from this expected global system optimum. As an example, the capabilities of a DSO to fulfil the requirement for reactive power exchange at its interface with the transmission system (as defined in the NC DCC) is impacted by the capabilities of the generating units connected within the distribution grid and the strength of the need for such a requirement is impacted by the capabilities of the generating units, demand users and transmission equipments connected within the transmission grid. The capabilities of the generating units is defined by the NC RfG and by the choices made for the MW thresholds between types A/B/C/D following national implementation of the NC RfG.

Finally, it needs to be highlighted that requirements at the T-D interfaces may greatly depend on the national differences in terms of split between transmission grid, distribution grids and close-distribution systems. However, the impacts of national differences are expected not to impact the global optimum if such a process is followed. Harmonisation of the T-D interfaces or of the requirements for the T-D interfaces is therefore not the main objective. However, the coordination foreseen in the NC RfG for the threshold between types A/B/C/D as well as the relations between EN standards and reactive power requirements of the smaller units (typically of type A & B) could lead to an iterative process for the definition of the requirements at the T-D interfaces.

Flow chart



Overview of the important steps:

1 - Identification of power system's needs for dynamic and steady-state voltage aspects, grid security and minimisation of losses

Transmission-connected distribution systems shall be capable of remaining connected to the network and operating at the voltage ranges and time periods specified in Annex II in the Network Code on Demand Connection. To keep the voltage in the defined required ranges, it is necessary to be able to control the voltage and to prevent a voltage collapse in the network and with that safeguard the security of supply. Different voltage control strategies are available in the distribution network, all based on keeping the reactive power balance.

To identify the needs for reactive power in the network, typical expected future operating situation may be analyzed. Not only steady state situations are of interest but also the dynamic behaviour of the network during transition from one stage to another stage (pre-fault and post-fault situations).

Transmission of reactive power is only possible over limited distances while respecting voltage limits. Furthermore it gives extra losses in network components like transformers, lines and cables. A loss analyses can be helpful to select an optimal utilisation of reactive power in the network.

2 – Identification of different sources to provide reactive power and voltage support at transmission and distribution level

The goal of this step is to identify the different capabilities to provide or absorb reactive power for voltage control and reactive power management. These capabilities can be divided in 3 types. First of all, the generators can absorb or provide reactive power, depending on the connection requirements. Secondly, the demand can help the system operator to manage the voltage level, for instance thanks to capacitors set up in its own installation. Thirdly, the system operators (DSO or TSO) can manage the voltage level with equipment set up on its grid (e.g. inductors, capacitors, SVC…). A difference should be done between dynamic and static capabilities to manage reactive power, taking into account the difference of the quality of the given service.

Stakeholder interactions (Consumers, Generators, DSO, TSO) are important to identify of capabilities of available and future technologies. A benchmark of the other grid code and a technological watch can also be a key input for this step.

3- High level allocation of capabilities to achieve reactive power balance, regional/local reactive power balance/local voltage control needs

The allocation of capabilities has to take into account the different levels of locality: system/regional/local reactive balance and voltage issues.
Based on the future need identification of step 1 and the existing and future sources for reactive power identified in step 2, the system, regional and local balances can be determined. To do that, it is recommended to take into account several aspects, such as

a) proximity factor: to take into account that reactive power is difficult to transport
b) availability rate of the reactive power sources: to take into account that some capabilities are not always available
c) utilization rate: to take into account the fact that some capabilities are very often needed while other would be much less often needed
d) etc.

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Based on these balances, the capabilities could be allocated:

1. First, to overcome (reactive power) system balance issues
2. Secondly, to overcome regional (reactive power) system balance issues
3. Thirdly, to overcome local (reactive power) system balance issues and local voltage problems

When dynamic voltage issues are expected, it can be helpful to make a difference between static and dynamic capabilities in the balance calculations.

4- Matching the high level allocation of reactive power capabilities with capabilities provided through network code requirements

The conclusions of step 3 for the different scenario considered should then be synthesized to fit within the extent of the requirements specified in the NC RfG for power generating modules and in the NC DCC for Demand users.

Input from the national implementation of the threshold between types A/B/C/D of power generating units, classification of generating units between PPM and SPGM and classification of demand users between transmission and distribution connected is considered in this step to define requirements..

The results of this step is therefore an adaptation of the high level allocation of the reactive power capabilities (step 3) in order to respect the principle of non-discrimination and not to deviate greatly from the global system optimum.

It must be noted that the output of this step could also be a driver, if the national process allows for it, for an update of the threshold between types A/B/C/D of power generating units.

5 - Targets for reactive power exchange at the T-D interfaces and at the T-T interfaces to define the shared responsibilities of System operators

Recognizing the results of previous step (mainly step 3 and 4), the reactive power capabilities needed on its interfaces with DSOs based on NC DCC article 15 will be defined in order not deviate from the global social welfare. However, the local differences of the reactive power exchange at T-D interfaces, the influence of local uncertainties in terms of future generation connection, local voltage problems as well as difference of structure for the TSO and DSO grids could be considered. On this aspect, the voltage level at the T-D interface is important: this voltage level at the interface is different in each country and is often related to the size of the DSO grids. Smaller DSO grids have then less available means to control the reactive power exchange at the T-D interface. This would result in the definition of general requirements or project specific requirements.

Even though that reactive power exchange between neighbouring TSOs is not within the scope of the NC, common practice (mentioned above for region reactive power balance) is to balance each transmission grid at planning stage.

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