Definition and Classification of Terms for HVDC Networks

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Abstract:
A systematic terminology for the field of HVDC networks has been developed, closing the gap between the well-established terminologies from AC power systems and HVDC technology. The most relevant items, topologies and concepts have been given clear and unique defined names, and these have been classified in a systematic way.

The motivation for this work has been to help to reduce the communication problems that are emerging when power system engineers talk to HVDC technology engineers. The main guidelines underpinning the approach taken here is to minimise conflicts with the mentioned two existing terminologies and with existing publications on HVDC networks. A significant effort has been made to make the terminology "future-proof" not only covering today's HVDC technology but also potential future developments like large meshed HVDC grids and high power HVDC-HVDC converters.

Index Terms:
- HVDC Grids
- HVDC Networks
- HVDC Power Systems
- Multi-Terminal HVDC
- Super Grid

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1. Introduction

The scientific community has gained a strong interest in the field of High Voltage Direct Current (HVDC) networks. In most publications these are referred to as HVDC grids or HVDC systems. The entire field of research is at the moment lacking a systematic terminology, as there are two existing fields merging: Electrical power systems (AC) and HVDC technology. This can result in communication problems, as many terms in use do not have a clear and unique definition.

The North Sea Offshore and Storage Network (NSON) Initiative [1] has identified this lack of a /terminology and definition of terms as problematic for the development of the electrical infrastructure in the North Sea region, and therefore worked to develop the missing /terminology, which is presented in this article and may be likened to taxonomies used in other fields such as zoology and computer science. In the presentation that follows, the terms that are defined here are written in *italics*.

1.1. Simplifications

In this article, a single-line-representation of all HVDC infrastructure is used. This is necessary to enable for a systematic view upon the network topology, without having to go into technical detail.

What is referred to here as one DC bus is in technical detail either two busses (e.g. positive and negative poles) or three busses (additional ground), and one DC transmission line might take the form of one conductor (with a ground or sea return), two (positive and negative poles) or three conductors (for positive and negative poles plus a metallic earth return). A particular HVDC system is described as having one single voltage level, even though, for example, an asymmetric monopole has a different voltage at the return (e.g. -150 kV / 0 kV). These details are, however, not in focus in this article.

All converters in the discussion presented below are regarded as ideal converters. Only the input and output are considered, and all technical details of the internal topology including intermediate voltage levels are disregarded.

Very short transmission lines are ignored. Two busses that are co-located and directly connected (by a very short transmission line) are combined into one equivalent bus (e.g. the conductors connecting converter terminals of a back-to-back system). Only lines beyond negligible length are considered as lines.

1.2. Visualisations

The concepts are visualised with figures using the symbols explained in **Error! Reference source not found.Error! Reference source not found.**.

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The CIGRE B4 DC Test Grid [2] drawn with this simplified visualisation scheme is shown in Figure 2. This can be compared with the regular electrical drawing of the same grid, shown in **Error! Reference source not found.** in Section 4.

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2. Definitions for HVDC Networks

The relevant definitions for HVDC networks are given in this section.

2.1. HVDC Networks

A *HVDC network* is an electrical network that utilises high DC voltage does not need to be purely based on DC can also include conversion through intermediate AC stages (DC-AC-DC conversion), but it cannot include AC transmission lines. A network consisting of AC and DC transmission lines (such as the interconnected European electric power grid) is a hybrid AC+DC network. Hybrid AC+DC networks are not the focus here.

In this definition a distinction is made between two types of HVDC networks: HVDC systems and HVDC grids.

2.1.1. HVDC System

A *HVDC system* is an autonomous *HVDC network*, which operates with a single high DC nominal voltage. In a *HVDC system*, all *busses* (defined in Section 2.3) are directly connected by conductors. Protection devices like circuit breakers can be series connected within a *HVDC system*, even though that is not really a direct conductor connection. An example of a *HVDC system* is shown in Figure 3.

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To be regarded as part of a single *HVDC System*, any DC-DC power converters must be series connected between two *busses* within that *HVDC system*. This is the case if these two *busses* are directly connected by conductors, meaning there is a direct connection path between the *busses* in parallel to the DC-DC converter, creating a loop within the *HVDC system* (controllable mesh, Section 2.4.2). Without that parallel direct connection path, the DC-DC converter would split the *HVDC system* into two *HVDC systems* connected by the converter.

A *HVDC system* can only have one nominal voltage level, due to the direct conductor connection. This is similar to a synchronous AC power system, which can only have one frequency.

If a short-circuit appears within a *HVDC system*, the voltage collapses in the entire *HVDC system*, if this is not prevented by a protection system, which quickly separates the faulty part from the healthy part. This is why large *HVDC systems* would have demanding requirements towards the protection system. This short-circuit behaviour is one of the most relevant differences between *HVDC systems* and *HVDC grids*.

A *HVDC system* can stand alone, or it can be part of a *HVDC grid*. In that case, it could also be referred to as a *HVDC sub-system*, to highlight the fact that it is not standing alone.

2.1.2. HVDC Grid

A *HVDC grid* is an interconnected *HVDC network*, consisting of two or more *HVDC systems, which can be referred to as sub-systems in that case*. Unlike a *HVDC system*, a *HVDC grid* does not require direct conductor connection of all *busses*. A *HVDC grid* can therefore (but does not need to) have multiple voltage levels, connected by power converters. A similarity to AC can be observed when regarding interconnected AC grids, consisting of several synchronous (sub-) systems which can (but do not need to) have multiple frequencies. In the European AC grid, all (sub-) systems have the same frequency (50 Hz), but in the Japanese AC grid, the two (sub-) systems have different frequencies (50 Hz and 60 Hz). An example of a *HVDC grid* (consisting of two *HVDC systems*) is shown in Figure 4.

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Different *HVDC systems* can be counted as belonging to the same *HVDC grid* if:

- They are connected by a DC-DC converter
- They connect to the same AC station via AC-DC converters (see *supernode*, Section 2.3.5)

As stated, the *HVDC grid* can also include conversion through intermediate AC stages (DC-AC-DC conversion), but it cannot include AC transmission lines.

If a short-circuit appears within a *HVDC grid*, the voltage does not collapse in the entire *HVDC grid*, but only in the affected *HVDC (sub-) system*. This is why large *HVDC grids* do not necessarily have as demanding requirements towards the protection system as large *HVDC systems* do, since the sectioning of a *HVDC grid* into several smaller *HVDC (sub-) systems* can avoid a short-circuit from critically disturbing the entire *HVDC grid*. This advantage of a *HVDC grid* requires sufficient fault-blocking capabilities of all converter interfaces between the *HVDC (sub-) systems*.

The word 'grid' somehow implies the presence of *loops* (defined in Section 2.4). However, a large *HVDC network* consisting of several *HVDC systems* with several voltage levels, but without any *loops*, could theoretically be realised in the future. Such a non-*looped HVDC network* with a tree-like structure should theoretically not be called a grid, as it lacks the characteristic *loops* of a grid. However, AC distribution systems are often also called 'distribution grids', even though many distribution systems do not have *loops*. It seems that the word 'grid' has already been used for non-*looped* networks for many years, so the use of the word 'grid' for networks without *loops* has to be accepted.

In several publications, large *HVDC systems* are called *HVDC grids*, even though they do not consist of at least two *HVDC (sub-) systems*. This is done without stating clearly what the difference is exactly between a large *HVDC system* and a *HVDC grid*. However, it can generally be observed that the term *HVDC system* [3] is mostly used for smaller well-defined *HVDC networks*, while *HVDC grid* [4] often refers to future larger *HVDC networks* like the envisioned European Super Grid.

2.2. Edges

An *edge* generally is a connection between two vertices, as known from graph theory. Regarding *HVDC networks*, an *edge* is defined as a connection between two *busses* of that network or the connection of one *bus* of that network with the external world.

This connection to the external world could be to an AC system, to a source (generation) or to a sink (load). For a *HVDC system* (not for a *HVDC grid*), it could also be the connection to another *HVDC system* by a DC-DC converter.

Parallel *edges* that connect to the same *busses* on both ends (e.g. double circuit lines, parallel converters) are seen as one *edge* of the network (observable when comparing Figure 2 with **Error! Reference source not found.**). This is relevant in the context of *connection points* (defined in Section 2.3.1).

2.2.1. Branch

A *branch* of a *HVDC network* is an *edge* that connects two *busses* of that network. *Branches* should have some 'significant' length or should connect locations which are electrically separate. If two *busses* are directly connected by a conductor with 'insignificant' length, they appear as one *bus* from a network point-of-view.

Branches are generally either HVDC lines or DC-DC converters. A HVDC transmission line always connects two *busses* of a *HVDC network*, so it is a *branch* of that network. A DC-DC converter connecting two *busses*, which belong to the same *HVDC system*, is also a *branch* of any type of *HVDC network*. A DC-DC converter connecting two *busses*, which do not belong to the same *HVDC system*, is a more complicated case, treated in Section 2.2.3.

Examples of *branches* are shown in **Error! Reference source not found.**.

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2.2.2. Terminal

A *terminal* of a *HVDC network* is an *edge* that connects one *bus* of that network with the external world (anything that is not part of the *HVDC network*). *Terminals* act as sources and/or sinks, or in other words as inputs and/or outputs to or from the *HVDC network*.

In most cases, a *terminal* is a connection of a *HVDC network* to a power converter. However, other non-converter-type *terminals* are theoretically possible (e.g. DC load, DC generator), but these are not common, especially at high DC voltage.

All AC-DC converters are *terminals* to any type of *HVDC network* (shown in **Error! Reference source not found.**). A DC-DC converter connecting two *busses*, which do not belong to the same *HVDC system*, is a more complicated case, treated in Section 2.2.3.

When considering the entire complete hybrid AC+DC grid, only generation and load would remain as *terminals*, while all converters become *branches*. However, the focus here is on *HVDC networks* and not on hybrid AC+DC networks.

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Terminals are the points of the network where most of the inflow and outflow (current/power) is located.

Concerning current, this flow-based definition holds very well for *HVDC systems*. Only small amounts of current enter and leave the *HVDC system* at *branches*. This is the leakage current on transmission lines and the difference between input and output current of a DC-DC converter (which is small for a DC-DC converter with the same voltage level on both sides). For *HVDC grids* with different voltage levels, this flow-based definition only holds when using per unit values. This is because of the significant difference between input and output current of a DC-DC converter connecting two different voltage levels (which disappears when converting to per unit).

Concerning power, this flow-based definition is not as exact as for currents. This is due to the transmission losses on the lines (mostly power losses, very little current losses). However, when considering power, *HVDC grids* with different voltage levels can be considered without having to look at per unit values.

It is important to distinguish between *busses* and *terminals*. These two terms are often confused, as the majority of existing *HVDC systems* has one *terminal* per *bus*. Based on the definition of a *terminal* as given here, a *terminal* is treated as an *edge* because of the net flow through it, whereas a *bus* has net flow of zero.

2.2.3. HVDC System Terminal / HVDC Grid Branch Duality

A special case that needs extra attention is a DC-DC converter, which connects to two different *HVDC systems* (shown in **Error! Reference source not found.**). This would typically be the case, when two different voltage levels are connected.

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Regarding the *HVDC grid* (which includes both *HVDC systems*), the DC-DC converter appears as a *branch* of the grid (just like any other DC-DC converter). Regarding the two *HVDC systems*, the DC-DC converter appears as a *terminal* for both systems (unlike other DC-DC converters than can appear as a *branch* within one *HVDC system*).

2.3. Busses

A *bus* is a point in the *HVDC network* where two or more *edges* are connected. Different types of *busses* are defined here. In graph theory the term 'vertex' is used for what here is called a *bus*.

2.3.1. Connection Point

A *connection point* is defined as a *bus* where exactly two *edges* are connected together (shown in **Error! Reference source not found.**). This is typically a connection of a converter to a transmission line or an overhead line to a cable. Since a double circuit line counts as one *edge* and not as two, a *bus* where a converter is connected to a double circuit line is considered a *connection point*.

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Theoretically, any point on any line (e.g. a cable joint) could be seen as a *connection point* of two line segments. Whether such *connection points* are relevant to be considered or not depends highly on the specific study case.

Connection points are not significant for power flow calculations, as the flow out of the first *edge* is exactly the flow into the other *edge*. There is no degree of freedom, so *connection points* (unlike the other *bus* types) need not add to the complexity of a power flow calculation.

2.3.2. Node

A *node* is a *bus* where at least three *edges* meet, and at least one of the *edges* has to be a *terminal*.

A *bus* appears as a *node* in both types of *HVDC network* if it has an *edge*, which connects to something outside the *HVDC grid*, and not just to another voltage level (which is part of the *HVDC grid* but not of the *HVDC system*). This usually means a connection to AC.

Examples of *busses*, which are *nodes* for both types of *HVDC networks*, are shown in **Error! Reference source not found.**.

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2.3.3. Hub

A *hub* is a *bus* where at least three *branches* meet, and where no *terminals* are connected. A *hub* here refers to a DC *hub* as a constituent part of a *HVDC network*, and not to any kind of AC *bus*. There are similarities with the term 'tee point' as used for AC networks.

A *bus* appears as a *hub* in both types of *HVDC networks* if it does not have an *edge*, which connects to something outside the *HVDC system*, not even to another voltage level (which is part of the *HVDC grid* but not of the *HVDC system*). DC-DC converters can be connected to a *hub*, if they are internal to the *HVDC system*, meaning that they connect to the same *HVDC system* on both ends. They are therefore *branches* of that *HVDC system* and not *terminals*.

Examples of *busses*, which appear as *hubs* for both types of *HVDC networks*, are shown in **Error! Reference source not found.**. The DC-DC converters shown in the examples are internal to the *HVDC system*.

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2.3.4. HVDC System Node / HVDC Grid Hub Duality

The definitions of *nodes* and *hubs* are identical for *HVDC grids* and *HVDC systems*, but the definitions of *edges* (*branches* or *terminals*) are not identical. This duality of *branches* and *terminals* in the case of DC-DC converters (explained in Section 2.2.3) results also in a duality of *nodes* and *hubs*. A *bus* with an *edge*, which is a dual *terminal/branch edge*, can be (but does not need to be) a dual *node/hub bus*.

A *bus*...

- where at least three *edges* meet
- where at least one of the *edges* is a dual *branch/terminal edge*
  (DC-DC converter connecting to another *HVDC system*)
- that has no connection to something outside the *HVDC grid*

...appears as a *node* for the *HVDC system*, but at the same time appears as a *hub* for the *HVDC grid*.

This is due to the fact that the DC-DC converter appears as a *terminal* to the *HVDC system* but as a *branch* to the *HVDC grid*. Examples are shown in **Error! Reference source not found.**.

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However, it should be noted that:

- all *busses* that are *nodes* of a *HVDC grid* also appear as *nodes* of the corresponding *HVDC system*, but not vice versa.
- all *busses* that are *hubs* of a *HVDC system* also appear as *hubs* of the corresponding *HVDC grid*, but not vice versa.

2.3.5. Supernode

A *supernode* is not really a *bus*, but rather a cluster of *busses*. It consists of at least two (DC) *busses* and one AC station, where the *busses* are connected to the same AC station through AC-DC converters. *Supernodes* are especially relevant in the context of *pseudo-meshes* (defined in Section 2.4.3).

Examples of *supernodes* can be seen in **Error! Reference source not found.**. The left-hand example shows a *supernode* connecting two *busses* of the same *HVDC system*, while the right-hand example shows a *supernode* connecting to different *HVDC systems*. All the converters shown are *terminals*, as they are AC-DC converters.

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If the two DC *busses* of a *supernode* have the same voltage level, a switch could be placed between them, being able to short-circuit them together. This would turn the *supernode* into a regular *node* (with two parallel AC-DC converters). It enables the flexible reconfiguration between *node* and *supernode* state, depending on what is better for the specific power flow situation.

A connection to two distant AC stations in the same AC system (synchronous area) does not qualify as a *supernode*, as it would include significant geographical transmission distance on the AC side into the *supernode*, which is in conflict with the 0-dimensional "point" character of a *bus*. For this definition, geographical distance is used instead of electrical distance. Within an AC station, there is almost no geographical distance, but the electrical distance usually is significant, due to the transformer series inductance.

A *supernode* can be seen as part of a *HVDC network*, even though it might contain an intermediate AC stage. The *supernode* (one AC station *bus* and two AC-DC converter *edges*) has some similar properties as an *edge* (DC-DC converter). It connects two DC *busses* and controls the flow between them. However, it does not fully behave like an *edge*, as the inflow on one side does not need to be equal (or almost equal) to the outflow of the other side.

Many dedicated DC-DC converter topologies also contain an intermediate AC stage (which is normally not operated at a typical AC system nominal frequency such as 50Hz). This does not, however, qualify as *supernode* as the AC *bus* is only an AC '*connection point*' between the two converter stages, without AC '*node*' characteristics. The DC-DC converter with an intermediate AC stage therefore truly behaves like an *edge*, while the *supernode* only shares some properties with an *edge*.

2.4. Loops

A *loop* is a circular structure of *branches* within a *HVDC network*. A *loop* is referred to as a cycle in graph theory. The different types of *loops* are defined here.

2.4.1. Mesh

A *mesh* is a *loop* within a *HVDC system*, where no power electronic converters are inserted in series into the *loop*, so all flows follow Ohm's and Kirchhoff's laws. The power flow in a *mesh* cannot be fully controlled. A *mesh* is shown in **Error! Reference source not found.**.

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2.4.2. Controllable *Mesh*

A *controllable mesh* is a *loop* within a *HVDC network*, where flows can be controlled by at least one DC-DC converter inserted in series into the *loop* as a *branch*. Examples for *controllable meshes* are shown in **Error! Reference source not found.**.

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The definition of a *controllable mesh* is identical for *HVDC grids* and *HVDC systems*. However, a *controllable mesh* of a *HVDC grid* can consist of different HVDC lines at different voltage levels belonging to different *HVDC systems*, which all are part of the same *HVDC grid* (as shown on the right of **Error! Reference source not found.**). This is a realistic scenario for future *HVDC grids* that will consist of several voltage levels.

2.4.3. Pseudo-*Mesh*

A *pseudo-mesh* is a *loop* within the *HVDC network*, which contains at least one *supernode* (Section 2.3.5). This means that not the entire *loop* is DC, but it is closed though a DC-AC-DC connection with two AC-DC converters and one AC station. Examples of *pseudo-meshes* are shown in **Error! Reference source not found.**.

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The definition of a *pseudo-mesh* is identical for *HVDC grids* and *HVDC systems*. However, a *pseudo-mesh* of a *HVDC grid* can consist of different HVDC lines at different voltage levels belonging to different *HVDC systems*, which all are part of the same *HVDC grid* (as shown on the right of **Error! Reference source not found.**). This is a likely scenario for future *HVDC grids* that will consist of several voltage levels.

If the *loop* would consist of AC and DC transmission lines, it is not regarded as a DC *pseudo-mesh*. It would be a hybrid AC+DC *loop* [5], but these are not considered here, as they do not belong to *HVDC networks* but to hybrid AC+DC networks.

3. Properties of *HVDC Systems*

The main attributes of a *HVDC system* are its complexity (in the sense of the number of inputs and outputs), its topology and its size. These three important aspects are classified here.

3.1. *HVDC System* Complexity

The input-output complexity of a *HVDC system* depends on the number of *terminals*. A distinction is generally made between two-*terminal* systems and multi-*terminal* systems.

3.1.1. Two-Terminal HVDC System

A *two-terminal* system is a *HVDC system* with two *terminals*. Only the number of *terminals* is specified, and it does not say anything about the number of *busses* and *branches*. However, systems with two *busses* and one transmission line are most common (Section 0). Some possible *two-terminal* systems are shown in **Error! Reference source not found.**.

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The term *two-terminal* system also includes back-to-back converters with a single DC *bus* and no transmission line (e.g. first stage of Tres Amigas [6]). However, such a system can also be considered as an AC-AC converter.

A *two-terminal* system can also have three or more *busses*. An example of this is when both cables and overhead lines are applied.

The term "point-to-point *HVDC system*" is often used synonymously for two-*terminal* system. This is, however, not correct since a *two-terminal* back-to-back system is not a point-to-point system. A point-to-point system requires 'significant' geographical distance between the points. For this definition, geographical distance is used instead of electrical distance. Within a back-to-back system, there is almost no geographical distance, but the electrical distance can be significant, e.g. if there is a DC series inductor.

3.1.2. Multi-Terminal HVDC System

A *multi-terminal* system is a *HVDC system* with at least three *terminals*. Only the number of *terminals* is specified, and it does not say anything about the number of *busses* and *branches*. Any number of *terminals* (including zero) can be located at a *bus*. Some examples of *multi-terminal* systems are shown in **Error! Reference source not found.**.

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The term *multi-terminal* system also includes *multi-terminal* back-to-back converters with a single DC *bus* and no transmission line (e.g. Shin-Shinano [7], described in Section 3.2.1).

A *multi-terminal* system can be a point-to-point system if at least one of the two *busses* with *terminals* has more than one *terminal* (e.g. one AC-DC converter and one DC-DC converter). Two *terminals* of a *HVDC system* are considered to be at the same *bus*, if they are geographically co-located, as explained in Section 1.1.

3.2. *HVDC System* Topologies

The different *HVDC system* topologies are defined here.

3.2.1. Back-to-back *HVDC System*

A back-to-back *HVDC system* is a *HVDC system* with a single *bus* and no *branches* (examples shown in **Error! Reference source not found.**).

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It usually has two *terminals* (left part of **Error! Reference source not found.**), but also a system with three *terminals* has been realised (right part of **Error! Reference source not found.**, e.g. Shin-Shinano [7]). More than three *terminals* are theoretically also possible, but this has never been applied yet, and it seems challenging to imagine an application where such a system would be the appropriate technical solution.

3.2.2. Point-to-Point *HVDC System*

A *point-to-point HVDC system* is a system where all *terminals* are located at exactly two *busses*. This implies a minimum requirement of at least two *busses*. Examples of point-to-point systems are shown in **Error! Reference source not found.**. A point-to-point system can also have three or more *busses*. This would typically appear when both cables and overhead lines are applied, leading to additional connection points (seen in the lower two examples of **Error! Reference source not found.**).

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The term "point-to-point" *HVDC system* is often used synonymously for "two-*terminal*" *HVDC system*. This is however not correct:

- Not every *two-terminal* system is a point-to-point system. If both *terminals* are located at the same *bus* (back-to-back system), the *two-terminal* system is not a point-to-point system.
- Not every point-to-point system is a *two-terminal* system. A point-to-point system can be a *multi-terminal* system if at least one of the two *busses* with *terminals* has more than one *terminal* (e.g. one AC-DC converter and one DC-DC converter). This is shown in in **Error! Reference source not found.** (the two point-to-point systems on the right are *multi-terminal* systems).

The term "point-to-point" system therefore contains no information about the number of *terminals*, but it rather relates to the *HVDC system* topology. This confusion originates from the fact that most of the existing *HVDC systems* are point-to-point *two-terminal HVDC systems*.

3.2.3. Radial HVDC system

A *radial HVDC system* is a multi-*terminal HVDC system* with no *loops*, and with at least three *busses* that have at least one *terminal* each. A *radial HVDC system* has exactly one branch less than the number of *busses*. Radial systems have the structure of a mathematical tree, as known from graph theory. All *branches* of a radial system need to be transmission lines, as a DC-DC converter *'branch'* would split the *system* into two *systems*, forming one *grid*. Examples are shown in **Error! Reference source not found.**.

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3.2.4. Pseudo-Meshed HVDC System

A *pseudo-meshed HVDC system* is a multi-*terminal HVDC system* with at least one *pseudo-mesh* and with no *controllable meshes* or *meshes*. Examples are shown in **Error! Reference source not found.**.

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No *pseudo-meshed HVDC system* exists or is planned at the moment of writing.

3.2.5. Controllable-Meshed HVDC System

A *controllable-meshed HVDC system* is a multi-*terminal HVDC system* with at last one *controllable mesh* and with no simple *meshes*. Examples are shown in **Error! Reference source not found.**.

PLACE FIGURE 22 HERE

No *controllable-meshed HVDC system* exists or is planned at the moment of writing.

3.2.6. Meshed HVDC System

A *meshed HVDC system* is a multi-*terminal HVDC system* with at least one *mesh*. Examples are shown in **Error! Reference source not found.**.

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No *meshed HVDC system* exists or is planned at the moment of writing.

3.3. *HVDC System* Size

In the literature, there is often reference to 'large' *HVDC systems* (e.g. [8]). There are some attributes which are granted to a 'large' *HVDC system*, but there usually is no definition of when a *HVDC system* is large. Some other technical phenomena become relevant only for 'very large' *HVDC systems*, but also here a definition is usually missing.

The terms 'large' and 'very large' are more often used in combination with *HVDC grids* rather than with *HVDC systems*. This is mostly based on the general consensus that large and very large *HVDC networks* will likely be *HVDC grids* consisting of several *HVDC (sub-)systems*.

3.3.1. Large *HVDC system*

A *HVDC system* can be considered large if its power flows are so large that a failure of the *HVDC system* would cause a severe disturbance for the connected AC grids. This especially relates to the primary control reserves or frequency containment reserves of the AC grids. A failure of a line or converter always needs to be acceptable within the security margins, but keeping reserves for the failure of a large *HVDC system* could not normally be justified. A large *HVDC system* rather needs sophisticated control and protection systems to avoid this scenario. This indicates advantageous properties of a large *HVDC grid* compared to a large *HVDC system*, since a *HVDC grid* is more robust and has less strict protection requirements [9].

There is no clear limit when a *HVDC system* can be considered large. However, a simple 'rule of thumb' can be proposed: "A *HVDC system* is large if the sum of all converter power ratings is one order of magnitude larger than the power rating of a single converter."

3.3.2. Very large HVDC system

A *HVDC system* can be considered very large when the power rating of the largest converter station is insignificant compared to the sum of all converter power ratings. In this case heavily centralised control concepts, e.g. where a single converter is operated as slack bus, become questionable. Very large *HVDC systems* are not foreseen in the near future.

There is no clear limit when a *HVDC system* can be considered very large. However, a simple 'rule of thumb' can be proposed: "A *HVDC system* is very large if the sum of all converter power rating is two orders of magnitude larger than the power rating of a single converter."

4. Example: The CIGRE B4 DC Test Grid

The CIGRE B4 DC Test Grid [2] (shown in **Error! Reference source not found.**) is given as an example to explain the definitions.

PLACE FIGURE 24 HERE

It is a *HVDC grid*, consisting of three *HVDC systems* (DCS1, DCS2 and DCS3). DCS1 and DCS2 are displayed in light blue and DCS3 in dark blue.

All the AC-DC converters are *terminals*. All the transmission lines are *branches*. The DC-DC converter at location B1 is a *branch*, because it is connected to the same *HVDC system* (DCS3) on both ends. The DC-DC converter at location E1 is a dual *terminal* / *branch*. It appears as a *terminal* to both of the *HVDC systems* at each end (DCS2 and DCS3) but it appears as a *branch* to the *HVDC grid*.

The *bus* types of the CIGRE B4 DC Grid Test System are specified in **Error! Reference source not found.**. The *HVDC grid* contains two *supernodes*, at locations A1 and B2. Bus Bb-E1 is a dual *hub* / *node*.

PLACE TABLE I HERE

The *HVDC systems* DCS1 and DCS2 do not contain *loops*. DCS3 contains a *mesh* and a *controllable mesh*. The *HVDC grid* contains all three *HVDC systems*, and since it contains DCS3, it automatically also contains the *mesh* and the *controllable mesh* from DCS3. However, the *HVDC grid* also contains a *pseudo-mesh* which is formed by the *HVDC systems* DCS2 and DCS3, together with the two *supernodes* A1 and B2. It should be noted that a *HVDC grid* can contain a *pseudo-mesh* even though none of its constituent *HVDC subsystems* contains one (as explained in Section 2.4.3). The *loops* are specified in **Error! Reference source not found.**.

PLACE TABLE II HERE

The defined properties of HVDC systems are given in **Error! Reference source not found.**.

PLACE TABLE III HERE

5. Acknowledgement

This publication is a result of work by the North Sea Offshore and storage Network (NSON) Initiative, which is an activity of the European Energy Research Alliance (EERA) Joint Programme (JP) on Wind Energy (http://www.eera-set.eu/eera-joint-programmes-jps/wind-energy).

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[9] K. R. W. Bell, L. Xu, and T. Houghton, "Considerations in design of an offshore network", *CIGRE Science & Engineering,* vol. 1, 2015.

7. Biographies

Til Kristian Vrana graduated from the Academic School of the Johanneum in 2001 in Hamburg/Germany. He received his bachelor in electrical engineering and information technology in 2005 and his master in electric power engineering in 2008, both at RWTH Aachen University in Aachen/Germany. He achieved his doctoral degree in 2013 at the Norwegian University of Science and Technology NTNU in Trondheim/Norway. Currently he is working as a research scientist in the energy systems department at Sintef Energi in Trondheim/Norway.

Keith Bell is the ScottishPower Professor of Smart Grids at the University of Strathclyde. He joined the University in 2005 having previously gained his PhD at the University of Bath and worked as an electrical engineering researcher in Manchester and Naples, and as a system development engineer in the electricity supply industry in Britain. He is Chartered Engineer, a co-Director of the multi-disciplinary UK Energy Research Centre (UKERC), an invited expert member of CIGRE Study Committee C1 on System Development and Economics and a member of the Council of the IET Power Academy, an initiative to promote electric power engineering as a graduate career in the UK.

Poul Ejnar Sørensen received the M.Sc. degree in Electrical Engineering in 1987 from the Technical University of Denmark. In 1987, he was employed as researcher at the Wind Energy Department of Risø National Laboratory. He currently holds the position as professor in Wind Power Integration and Control at the Technical University of Denmark. His research in wind power integration and control include a variety of technical disciplines including power system control and stability, dynamic modelling and control of wind turbines and wind farms, and wind fluctuation statistics. He has many years of experience with standardisation, and is currently the convener of IEC 61400-27 on Electrical Simulation Models for wind power.

Tobias Hennig was born in Meiningen/Germany and received the Master Degree in Electrical Engineering (with distinction) from the University of Duisburg-Essen, Germany. Since 2013 he is working at the Department Transmission Grids at Fraunhofer IWES, Institute for Wind Energy and Energy System Technology in Kassel, Germany. His project works are dealing with power system stability of electrical grids with high penetration of renewable energy sources. His current research interests are planning and operation aspects of large-scale offshore and continental power systems including HVDC applications.

8. Pictures

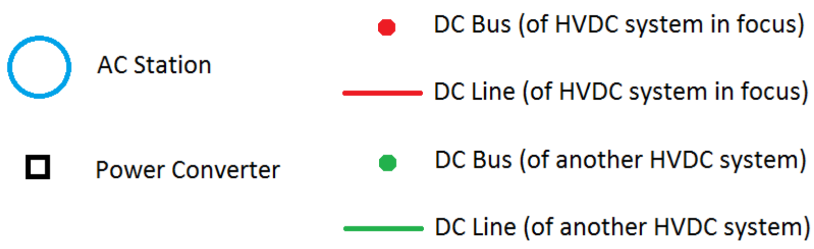

Figure 1: Symbols

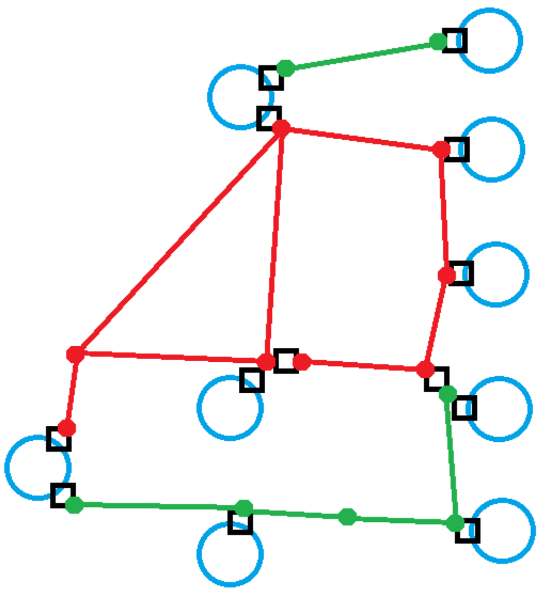

Figure 2: The CIGRE B4 DC Test Grid

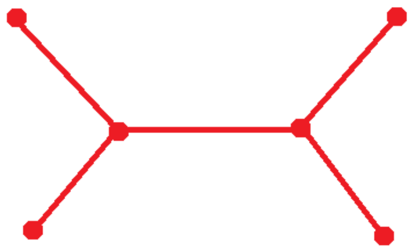

Figure 3: HVDC system

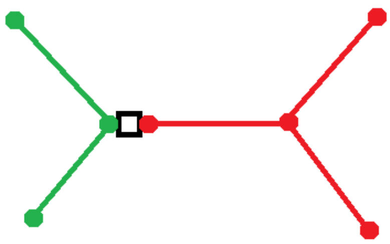

Figure 4: HVDC grid

Figure 5: ***Branches***

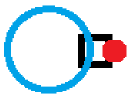

Figure 6: ***Terminal***

Figure 7: ***HVDC system terminal - HVDC grid branch***

Figure 8: ***Connection points***

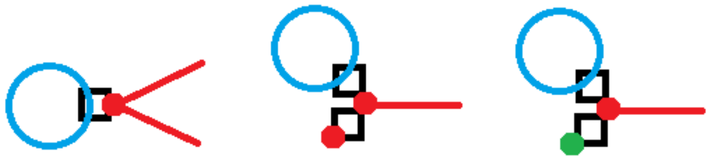

Figure 9: ***Nodes***

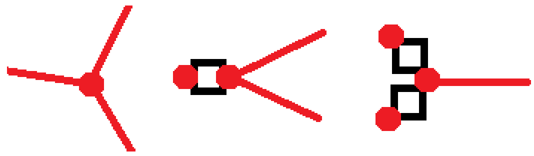

Figure 10: ***Hubs***

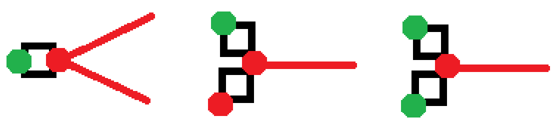

Figure 11: ***HVDC system nodes – HVDC grid hubs***

Figure 12: ***Supernodes***

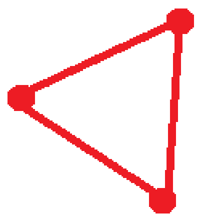

Figure 13: ***Mesh***

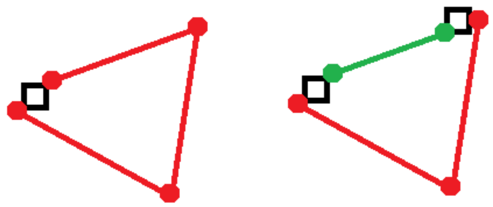

Figure 14: ***Controllable meshes***

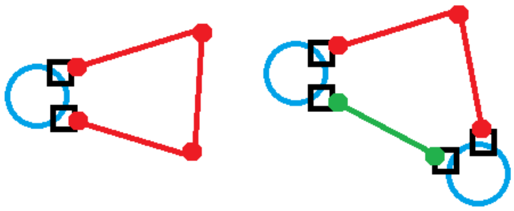

Figure 15: ***Pseudo-meshes***

Figure 16: Two-*terminal HVDC systems*

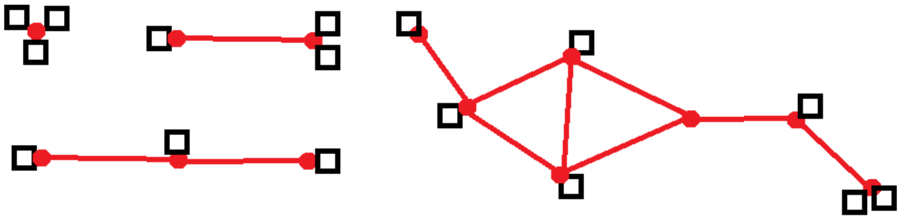

Figure 17: Multi-*terminal HVDC systems*

Figure 18: Back-to-back *HVDC systems*

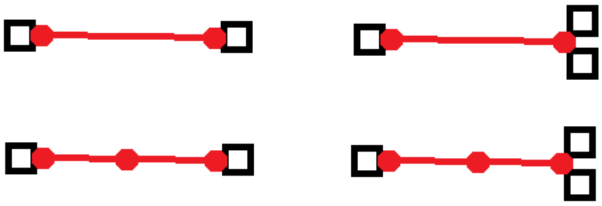

Figure 19: Point-to-point *HVDC systems*

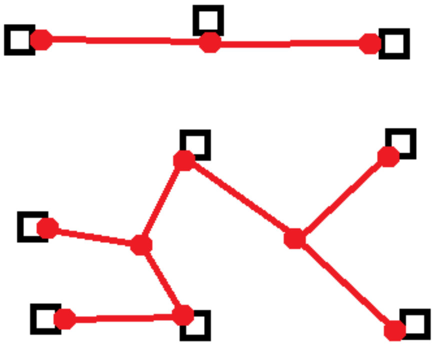

Figure 20: Radial *HVDC systems*

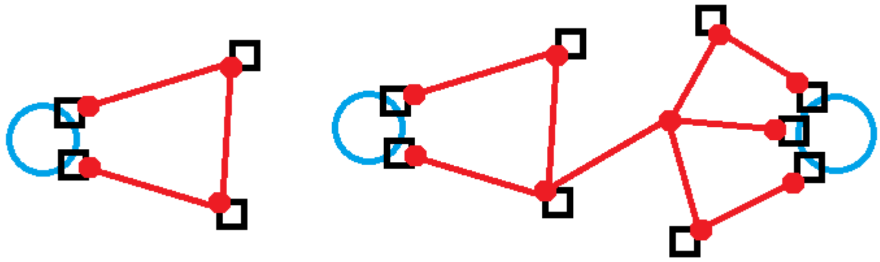

Figure 21: ***Pseudo-meshed HVDC systems***

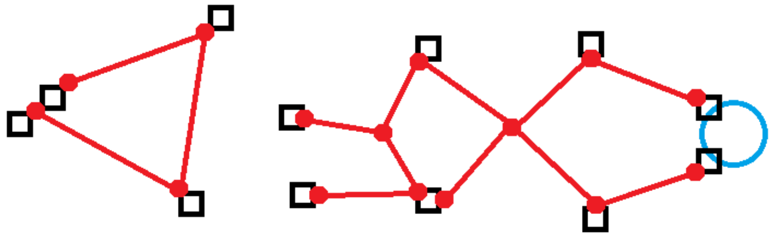

Figure 22: ***Controllable-meshed HVDC systems***

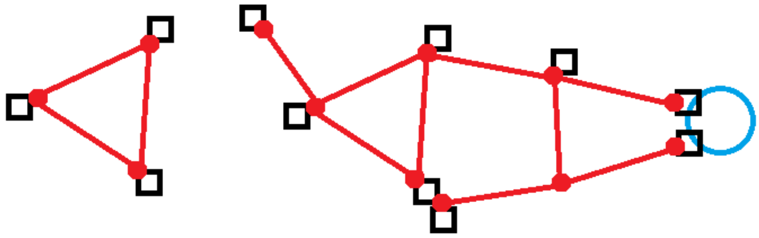

Figure 23: ***Meshed HVDC systems***

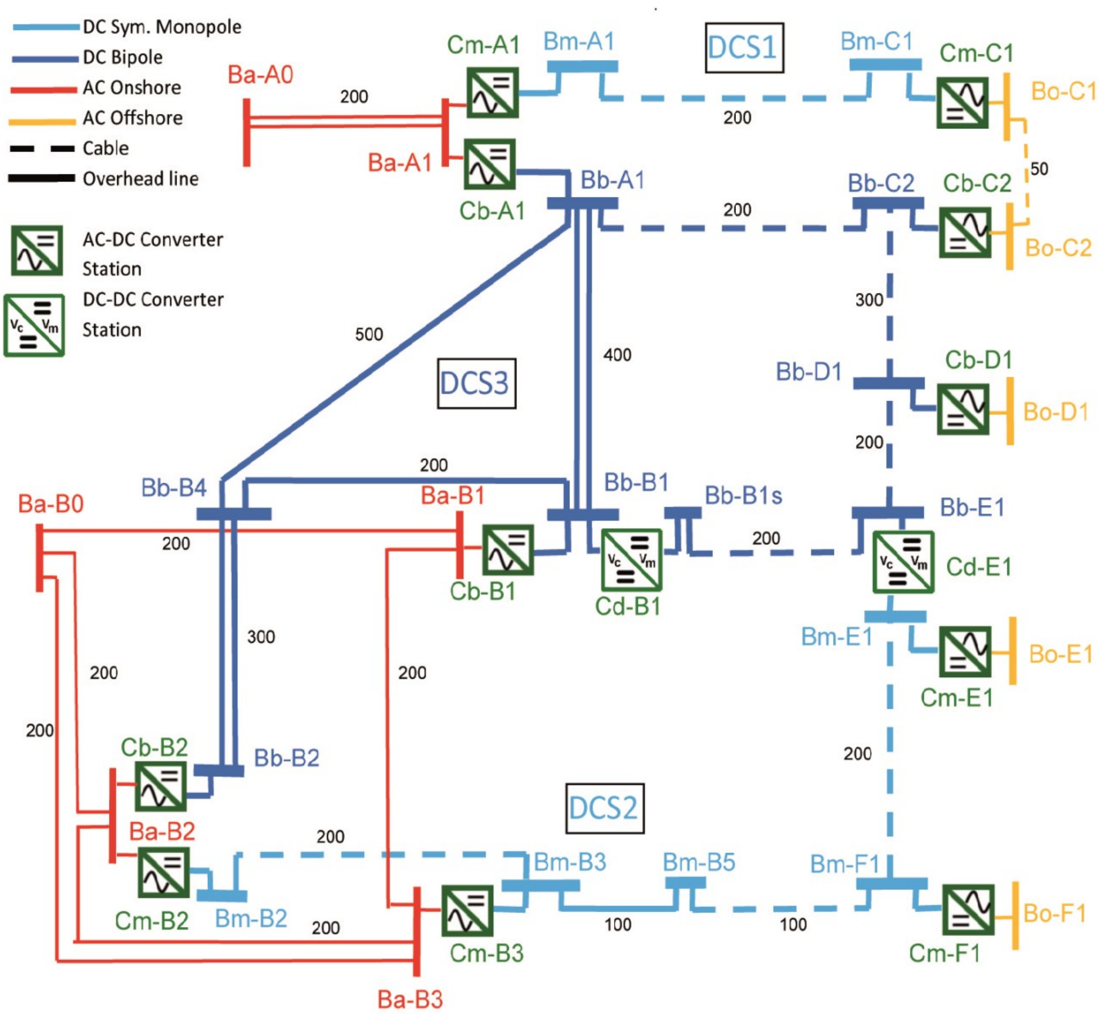

Figure 24: The CIGRE B4 DC Test Grid

9. Tables

Table I: *Bus* types of the CIGRE B4 DC Test Grid

DC *bus*	*Bus* type	*Supernode*
Bm-C1	*Connection point*	No
Bm-A1	*Connection point*	Yes
Bb-A1	*Node*	
Bb-C2	*Node*	No
Bb-D1	*Node*	No
Bb-B4	*Hub*	No
Bb-B1	*Node*	No
Bb-B1s	*Connection point*	No
Bb-E1	*Hub / Node*	No
Bm-E1	*Node*	No
Bb-B2	*Connection point*	Yes
Bm-B2	*Connection point*	
Bm-B3	*Node*	No
Bm-B5	*Connection point*	No
Bm-F1	*Node*	No

Table II: *Loop* types of the CIGRE B4 DC Test Grid

Loop type	*Mesh*	*Controllable-mesh*	*Pseudo-mesh*
Involved *busses*	Bb-B1	Bb-B1	Bb-B1
	Bb-B4	Bb-A1	Bb-B1s
	Bb-A1	Bb-C2	Bb-E1
	Bb-B1	Bb-D1	Bm-E1
		Bb-E1	Bm-F1
		Bb-B1s	Bm-B5
		Bb-B1	Bm-B3
			Bm-B2 Bb-B2
			Bb-B4
			Bb-B1

Table III: *HVDC system* properties of the CIGRE B4 DC Test Grid

HVDC system	Complexity	Topology	Size
DCS1	Two-*terminal*	Point-to-point	Not large
DCS2	Multi-*terminal*	Radial	Not large
DCS3	Multi-*terminal*	*Meshed*	Large