High Penetration of Inverter Based Generation in the Power System: A Discussion on Stability Challenges and a Roadmap for R&D

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***Abstract*—This paper presents an overview of the main technical challenges that are derived from the high penetration of power electronic interfaced generation (PEIG) units in the power system by 2030. In order to cope with all these challenges, innovation, research and development in the electrical energy business is crucial. The paper provides a roadmap towards the successful integration of large scale PEIG in the power system focusing on system observability, controllability, flexibility and coordination as boundary conditions. It is concluded that international and multilateral developments are essential to achieve a secure and sound socio-economic system operation. Coordinated decisions lead to enhanced network security and cost efficiency. The common understanding of roles, interoperable or common analysis tools and procedures are key factors for successful realisation of future networks.**

Keywords- HVDC, PEIG, High penetration of inverter based generation, System Operation Challenges, Power System Stability, Roadmaps for R&D.

I. Introduction

The penetration of power electronics interfaced generators (PEIG) and high voltage direct current (HVDC) transmission is anticipated to increase rapidly in the European power system by 2030 [1]. Figure 1 presents the anticipated PEIG installed capacity in the European system by 2030 which can reach up to 60% of the total installed generation capacity. For some regions within Continental Europe (notably peripheral systems with weak interconnection) the challenges associated to PE will be more prominent and could appear sooner than in the rest of the Continental EU.

PEIG is mainly connected to the distribution level. In comparison to conventional synchronous generators, PEIG exhibits small overloading and nearly no inherent energy storage capability. Depending on the technology, the prime mover of PEIG might contain the possibility to store or release energy (e.g. inertia of wind turbine rotors). The prime mover is generally decoupled from the grid through the power electronic interface. The dynamic behaviour of PEIG is mainly dominated by their control loops. These control loops can exhibit a broad frequency bandwidth and it can be shaped within very short time frames to achieve the desired behavior. On the other hand, the large bandwidth can also trigger control interaction phenomena that today are not yet visible in the power system but might arise in areas with low short circuit power and/or high penetration of PEIG. PEIG need – at least with todays' state of the art control – a stable grid voltage and a minimum short circuit power level in order to operate properly.

In consequence, the transition from a power system based on conventional synchronous generators (centralized) to one with PEIG mainly in the distribution levels would result into a different dynamic profile for the power system, above all concerning with the decrease of system inertia and the reduction of short circuit power levels in the transmission network (with all the effects it introduces e.g. for system protection, voltage and rotor angle stability). With regard to the interconnected European Continental Power System, those effects might not become evident in the short term, but they will become more and more visible in case of severe contingencies (system split scenarios when the penetration of PEIG in parts of the grid might reach up to 100%). In smaller systems (e.g. GB) the impacts of the above mentioned interactions are already noticed today.

In TYNDP 2018 [1] scenarios, cross-border AC connections were analysed and showed severe bottlenecks which can be solved by network reinforcements allowing the increase of the cross-border exchange capacity. However, the reinforcement by AC connections would require enormous grid extension. Using high voltage direct current (HVDC) transmission technology, the grid reinforcement can be kept much smaller and additional features of HVDC technology can be used stabilizing the existing AC grid. The integration of large scale power electronic interfaced generation (PEIG) in the European power system also requires for large transmission capacity and grid expansion planning, facilitated by means of HVDC transmission. Figure 2 presents the planned installed capacity of HVDC systems in Europe by 2030 (including also the share of embedded links). Additionally to HVDC systems, FACT devices such as SVC or STATCOM will be needed for reactive power compensation, voltage control and enhancement of transmission capacity of existing lines [2]. Consequently Transmission System Operators (TSOs) have to ensure a stable and secure power system under these changing conditions, taking into account various scenarios and contingencies including a system split (as occurred in 2006). TSOs have to lay the foundation to integrate large amounts of PEIG, HVDC and other power electronic based devices by developing adequate connection rules etc.

This paper provides an overview and discussion of the main system operation challenges linked to the high penetration of PEIG. The focus is placed mainly on system stability and the way that the dynamic profile of the system is anticipated to change. Moreover, the paper addresses the potential solutions which are part of the roadmap towards the power system development of 2030, where innovation will play a crucial role.

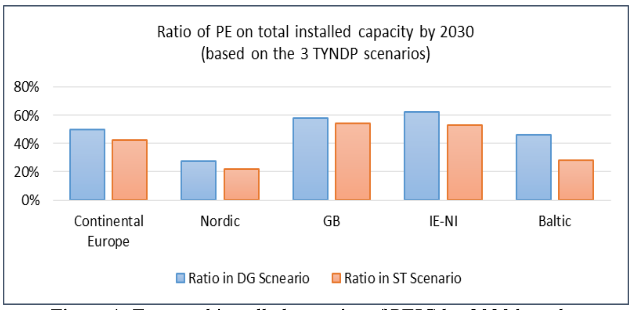


Figure 1: Expected installed capacity of PEIG by 2030 based on ten year network development plan TYNDP 2018 data.

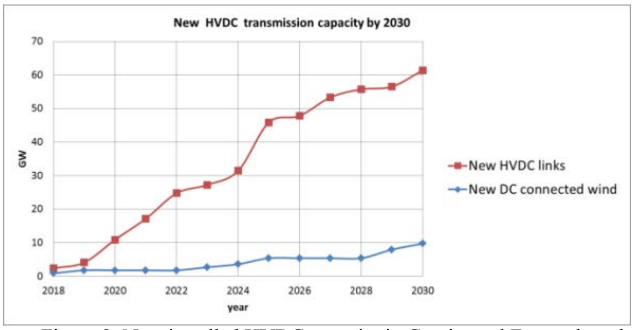


Figure 2: New installed HVDC capacity in Continental Europe based on TYNDP 2018 data.

II. TOWARDS AC-DC TRANSMISSION NETWORKS

A. *Embedding fully controllable technology*

Modern HVDC transmission systems use voltage source converter technology (VSC) with modular multilevel converter (MMC) and exhibit a high degree of controllability [3]. More specifically, HVDC transmission links are capable to independently regulate their active and reactive power infeed in very short time, capable to facilitate dynamic voltage control, provide black start functionality and enhance the power system stability, for instance by local control (fast reactive current injection, Power Oscillations Damping, etc.) or integrated with advanced wide area control schemes. Similar to PEIG, HVDC have usually very limited overloading capability and short circuit current contribution [4].

Both HVDC and phase-shifting transformer (PST) are important technologies for load flow control. HVDC links utilizing VSC for bulk power transmission have the advantage of being fully controllable, while PSTs are installed to re-direct power flows [7]. Using HVDC technology, higher capacities can be provided compared to upgrading existing AC links. Besides accommodating large transmission capacity with minimum footprint, HVDC systems could enhance the AC transmission system performance transforming it to a so called AC/DC transmission system (cf. Figure 3) which exhibits enhanced controllability, flexibility and resilience. Additionally, HVDC links could be integrated in the optimal N-1 secure dispatch of the system optimizing system operation [5, 6].

B. *Towards interconnected HVDC systems*

Currently HVDC systems in Europe are predominantly planned to be used either as bulk transmission corridors (e.g. interconnectors) or used for grid connection of large and far from shore offshore wind power plants (North Sea) [8]. Embedded HVDC systems, based on VSC technology, offer a high potential for increasing AC/DC system operation flexibility, acting as a backbone system mitigating the local grid congestion and maximizing transmission capacity. In a next step interconnected HVDC structures based on existing HVDC systems, which may expand in large geographic zones through continental Europe, could further help the transmission of renewable energy resources more effectively, stabilizing the AC grid operation (e.g. balancing), reducing re-dispatch costs and incorporating effectively a large mix of renewable power generation (wind, photovoltaic, hydro and geothermal).

The construction of such backbone HVDC transmission systems could also effectively tackle power system stability bottlenecks (congestions) as a result of large penetration of PEIG (frequency, voltage stability and damping electromechanical oscillations). In some parts of the European systems, HVDC converters could provide grid forming functionality and system restoration services which are usually provided today by means of conventional generation units. To which extent a meshed HVDC system is required, or if an expanded multi-terminal system might be sufficient, is still an open question.

Point-to-point HVDC systems have a rather straight-forward control philosophy and are mainly viewed from TSOs as highly controllable (in terms of active and reactive power) bulk transmission systems. On the other hand, multi-terminal HVDC grids introduce additional complexity in the equation of the system operation and security of supply which is primarily reflected in the control and the interoperability of HVDC stations [9, 11]. In contrast to point-to-point HVDC connections where commonly a single manufacturer is responsible for the project delivery and design, in multi-terminal HVDC grid structures various vendors and technology solutions need to be effectively integrated in order to minimize CAPEX costs. Hence, the interoperability, the robust control design, the optimal system operation and protection are key variables. All these components lead to the so called need for requirement on the DC side of HVDC grids which is the topic on technology research and regulatory ongoing activities [12-16].

III. Power System Challenges due to Massive Pentration of Power Electronic Interfaced Generation

Besides the classical widely accepted definitions of frequency, voltage and rotor angle stability, the non-linear nature of PEIG and HVDC systems has resulted in the definition of a new stability phenomenon mainly associated to the control interactions of power electronics. A good example is the harmonic stability which reflects the interactions of PEIG and HVDC controls with the grid resonance in a wide frequency range. With the previous facts as boundary conditions, the next paragraphs present the main stability challenges that are linked to the high levels of PEIG penetration in the power system [17-18].

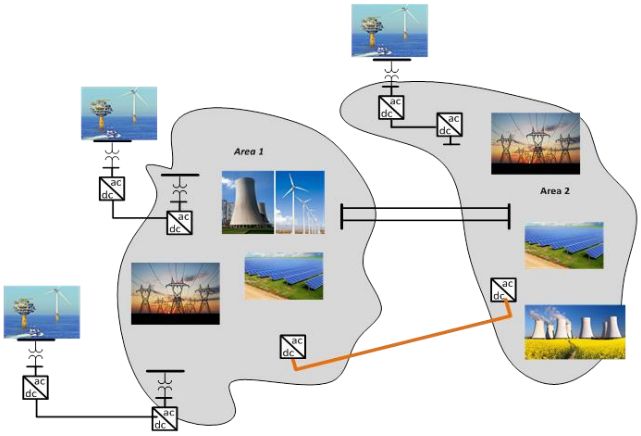


Figure 3: Generic overview of a hybrid AC-DC transmission system accommodating high penetration of PEIG and HVDC transmission.

A. Frequency stability

The total system inertia (TSI) reflects the amount of kinetic energy stored in the rotating shafts of the conventional synchronous generators and motors. The direct consequence of reduced TSI (as reported already in the TYNDP 2018) for the frequency stability in the containment period is the increased rate of change of frequency (RoCoF), which can be problematic if exceeding the RoCoF withstand capability of synchronous generators. The capability of PEIG and HVDC to react to frequency changes depends entirely on the control loops and sensors that are implemented (time window for RoCoF estimation) as well as on the stored energy that can be released by the PEIG. For the Continental European system, the case of a system split becomes a critical challenge when high penetration of untuned PEIG is considered.

B. Rotor angle stability

Rotor angle stability is mainly associated with the capability of conventional synchronous generation units to remain in synchronism when exposed to network disturbances (mainly grid faults). Rotor angle stability is classified into transient and small signal stability. When referring to transient stability, the reduction of the total system inertia (TSI) would affect significantly the critical clearing times of remaining conventional units (which is a metric that reflects the tolerance of synchronous generation units to grid faults). In addition, the reduction of critical clearing times, affects also the system protection settings (time that grid fault need to be cleared before the generation units would trip).

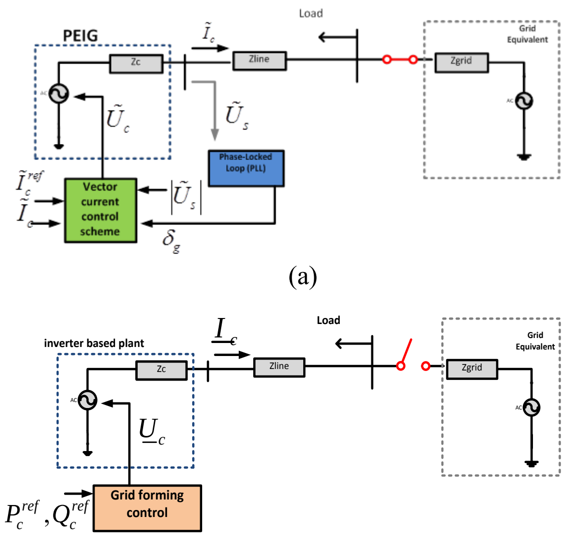
The second category of rotor angle stability refers to small signal stability (or interarea electromechanical oscillations which are present through the continental European system). The increased penetration of PEIG would displace large conventional generation units which are equipped with power system stabilizers (PSS). Substituting synchronous generators with PSS will improve the small signal stability if the PEIG are accompanied by power oscillation damping (PODs) controllers. Otherwise, these technologies might worsen the damping of the oscillatory modes. FACTs and HVDC systems could enhance small signal stability in PEIG dominated grids.

C. Voltage stability and reduced short circuit currents

Voltage stability is associated with the reactive power flow in the network and the ability to maintain stable voltage profiles during steady state and grid fault conditions. Conventional synchronous generators are capable by means of their automatic voltage regulators (AVRs) to effectively control the grid voltage within the P-Q curves. Additionally, during grid faults synchronous generators provide high levels of short-circuit currents, in contrast to PEIG and HVDC which can typically only inject between 1 and 1.2 times their rated current as fault-current. The reduction of short circuit power in the network under high penetration of PEIG would lead to a wider propagation of voltage dips during grid faults (on a larger geographic area), more noticeable effect in the medium and low voltage levels leading to potential disconnection of distributed generation (depending on the Grid-code and applied protection schemes) posing risks to frequency stability (voltage dip induced frequency dip phenomena). In principle adequate setting of fault-ride-through capabilities and protection setting of distributed generators would prevent these consequences.

D. Voltage formation and grid forming control

PEIG and HVDC transmission exhibit a main property: their robust and stable operation depends on the presence of a stiff voltage (sinusoidal, harmonic-free waveform) at the grid connection point. It is common to identify this grid connection point stiffness in terms of short circuit ratio (SCR), defined as the ratio of the short circuit power at the connection points to the rated apparent power capacity of PEIG or HVDC unit. As a rule of thumb, values of SCR below 2 are prone to instabilities (mainly control interactions and loss of synchronization). Hence, any PEIG could be seen today from grid synchronization perspective rather as a negative load with grid supporting functionality. This control principle of PEIG is usually called "grid following" operation (cf. Figure 4(a)). It has been identified through recent studies that power systems with high penetration of PEIG (above 65%) applying grid following control are prone to instabilities, of mainly control interactions nature [19-23]. Opposite to grid following control, grid forming control is introduced as a new control operating in PEIG dominated systems (cf. Figure 4(b)).



(a)

(b)

Figure 4: Generic schematic overview of a PEIG with (a) grid following control, (b) grid forming control.

E. Control interactions

Control interactions of HVDC systems and/or PEIG with the grid resonance are mainly affected by the utilized control strategies and the electrical parameters of the external AC transmission grid impedance (including the level of grid SCR). These interactions are visible as sub-synchronous, near synchronous or higher order frequency oscillations up to 9kHz. HVDC systems with potentially different converter technologies will be installed and operated in the high voltage transmission system. In some cases, two or three HVDC stations will be connected to the same or electrically close substations (as it is already the case in Germany) [24].

The interoperability and controllers interactions of such HVDC stations in a future power electronic dominated grid with high penetration of PEIG is a challenge that TSOs have to address and mitigate in order to ensure a certain level of power system security of supply while accommodated large penetration of PEIG. Interoperability is associated to the robust operation of HVDC systems and PEIG minimizing the undesired control interactions. Identification and mitigation of such control interactions during critical grid situations (especially the one with reduced levels of short circuit current levels) and various grid configurations will become essential in order to avoid unnecessary HVDC link trips that could jeopardize the security of supply. An example of such case is provided in Figure 5. The simulation result is from a real case where grid topology changes could trigger resonances between the control loops of HVDC stations and the grid impedance, here at 1.1kHz.

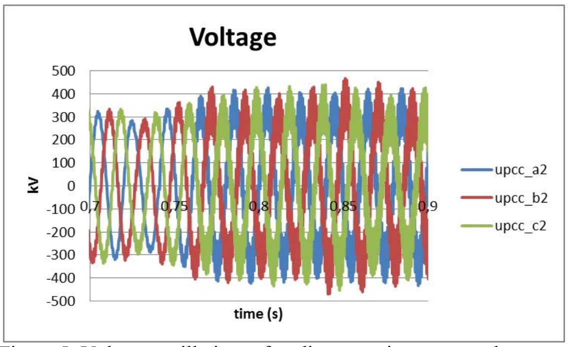


Figure 5: Voltage oscillations after disconnecting two synchronous generation units.

Although control interaction is a local TSO challenge, it can become an inter-TSO problem or global system issue when significant amount of DC connected transmitted generation and transmission is tripped. Current grid codes, including NC-HVDC, clearly mention that all control interactions need to be alleviated and mitigated. However, in this direction there are not yet standard methodologies on control interactions studies, widely accepted. Some TSOs already facing such issues have adopted the impedance based harmonic stability approach as a methodology [25, 26]. However, its validity needs further standardization and meticulous analysis especially for MMC-HVDC stations where the impact of frequency coupling in the near to frequency region is of paramount importance. From TSO perspective, a thorough analytical modelling is a challenge that is in principle limited to the data confidentiality and lack of open or white box model. So, numerical methods and impedance based approached seem more realistic for such control interaction studies.

F. Protection malfunction

Another risk associated to the reduced levels of short-circuit currents in the system is the malfunction of fault detection and protection schemes both for transmission and distribution systems. Classical overcurrent and distance protection might not be able to effectively detect and clear grid faults in a fast and effective manner, especially if the fault levels are very close or equal to the steady state currents. Also, fault selectivity, especially for unbalanced grid faults becomes a challenging task primarily due to low short-circuit currents and secondary due to the positive sequence oriented control operation of the PEIG and HVDC today.

IV. Roadmap towards Power Electronic Dominated Power Systems

This section presents a roadmap that would enable the stable and robust operation of power systems with high levels in PEIG. The roadmap is based on five main pillars, namely: the enhancement of system stability, enhancement of system observability, flexibility, advanced tools and models and enhancement of coordination (cf. Figure 6).

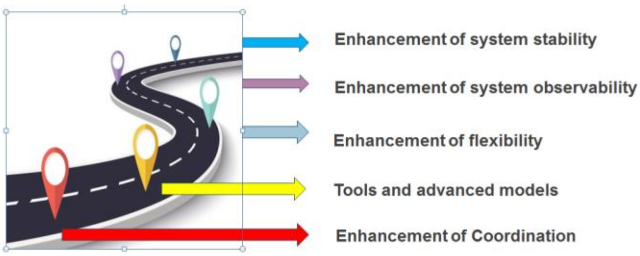


Figure 6: Roadmap for inverter based dominated power systems.

A. Enhancement of system stability

PEIG and HVDC transmission introduce increased control potentials that can be further developed to enhance system operations and system stability, such as: synthetic inertia, grid forming controls, supported system restoration, active and reactive power control, dynamic voltage control, power oscillation damping and active harmonic filtering among others. Two broad categories of such solutions could be identified in order to accommodate high penetration of PEIG, namely already implemented short term solutions and long terms solutions. Figure 7 presents the mapping of main short-term and long-term solutions towards strengthening power system stability.

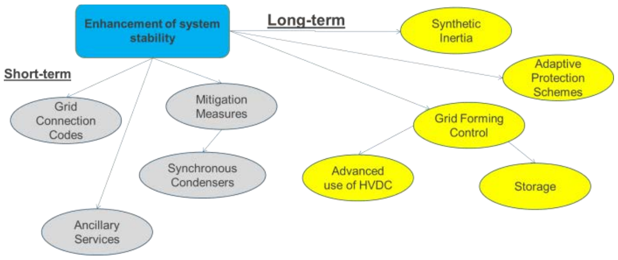


Figure 7: Enhancement of system stability in short and long term actions.

1) Short-term solutions

From the TYNDP 2018, the reduction of total system inertia is identified as a stability bottleneck. The rate of change of frequency (RoCoF) is an indicator that enables the quantification of frequency stability in the frequency containment period. Conventional generation units need to ensure stable response under high levels of RoCoF which are expected in cases of increased levels of PEIG. Grid Connection Codes for generation units prescribe the withstand capability of conventional units. Various short term solutions (e.g. synchronous condensers and rotating masses) could limit the RoCoF and keep a certain threshold of minimum inertia in the system.

2) Long term solutions

Grid forming control concepts could facilitate the stable operation of a PEIG dominated power system. Novel grid forming control schemes applied to PEIG, grid connected storage and HVDC links could ensure natural voltage-source behaviour of PEIG instead of "negative constant load" behaviour of the grid following control today. Grid forming control could remove the dependency of PEIG and HVDC on the short-circuit power levels in the network, increasing the hosting capacity in weak grids, could provide local frequency smoothing capability, ensure high RoCoF withstand capability and an inherent response to power imbalances.

Grid forming control is in principle associated with the stable and robust operation of PEIG and HVDC links with low short-circuit power levels. Moreover, the inherent provision of synthetic inertia without the need for frequency and angle measurement elements. Although grid forming control is not yet inserted in the majority of national implementations of RfG and HVDC connection Codes, it is anticipated by 2030. An example is the network code (NC) HVDC national implementation in Germany where grid forming control for HVDC connections will already enter in force in 2020.

Grid connected storage combined with FACTs (Flexible Alternating Current Transmission systems) have been so far mainly restricted to the control of reactive power and the upgrade of transmission capacity. Integrating energy storage technology with FACTs and grid forming control could improve power system stability and ensure cost-effective grid operation of systems with high level of PEIG. The FACTs integrated with storage not only increase system controllability, but optimise system operation, controlling active and reactive power flows and dispatch. The primary active power source could be battery storage or other fast active power source such as flywheels or supercapacitors, depending on the time constants that are needed for the specific system application.

B. Enhancement of system controllability and observability

The fast system dynamics in AC/DC networks adds complexity to power system operation which therefore requires effective tools to measure in real time the dynamic stability margins and evaluate stability indicators to settle the acceptable stability limits.

1) Real time monitoring tools

Wide Area Monitoring Systems based on Phasor Measurement Units (PMUs) are being used by TSO/ISOs world-wide in the operational environment, giving the control room information about the dynamic behaviour of the network and, consequently increasing awareness for system dynamics. PMUs combined with communication technology bring the possibility to TSOs to monitor system dynamics in real-time with synchronised information, allowing the development of remedial actions, automatic control schemes, restoration strategies in order to secure system's stability.

Monitoring coupled with new generation of EMS/SCADA will allow more analysis of capabilities, such as dynamic security assessment, short-circuit power levels, and evaluation of TSI, and provide decision support to control room operators, such as remedial actions optimisation.

2) Definition of Power quality criteria

Power quality challenges during normal operation and transients have started to be observable due to the high penetration levels of PE in some control areas. The latter manifests itself as high levels of high order harmonic distortion as well as control interactions that could lead to trip of PE units. New power quality criteria are needed in order to ensure the minimum level of acceptable distortion. Models and tools would enable identification of potential risks in the planning phase of projects as well as mitigation techniques to be implemented.

3) Enhancement of coordination between TSO and DSOs

The integration of distributed generation forecasts into the power system planning and operation is required to effectively tackle the challenges of large scale integration of PE. The presence of significant generation capacity embedded in the distribution level creates possibilities for their participation in providing the capabilities and ancillary services which are needed to maintain a secure transmission system, e.g. active participation in frequency control.

Cooperation between the different actors of the power system is needed in order to gather the data for grid models that will enable assessment and enhancement of the power system stability in the future. Especially, the reinforcement of cooperation between TSOs and DSOs also needs fast pace developments. The role of distributed resources in the participation of system flexibility provision is expected to increase. In this context, the amount of information exchanged among players is expected to expand rapidly, because it improves the awareness, controllability of the system and, consequently, network security.

4) Tools and advanced models

The presence of highly non-linear PEIG and HVDC systems increases the need for an accurate representation of the AC-DC transmission systems both in the time and frequency domain. The dynamic security assessment (not limited to the classical rotor angle, voltage and frequency stability) of such power electronic dominated networks will require both for accurate and computationally efficient models.

The complexity of HVDC systems and PEIG in conjugation with the intellectual property concerns linked to their models, controls and data, requires for the proper legal requirements for promotors to provide the necessary data to the TSOs, and for TSOs to have adequate and interoperable tools and advanced modelling methodologies in order to account for instability risks, mainly the one linked to the control interactions. Moreover, the network models need to be enhanced in order to capture their frequency dependent behaviour (grid resonance), especially in control zones when the penetration of HVDC and PEIG is high. Advanced modelling methodologies, tools and platforms in offline and potentially in real-time platforms (if needed) will facilitate the dynamic security assessment of networks with high penetration of HVDC and PEIG units. A good cooperation among TSOs will enable effective network studies at national, regional as well as on a pan-European level.

5) Enhanced HVDC system control, protection and interoperability

A variety of HVDC technologies is already installed or planned to be installed in Europe (e.g. LCC, VSC, 2-Level topology, Modular Multilevel Converters (Full Bridge, Half Bridge, HVDC Cables and overhead lines). The interoperability of HVDC stations needs to be ensured with respect to control and protection allowing different HVDC system topologies, vendor specific technologies to be integrated in a technically cost effective manner. The question which arises is which technologies/concepts/design are still required/missing in order to reach technological interoperability within a multi-terminal HVDC system frame incorporating already commissioned and future HVDC technologies/projects. Therefore a common understanding of control interactions of existing and future connections need to be analysed and well understood, addressing TSO specific research questions (e.g. sub-synchronous interactions, harmonic stability, DC disturbance propagation and compatibility with existing assets). In addition to managing possible control interactions, design and implementation of advanced tools for the assessment of different HVDC technologies within a DC multi-terminal system or grid requires attention in further research initiatives.

Additionally, standardization of DC voltage levels and coupling is still an open regulatory topic. Due to the developments in HVDC cable technology and the individual national planning within Europe a common voltage level is not available. Thus, research activities need to explore the possibility of coupling different voltage levels for incorporating a high amount of already commissioned installations or if specific installations should be left out. The coupling of different voltage levels could be achieved by either using dedicated DC-DC converters or DC-AC-DC conversion. Therefore also a variety of open issues needs to be addressed especially with respect to a robust operation and power balancing between the different voltage levels in normal operation and during power set-point changes and contingencies.

Currently the protection system design of (meshed) HVDC grids and its fault selectivity of HVDC line sections are not incorporated in existing or planned projects - neither is it a standard process. The latter was performed under the assumption that faults in point-to-point HVDC projects (DC interconnectors) require mostly current interruption at both connected converter stations (sending and receiving terminal). Hence, a DC breaker or fault blocking converters (with the capability to block the DC fault currents) is not yet utilized/exploited in European projects. Utilizing DC circuit breakers (or the full functionality of fault blocking converters with residual current breakers) in future HVDC grid systems will be needed in order to ensure that only the affected grid section would require disconnection from the HVDC grid. The latter will ensure safe operation and security of supply of AC-DC systems. Moreover the expansion of point-to-point HVDC links to HVDC multi-terminal systems up possibly up to HVDC grids requires harmonized and coordinated planning. Thereby a robust backbone system for the AC grid can be formed (cf. Figure 8). Further research efforts need to present the level that an HVDC grid can be operated unselectively and at which level of meshed interconnection (number of converters and topology – and therewith loss of power) the installation of DC circuit breakers is required.

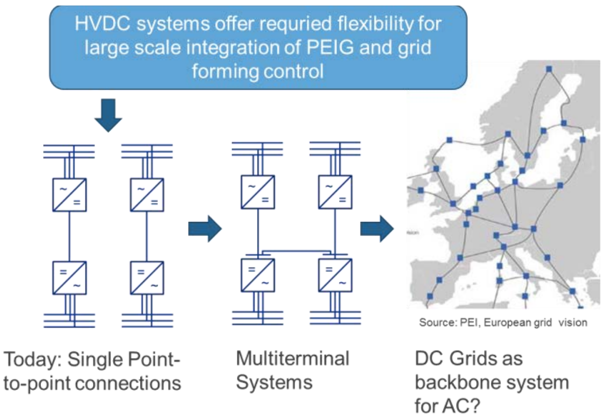


Figure 8: Possible evolution of HVDC systems

V. Conclusion

The power system is migrating from the traditional conventional generation based AC system to a hybrid AC/DC system which will accommodate a high level of PEIG. The operational challenges due to the high penetration of PEIG are identified within the context of this report. New HVDC interconnectors and FACTs introduce a higher level of control possibilities, which can be used to enhance system security of supply. In addition, the utilisation of novel control concepts to effectively use the technologies available will have a significant impact on how to operate the electrical energy system in the future.

In order to cope with all the challenges, innovation, research and development in the electrical energy business is crucial. Moreover, a roadmap is provided here in the context of this report towards the successful integration of large scale PEIG in the system focusing on system observability, controllability, flexibility and coordination with power system stability as boundary conditions. It can be concluded that international and multilateral developments are essential to achieve a secure and sound socio-economic system operation. Coordinated decisions lead to enhanced network security and cost efficiency. The common understanding of roles, interoperable and common analysis tools and procedures are key factors for a successful realisation of future networks. TSOs are confident that the provided road-map will lead to advanced system operation ensuring system security of supply with high levels of PEIG.

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