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Comparison of European Network Codes for AC- and HVDC-connected Renewable Energy Sources

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***Abstract*—Developing an integrated pan-European energy system based on renewable energy sources (RES) has technical and economic benefits. In this way, harmonized rules for grid connection of RES are required at the international level. Wind energy is one of the most promising renewable energy worldwide. The integration of wind energy into the power system is overgrowing through onshore and offshore installations. The European network codes have been drafted and regulated for AC- and HVDC-connected power-generating modules (PGM) in two separate international network codes. This paper presents the main aspects of the regulated European network codes and compares them. Accordingly, it is recommended to define the European network codes based on RES connection type (AC and HVDC) rather than the onshore and offshore categorization. Also, the main requirements for HVDC-connected generations are being regulated all around Europe. Therefore, the integration of RES into European power systems via HVDC transmission would be easier.**

***Index Terms*—European network codes, renewable energy sources, power-generating modules, HVDC-connected PGMs**

I. Introduction

The integration of renewable energy sources (RES) into the power system has been an important challenge for power system developers and operators. The European Commission has planned a fully renewable power grid by 2050, which is called the pan-European super grid to ensures a reliable, uniform and carbon-free European power grid [1-5]. In this regard, a harmonized international rules for grid connection of power generations should be set out to provide a clear legal framework for interconnection of different grids and facilitate the RES integration.

Wind energy is one of the most promising renewable energy resources worldwide. The expected cumulative installed capacity of onshore and offshore wind power plants (WPP) with an outlook to 2022 in Europe is shown in Fig. 1. Accordingly, the new installations of wind energy capacity at an average rate of 16.5 GW per year is expected in Europe. The total installed capacity would reach 253 GW with a share of 20% from offshore WPPs [1-3].

Harmonization of network codes can improve integration of this substantial amount of wind power along with other RES. The European commission has asked the European network of transmission system operators for electricity (ENTSO-E) to harmonize the network codes in Europe. In this way, European network codes have been regulated for AC- and HVDC-connected power plants in two exclusive codes [2-5].

This paper presents the main aspects of the latest European network codes for the harmonization of European renewable energy generation and interconnections. In section II, the grid interconnections of power plants in general are introduced. In section III, harmonization of European network codes is discussed. Finally, the main aspects of the European network codes are reviewed in section IV, and the main differences and similarities between HVDC and AC connections in the network codes are illustrated.

II. Interconnections of RES

RES can be connected to the main power grid through high voltage direct current (HVDC) or AC transmission systems. The main applications of HVDC are the interconnection of non-synchronous networks, long-distance transport of electrical power, and submarine and underground cable transmission. Therefore, different types of power generation units can interconnect through HVDC transmission systems from offshore or onshore areas. In this regard, HVDC transmission provides an economically viable solution for long distances, especially in case of offshore power plants [5-8].

Currently, wind generation is predominately onshore; however, there is an increasing interest in offshore wind generation

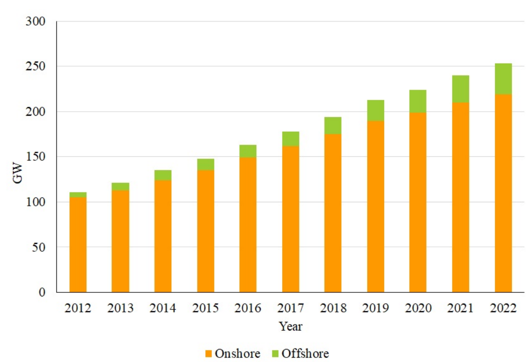

Fig. 1. Expected cumulative installed capacity of onshore and offshore WPPs until 2022 in Europe [3].

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due to limited onshore sites, less public opposition to offshore and maturation of the associated technologies. Evaluation and comparison of different types of topologies and interconnections for WPPs have been done in the literature [8-12]. WTs are connected through medium voltage submarine cables typically at voltage level of up to 33-66 kV to the Offshore AC substation. The transformers in offshore AC substation step up the voltage to 132-200 kV for further power transmission with lower power loss. Offshore AC substation can be connected to the grid at shore either directly through AC cables or HVDC power transmission systems. Fig. 2 displays a typical structure of HVDC-connected offshore WPPs. As it can be seen in this figure, offshore power transmission consist of offshore and onshore HVDC converter stations, AC and DC cables, and offshore AC substations. Hence, the structure and behavior of the HVDC connection are different than a conventional AC grid connection which needs to be considered in regulations and standards for WPPs and, in general, RESs.

III. Network Codes

Power plants are required to provide a certain level of reliability and stability. The integration of generated power into the power system is one of the most critical challenges in renewable energy technologies, especially wind energy. Motivated by the power system reliability and stability issues, grid interconnection requirements, called network codes, have been developed by transmission system operators (TSOs) in different countries. In response to these codes, manufacturers provide their products with features that cope with demanded grid connection requirements. Also, the international collaborations in technology and market of RES demand uniform regulations and standards.

A. Harmonization of European Network Codes

The evolution of network codes has mostly happened at national levels, but considering the recent trends towards an integrated pan-European energy system, focusing on a national level can lead to technical and economic problems in international level. The main aspects of network code requirements for the integration of renewable energy in European countries at the national level have been presented in [13-16].

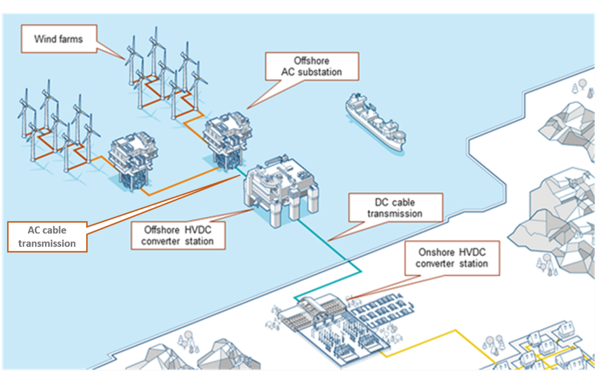


Fig. 2. Typical structure of HVDC-connected offshore WPPs [10].

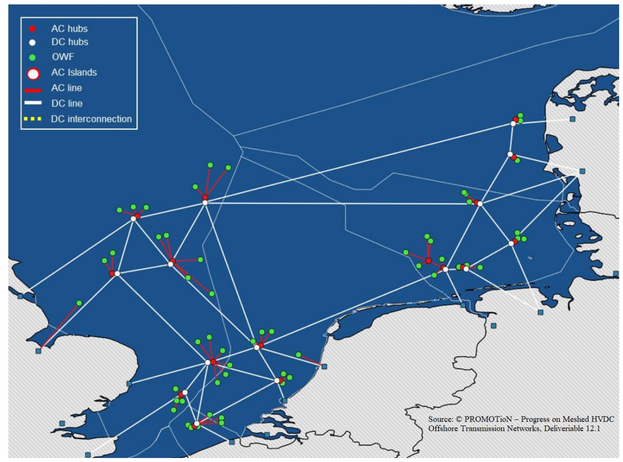


Fig. 3. European distributed hubs concept for offshore grids in the North Sea [4].

The pan-European super grid must facilitate the integration of RES, and manage the power systems interconnections caused by the pan-European electrical energy trade. In this way, the European network of transmission system operators for electricity (ENTSO-E) is founded as an umbrella organization for harmonization of European TSOs. Different scenarios for implementation of the pan-European super grid have been offered by ENTSO-E and relevant industrial and academic partners [2-5]. As an example, Fig. 3 shows the European distributed hubs concept for offshore grids in the North Sea, which is visualized in PROMOTioN's Deliverable 12.1 [4]. This concept presents a meshed international offshore power grid using AC and HVDC transmissions with a high level of flexibility, reliability, and coordination among neighboring countries; however, it demands international regulations and framework.

In this regard, the European Commission requested ENTSO-E to harmonize the national network and market codes for Europe in consultation with all stakeholders. Consequently, the European network codes are drafted by ENTSO-E with guidance from the agency for the cooperation of energy regulators (ACER). Thus, the network code on requirements for grid connection of generators (EU NC-631) [17], and network codes on requirements for grid connection of HVDC systems and DC-connected power park modules (EU NC-1447) [18] came into force as European Commission Regulation in 2016.

The European network codes are serving as a framework for individual TSO network codes. Many TSOs currently are in an adaption process, to align with the European regulation. However, the current implementation of EU network codes is still done in national level, with some (less than before) differences between them. In EU NC-631, the European AC power systems have been divided into five synchronous areas as it is shown in Fig. 4 and listed below.

- Continental Europe
- Great Britain
- Nordic (East Denmark, Finland, Norway, and Sweden)

- Ireland (Ireland and Northern Ireland)
- Baltic (Estonia, Latvia, and Lithuania).

In each of these synchronous areas, the power generating modules are subdivided based on their PCC voltage level and their generation capacity. The capacity thresholds need to be determined at national level to consider the national power system characteristics; however the maximum values for lower thresholds are given in EU NC-631 as illustrated in Table I [17]. Based on this table, the offshore power generations can be considered as type D considering high power capacities ($P > 75MW$) and high voltage connection points ($U \geq 110kV$).

B. Terminology of European Network Codes

Some of the terminologies used in EU regulations for network codes are shortly described in the following to have a better understanding of the regulations [17-18]:

- Connection point: the interface at which the power-generating module, demand facility, distribution system or HVDC system is connected to a transmission or distribution system, offshore network or HVDC system.
- Power park module (PPM): a unit or a group of units generating electricity. This unit is either non-synchronously connected to the network or connected through power electronics which has a single connection point to a transmission, distribution, or HVDC system.
- Offshore PPM: a PPM located offshore with an offshore connection point.
- DC-connected PPM: a PPM connected to one or more HVDC systems via HVDC interface points.
- Power-generating module (PGM): either a synchronous PGM (SPGM) or a PPM.

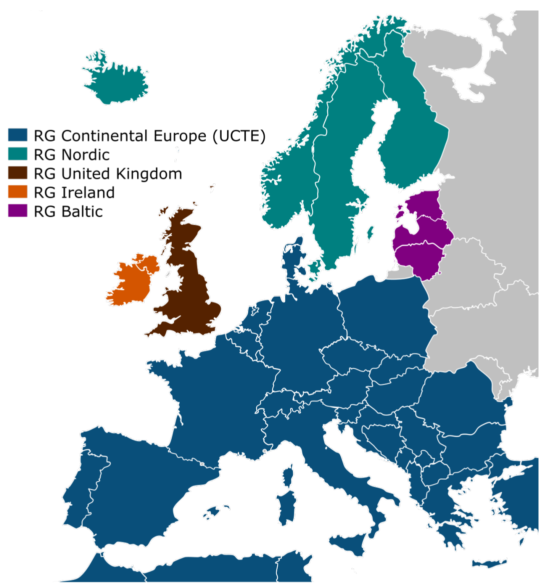


Fig. 4. Different synchronous areas (regional groups) in Europe according to ENTSO-E [5].

TABLE I
MAXIMUM VALUES FOR LOWER THRESHOLD OF CAPACITY, WHICH POWER PLANTS CAN BE ADDRESSED TYPE A, B, C OR D [17].

Synchronous area	$U < 110kV$			$U \geq 110kV$
	A	***B***	***C***	***D***
Continental Europe	0.8 KW	1 MW	50 MW	75 MW
Great Britain	0.8 KW	1 MW	50 MW	75 MW
Nordic	0.8 KW	1.5 MW	10 MW	30 MW
Ireland	0.8 KW	0.1 MW	5 MW	10 MW
Baltic	0.8 KW	0.5 MW	10 MW	15 MW

IV. European Network Codes for RES

The European network codes (EU NC) do provide a good overview of the differences and similarities of network codes among European countries. In EU NC-631, the requirement for PGMs have been stated in four divisions: general requirements for PGMs, requirements for SPGMs, requirements for PPMs, and requirements for AC-connected offshore PPMs. However, many of these requirements are in common, especially between requirements for PPMs and AC-connected offshore PPMs. According to EU NC-631, the connection requirements for offshore AC power generation units are similar to onshore power generations, except for following two conditions [17]: First, the relevant system operator (SO) modifies the requirements. Second, the connection of power plants is via an HVDC connection or an asynchronous network.

Therefore, the network codes for AC-connected onshore and offshore PGMs are mostly similar. In other words, the main differences in the European network codes are between AC- and HVDC-connected PGMs rather than onshore or offshore. This section reviews and compares the EU network codes for AC- and DC-connected PGMs. It should be noticed that the European network codes propose regulations at the international level, and the national implementations of them will not be discussed in this paper.

A. Frequency Stability Requirements

Frequency stability refers to the ability of a power system to maintain the frequency within a specified acceptable range during a severe system upset [19]. PGMs should be capable of remaining connected to the network based on frequency stability requirements, PGMs need to remain connected to the network for a specified time, which depends on value of frequency deviations.

The minimum operating time in different synchronous AC regions as well as HVDC-connected PPMs as a function of frequency deviation are depicted in Fig. 5. The AC-connected power plants consist of the five synchronous areas, which are listed in section III-A. According to the European network codes, the time duration for Nordic, Baltic and Continental European countries are identical. Also, the values for GB are similar to DC-connected PPMs. Apart from the required operating time, there are two main differences in frequency

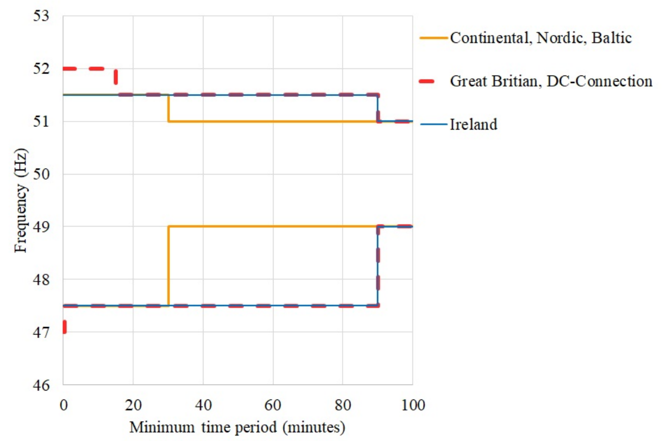


Fig. 5. The minimum operating time in different synchronous AC regions as well as DC-connected PPMs as a function of frequency deviation [17-18].

stability requirements of AC- and HVDC-connected power plants as follows.

- One difference is in the rates of change of frequency (RoCoF) of the system. In DC-connected PPMs, the value of RoCof is specified in the associated network code (± 2 Hz/s), while in AC-connected power plants individual TSOs can specify RoCoF.
- The second difference is that the DC-connected power plants, which connect with more than one control area, should be capable of delivering coordinated frequency control [18], which is not a requirement for AC-connected power plants.

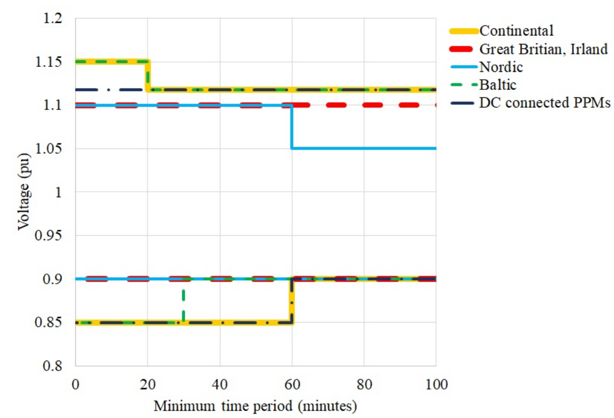
Regarding the RoCoF in DC-connected PPMs, the HVDC converters control the frequency of the local AC grid. Consequently, frequency variation is smooth and RoCoF is expected to be way below the specified limit of 2 Hz/s.

B. Voltage Stability and Reactive Power Requirements

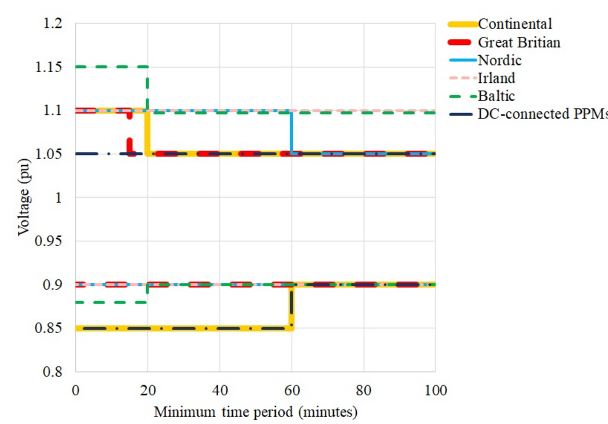
Power systems should be able to maintain steady voltages at all buses in a specified range after being subjected to a disturbance. Voltage instability occurs in the form of a progressive fall or rise of voltages of some buses which may lead to tripping of transmission lines and cascading outages [19].

The minimum time duration, during which a PGM must be capable of operating over different voltage ranges without disconnecting, is given in Fig. 6-a and Fig. 6-b. In case of DC-connected PPMs, the periods for a voltage range of 1.118 to 1.15 pu in a voltage range of $110kV \leq U < 300kV$ and 1.05 to 1.15 pu in range of $300kV \leq U \leq 400kV$ should be specified by the relevant system operator. In EU NC-631, the voltage-time duration requirement is only given for type D PGMs and AC-connected offshore PPMs and the specified values for them are very similar. The only difference is that the upper voltage level of unlimited operation range for Ireland is always 1.1 pu in case of offshore PPMs, while for type D PGMs, it is 1.118 pu for voltages below 300 kV and 1.05 pu for higher voltages. According to Fig. 6, the voltage-time duration requirements for DC-connected PPMs are more demanding. In addition, the requirement for type D PGMs in Baltic and Continental countries are more demanding than other regions, which means they should be more robust against voltage deviations.

Another essential option for voltage support is reactive power (Q) capability to control the voltage locally across a power grid [13]. The requirements for reactive power capability at active powers $P \leq Pmax$ are specified by P-Q/Pmax and U-Q/Pmax profiles in the network codes for type c and D PGMs, and AC-connected offshore PPMs. The ratio Q/Pmax is defined as ratio of the reactive power (Q) and the maximum capacity (Pmax). The maximum ranges of reactive power requirements for PGMs are same as AC-connected offshore PPMs and the only difference is that the maximum range of Q/Pmax in GB is 0 or 0.33 pu (based on the configuration of PPM) offshore, while onshore it is 0.66 pu [17]. Besides, concerning the injection of fast fault current in asymmetrical (1-phase or 2-phase) fault conditions, there is no specific requirement in EU codes, but the relevant system operator can specify a requirement for asymmetrical current

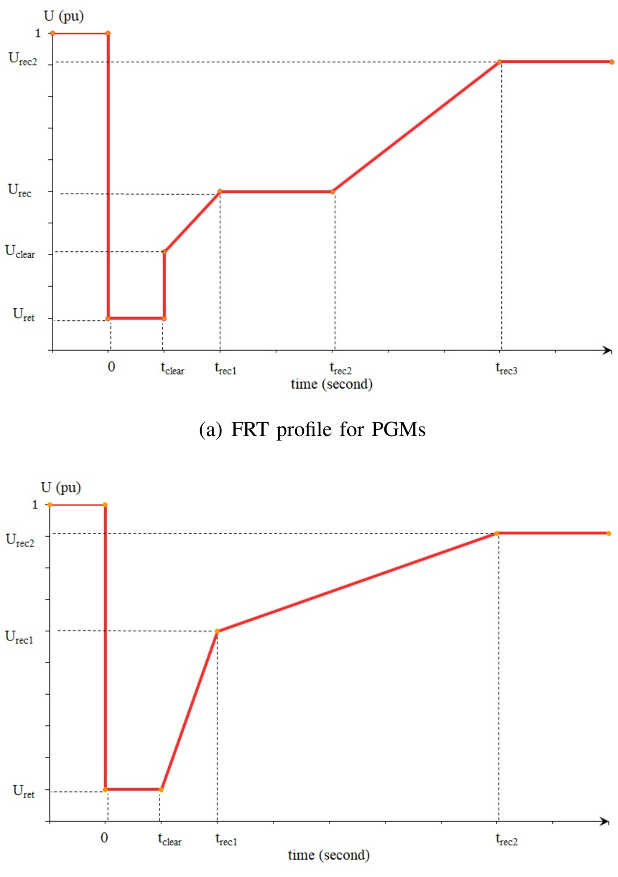


(a) $110kV \leq U < 300kV$



(b) $300kV \leq U \leq 400kV$

Fig. 6. The minimum required operating time as a function of voltage-amplitude for AC- and DC-connected PPMs [17-18].



(a) FRT profile for PGMs

(b) FRT profile for HVDC station

Fig. 7. The voltage-period profile for FRT limits of the voltage at the connection point [17-18].

injection.

C. Robustness Requirements

The aim of robustness requirements is that in the event of power oscillations, PGMs be able to retain steady-state stability when operating at any operating point of the P-Q capability diagram. Fault ride-through (FRT) capability is the main requirement for robustness, which refers to the ability of a PGM to remain connected to the power system during short periods of under-voltage or over-voltage. Fig. 7-a shows the voltage-time profile in network codes representing lower limits of the line voltages at the connection point during a symmetrical fault for PGMs. In addition, FRT profile of an HVDC converter station is shown in Fig. 7-b. The HVDC systems should be capable of finding stable operation points during and after any change in the HVDC system or the connected AC network.

Table II shows the specified range of parameters for FRT profiles in European network codes. The FRT profile parameters depend on PGMs and connection types. As it is introduced in section III, PGMs are either synchronous PGM (SPGM) or non-synchronously connected (PPM). Also, the PGMs are distinguished by power rating which addresses the type of generation consisting A, B, C and D according to Table I. The given parameters by EU NCs are only for low voltage ride-through (LVRT) capability and there is no FRT capability for type A PGMs. Fig. 8 illustrates the most possible demanding LVRT capability profiles for SPGMs, PPMs and HVDC station converters. Accordingly, the LVRT capability of HVDC station is enormously demanding. Also, it is expected that PPMs (type B, C and D) should tolerate deep faults better than SPGMs. In addition, the network codes for type D generation (both D SPGM and D PPM) are more demanding rather than type B and C; especially, since they should tolerate 100% deep faults at least for 140 ms period.

HVDC-connected PPMs may not detect the occurrence of faults in onshore AC grid, but it can affect the level of active power that can be transferred to the onshore side and therefore subject the offshore PPMs to a load rejection [20]. Also, the individual TSOs should specify the requirement for FRT capabilities in case of asymmetrical faults.

D. System Restoration Requirements

System restoration requirements aim to the capability of reconnecting of PGMs to the network after an incidental disconnection caused by a network disturbance. The system restoration requirements for AC-connected onshore and offshore PGMs consist of black start, island operation, and quick re-synchronization capabilities.

In an HVDC system with black start capability, after system shut down, one converter station should be energized by a storage system. Then, the HVDC system should be able to energize the busbar of the AC substation to which another converter station is connected. The relevant TSO determine the time frame of the black start operation for HVDC systems [18]. However, the interactions between the AC and DC sides of HVDC connections have not been considered in the grid codes yet [21-22]. According to [22], the interactions between AC and DC grids can be defined such as AC transmission reserve, DC transmission reserve, AC power flow control, and DC power flow control.

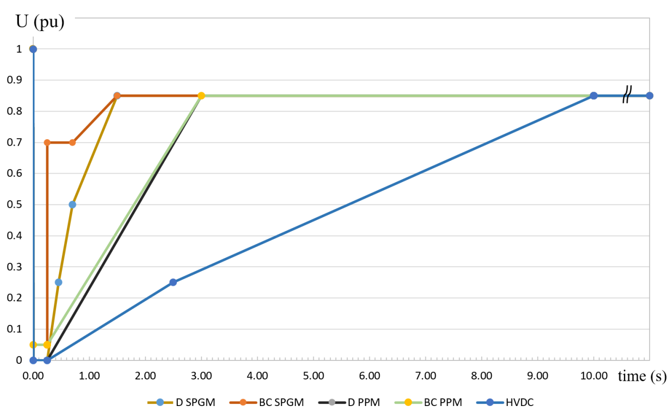


Fig. 8. The most demanding LVRT capability profiles for different PGMs and HVDC station [17-18].

TABLE II
PARAMETERS FOR THE FRT CAPABILITY OF AC-CONNECTED PPMS AND HVDC CONVERTER STATION [17-18].

Voltage parameters [pu]				Time parameters [s]			
	SPGM	PPM	HVDC		SPGM	PPM	HVDC
Uret	*D:0, **BC: 0.05∼ 0.3	D:0, BC:0.05∼ 0.15	0∼ 0.30	**tclear**	0.14∼ $0.15 or 0.25$	0.14∼ $0.15 or 0.25$	0.14∼ 0.25
Uclear	D:0.25, BC:0.7∼ 0.9	D:$U_{ret}, BC : U_{ret} \sim 0.15$	-	**trec1**	$t_{clear}(D : t_{clear} \sim 0.45)$	t_{clear}	1.5∼ 2.5
Urec1	D:0.5∼ $0.7, BC : U_{clear}$	U_{clear}	0.25∼ 0.85	**trec2**	$t_{rec1} \sim 0.7$	t_{rec1}	$t_{rec1} \sim 10$
Urec2	D: 0.85∼ $0.9, BC : 0.85 \sim 0.9 and \geq U_{clear}$	0.85	0.85∼ 0.90	**trec3**	$t_{rec2} \sim 1.5$	1.5∼ 3	-

*D: type D and, **BC: type B and C power plants.

E. General System Management Requirements

These requirements, which are common between all PGMs, are divided into several system operation considerations consisting protection and control schemes and settings, loss of control, instrumentation, simulation models, earthing arrangement, and synchronization facilities and settings. The general system management schemes and settings should be coordinated and agreed among the relevant TSO, system operator and the power-generating facility owner.

V. CONCLUSION

The international interconnection of power systems has many technical and economic benefits for European countries. In this regards, the trends are towards development of an integrated pan-European energy system. This goal demands regulation and standards at an international level. In this way, the network connection codes have been drafted for generators (EU NC-631) and HVDC systems (EU NC-1447) and regulated as European network codes in 2016. According to EU NC-631, the network codes for AC-connected onshore and offshore power-generating modules are mostly similar. Therefore, the main differences in the network codes are between AC- and HVDC-connected PGMs rather than onshore or offshore. The European network codes leave some aspects to be specified at national implementation level; however, it provides an excellent framework and overview of network codes among European countries. Accordingly, requirements for HVDC connections are more similar and at the same time more demanding rather than AC connection codes for European countries, which are promising for international interconnection of power systems and harmonization of HVDC-connected PPMs, especially offshore WPPs.

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