Fault current contribution from PPMS & HVDC

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

Draft of Expert Group FFCI

29 March 2017

DESCRIPTION	
Code(s) & Article(s)	**NC RfG -** Articles: 20 2 (b) and (c); **NC HVDC -** Article 19
Introduction	This IGD will give guidance on the background of fast fault current contribution. It will divide the fault incidents in different phases and give the system needs in these phases considering the grid topology, size of the synchronous area and the penetration level of power electronic interfaced power sources. The influence of reaction to unbalanced faults is pointed out. However, the IGD will not recommend exact values for parameter related to fast fault current contribution. The reaction on grid faults should not be treated as an isolated requirement. Furthermore many aspects have to be considered. These aspects and their relations are described in the IGD on "High Penetration of Power Electronic Interfaced Power Sources". As a result of conventional power units displacement, the total contribution to system faults will decrease further with voltage sensitivity, increasing if no other measures are taken in the system. Reactive current injection during faults helps to both recovering the voltage during faults and to injecting enough current quickly enough for system protections to function reliably. Both of these aspects which are part of the performance aspects of fault-ride-through family of requirements are essential to wider system stability. The requirement is specific for power park modules or HVDC systems connected to distribution or transmission networks to deliver an adequate current injection during short circuits and after fault clearing when the voltage has not recovered. The objective of this requirement is to limit the consequences of a short circuit with regards to unwanted operation of protection devices and to stabilize the voltage after secured faults on transmission level. As in case of a fault on the transmission system level a voltage drop will propagate across large geographical areas around the point of the fault during the period of the fault. The increased levels of distributed generation (including Type B generators) must add value to such conditions. The time period for current injection can be divided into 3 parts according to their foremost objective. Requirement during these time periods may require different control capabilities of the PPMs and HVDC system. The nature of and scale of the problems associated with absence of short circuit current contribution during and directly after the fault depends on the location of the short circuit and the characteristic of the local grid (e.g. onshore/offshore grid, long/short AC connections, local grid with surplus of generation or surplus of consumption, meshed/radial network, protection design). Taking these aspects into account any requirements regarding this issue should ideally be considered for each network area. It may even be necessary to vary requirements locally. However, it may not be practical to implement such fine tuning of the requirement, due to engineering resource implications, including those of DSOs (and possibly also TSOs).

	The requirement is a valuable balance between a clear statement of the common developing system needs (driven by increases in renewable energy sources (RES) penetration) and opportunities to build on national existing arrangements, without prescribing detailed technical specifications or implementations. System conditions during a fault need to be carefully considered together with requirements for reactive power control modes (IGD Reactive power control mode) and active power recovery (IGD Post fault active power recovery).
NC frame	According to Article 20 of NC RfG type B (and above by default) power generating modules shall be capable of providing a fast fault current. The relevant TSO shall have the right to specify the: – characteristics, timing and accuracy of the fast fault current – interdependency between fast fault reactive current injection requirements and active power recovery Furthermore, according to article 19.2 of NC HVDC, if specified by the relevant TSO, HVDC systems shall have the capability to provide fast fault current.
Further info	[1] KEMA: “Technical report on ENTSOE Network Code: Requirements for generators”, https://ec.europa.eu/energy/sites/ener/files/documents/KEMA_Final%20Report_RfG%20NC.pdf [2] Muljadi, E., Gevorgian, V., et al: “Short circuit current contribution for different wind turbine generator types” IEEE Power and Energy Society 2010 General Meeting, Minneapolis, Minnesota, July 25–29, 2010 [3] Bolik, S. M.: “The impact of Grid Codes on the development of wind turbine technologies”, Proceedings of 7th international workshop large-scale integration wind power into power system. Madrid, Spain; 2008 [4] Erlich, I.:” Effect of wind turbine output current during the faults on grid voltage and the transient stability of wind parks”, Proceedings of Power & Energy Society General Meeting, July 2009 [5] Fortmann, J., Pfeiffer, R., Martin, F., et al: “The FRT requirements for wind power plants in the ENTSO-E Network Code on Requirements for Generators”, Proceedings of 12th International Workshop on Large-scale Integration of Wind Power into Power Systems as well as on Transmission Networks for Offshore Wind Power Plants, October 2013, London [6] Fortmann, J, Pfeiffer, R. et al: ”FRT requirements for wind power plants in the ENTSOE network code on requirements for generators”, IET Renewable Power Generation, Volume 9, Issue 1, January 2015 [7] Erlich, I., et al: ”Dynamic behavior of offshore wind farms with AC grid connection”, Proceedings of 7th International Workshop on Large Scale Integration of Wind Power and on Transmission Networks for Offshore Wind Farms, Madrid, Spain, 2008 [8] Kühn, H.: Strom- und Spannungsquellen im Netz, Omicron Anwendertagung 2012 [9] Erlich, I., Winter, W., et al: “Advanced Grid Requirements for the Integration of Wind Turbines into the German Transmission System”, 6th International Workshop on Large-scale Integration of Wind Power and Transmission Networks for Offshore Wind Farms, Delft, The Netherlands, 2006 [10] Li, R., Booth, C., Urdal, H., et al: “A systematic evaluation of network protection

	responses in future converter-dominated power systems", 13th International Conference on Development in Power System Protection 2016 (DPSP), Edinburgh, United Kingdom, 2016 [11] Urdal, H., Martinez Villanueva, S., Kilter, J., Jahn, J., Sprooten, J., Baranauskas, A.: "Future System Challenges in Europe. Contributions to Solutions from Connection Network Codes.", CIGRÉ USNC International Colloquium Evolution of Power System Planning to Support Connection of Generation, Distributed Resources and Alternative Technologies, Philadelphia, United States of America, 2016 [12] Roscoe, Andrew J., et al: "A VSM (Virtual Synchronous Machine) Converter Controls Model Suitable for RMS Studies for Resolving System Operator / Owner Challenges" (WIW16-217), 15th international workshop on large-scale integration of wind power into power systems as well as on transmission networks for offshore wind power plants, Vienna, Austria, 2016 [13] Ierna, R., et al: "Effects of VSM Converter Control on Penetration Limits of Non-Synchronous Generation in the GB Power System"(WIW16-218), 15th international workshop on large-scale integration of wind power into power systems as well as on transmission networks for offshore wind power plants, Vienna, Austria, 2016 [14] Buelo, Th., Premm, D., Engel, B., Laudahn, S., Seidel, J.: "Substitution of Synchronous Generator Based Instantaneous Frequency Control Utilizing Inverter-coupled DER", 7th International Symposium on Power Electronics for Distributed Generation Systems (PEDG 2016) 27.-30. June 2016, Vancouver, Canada [15] Implementation Guidance Document on "High Penetration of Power Electronic Interfaced Power Sources" [16] Glinka, F., et al: "Veränderte Rahmenbedingungen für Betriebsmittel des Netzschutzes in zukünftigen Verteilungsnetz", 23. Fachtagung Albert-Keil-Kontaktseminar, 7 - 9 October 2015 Karlsruhe, Germany [17] Coster, E.: "Distribution grid operation including distributed generation: impact on grid protection and the consequences of fault ride-through behaviour", Dissertation, Technical University Eindhoven, 2010

INTERDEPENDENCIES

Between the CNCs	NC RfG NC HVDC
With other NCs	No interdependencies with other NCs

System characteristics	The below two figures are extracted from the international conference "International Workshop on Large-scale Integration of Wind Power into Power Systems" (October 2013). The joint TSO / Manufacturers' presentation [5] was based on a joint paper with multiple wind manufacturers and TSOs as well as ENTSO-E and EWEA (European Wind Energy Association, now called WindEurope). The diagram below illustrates typical response of a synchronous generator to a 3-phase fault. The vertical lines divide the fault in three periods which are described further down. • Blue: Instantaneous value of generator reactive current. • Green: positive sequence value

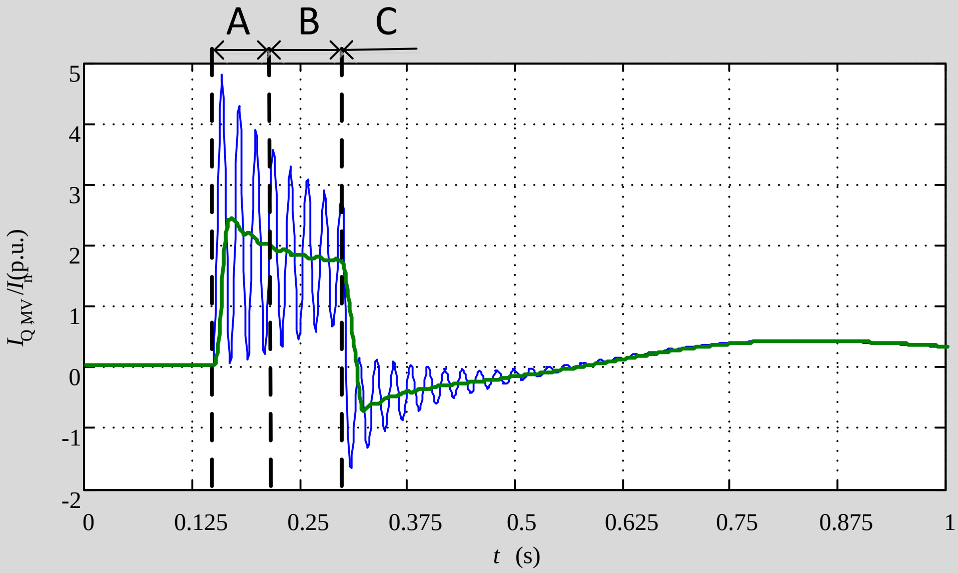

Figure 1: Typical response of synchronous generator to a 3-phase fault including fault periods A, B and C [5]

The response in Figure 1 could be divided into three time periods regarding the system needs:

<u>Initial period of a fault (time period A):</u>

Delivery of a faster fault current (e.g. within 40 ms) is important to recognize, locate and initiate fast and selective clearance of the fault by electrical protection systems. In this time period a fast fault current contribution at all is more important than meeting a possible accuracy requirement (to both magnitude and phase angle).

<u>Later period of the fault (time period B):</u>

Delivery of fast fault current supporting voltage retention/frequency. Accuracy requirements have to be met in this period in order to allow for benchmarking and thus a reference for compliance testing. The tolerances do not have to be too tight and should allow for at least a positive tolerance. In this time period the fast fault current requirement should reflect the foremost problem of the respective synchronous area (SA). While in larger SAs the system voltage is of highest importance the frequency is the most important criterion in smaller SAs. The first sets the priority on a reactive fault current contribution the latter on a real fault current contribution.

<u>After fault clearance (time period C):</u>

Delivery of a current to restore voltage and active power to remove power imbalances and corresponding frequency deviations. Control accuracy is crucial to avoid over-voltages. In this time period the transition to normal operation (achieving pre-fault values of active and reactive power) is carried out. Note that the topic of active power recovery is covered in a separate IGD. However, the transition to normal operation is still part of the fast fault current contribution if reactive current is required.

The visibility of the fault (depth of voltage dip) reduces continuously with increasing distance from the fault location. However, contribution to the 3 periods remains important.

Measurement challenges, particularly for period A: Positive sequence versus instantaneous. A phase jump of 90 ° of the current causes an immediate jump of the reactive power. The sequence component values do not show this jump until a full cycle is completed (20 ms). Knowledge about these differences is important to define requirements and their verification.

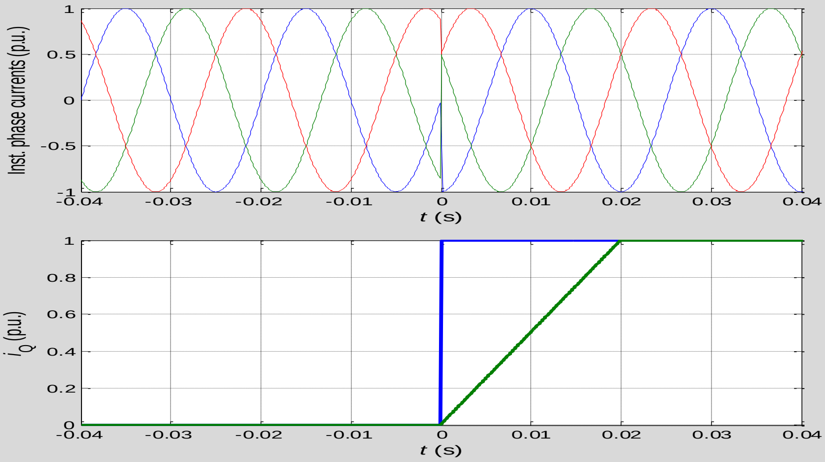

Figure 2: Phase jump of currents. Instantaneous value (above), space vector (lower, blue), positive sequence component (below, green)

<u>Evaluation of 3-phase-measurements</u>:

Voltages and currents can be described e. g. by space vector or sequence components.

- <u>Space vector</u>: directly derived from instantaneous. Fastest approach for evaluation. Magnitude of space vector only constant (and thus useful) in balanced conditions.
- <u>Sequence components</u>: evaluation over one fundamental frequency period. This is the default description method for in the NC RfG. In this context the required FRT capability is described in the positive sequence of the fundamental wave.

Resulting time restrictions: Using a sequence based approach, a clearly defined response cannot be detected in less than 20 ms. This has to be considered during national implementation and refers to definition and verification of requirements and is completely independent from the control approach in the PPM or HVDC system respectively.

System characteristics relevant to fast fault contribution and generation mix have significant impact on inter alia

- voltage control mode implementation
- voltage stability
- voltage recovery after fault clearance
- operation of protection devices
- negative sequence if required for national implementation

and should be taken into account reasonably by the relevant TSO/DSO when selecting the fast fault current parameters within the frames given in NC RfG and NC HVDC. Below the proposed performance criteria for different penetration ratios are listed. For further details see IGD on ”High Penetration of Power Electronic Interfaced Power Sources”.

Performance for Period A for extreme high penetration:
In the following the presented percentages represent indicative (!) values of instantaneous penetration levels. See [15] (incl. appendix) for definitions and expected instantaneous penetration levels.
For systems with extreme high PE penetration, SA or country sometimes exceeding 75 %, fast fault current injection is recommended to be required to be delivered in the first cycle on occurrence of a fault (low system voltage, e. g. below 90 %) in order to secure adequate transmission system protection performance (see [10]). Both balanced and unbalanced contribution should be included and for severe faults (e.g. greater than a value defined between 10 and 30 % voltage reduction on any phase). The full converter current (very short term rating) should be delivered. R&D [10] indicates protection performance (distance protections tested) is good even without this contribution, at least up to 75 % penetration.
It is expected that this may require one of the new concepts of converter controls for PPMs and HVDC which deliver the first cycle current contribution independent of voltage and current measurements, sequence component calculation and control calculations. Examples of such capabilities are described in references [12], [13] and [14]. The IGD on ” High Penetration of Power Electronic Interfaced Power Sources” [15] suggests this contribution should be made within a holistic performance context for first cycle delivery, in order to safeguard overall system stability during high penetration. Care should be taken at national level to consider appropriate timing of such a contribution, allowing manufacturers reasonable time to develop the relatively new designs, so far mainly used in isolated power systems, such as marine applications. There should be no performance requirement (accuracy is not important) other than deliver full current capability immediately.
In addition to the need for very fast fault current contribution to secure optimal performance of transmission protections, there are other needs reflected in the “holistic approach”, including a number of control related aspects, such as avoiding and preventing super synchronous instability (see [15], [11], [12] and [13]). Studies reported in [11] and [13] indicate this risk starts at about 65 % PE penetration within

a SA. Low total system inertia is another reason for its introduction. It may therefore be prudent to introduce the above extreme high penetration counter measure from 65 % (on a SA level) rather than 75 % as indicated by transmission protection.

<u>Performance for Period B for high penetration (and also for very high):</u>
In countries expected by 2030 to reach at times up to between 50 and 75 % PE penetration, introduction of first cycle performance for extreme high penetration can be deferred. However, for period B (post protection detection time to fault clearance) current injection will still be needed. This contribution can be delivered for example within 20-40 ms. Again accuracy of current delivery to a target value is not important, the volume should still be the main focus to aid voltage recovery and support first swing stability. Providing an unbalanced contribution is valuable, to avoid the case of injecting current in the healthy phases.

<u>Performance for Period C for all:</u>
Post fault clearance (e. g. voltage recover into normal operating band) current injection should support a smooth recovery towards the target system voltage. Accuracy of current to the control value is of importance. As the fault has been removed, the unbalance contribution is not critical.

The following paragraphs will describe the situation for TSO and other meshed networks. Radial networks will be covered later on.

Fast fault current contribution is important in order to restore the pre-fault operation (in terms of load/generation balance or restore voltage/frequency at or close to pre-fault value) after fault clearance. For this fast fault contribution should support as well the voltage after fault clearing in combination with the slower voltage control modes.
The requirement for fast fault current contribution can either be fulfilled at the connection point or the terminals of the individual generator since signal transmission might not be possible due to the required dynamics. The relative priority of restoring the reactive power and voltage versus real power and frequency depends upon the system size, predominantly of the synchronous area (see IGD Post fault active power recovery). For smaller synchronous areas (with less system inertia, and higher frequency sensitivity than larger areas) the active power restoration is particular time critical, in order to avoid reaching a system frequency following a large sudden power imbalance which results in demand disconnection. For larger synchronous areas, a moderate active power recovery after a cleared fault may be sufficient and the emphasis may be laid on the post fault reactive power support. The provision of reactive current supports the grid voltage, provision of active current will help to stabilize the frequency in the system. One should note that scenarios including a system split might shift the priorities. However, this cannot be predetermined for every situation.

Regarding required time to deliver a contribution in period A, an earlier draft of RfG (about 2012) defined the longest time before starting to deliver fast fault current as 10 ms. This was justified based on anticipated problems of adequate protection performance. In particular linked to extreme cases of non-synchronous generation (with DQCI based control approach) penetration in comparison to demand. In Denmark this penetration has already exceeded 100 % and several other countries anticipate in their future energy scenarios operating conditions exceeding 100 %, even for a full synchronous area (prior to constraining off actions, e. g. GB>150 % in

	the most challenging hour for 2030). At the time the manufacturing industry responded strongly against the 10 ms parameter and it was withdrawn for determination in individual countries. The manufacturers also challenged the lack of evidence for the 10 ms need. In response R&D work was initiated, in particular by National Grid. This R&D (focused on University of Strathclyde) is still in progress. A paper focused on the extreme case of 100 % NSG [10] generation was published in 2016. Its main focus has been on operating time and accuracy of distance protection when the system is weak. It demonstrates that protection operating times may increase dramatically (e. g. from 10-20ms to >100ms) if the current injection is much delayed. It also demonstrates some impact (but less than on operating time) on effective reach of the distance protection. In radial networks current protection schemes may isolate a fault by opening an upstream circuit breaker only (e. g. definite time-delayed overcurrent protection). In this case all generators that are connected between this circuit breaker and the fault will contribute to the fault current, increase the local voltage and reduce the fault current from the upstream grid. This may lead to a “blinding” [16][17] effect of both current and impedance based protection devices. Furthermore auto-reclosure might lead to asynchronous reconnection. In such cases fast fault current contribution should be required with respect to the (expected) NSG penetration, the protection scheme and the needs of upstream grids.
Technology characteristics	**Background:** Fast fault current contribution needs to be defined for non-synchronous equipment such as Wind turbines with partial or full-size converter, Photovoltaics or HVDC converters. Non-synchronous implying in this context that at least a portion of the active power is fed to the grid via Power Electronics (PE). These devices can be utilized very flexibly since their behaviour is predominantly determined via software (performance by design). However, inherent hardware limits have to be considered. In contrast, synchronous generators react inherently to any voltage deviation. Hence, they do not have to be considered regarding this requirement. Most state of the art PE interfaced generators inject controlled currents with an orthogonal reference system (DQCI, see [15] for details). Such devices need clear requirements for distinguishing between normal operation and fault operation. The only criteria for this distinction are the terminal voltages. Furthermore the expected behaviour during fault operation has to be precisely defined. This behaviour includes reactive and active current treatment during the fault, active power recovery and reactive current transition to steady-state operation. This might lead to very complex requirements and subsequently complex compliance testing. **<u>Classification:</u>** Network codes usually distinguish between synchronous generator and all the rest which is considered as non-synchronous. The vast majority of non-synchronous generators use PE as interface to the grid. In case the full output power is delivered via this PE interface only, this concept is referred to as full-size converter (FSC). The

electrical behaviour of such FSCs is predominantly determined by the PE interface, its software and associated parameters. Due to common effectively FSC characteristics, requirements for Wind Turbines (WT) with FSC, for PVs and even for HVDC can be shared although there are basic differences, too.
Within the PE interfaced PPMs the Doubly Fed Induction Generator (DFIG) takes on a special position since only the rotor winding is grid interfaced by PE while the stator winding of the induction machine is directly connected. In this concept the inherent behaviour of an induction generator is combined with a programmed behaviour of a converter at the terminals of such PPMs.

Fundamental capabilities and constraints of wind turbine generators (WTGs) and Photovoltaic (PVs) based power stations and synchronous generators to withstand the faults, remain connected and their contribution to support the grid during the faults and directly after the faults (i.e. to provide active power recovery and/or reactive power during/after the fault) are closely linked to the inherent technology features.

PE is sensitive to thermal overload and thermal capacity is rather low resulting in low overload capability. For this reason injection of reactive current is possible within the maximum current limits of the PE. Short-term overload capability (in the range of a few hundreds of milliseconds) may be given depending on the PE layout and DC behaviour during voltage dips. However, some concepts do not offer overload capability at all.

Full-Size Converter (FSC) with DQCI control approach
The full scale converter almost totally decouples the DC power source from the grid. The converter has to produce a reactive current based on network voltage measurements. Due to the dynamic requirements during faults measurement values can only be considered when there they are transmitted without significant delay. Otherwise the terminal voltages have to be used as reference.

This requires measurement, transmission of measurement values (if necessary), calculation and control time. Regarding speed of initial response in time period A the desired first cycle response is considered challenging for most PPM full-size converter systems, in many cases requiring significant changes to the design. For time period B, reaching the target value with a high accuracy (e.g. 10 % within 60 ms) is also controversial. Such tight specification is however unlikely to be needed until time period C when a more generous settling time can be allowed. All responses are controlled and need to be explicitly specified, but only as tight as is really justified. A key issue is the definition of current for time period A.

The main limitation is with respect to magnitude of fast fault current contribution is the converter’s current rating.

Partial Converter / DFIG
For generators with a direct connection of the stator winding of the rotating generator to the grid, by nature of this connection, a voltage dip will automatically cause a reactive current injection without delay. But the amplitude depends on the generator characteristics and will decline within a few ten milliseconds. When the voltage is decreased, power park modules based on Double Fed Inductive Generator (DFIG) (i.e. WTG with asynchronous generator, rotor converter and stator directly connected to the grid), transiently provide the short circuit currents into the grid due to natural

asynchronous generator behaviour. The support to the grid is provided during the first 10-30 ms following faults by discharging the magnetic field energy with the risk of losing internal magnetization. The converter is able to control the current after the period of some tens (~50) of milliseconds and is able to feed in controlled currents into the grid. However, the short circuit current decays faster than in case of conventional power plants due to typical parameters of the induction generator on the one side and the converter current control internal requirements to reduce the high currents on the other. Without specific measures to protect against voltage dips and the subsequent outrush currents a DFIG WTGs risks damage to its PE devices and DC link capacitors due to resulting over-current and over-voltage on the rotor side. But to solve this problem DFIG WTG are equipped with DC chopper systems. It keeps the DC link parameters within an acceptable range by shunting the short circuit current into a DC link resistor which dissipates the unbalance energy.

Reaction on unbalanced faults

RfG describes requirements on balanced faults. These faults are most critical in terms of system stability, but unbalanced faults occur more numerous than balanced ones. Article 20 (2)(c) enables the relevant system operator in coordination with the relevant TSO to require for asymmetrical fast fault current. Requiring a defined reaction to balanced faults could imply to use symmetric components and reacting exclusively in the positive sequence since this will fulfil all requirements on balanced faults. Regarding unbalanced faults fast fault current contribution in the positive sequence only will be smaller since contribution in the negative sequence component is missing [8]. The foremost objective in meshed networks during time period A of getting a fault current contribution that is as large as possible, will not be reached. The foremost objective during time period B of boosting the voltage could result in undesired over-voltages in the unaffected phase(-s). The strongest effect of fast fault current contribution in terms of restoring voltage back to balanced conditions will be achieved by an additional requirement in the negative sequence.
The zero sequence can be disregarded since usually at least one delta/wye transformer will be found between the fault location and the generator terminals which will eliminate the zero sequence component.

Symmetric components are based on complex rms values. Calculation of symmetric components usually take per definition one period (20 ms in 50 Hz grids). This has to be taken into account when defining requirements on rising and/or settling times and accuracies for fast fault current contribution.

Main aspects to be considered for fast fault current contribution

In the NC RfG and NC HVDC there are requirements for the provision of fast fault current injection.
In the NC RfG, TSOs have to specify requirements during and immediately after the fault and in the NC HVDC, if specified by the relevant TSO, the HVDC shall have the capability to provide fast fault current.
The main aspects to consider are:

1. Priority between real and reactive current
2. Different needs in different time periods of the fault, taking the grid topology into account
3. Need for asymmetric contributions

4. Consideration of technological characteristics

1. *Priority between real and reactive current*

Further aspects are reported in relation to the content of IGD on “post fault active power recovery”.

2. *Different needs in different time periods of the fault*

Representatives of TSOs and wind turbine manufacturers have agreed that the challenge of finding suitable compromises between adequately covering the system needs today and into the future of TSOs can best be achieved by detailed attention to the three separate time periods which were described in previous sections. System needs are described in detail in the IGD on ” High Penetration of Power Electronic Interfaced Power Sources” issues.

3. *Need for asymmetric contributions*

Providing asymmetric reactive current to contribute towards restoring balanced voltages during faults is optional but highly recommended for systems with a noticeable NSG penetration. The voltage during an unbalanced fault (1- and 2-phase faults) can only “pushed” towards symmetry when both positive and negative sequence currents are supplied. Feeding balanced fault current to unbalanced fault could result in too high voltages in the phase(s) that are not affected by the fault. Zero sequence will be blocked e. g. by delta/wye transformers which usually are installed on the way between generator terminals and transmission grid. For this reason the zero sequence does not have to be considered. Furthermore referring only to the positive sequence would result in less fault current contribution since the change of the positive sequence in unbalanced faults is less than in balanced ones.

4. *Consideration of technological characteristics*

All fully rated converters from PV, WTG and VSC based HVDC have similar capabilities, in principle. The main differences between the three applications are the sizes of the converters which may typically be respectively kVAs, MVAs and to GVAs. Care may be needed regarding the most complex requirements regarding the smallest units, when the cost of controls may become excessive in pu terms.

For WTG using DFIG configuration it is expected that the part directly connected stator may make it easier rather than more difficult to meet requirements. Especially during unbalanced faults the partial converter would have to compensate for the negative sequence current if balanced fault current contribution only is required.

For HVDC applications employing LCC configuration (with thyristor technology) special care is needed and individual treatment may be necessary. LCC technology uses the grid voltage for commutating the current from one leg to the next. Distortions in the grid voltage or changes in its magnitude may lead to commutation errors resulting in a complete blocking of the power flow. Furthermore this technology shows a natural, non-controllable reactive power demand. Specific reactive power requirements can be met by switching of external compensation. On fault initiation (Phase A) the external compensation will inject a short discharge current while the LCC HVDC outputs are being blocked. Afterwards the external compensation will provide reactive power/current according to their characteristics at the respective (reduced) voltage if not disconnected on the blocking of the HVDC.

COLLABORATION	
TSO – TSO	According to NC provisions RfG/HVDC TSO – TSO collaboration is not required.
TSO – DSO	According to NC provisions RfG/HVDC TSO-DSO collaboration is required for DSO connected PPMs and HVDC systems. This coordination should take into account that the requirements to fast fault current contribution may differ with the grid topology
RSO – Grid User	According to NC provisions RfG/HVDC RSO – Grid Users collaboration is not required.

Non-Exhaustive Requirement	Non-Mandatory Requirement	Article	Applicability	Parameters to be defined	Definition
Fast fault current contribution		20(2)(b) NC RfG	B, C, D	Characteristics, timing and accuracy of fast fault current contribution including voltage deviation, reaction to asymmetrical faults	RSO in coordination with the relevant TSO
Fast fault current contribution		19 NC HVDC	HVDC Systems Type B, C and C of DC connected PPM	Characteristics, timing and accuracy of fast fault current contribution including voltage deviation, reaction to asymmetrical faults	RSO in coordination with the relevant TSO

<u>Example(s):</u>

Existing fast fault contribution requirements:

Existing requirements referring to fast fault current contributions vary across Europe. Below examples of this requirement are specified can help to define this at the national level, although the fast moving system characteristics makes it essential to have a fresh view of the needs:

In GB simple requirements go back to 2005, with the prime objective linked to frequency stability, the determining factor in GB for the FRT requirements. In Germany but also in other countries it has been required for PPMs to provide short circuit current during the fault in order to prevent failure of protection's operation and to stabilize the voltage during and after short circuits in the transmission system.

<u>GB requirements:</u>

When the system voltage drops below 90%, deliver without delay during the fault a current using the full dynamic current capability. The requirement is simple, deliver the full capability when U<0.9 and return to normal fast acting voltage control when U>0.9pu.

It was suggested by some commentators that this may be an unstable control arrangement, that instability could result (system voltage oscillating around 0.9pu). This has not proved to be the case in numerous installations over 10 years.
The component of the total current capability available to reactive current is in GB limited by a requirement to continue during the fault duration the real component of current, with priority over reactive current. This was introduced due to the greater concern for frequency instability. The largest loss for which reserves are scheduled is made up from a single contingency loss, therefore having no spare reserves for simultaneous loss of PPMs.
In practice, the GB requirement has been proven to have a significant legal weakness, lack of clarity in the term "without delay during the fault duration". This has been extensively misinterpreted as 60ms, very different from the original intent made in context of normal target fault clearance time of 80ms.

<u>Germany TSOs requirements:</u>
Transmission Code 2007: 100 % of the required fault current 20 ms after fault detection (still in force but to be replaced).

VDE AR-N-4120 TAR Hochspannung (HV directive, in force, currently under revision):
Rise time of the short-circuit current contribution < 30 ms, settling times < 60 ms in **both positive and negative sequence** These requirements are considered as fulfilled, when the positive/negative sequence values in the period of 30 – 50 ms (60 – 80 ms respectively) fulfill the requirements. Examples for definition of rise time and settling time are given in VDE AR-N-4120.

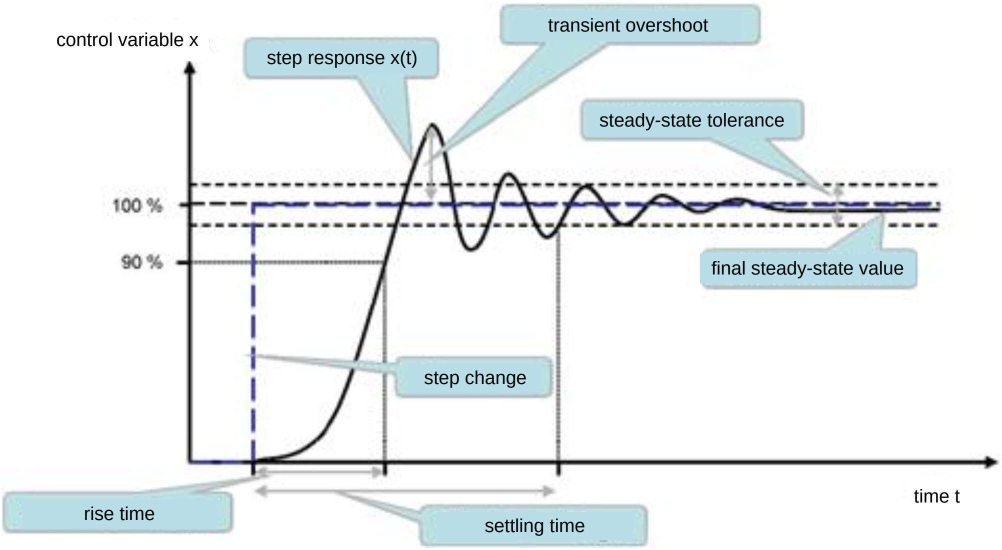

Figure 3: Step response, rise and settling time

Rise time: Time between a setpoint step-change and the step response reaching a certain ratio (e. g. 90 %) of the desired value for the first time.
Settling time: Time between a setpoint step-change and the step response entering the desired range of tolerance (which may differ from 90 %) for the last time.
Minimum requirement 100 % of rated current at least in one phase. Priority to reactive current.

In grids which are mainly radially structured or operated in open rings the NSG is required to limit the fault current contribution in the time periods A and B to their technical minimum. This applies to most MV connected NSG that is not directly connected to the busbar of the MV/HV transformer.

But they have to stay connected to the grid in order to continue in-feed directly after fault clearances (time period C).