European Network of
Transmission System Operators
for Electricity

# Fault current contribution from PPMS & HVDC

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

## Draft for consultation 1 July -15 August 2016

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| DESCRIPTION | |
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| Code(s) & Article(s) | **NC RfG -** Articles: 20 2 (b) and (c);<br>**NC HVDC -** Article 19 |
| Objective | 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. 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.<br><br>The time period for current injection can be divided into 3 parts:<br>A Immediately after the fault, while the main transmission system protections are measuring, e.g. 0-40ms.<br>B The remainder part of the fault duration until fault clearance.<br>C Immediately following fault clearance.<br><br>For period A the foremost transmission system objective is to ensure adequate magnitude of current to allow protection to detect the fault both fast and selectively. For this period making a large enough contribution is more important than delivering to an exact magnitude target. To achieve the highest speed, a distinction between real and reactive current injection components may not be practical.<br>For period B the foremost transmission system objective is to boost the voltage as much as possible to aid generator stability. Again high magnitude rather than meeting an exact magnitude targets is the key consideration, as long as the voltage remains low (e.g. below normal voltage operating range).<br>For period C the foremost objective in large systems (with substantial total inertia) is to restore system voltage towards the target voltage, limiting the voltage target overshoot and achieving a reasonably short settling time.<br>For small synchronous areas (SAs) and for systems with little and diminishing total inertia, real current injection to contribute towards frequency stability may be a consideration in period C (even before voltage settling time) and may even be a consideration in period B in the smallest SAs.<br><br>The nature of and scale of the problems associated with absence of short circuit current contribution provided by Power Electronics (PE), such as Power Park Modules (PPMs) and HVDC converters, 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). 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).<br><br>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, particularly for the less severe asymmetrical faults (which have less widespread impact, but occur more numerous), without prescribing detailed technical specifications or implementations. System conditions |

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| | 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).<br><br>The requirement is specific for power park modules or HVDC systems connected to distribution or transmission networks to deliver an adequate reactive 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. |
| 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 capability:<br>– the magnitude and<br>– time period for providing 90% of the required fast fault current contribution<br>– interdependency between fast fault reactive current injection requirements and active power recovery<br>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<br>[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<br>[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<br>[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<br>[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<br>[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<br>[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<br>[8] Kühn, H.: Strom- und Spannungsquellen im Netz, Omicron Anwendertagung 2012 |



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| | [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 |

*INTERDEPENDENCIES*

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| Between the CNCs | NC RfG<br>NC HVDC |
| With other NCs | No interdependencies with other NCs |

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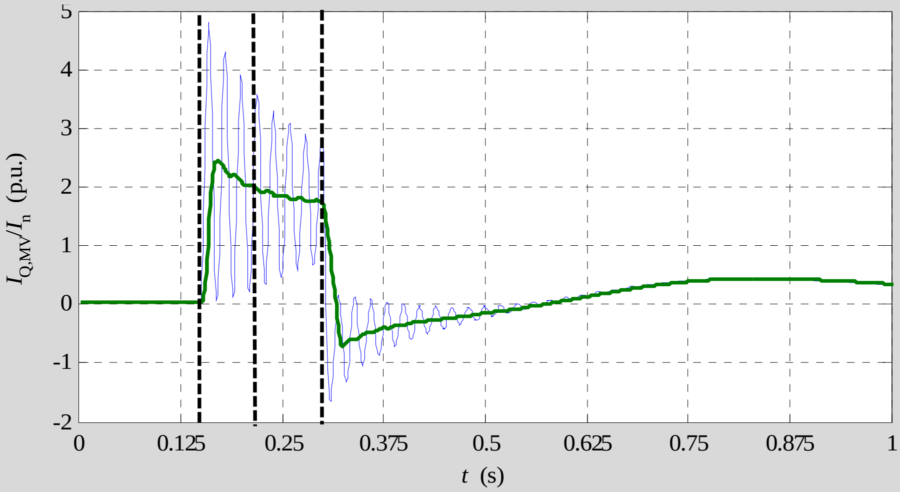
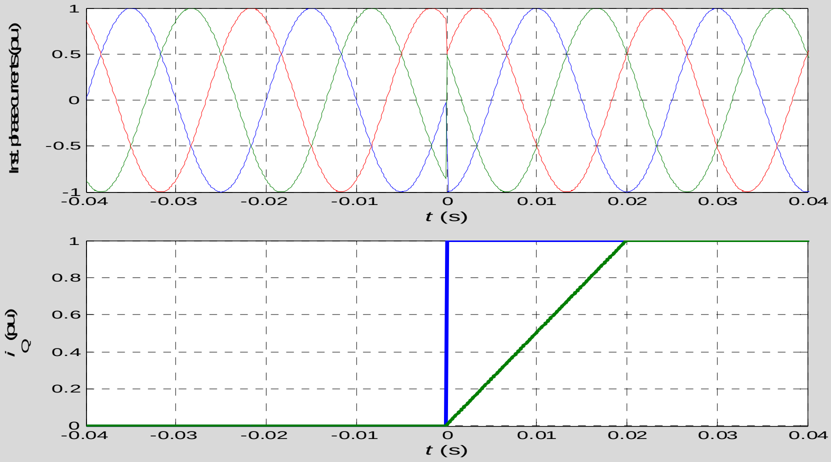
| System characteristics | The below two figures and text are extracted from the international conference "International Workshop on Large-scale Integration of Wind Power into Power Systems" (October 2013). The joint TSO / Manufacturers' presentation [5] was based on a joint paper with multiple wind manufacturers and TSOs as well as ENTSO-E and EWEA (European Wind Energy Association).<br><br>The diagram below illustrate typical response of a synchronous generator to a 3-phase fault in periods A, B and C (defined by the vertical lines).<br><br>• Blue: Instantaneous value of generator reactive current.<br>• Green: positive sequence value<br><br><br><br><br>• <u>Initial period of a fault (Phase A):</u> Delivery of a fault current within 20 ms to recognize, locate and initiate clearance of the fault by electrical protection systems.<br>• <u>Later period of the fault (Phase B):</u> Delivery of (additional) reactive current supporting voltage retention. Magnitude of current prevails over control accuracy.<br><br><u>After fault clearance (Phase C):</u> Delivery of a reactive current to restore voltage and restoration of active power to remove power imbalances and corresponding frequency deviations. Control accuracy is crucial to avoid over-voltages. |

Measurement challenges, particularly for period A: Positive sequence versus instantaneous:




Evaluation of 3-phase-measurements:

Voltages and currents can be described e.g. by instantaneous values or sequence components.

- Instantaneous values: magnitude of space vector. Only useful for balanced faults.
- Sequence values: evaluation over one fundamental frequency period. This is the default requirement in the NC RfG. Applicable to all faults.
- Time Restrictions: Using a sequence based evaluation, a response faster than 20 ms is not possible.

The presentation further contained the following Wind Power Plant (WPP) viewpoint:

Phase A – initial period of fault:

Fault Current Injection - Challenges for WPP

The NC RfG refers to ***positive sequence*** values. This excludes implementation of controlled action in less than 20 ms. Further time for ***initiation of control action and resulting WPP response*** needs to be allowed for as well.

What should be defined:

The NC RfG shall ***not introduce barriers to certain technologies***. Flexibility is in particular needed with regard to the fault current injection during Phase A.

Voltage support - WPP viewpoint

Phase B – later period of fault:

Challenges for WPP

***Accuracy requirements*** of WPPs (partially) coupled directly to the grid (doubly fed induction generators, DFIGs) are deemed not critical and need to be compared to synchronous generators.

***Exceeding the minimum requirements*** for fault current provision in a stable and secure way is fully compliant.

Phase C – after fault clearance:

Challenges for WPP

Accuracy is of major importance only during Phase C to ***avoid over-voltages***.

Especially in "weak" networks and/or under rules for strong reactive current provision during a fault, ***voltage transients*** at the beginning of Phase C can become an issue.

End of quote from Wind Integration Workshop 2013.

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 when selecting the fast fault current parameters within the frames given in NC RfG and NC HVDC.

Fast fault current contribution is important in order to restore the pre-fault operation 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.

Regarding required time to deliver a contribution in Phase A, an earlier draft of RfG (about 2012) defined the longest time before starting to deliver fast fault current as 10ms. This was justified based on anticipated problems of adequate protection performance. In particular linked to extreme cases of non-synchronous generation

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| | 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 10ms parameter and it was withdrawn for determination in individual countries.<br>The manufacturers also challenged the lack of evidence for the 10ms 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 generation is ready for publication 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. |
| Technology characteristics | **Background:**<br>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). In contrast, synchronous generators react inherently to any voltage deviation. Hence, they do not have to be considered regarding this requirement.<br><br>Efforts have been made to distinguish between steady-state operation and fast fault current contribution. Requirements on behaviour during voltage dips also impact on behaviour after fault clearance, mainly active power recovery and transition to steady-state voltage support.<br><br>**Classification:**<br>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 are 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.<br>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.<br><br>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.

**Full-Size Converter (FSC)**

The full scale converter 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 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 phase A the desired 10 ms response time (½ cycle) is considered challenging for most PPM full-size converter systems, in many cases requiring significant changes to the design. For phase 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 phase 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 Phase A.

The main limitation is only converter size which also limits the short circuits contribution of this type.

**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 hundred 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.



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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. The foremost objective during phase A of getting a fault current contribution that is as large as possible, will not be reached. The foremost objective during phase 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 one period (20 ms in 50 Hz grids). This has to be taken into account when defining rising and/or settling times for fast fault current contribution.

**Conclusions**
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
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 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 3 separate time periods:

Phase A First part of the fault duration, while transmission protection is most active, e.g. first 40ms.
Phase B Remainder duration of the fault
Phase C After fault clearance



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2A For phase A the main focus is to ensure adequate fault current for transmission system protections. Investigations of protection performance under extreme high PE penetration suggest requirements reflect highest possible amplitude, e.g. using the full dynamic current capacity of the PE converters with least possible delay. Magnitude accuracy is not important. Simple criterion, such as voltage below the system operating range, may aid the speed of delivery. In this time period, it is critical to avoid a simple focus on the normal definition of current, namely rms and positive sequence. Criteria should not be defined in terms of sequence components, but instead in phase voltages.
2B For Phase B the main focus is to support the system voltage at locations away from the fault to support system stability. Again the high magnitude is important, but accuracy of delivery is not, while the voltage remains below normal range. Use of current definition in sequence components is fine.
2C For Phase C post fault clearance, the focus is on returning system voltage towards normal range and to support power recovery. In this period the focus is on containing voltage overshoot, meeting the magnitude target and achieving a reasonable settling time contributing to system voltage settling.
During phases A and B the priority should be clearly set on the minimum time delay and maximum magnitude for fast fault current contribution while accuracy of the current angle is of subordinate importance.

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 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 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



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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* | |
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| 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 |
| RNO – Grid User | According to NC provisions RfG/HVDC RNO – Grid Users collaboration is not required. |

Example(s):
**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 unwanted operation of protection and to stabilize the voltage during and after short circuits in the transmission system.

GB requirements:
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.

Germany TSOs requirements:
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.

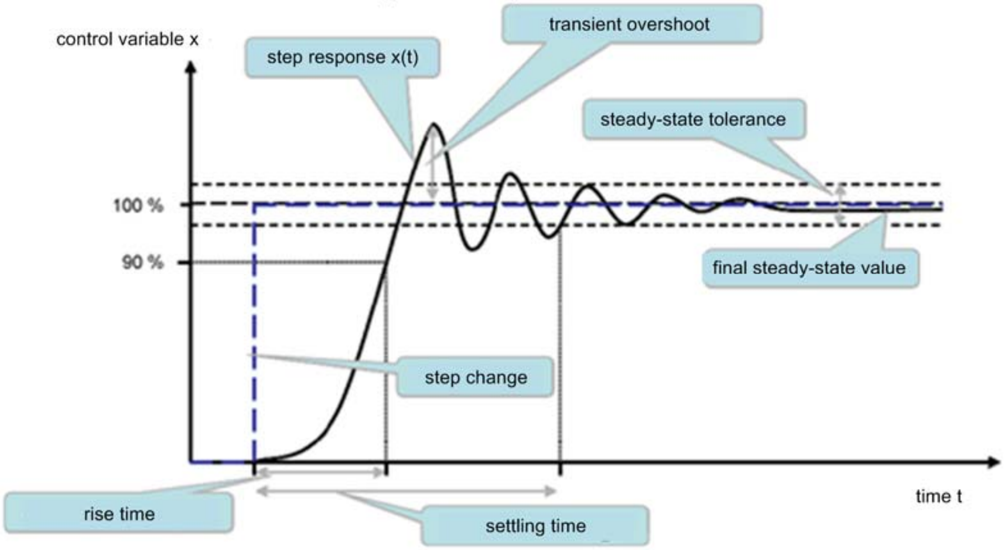


**Figure 1: Step response, rise and settling time**

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.

**New approach to be implemented: Continuous Dynamic Grid Support**
Many connection codes made great efforts to properly distinguish between “normal” (steady-state) operation and operation in case of dynamic events such as sudden voltage deviations. This results in defining the transition between both operating modes.
The approach of continuous dynamic grid support emulates the behaviour of the synchronous generator (immediate reaction to voltage deviations and additional AVR).

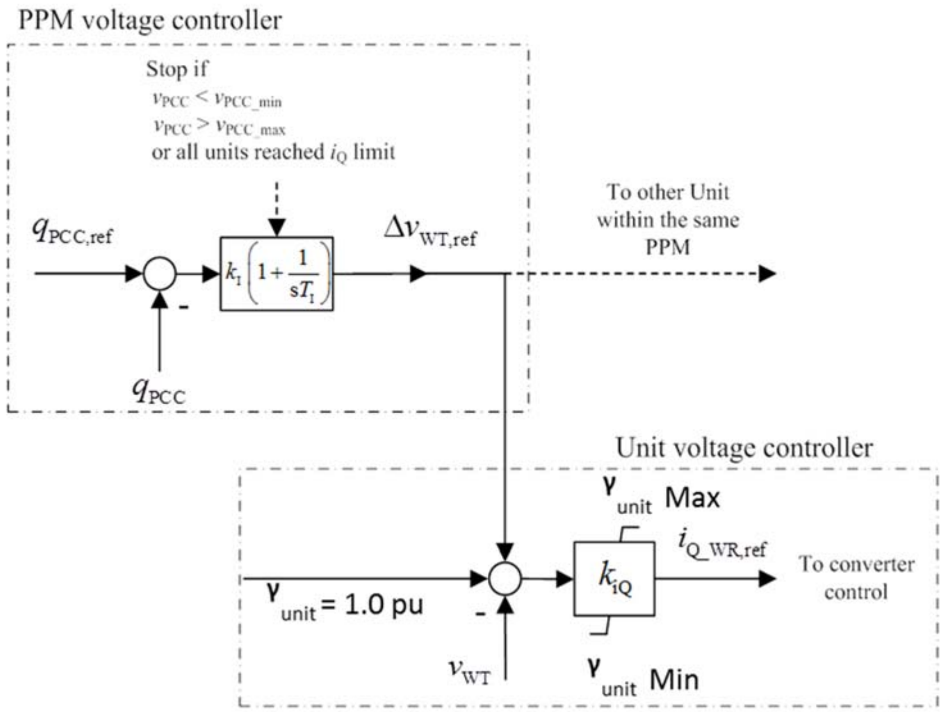


**Figure 2: Combination of steady-state voltage control and fast fault current contribution**

In Figure 2a combined control principle including steady-state voltage control and fast fault current contribution is presented. The “unit voltage controller” represents a droop control based on local voltage measurement (e. g. terminal voltage). Since it only contains a proportional controller there is no further delay in case the local voltage $v_{WT}$ is changing. This is a key requirement for fast fault current contribution. The nominal value of the local voltage serves as reference value and the unit will provide reactive current (reactive power respectively) whenever the local voltage $v_{WT}$ differs from its nominal value. To combine this local control with a superposed control based on measurements that may be remote (e. g. connection point of a PPM) the output of this superposed control is added. This will result in a varying set-point for the local droop control.

The superposed control may include a PI controller for stationary accuracy. Superposed control may power factor control, reactive power control or even a second voltage droop with reference to the voltage at the connection point. By tuning the PI controller the transition between the local and the superposed control can be influenced.



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