European Network of
Transmission System Operators
for Electricity

Post-fault active power recovery

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

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DESCRIPTION	
Code(s) & Article(s)	**NC RfG -** Articles: 17(3) and Article 20(3); **NC HVDC -** Article 28
Objective	The requirement is specify for synchronous power generating modules (PGMs) and power park modules (PPMs) connected to distribution or transmission networks to deliver active power after the fault clearance on the transmission level within a certain time. The objective of this requirement is to limit the consequences of a short term loss of active power infeed and to stabilize the frequency and local voltage after secured faults on transmission level. Finally in order to prevent tripping caused by large frequency deviations within a synchronous area. 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 post fault conditions. From a system operation perspective it can be of crucial importance that all generators (type B and above), including PPMs are able to restore active power production fast after fault clearance. As a result of conventional power units displacement, the total system inertia will decrease further with frequency sensitivity increasing if no other measurements are taken in the system. Active power recovery (APR) after the fault is an essential issue in context of frequency stability, in particular for smaller synchronous areas and for large synchronous zones in case of their split, asynchronous operation of the national power systems or islanding which tend to have lower inertia and greater frequency sensitivity. Due to mass connections of PPMs to the distribution network lack of the standardized post-fault active power requirements on national level may lead in the close future to the frequency instability in whole synchronous area. Loss of the active power during and directly after the fault affects negatively on frequency stability which is linked to the system inertia but also can lead to the local voltage problems: - voltage drop phenomena which propagates across large geographical areas around the point of the fault - temporary overvoltage phenomena which can occur in long AC connections of off shore PPMs, that in turn increases the risk of the PPMs trips therefore even if there is no risk of loss of frequency stability, post-fault active power recovery should be considered as a countermeasure to ensure voltage stability independently for each new PPM connection projects to minimalize the risk of disconnection due to local voltage problem which have to be studied individually. The requirements for operation during a fault event have a large impact on the capabilities to increase active power after fault clearing. Therefore operation conditions during a fault need to be carefully considered together with requirements for active power recovery after the fault. Requirements to the generator technology behaviour during active power recovery may have a significant effect on the generator mechanical loads and affect its structural design i.e. careless choice of recovery time parameters may negatively interfere with end turbine drive train dynamics and result in excessive wind turbine drive train loads. Taking into account the importance of supplying the network load with active power as quickly as possible following a fault clearance in order to avoid frequency

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	instability and under frequency load shedding this requirement have to be defined on national level by the relevant TSO.
NC frame	According to Article 17(3) of NC RfG type B synchronous (and above by default) Power Generating Modules shall be capable of providing post-fault active power recovery. The relevant TSO shall specify: – the magnitude and – time for active power recovery that power generating module shall be capable of providing. Whereas Article 20(3) of NC RfG define adequate requirement for type B Power Park Modules. There are predefined framework principles that shall to be taken into account in the process of implementation on national level: – interdependency between fast fault reactive current injection requirements and active power recovery, – dependence between active power recovery times and duration of voltage deviations, – specified limit of the maximum allowed time for active power recovery, – adequacy between the level of voltage recovery and the minimum magnitude for active power recovery, – adequate damping of active power oscillations. The relevant TSO shall specify especially: – when the post-fault active power recovery begins (based on a voltage criterion), – a maximum allowed time for active power recovery, – and a magnitude and accuracy for active power recovery. According to the Article 26 (*Post fault active power recovery*) of NC HVDC the relevant TSO shall specify the magnitude and time profile of active power recovery that the HVDC system shall be capable of providing, Furthermore, in accordance with Article 27 (*Fast recovery from DC faults*) of NC HVDC, the HVDC systems (including DC overhead lines), shall be capable of fast recovery from transient faults within the HVDC system. Details of this capability shall be subject to coordination and agreements on protection schemes and settings. The HVDC converters must be able to recover active power output following fault clearance for AC and transient DC faults or recovery from voltage dips. This ability shall help to restore frequency and voltage stability and shall reduce any consequential thermal overload. The speed and magnitude of recovery is to be determined by the local TSO.
Further info	[1] KEMA: “Technical report on ENTSOE Network Code: Requirements for generators”, 12 November 2013 (see attachment) [2] ENTSOE, NC RfG Implementation Guideline, October 2013

INTERDEPENDENCIES

Between the CNCs	NC RfG NC HVDC
With other NCs	No interdependencies with other NCs
System characteristics	Frequency and voltage stability The active power balance needs to be maintained at all times to ensure frequency

stability and needs to be restored urgently, if disturbed[1]. As long the system inertia is large enough and the total imbalance of active power is within the anticipated, planned level (varying between 3000 MW in Continental Europe and 500 MW in Ireland) covered by sufficiently fast available primary reserves in a synchronous area the automatic release of the reserves will prevent frequency instability. The urgency for restoring active power directly following voltage dips varies greatly between the large synchronous areas (Continental Europe) and the smaller (GB and Ireland). It is obvious because of the much higher frequency sensitivity of the smaller systems with less inherent inertia. Nowadays, the post fault requirements vary between synchronous areas and between the systems within synchronous zone. In synchronous areas with strong frequency sensitivity a very fast active power recovery is needed in order to stabilize the power system frequency, in other areas a moderate active power recovery is sufficient.

System characteristics like network topology and generation mix have significant impact on:

- frequency stability;
- voltage recovery after fault clearance which in turn affects the ability of active power recovery

and should be taken into account reasonably by the relevant TSO when selecting the active power recovery parameters within the frames given in NC RfG.

Active power recovery after a fault is important in order to restore the pre-fault operation after fault clearance. 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. 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 For larger synchronous areas with relatively low penetration of PPMs, the importance of post fault active power recovery performance to ensure the frequency stability is smaller and the emphasis may be laid on the post fault voltage stability and reactive power support, depending on the local voltage conditions.

Studies[2]show that in long AC lines which their power flow mainly comes from wind farms slow active power recovery can lead to high capacitive charge feeding to grid causing post-fault over-voltages that can result in overvoltage protection trips. The significant temporary over-voltages can be expected in both the offshore and onshore power systems that jeopardize the security of the system. The over-voltages occur as a result of the drop in active power generation during faults and the slow recovery of the active power after fault clearing. In order to avoid that effect to the system, fast Active Power Recovery is a proper countermeasure to stabilize frequency as well as to mitigate over-voltages problems being that the AC connection lines of the wind farms is maintained active power flow loaded.

[1] 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”, WIW, October 2013, London
[2] Lilje, I., Lummer, J.:”Overvoltages in Transmission System following Integration of Offshore Wind Farms” 14th wind Integration workshop Proceedings International Workshop on Large-Scale Integration of Wind Power into Power Systems as well as on Transmission Networks for Offshore Wind Power Plants

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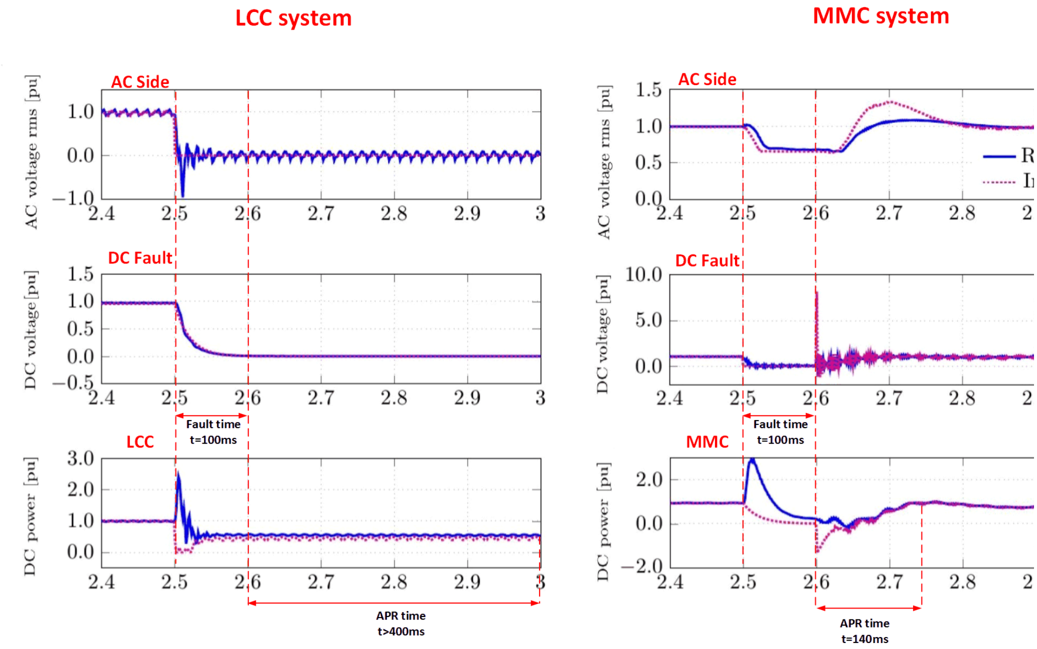
	Active vs reactive power prioritizing during the fault According to the art 21(3)(e) NC RfG, taking into account the characteristic of the system the relevant TSO shall specify whether active power contribution or reactive power contribution has priority during the faults. For small systems with low inertia and high frequency sensitivity and consequently high rate of change of frequency (RoCoF) the main aim should be to provide during the fault first active current to support the frequency and reduce the risk of load and units disconnection due to frequency reduction. Reactive has lower priority and it can be generated what is left over. Reduction of the active power during the fault is allowed but has to be proportionally to the retained voltage in the connection point. For larger systems, at least consumption of the active and reactive power during the faults should be forbidden but the specific solutions have to be adopted by each TSO considering the local voltage and global frequency stability. Technology constraints related to the active vs reactive power prioritizing is presented below in *Technology characteristics* section.
Technology characteristics	HVDC converters constraints HVDC systems in principle should participate in active power recovery after the faults. The core of these systems is the power converter that connect the DC and AC systems together. There are two main topologies of electronic converters for HVDC systems available nowadays: - Line commutated converters (LCC) which are current source converters (CSC) based on thyristor valves commutated by AC voltage - Voltage Source Converters (VSC) based mainly on insulated gate bipolar transistors (IGBT), which are self-commutating. In context of APR after the faults, LCC technology have some essential constraints that lead to the loss of controllability of the inverter controller (see diagram below)[3]. Conventional LCC converters require a synchronous voltage source in order to ensure proper commutation of the thyristor valves. Commutation is the transfer of current from one phase to another in a synchronized firing sequence of the thyristor valves. The feature of the LCC is that the commutation of the thyristors is provided by the AC voltage, therefore proper operating conditions of AC system such as minimum short-circuit power is required. Failure of commutation occurs when the commutation of current from one valve to another has not been completed before the commutating voltage reverses across the ongoing valve. It is very important to avoid longer failure of commutation being it introduced temporary zero power transmitted by the HVDC to the system consequently affecting system stability. The sensitivity of the inverter to commutation failure depends on the strength of the AC network and the control system, therefore, in order to avoid system instability issues due to the temporary stop of the active power transmitted by the LCC HVDC, the requirements defined for the active power recovery must be defined in coordination to the requirements of the fault ride through capability Art 25(4) HVDC NC stating the TSO may specify block voltage (U_{block}) at the connection point under specific conditions whereby the HVDC system is allowed to block i.e. HVDC system below U_{block} voltage level should remain connected to the

[3] Norwegian University of Science and Technology: “HVDC Transmission Using a Bipolar Configuration Composed of an LCC and MMC”

grid but with no active and reactive power contribution for agreed time frame.



<u>PPMs constraints</u>[4]

Abilities and constraints of wind turbines and photovoltaic (PV) based PPMs and synchronous PGM to withstand the faults 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 strictly combined with the inherent technology features. In principle the dynamic response of wind farm can be much faster than conventional power unit response. The transient wind turbines behaviour during the faults – opposite to conventional power units – is not characterized by the electromechanical rotor oscillations but it is strongly related to the power electronics and the converter capabilities and attributes its control system. In a synchronous generator, the magnetizing flux is controlled by the field current exciting the field winding, thus, the electromagnetic force driving the fault currents is available during the fault. In contrast, in an induction generator the magnetizing flux is depleted during the fault and the fault currents are not sustainable for a long duration.

For wind turbine 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, wind power park modules based on Double Feed Inductive Generator (DFIG) i.e. asynchronous generator with rotor converter and stator directly connected to the grid, provide the transiently short

[4] Erlich, I. Winter, W.: "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
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
Wessels, Ch.,Genius, A.:"Flexible fault ride through of DFIG wind turbines with DC-chopper solution"

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. The converter is able to control the current after the period of tens ms and is able to feed in controlled currents into the grid. However the short circuit current decays faster than the case in conventional power plants due to typical parameters of the induction generator on the one side and the forces converter current control on the other.

The connection of the stator directly to the grid gives a number of features – positive and as well negative in the context of system needs. The DFIG based PPMs are sensitive to grid voltage dips in supply voltage due to directly connected generator. The induction generator very quickly loses internal magnetization producing outrush currents on both stator and rotor circuits. Without specific measures to protect against grid faults a DFIG risk damage to its power electronics devices and DC link capacitors due to resulting over-current and over-voltage. But to solve this problem DFIG based PPMs are equipped with DC choppers. It keeps the DC link within an acceptable range by shunting the short circuit current into a DC link resistor which dissipates the unbalance energy.

The full scale converter based PPM decouples the wind turbine from the grid. PPMs connected by a converter don't have direct connection between the network and the rotating generator. The converter has to produce a reactive current based on network voltage measurements. This requires measuring, calculation and control time. It is estimated that the 10 ms response time (½cycle) is not currently possible for full converter wind turbine generators. Reaching the target value with an accuracy of 10% within 50 ms is also ambitious but may be feasible. The active power recovery issue refers to the condition after the fault. According to the NC RfG requirements the fault should normally be cleared within 140 -150 ms (excluding exceptional circumstances when the fault is only cleared by slower back-up protection). Thus time control technology limitation (ca 20 ms) is not critical to meet this post fault active power recovery requirement.

The above is in contrast to fast current contribution during the fault where the response immediately when the fault occurs is expected with time delay as short as possible. For these different purposes (see guidance on fault current contribution from PPMs and HVDC) therefore time control technology limitation is critical.

All responses of full converter are controlled and need to be specified. Therefore wind or PV PPMs based on full scale converters, independent of the generator used, gives large scale of control which enables this type to be connected in different systems with different needs. The main limitation is only converter size which also limits the short circuits contribution of this type.
Requirements to the generator technology behaviour during active power recovery may have a significant effect on the generator mechanical loads and affect its structural design i.e. careless choice of recovery time parameters may negatively interfere with end turbine drive train dynamics and result in excessive wind turbine drive train loads[5].

<u>Active vs reactive prioritizing - current limitation due to overloading</u>
The output current of wind turbine during the fault is limited primarily by the

[5] "EWEA and EPIA main concerns and proposals for solutions NC RfG" January 2013

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semiconductors devices as they are particularly sensitive to overloading. E.g. DFIG based PPMs face high rotor currents during fault- first peak may exceed the limitations of IGBT valves. The amplitude can be obviously reduced by decreasing either the real or reactive part of the current. However, in the systems with the high inertia/low penetration of PPMs the voltage support requirement precludes reduction of the reactive current and as the result, the wind turbine control switches from active current priority (which was the case during normal operation) to reactive current priority when the voltage falls below a certain threshold. In principle, in reducing the output power for the duration of the fault does not significantly affect the overall balance between generated and consumed power adversely. In systems with low inertia and high penetration of PPMs the opposite strategy can be chosen.

Current limitation due to generator stability[6]
Post-fault active power oscillations similar to those of synchronous generators may also occur at wind power park (e.g. in conjunction with significant voltage oscillations) and should hence be acceptable as well. Thus the wind turbine stable operation may necessitate the further reduction of the output current. To improve transient stability performance of the wind farm a voltage dependant active current reduction controller is used. Its action can be in contradiction to common system needs. The aim of this control measure is to reduce the risk of pole slippage and lose of synchronism by the machine. This controller basis of the voltage dip experienced, reduce the active power output of the turbine. This action can be against the active power recovery requirements but the real and reactive power oscillations are much more damped and significantly reduce the risk of loss of synchronism.

Conclusions

- Why do we need fast post fault active power recovery?
  1. To stabilize frequency of power systems particularly for those with low inertia and high frequency sensitivity;
  2. To ensure voltage stability to mitigate overvoltage problem after the faults.

- Is fast post fault active power recovery always needed and should it be always required?

  Taking into account the fast grow of penetration of PPMs, the fast post fault active power recovery is strongly requested to ensure the frequency stability and mitigate the risk of overvoltage trips of PPMs that can occur in long AC connections. But in the context of voltage stability, local network constraints and generator stability problems that may appear sometimes slower active power recovery than reference characteristic (specified below) can be considered to avoid local overloading of the lines and/or to ensure proper voltage control and/or to ensure PPM stability. In these cases deep project studies are needed to identify the needs to adjust (slow down active or speed up) active power recovery performance after the fault to the system needs and technology constraints.

[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[6]
Erlich, I.,Shewarega, F.: “Effect of wind turbine output current during faults on grid voltage and the transient stability of wind farms”, 2009

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Taking into account the:
- technical capabilities of PPMs,
- now existing requirements,
- system needs even in the future evaluation,
- now existing process of displacements of synchronous PGMs by PPMs

based on the frames given in the Network Codes below following criteria are identified referring to the post-fault active power recovery, that can be adopted to define this requirement on national level :

- the-post fault active power begins, at a voltage level of (80 – 90)% pre fault voltage at connection point;
- the maximum allowed time for active power recovery depends even on the clearing time T_{clear} of the fault by means of protection devices action and consequently this time may change between 0,5s and 10s, whereby shorter clearing time corresponds to faster response capabilities;
- the magnitude for post-fault active power recovery depends on the time the fault is cleared and basically on the availability of the primary energy source. Therefore the magnitude for active power recovery may be adopted on the level of 90 % of pre-fault active power;
- accuracy for active power recovery – 10% of pre -fault active power.

Due to inherent feature of synchronous generator directly connected to the grid there is no justification to specify post fault active power recovery performance. Taking into account the feature of synchronous generator technology directly connected to the grid inherent active power response after the fault of synchronous PGMs is fully acceptable. In contrast to synchronous PGM, PPMs connected to the grid through the power electronics have possibilities to control the response after the faults therefore detailed requirements on national level have to be defined during the implementation process.
Synchronous generator response should be treated as the model response of active power after the fault. The objective of the requirements for PPMs is to ensure their response close to the synchronous thus any requirements for synchronous PGM are not justified.

COORDINATION	
TSO – TSO	According to NC RfG provisions TSO – TSO coordination is not required. In context of frequency stability, TSO – TSO collaboration is recommended for the systems with high penetration of PPMs.
TSO – DSO	According to NC provisions TSO – DSOs coordination is not required. As most of the renewable generation will be connected at the distribution level a cooperation between TSO- DSOs shall take place.
RSO – Grid User	According to NC RfG provisions Relevant System Operator (RSO) – Grid Users coordination is not required.

<u>**Examples**</u>

Current situation on active power recovery requirements*

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Now existing APR requirement for PPMs are varying across the Europe. Below specified the examples of these requirements which can be the considered to define it on the national level:

EWEA and EPIA common proposal made during the consultation process:

- When the post fault active power begins, based on voltage criterion:
  90% Un pre-fault voltage
- maximum allowed time for active power recovery
  $T_{clear} \leq 140$ ms → 0,5 – 10 s.
  $140 \leq T_{clear} \leq 250$ ms → 1,0 – 10 s
- magnitude for active power recovery
  90 % of pre-fault power
- accuracy for active power recovery – not defined

It should be noted, that in its NC RfG review report KEMA[1] concludes in respect of the above two time ranges, the following: *"However, the importance of supplying the network load with active power as quickly as possible following a fault clearance in order to avoid under frequency load shedding must be recognised. The proposed active power recovery time ranges of 0.5 – 10s and 1 – 10s therefore appear too wide. If the EWEA/EPIA proposal is adopted, the lowest figures proposed would appear to be more appropriate, i.e. 0.5s and 1s respectively."*

Portugal requirements:
After the fault clearance: 5% of P_n/s.

German requirements:

Generators connected to the:

- EHV (220 and 380/400 kV) have to continue active power feed-in immediately after fault clearance with a gradient of at least 20 % P_{nom}/s (or 10 %/s if generators had to perform a short-time disconnection to prevent instability);
- HV (110 kV) the active current shall be increased immediately and continuously with a gradient of at least 20 % I_r/s. On request of the relevant system operator it shall be possible (within technical capabilities) to have larger gradients.

GB requirements:

- When the post fault active power begins, based on voltage criterion:
  90% Un system voltage
- maximum allowed time for active power recovery
  $T_{clear} \leq 140$ ms → 0,5 s.
  $T_{clear} > 140$ ms → 1,0 s.
- magnitude for active power recovery
  90 % of pre-fault power
- accuracy for active power recovery – not defined

Irish requirements:

- When the post fault active power begins, based on voltage criterion:
  90% Un system voltage
- maximum allowed time for active power recovery
  $T_{clear} \leq 140$ ms → 0,5 s.
  $T_{clear} > 140$ ms → 1,0 s.
- magnitude for active power recovery
  90 % of max available active power

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- accuracy for active power recovery – not defined

**) In principle, there is no active power recovery requirements for synchronous PGMs in the Grid Codes. Taking into account the feature of synchronous generator technology directly connected to the grid inherent active power response after the fault of synchronous PGMs is fully acceptable.*

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