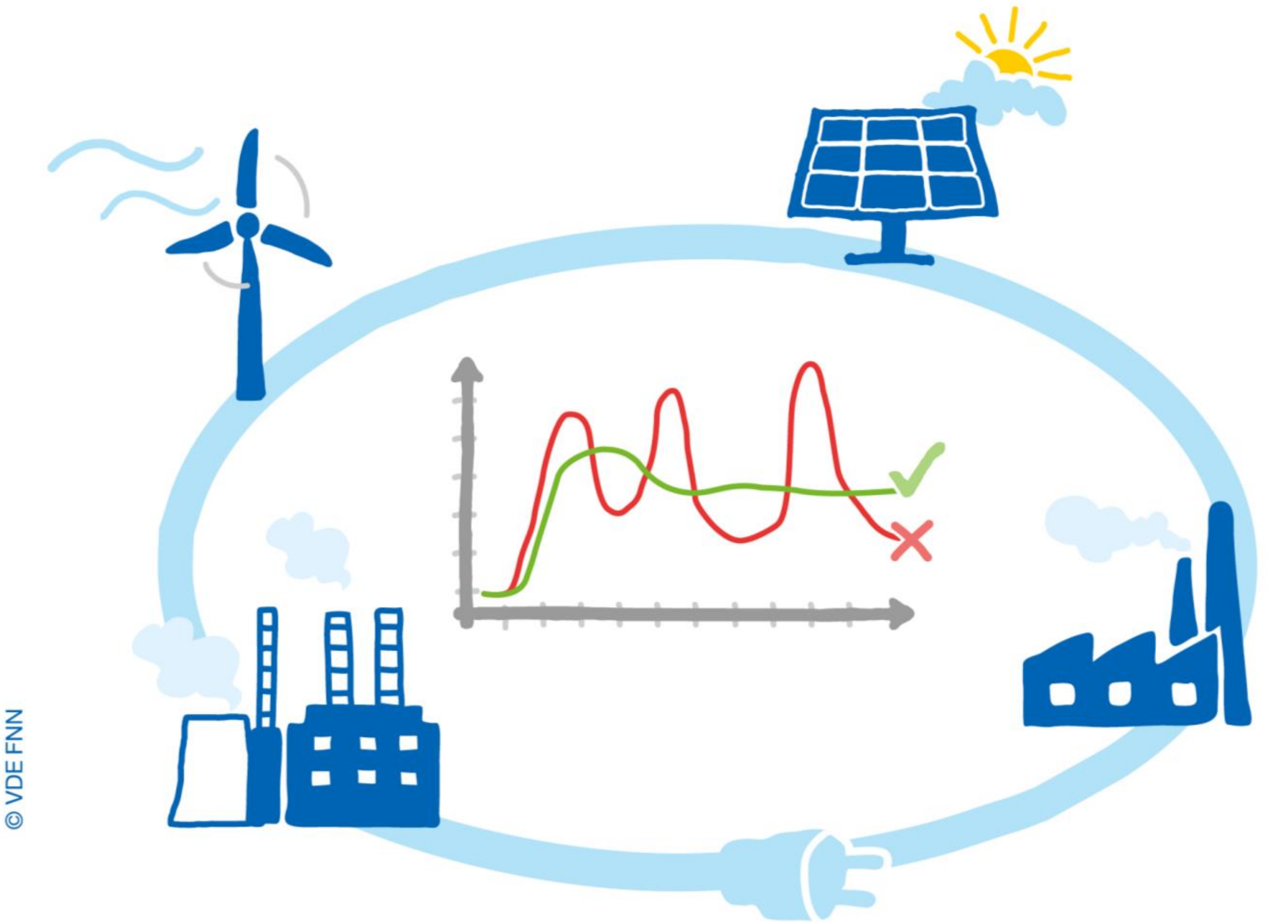

Grid-forming & system-supporting behaviour of power-generating modules

Version 1.0

December 2021

VDE FNN

Content

Foreword 4

1 Introduction 6

1.1 Stability properties of power-generating units 6

1.2 Current requirements for frequency and active power control 7

1.2.1 Island operation and separate network operability in accordance with Chapter 10.2.1.4 from VDE-AR-N 4130 7

1.2.2 Active power output in accordance with Chapter 10.2.4 7

1.2.3 Primary control power in accordance with Chapter 10.5.3 8

1.3 Assessment and further development of requirements 8

2 Abbreviations and definitions 9

2.1 Abbreviations 9

2.2 Definitions 9

3 Requirements for power-generating modules and continuously adjustable storage systems and consumption equipment 13

3.1 Response to a critical network frequency 13

3.2 Response to steep frequency gradients (RoCoF) and to angular steps 13

3.3 Requirements for type 1 and type 2 power-generating modules 13

3.3.1 Contribution to primary control based on network security 13

3.3.2 Requirements limited or extended due to technology-specific restrictions 16

3.3.3 Further requirements for frequency deviations 16

3.4 Requirements for continuously adjustable storage systems 17

3.4.1 Contribution to primary control based on network security 17

3.5 Requirements for continuously adjustable consumption equipment 18

3.6 End of critical network state and return to normal operation 18

4 Basic approach for verification of the primary control based on network security 19

4.1 Verification procedure for type 1 PGMs 19

4.1.1 Simulation verification (detailed modelling, measurements and simulation) 19

4.1.2 Example for verification of the requirements for type 1 PGUs in a fictitious island network 20

4.1.3 Extent of simulation verifications for primary control based on network security 22

4.1.4 Description and characteristic values of the model for a steam turbine generation unit 22

4.1.5 Small-signal behaviour 23

4.1.6 Large-signal behaviour 23

4.2 Verification procedure for type 2 PGMs 25

4.2.1 Detailed modelling, measurements and simulation 26

4.2.2 Example for the verification of the requirements for type 2 PGUs in a fictitious island network 27

4.3 Verification procedure for type 2 PGCM 30

4.3.1 Detailed modelling, measurements and simulation 30

4.4 Verification procedure for continuously adjustable consumption equipment 32

4.5 Additional reports within the PGM certification process 32

Annex A – Dynamic frequency response with rule-compliant turbine control 33

Bibliography 36

Table of Figures

Figure 1 - Requirement for the output power of power-generating modules in dynamic short-time operation 16
Figure 2 - Fictitious island network for verifying the properties of a type 1 PGU....................21
Figure 3 - Step response of type 1 PGUs at a load application of 10% (standard and classic models) 21
Figure 4 - Principal block diagram of the frequency-controlled power controller in a summation circuit 22
Figure 5 - Checking the small-signal stability within the operating range of 75% to 100% 23
Figure 6 - Partial load disconnection of the PGM from full load to a partial load of 55%.........24
Figure 7 - Load increase of the PGM from a partial load of 55% to 70%...............................24
Figure 8 - Fictitious low-voltage island network for verifying the properties of a type 2 PGU..25
Figure 9 - Fictitious MV and HV island network for verifying the properties of a type 2 PGU..25
Figure 10 - Simulation of a type 2 PGM (PV plant in accordance with a WECC model [15]); load disconnection from 100% to 55%....................28
Figure 11 - Simulation of a type 2 PGM (PV plant in accordance with a WECC model [15]); load disconnection from 55% to 10%....................28
Figure 12 - Simulation of a step load application from 65% to 75% 29
Figure 13 - Reduction to a partial load (from 90% to 55%) and a load increase back to 90% 29
Figure 14 - Model of a steam turbine with speed control..34
Figure 15 - Model of steam turbine with frequency-controlled power control (deviations from the steady state)....................34
Figure 16 - Simulation of electric power after a step change of the actual frequency by 125 mHz (operation on a large network)....................34
Figure 17 - Simulation of the frequency at a step load change (0.05 p.u.) (separate network operation) 35

Table of Tables

Table 1 - Dynamic requirements regarding primary control for the setting ranges of type 1 and type 2 PGM/PGCM....................15

Foreword

This Technical Guideline is intended to initiate promptly necessary developments in the field of power-generating modules and further progress in the field of the VDE Technical Connection Rules (TCRs) which, given the changing structure of power generation, become increasingly important for the stability of interconnected systems. The focus here is on the three system-relevant capabilities of power-generating modules described below, which can be achieved by means of control measures and will only ever be fully required in rare disturbance events; hence they do not place additional demand on the power-generating module in normal operation.

- **Separate network operability of power-generating modules with synchronous generators**

In both small networks and large interconnected systems, the frequency response is given by the summated effect of all frequency-dependent active power feed-in and consumption. This applies not only to the handling of a spontaneous power imbalance but also to the capability of maintaining a stable operating point during undisturbed operation.

The currently applicable Network Connection Rules for HV, MV and LV networks are designed such that new power-generating modules are not required to contribute to the network frequency stability during undisturbed operation. When implementing the requirement "operation along the characteristic", a reduction in frequency response damping has been observed in both small networks and large interconnected systems. Extreme cases may also result in resonating oscillations, even without the occurrence of any power imbalance.

The separate network operability of power-generating modules ensures their positive contribution to the frequency response damping in an interconnected system. While in undisturbed standalone operation at a stable operating point, power-generating modules with separate network operability are able to maintain constant frequency and voltage and provide sufficient damping of the frequency and voltage control.

Separate network operability is achieved only by means of suitable controller structures and parameters. As an example, steam turbines with a centrifugal governor as designed by James Watt are inherently provided with separate network operability. Special capabilities with respect to the plant's generating process (such as control range, control speed) are not required for this purpose. These are only of relevance as far as the disturbance to be handled is concerned. Suitable control strategies fulfilling the requirements for separate network operability and ensuring a positive contribution to frequency control damping have already been described in the 1990s [1] [2] [3]. This is illustrated by simulation results obtained using different turbine controllers (see Annex A on page 33).

In small networks, the absence of separate network operability in individual systems becomes directly apparent through a decrease in frequency control damping. Hence, there have been past reports on small networks where the commissioning of a given power-generating module resulted in a more "unsettled" frequency.

In large interconnected systems on the other hand, operational effects of individual systems are not detectable. The absence of separate network operability in large interconnected systems often remains concealed as long as the malfunction is sufficiently compensated by other systems. Hitherto, the TSOs have been able to check power-generating modules with synchronous generators connected to the transmission network for their separate network operability. In the future, however, such plants will be replaced by many small power-generating modules connected on lower network levels. Checking their control behaviour and taking individual corrective measures will then no longer be feasible.

Therefore, there is a risk of a creeping unwanted development in the German and the European Interconnected System, which may remain unobserved in operation over a relatively long period. However, this problem will be revealed spontaneously as soon as a separate network is formed (system split) or the ±200 mHz deadband is exceeded, in which case the stability of the separate network or even of the entire interconnected system can be put in jeopardy.

- **Separate network operability of inverter-based power-generating modules**

All future and current inverter-based plants installed following the current TCR requirements have a current-source characteristic due to their control strategy. An operational configuration is only possible through parallel operation with a synchronous generator. Here, the synchronous generator provides a sinusoidal voltage at the connection point, which is a prerequisite for the functioning of inverter-based power-generating modules. By means of the inertia and the grid-forming properties of synchronous generators, an inverter-based power-generating module can contribute to a stable and sufficiently damped frequency and voltage control.

However, the parallel operation of sufficient capacities of synchronous generators cannot be assumed for the future grid. The associated unfavourable development in the dynamic properties will initially remain unobserved in the operation of a large interconnected network. However, it may lead to uncontrollable conditions when a separate network is formed or the frequency falls outside the ±200 mHz deadband. Grid stability can then only be ensured if there is sufficient capacity of systems with the capability to operate partial networks.

- **Over-frequency control**

With the increasing long-range transmission of electrical energy, rare disturbance events increase the risk of spontaneous separation of the interconnected system. In this case, the previously transferred power appears as a spontaneous power imbalance in the separate networks. In order to handle the spontaneous power shortage, frequency-dependent load disconnection is used as a rescue measure for the separate network.

Handling the spontaneous power excess requires a very prompt reduction in the power fed in by power-generating modules. Since this requirement is rarely necessary to its full extent, aspects such as carbon emissions and impact on service life are of minor importance. Considering the almost incalculable economic, ecological, and political consequences of a potentially transnational blackout, system rescue takes precedence.

Conclusion

Due to its extremely high importance for system security, it is deemed necessary to generally specify separate network operability as a minimum requirement for power-generating modules in accordance with §19 EnWG (German Energy Industry Act). This is primarily based on the fact that it describes an essential inherent property of the system.

This Technical Guideline does not constitute a legally binding requirement. Adoption of its contents is subject to the revision of the TCRs [4] [5] [6] [7] [8].