21th International Conference on Renewable Energies and Power Quality (ICREPQ'23)
Madrid (Spain), 24th to 26th May 2023
Renewable Energy and Power Quality Journal (RE&PQJ)
ISSN 2172-038 X, Volume No.21, July 2023

A Benchmark and Validation Guide for the Hungarian Implementation of the Common European Requirements for Electricity Generators

Dr. Istvan Vokony
Associate Professor
Department of Electric Power Engineering
Budapest University of Technology and Economics
Egry József Str. 18. – 1111 Budapest (Hungary)
Phone number: +36-30/640-9013
E-mail: **vokony.istvan@vik.bme.hu**

Kristóf Juhász
Engineering Consultant
F4STER-Future 4 Zrt.
Építész Str. 24. – 1111 Budapest (Hungary)
Phone number: +36-20/568-0944
E-mail: **kristof.juhasz@f4ster.hu**

Márk Somogyi
Engineering Consultant
F4STER-Future 4 Zrt.
Építész Str. 24. – 1111 Budapest (Hungary)
Phone number: +36-20/568-3093
E-mail: **mark.somogyi@f4ster.hu**

Abstract. In the Hungarian electricity system, as well as in other European countries, the share of renewable based production is increasing. These power generating modules do not contain rotating masses like those of traditional synchronous power generating modules which creates new challenges on the electric grid with respect to system stability and frequency control. The distribution system operators (DSOs) of the different countries need to cope with this problem and set frequency, voltage thresholds and robustness requirements for the electricity generating power plants. This project aims to create specific requirements for the Hungarian generators considering the former implementations of other countries (UK, Germany, Denmark and Finland). The different requirements of these foreign areas are introduced in a benchmark study, which is the first essential part of the whole project. Such implementations are only partially defined for Hungary; therefore, in some cases it is necessary to use the implementations of other foreign countries which have similar grid characteristics and are dealing with the same control and operation challenges. Another important milestone of this work besides the benchmark study is to present a validation guide for the Hungarian transmission system operator (TSO) that can be sent directly to the operators of electric power generating modules with six different types. These guides contain compliance tests for the power plants to examine whether they meet the requirements of grid connection or not.

Key words. synthetic inertia, synchronous power generating module, power park module, renewable energy sources, frequency threshold, voltage threshold, robustness requirements, synchronous area, Fault-Ride-Through.

1. Introduction

In the Hungarian electricity system, as in other European countries, the share of renewable electricity producers is increasing. A significant proportion of these – mainly solar and wind power plants – are connected to the grid through power electronics, unlike conventional fossil-fuelled power plants. The weather dependency, distributed nature and electrotechnical differences in connection have led to an increase in the requirements for generating units. The grid connection requirements for generating units are regulated by the European Union (EU), the implementation of which is the responsibility of the Member States. In this process, it is the task of the Hungarian distribution system operator (DSO) to analyse the situation and to develop test methodologies and processes in principle. This Hungarian institution in called MAVIR. In relation to the requirements for the power plants, technical capabilities are in the spotlight to be verified at the time of commissioning. Connectivity tests, network calculations by computer simulation and the capabilities managed in the accreditation process for system services are not part of the assignment. Accordingly, as part of the first milestone, relevant regulation and related codes are analysed and capabilities identified and listed that are relevant to the implementation of the assignment, exact content is defined of the further work. An international overview of limits and test methods in other European countries is provided as well.

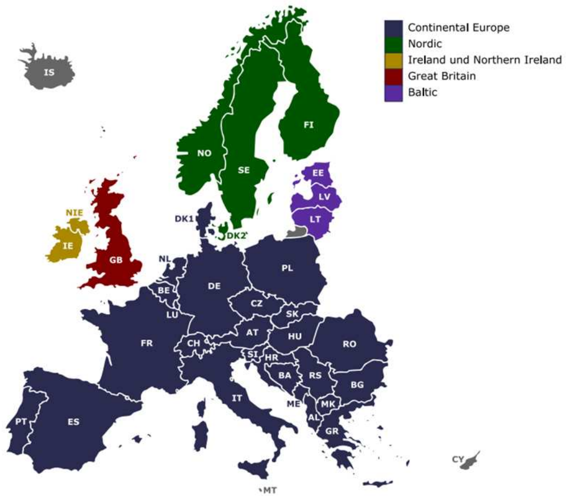

Fig. 1. Synchronous areas in Europe

In the first phase of this work, a comparative analysis of the electricity systems in three European countries is presented. In all the analysed countries, a regulatory framework for generating units is already in place. The first example is the system in the United Kingdom, operated by the British TSO which is called NATIONAL GRID. This company started developments in this field in 2010, aiming to minimise the frequency deviation from the nominal 50 Hz through fast frequency response and continuous regulation. Great Britain is a relatively small synchronous area (GB in Figure 1) as it is located on an island. Thus it is especially important to set thresholds for well-functioning frequency control and stable system operation. The other two examples are from the synchronous area of Continental Europe. One from Germany (DE in Figure 1) where the TSO is called 50HERTZ and the other from Denmark (DK1/DK2 in Figure 1) where the TSO of the country is called ENERGINET. A description and comparison of the practices in these three countries is the milestone assignment.
Another chapter is added to the benchmark study with the analysis of the electric grid operation of a country in the North European (NORDIC) synchronous area: Finland (FI in Figure 1). Finland's TSO is called FINGRID, and this institution sets the requirements for the grid connection of electricity generating installations in the Scandinavian country. This chapter gives another outlook to the benchmark and helps to understand the implementation in a certain area.

2. Grid connection requirements

In this section of the project, frequency, voltage thresholds and robustness requirements have been introduced and compared between the different sample countries in the benchmark study (Great Britain, Germany, Denmark and Finland). In some cases there are already implemented requirements for Hungary as well but in most cases a recommendation is made for Hungary based on the implementation of the sample countries (e.g. Germany). The requirements are different according to the size of a power generating module all over the world. There are usually four categories: Types A, B, C and D. These categories are defined by the output power and boundaries of categories may vary according to a country. In Hungary the power generating modules with an output power between 0,8 kW and 200 kWs are named Type A, from 200 kWs to 5 MWs Type B, between 5 MWs and 25 MWs Type C, and from 25 MWs up Type D.

A. Frequency requirements

The implementations of the Requirements for Generators Network Code (RfG NC) require that connection between the grid and the generating unit should be maintained even if the actual frequency value is not 50 Hz or there is a certain Rate of Change of Frequency (RoCoF) value in time. These deviations might occur when something unexpected happens on the grid, like a fault, a breakdown or generating units fall out.
The frequency limits and the shortest expected operating time requirement should be set for the power plants that are larger than Type A. The grids of the countries in the Continental synchronous area are connected to each other across the borders, and thus they have larger synchronous inertia as the separated countries like Great Britain. This is the reason why countries in smaller synchronous areas need to set stricter limits. The power plants need to operate in a wider frequency interval to increase the stability of the whole electric power system. The implementations for this requirement in the sample countries and Hungary can be seen in Table I below.

Table I. – Frequency limits and shortest expected operating times

	Range [Hz]	GB [min]	DE [min]	DK [min]	**HU [min]**
FR0	47-47.5	1/3	0	0	**0**
FR1	47.5-48.5	90	30	30	**30**
FR2	48.5-49	90	30	30	**60**
FR3	49-51	∞	∞	∞	∞
FR4	51-51.5	90	30	30	**30**
FR5	51.5-52	15	0	0	**0**

As Table I shows, only GB requires operation in F0 and F5 intervals. The Continental power plants will disconnect from the grid at such a deviation.
There is another frequency related threshold called Rate of Change of Frequency (RoCoF). For power parks, synchronous inertia is zero. As opposed to synchronous power generating modules, in power parks the generator has no synchronously rotating mass connected to the power grid. The rotation speed of this mass changes (increases or decreases) if generation and consumption are not the same. In such cases, system frequency increases or decreases, and the time derivative of this is the RoCoF value. The limit value of this shows the threshold value above which the generator disconnects from the network. The RoCoF value is generally calculated as a mean of values measured in a time window. This value is prescribed only for Type A generators in Hungary (2.5 Hz/s); thus the validation test should be carried out according to the values prescribed in Germany because of the similarities of the two

countries' grids. The implementations in the sample countries can be seen in Table II below.

Table II. – The implemented thresholds of RoCoF

	GB	**DE**	DK	HU
RoCoF [Hz/s]	1	**1.25 or 1.5 or 2**	2	2.5 (only for Type A)
Time window [s]	0.5	**2 or 1 or 0,5**	-	0.5

There are no concrete values defined by RfG NC for RoCoF, so the DSOs of the member states are free to set the thresholds. Typically, the island countries (e.g., Great Britain) implemented the strictest requirements in this context, because system stability is essential to them.

The frequency changes are not only controlled outside the normal operating interval. The larger power plants need to be capable of increasing or decreasing their power output with changing frequency. The admissible active power reduction from maximum output (P_{max}) is another frequency requirement defined by RfG NC. It limits the power reduction in the case of falling frequency [$\%P_{max}$/Hz] when the output power should be increased to reach the nominal frequency value on the electric grid again. The RfG NC document does not specify a given value for the admissible reduction, only a range is specified. There is no implementation for Hungary, so the German limits can be implemented again. The implementations of the different sample countries are given in Table III below.

Table III. – Admissible active power reduction from maximum output at falling frequency

	GB	DE	DK	**HU**
Admissible P_{max} reduction [$\%P_{max}$/Hz]	2*	10*	6**	**10* 2****

* below 49.5 Hz
**below 49 Hz

If the grid frequency rises beyond 50 Hz nominal value, for Type C and Type D power plants Limited Frequency Sensitive Mode – Overfrequency (LFSM-O) is required. For this case a frequency threshold and a droop [%] is defined by the DSOs, shown in Table IV for the sample countries below.

Table IV. – LFSM-O values defined by the DSOs of the sample countries

	GB	**DE**	DK
Frequency threshold [Hz]	50,4	**50.2…50.5 (50,2)**	50.2 (DK1) 50.5 (DK2)
Droop [%]	2…10 (10)	**2…12 (5)**	5 (DK1) 4 (DK2)

If the grid frequency goes below the nominal value, there is another requirement for Type C and Type D power plants that is called Limited Frequency Sensitive Mode – Underfrequency (LFSM-U) which is similar to LFSM-O, but the generator has to operate differently. Instead of increasing output power it must decrease it in this case. The implementations for the sample countries regarding LFSM-U are specified in Table V below.

Table V. – LFSM-U values defined by the DSOs of the sample countries

	GB	**DE**	DK
Frequency threshold [Hz]	49.5	**49.5…49.8 (49.8)**	49.8 (DK1) 49.5 (DK2)
Droop [%]	2…10 (10)	**2…12 (5)**	5 (DK1) 4 (DK2)

For power generating modules with a larger size (Type C and D), it is also required to control changing frequency inside the normal operating period. This capability is the Frequency Sensitive Mode (FSM) (Figure 2).

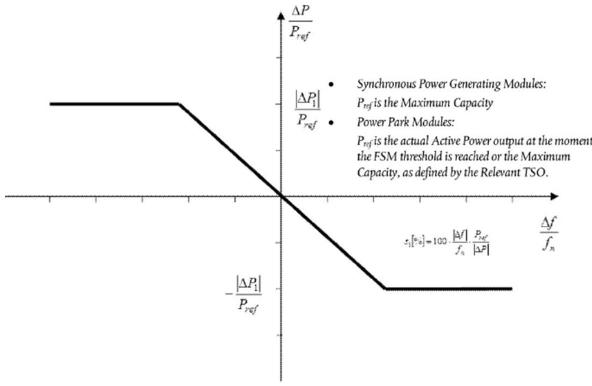

Fig. 2. Active power frequency response capability of power-generating modules in FSM illustrating the case of zero deadband and insensitivity

Table VI. – FSM values defined by the DSOs of the sample countries

	GB	DE	DK	**HU**
Deadband [mHz]	0	0…200	0…200 (DK1) 0…500 (DK2)	**0**
FSR* [mHz]	±15	±10	±10	**±10**
Droop [%]	3…5 (-)	2…12 (-)	2…12 (-)	**2…12 (-)**
ΔP_1 [$\%P_{max}$]	10	2	1,5…10	**1,5…10**
$t_{1,\ SPGM}$ [s]	2	2	2	**2**
$t_{1,\ PPM}$ [s]	1	1	2	**1**
t_2 [s]	10	30	30	**30**
t_3 [min]	-	15	15	**15**

*FSR = Frequency Sensitive Response

B. Voltage requirements

Electricity generating units must meet voltage requirements before being connected to the grid. The following validation tests should be completed:

1) *Reactive power capacity of the generating plants:* the voltage stability requirements include the definition of the reactive power supply and control by a power generating module. The generators connected to the grid should contribute to the efficient and stable operation by providing reactive power – both inductive and capacitive. This requirement is defined in the form of U-Q diagram which describes the ability to deliver reactive power at the grid connection point at different voltages at maximum capacity.
2) *Reactive power capacity below the maximum capacity for Power Plant Modules*: renewable based generating modules (solar or wind) must also be able to provide reactive current below the maximum capacity. This requirement is defined in the form of P-Q diagram.
3) *Voltage ranges and operating periods:* similar to frequency ranges there are also voltage ranges defined for different power generating modules in which they should stay connected to the grid.

C. Requirements regarding robustness

The requirements of RfG NC for robustness basically include the Fault-Ride Through (FRT) capability of power generating modules of type B, C, D. This means that they should be able to remain connected to the synchronous network and operate through periods of low voltage at the connection point at typically network side faults. FRT requirements are defined by the RfG NC with the key points of the U-t profile (voltage-against-time profile) given in Figure 3 below.

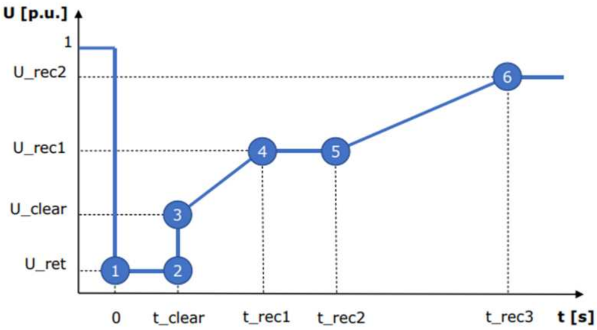

Fig. 3. Fault-Ride-Through (FRT) profile

3. Validation guide

One of the most important outputs of our research is a framework for validating expectations for power plants of different size ranges and operational types. The types A, B, C and D are distinguished. There is no measurement guide for Type A due to its relatively small size compared to the others. For type B, C and D power plants, a measurement guide has been prepared for synchronous and non-synchronous power plants. The aim of the guide is to validate the compliance with the RfG NC specifications and to perform this assessment in a reliable, verified and auditable way under the guidance of MAVIR as the Hungarian transmission system operator (TSO), the authority responsible for the local implementation of the RfG NC. Table VII below summarises all test cases that have been introduced in Chapter 2 and provides guidance on how it is proposed to perform the measurement. This guide contains a list of parameters to be measured, a schematic diagram of the measurement circuit, a schematic diagram of the measurement, the requirements for the measuring instruments and a support tool to support the evaluation of the measurement both numerically and graphically.

The general setup for the measurements can be seen in Figure 4 and Figure 5 according to the type of the power plant that should be validated in the test.

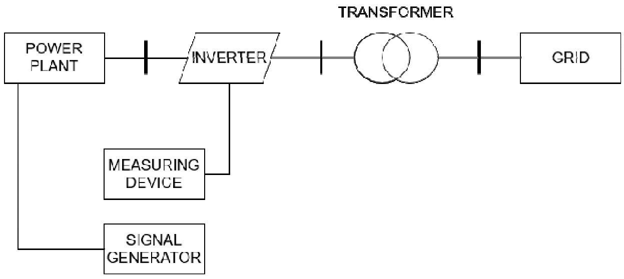

Fig. 4. General measurement setup for PPMs

All Power Park Modules (PPMs) contain an inverter where the current produced in the generator is converted to AC. In Solar Power Parks, the generated current is DC, so the device is a DC/AC converter. In Wind Power Parks it is an AC/DC/DC converter. Afterwards, the voltage level is transformed to the voltage level of the grid by the transformer marked in the Figure. The Signal Generator is the device which creates the frequency or voltage sign which is used to test the power plant whether it meets the connection requirements or not. During the validation test the power plant does not notice being separated from the grid because the Signal Generator creates the same circumstances. The Measuring Device records the data during the validation test.

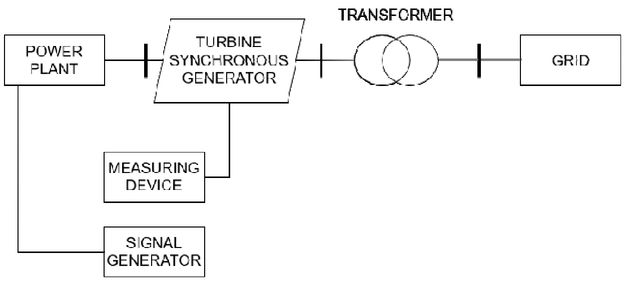

Fig. 5. General measurement setup for SPGMs

In a traditional Synchronous Power Generating Module, the inverter is replaced by the Turbine and the Generator. These devices are rotating synchronously on the same axis. This type of power plants usually has significant system inertia for frequency control. The Measuring Device is connected to the Turbine Synchronous Generator in this case. The Signal Generator is connected to the power plant the same way as in the previous one.

Table VII shows that compliance tests for checking both Fault-Ride-Through (FRT) capability and Limited Frequency Sensitive Mode – Overfrequency (LFSM-O): these are required for all the examined power generating types. For Type B (0.2-5 MW) Synchronous Power Generating Modules (SPGMs) or Power Park Modules (PPM) it is not necessary to do any other compliance tests besides the two former ones. As the size of the generating power plant grows, the number of required tests is growing as well.

For Type C (5 – 25 MW) and Type D (> 25 MW) SPGMs frequency limits and expected operation time, Rate of Change of Frequency (RoCoF) requirement, maximum admissible active power reduction at lowering frequencies, Limited Frequency Sensitive Mode – Underfrequency (LFSM-U), Frequency Sensitive Mode (FSM) settings, frequency recovery test and reactive power capability at maximum capacity (U-Q diagram) should be tested.

Table VII. – Validation requirements for different types of power generating modules

			Power generator types					
			„B" SPGM	„B" PPM	„C" SPGM	„C" PPM	„D" SPGM	„D" PPM
Compliance tests	Frequency requirements	Frequency limits and expected operating time			x	x	x	x
		Rate of Change of Frequency (RoCoF)			x	x	x	x
		Limited Frequency Sensitive Mode for frequencies over 50 Hz (LFSM-O)	x	x	x	x	x	x
		Maximum admissible active power reduction at lowering frequencies			x	x	x	x
		Limited Frequency Sensitive Mode for frequencies under 50 Hz (LFSM-U)			x	x	x	x
		Frequency sensitivity setting (FSM)			x	x	x	x
		Frequency recovery test			x	x	x	x
	Voltage requirements	Reactive power capability at maximum capacity(U-Q diagram)			x	x	x	x
		Reactive power capability below maximum capacity (P-Q diagram)				x		x
		Voltage control mode test				x		x
		Reactive power control mode test				x		x
		Power factor control mode test				x		x
		Voltage ranges and the respective expected operating times					x	x
		Automated voltage control device					x	
	FRT	Fault-Ride-Through (FRT-profile)	x	x	x	x	x	x

A) *Reactive power capability at maximum capacity (P_{max}):*

The U-Q/P_{max} profile is a profile representing the reactive power capability of a power-generating module or HVDC converter station in the context of varying voltage at the connection point. The value must be determined at the $P = P_{max}$ point.

The relevant Distribution System Operator (DSO) must cooperate with the relevant Transmission System Operator (TSO) to determine the reactive power capability requirements in the context of varying voltage. Thus, the relevant system operator must specify a U-Q/P_{max} profile, within the limits of which the power park can provide reactive power even at maximum capacity.

Outer limits determined by the *RfG NC*:

- U_{min} = 0.875 pu
- U_{max} = 1.1 pu
- min(Q/P_{max}) = -0.5
- max(Q/P_{max}) = 0.65

Inner limits determined by the *RfG NC*:

- max. U range = 0.225 pu
- max. Q/P_{max} range = 0.75 pu

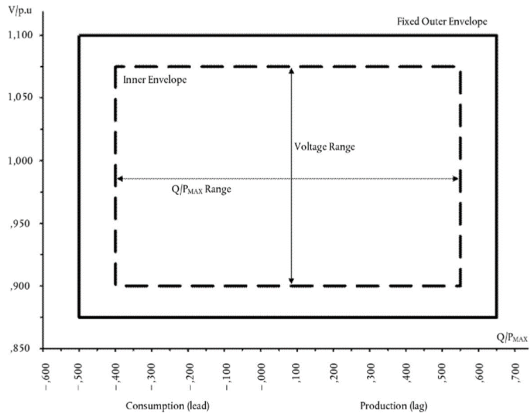

Fig. 6. Reactive power capability at maximum capacity (P_{max})

The U-Q/P_{max}-profile shall be specified by the relevant system operator in coordination with the relevant TSO, in conformity with the following principles:

– the U-Q/P_{max}-profile shall not exceed the U-Q/P_{max}-profile envelope, represented by the inner envelope in Figure 6;

– the dimensions of the U-Q/P_{max}-profile envelope (U-Q/P_{max} range and voltage range) shall be within the range specified above; and

– the position of the U-Q/P_{max}-profile envelope shall be within the limits of the fixed outer envelope in Figure 6;

– the specified U-Q/P_{max} profile may take any shape, having regard to the potential costs of delivering the capability to provide reactive power production at high voltages and reactive power consumption at low voltages.

B) *Reactive power capability below maximum capacity ($P<P_{max}$):*

The P-Q/P_{max} diagram shows the expected reactive power capability *(Q)* of a power-generating module in the context of varying output active power *(P)* at the connection point if $P < P_{max}$ point.

Below the level of maximum capacity, concerning reactive power capability:

a) the relevant system operator in coordination with the relevant TSO shall specify the reactive power provision capability requirements and shall specify a P-Q/P_{max}-profile that may take any shape within the boundaries of which the power park module shall be capable of providing reactive power below maximum capacity.
b) the P-Q/P_{max}-profile shall be specified by each relevant system operator in coordination with the

relevant TSO, in conformity with the following principles:
- the P-Q/P_{max}-profile shall not exceed the P-Q/P_{max}-profile envelope, represented by the inner envelope in Figure 7;
- the Q/P_{max} range of the P-Q/P_{max}-profile envelope is specified below.
- the active power range of the P-Q/P_{max}-profile envelope at zero reactive power shall be 1 pu;
- the P-Q/P_{max}-profile can be of any shape and shall include conditions for reactive power capability at zero active power; and
- the position of the P-Q/P_{max}-profile envelope shall be within the limits of the fixed outer envelope set out in Figure 7;

c) when operating at an active power output below maximum capacity ($P<P_{max}$), the power park module shall be capable of providing reactive power at any operating point inside its P-Q/P_{max}-profile, if all units of that power park module which generate power are technically available that is to say they are not out of service due to maintenance or failure. Otherwise there may be less reactive power capability, taking into consideration the technical availabilities.

Outer envelope specified in the *RfG NC*:

d) min. P/P_{max}: 0 pu
e) max. P/P_{max}: 1 pu
f) min. Q/P_{max}: -0,5 pu
g) max. Q/P_{max}: 0,65 pu.

Inner envelope specified in the *RfG NC*:
h) max. Q/P_{max} range: 0,95 pu

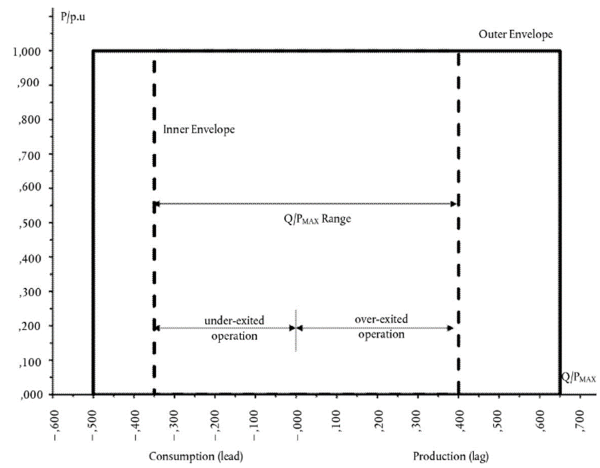

Fig. 7. P-Q/P_{max}-profile of a Power Park Module (PPM)

Checking the required voltage ranges and the respective excepted operating times for Type D SPGMs is also necessary and these units must contain an Automated Voltage Control Device as well.
Type C (5-25 MW) and D (>25 MW) PPMs need further compliance tests like reactive power capability below maximum capacity (P-Q diagram), voltage, reactive power and power factor control mode tests.
At each test measurement, the power generating module is separated from the grid, and the applied signal generator produces the voltage, frequency or current value for the check. The plant operates as if it would be connected to the grid. The results of the measurements are recorded in a measuring device.

4. Conclusion

As a conclusion of this project, a recommendation for the RfG implementations in Hungary is worked out considering other highly developed countries with already existing implementations. A validation guide is created for the Hungarian power plant operators to be able to validate their own power generating module before connecting to the grid or to make their own facility to meet the common European requirements.
It turned out that the Hungarian grid is very similar to the German one, as both are parts of the Continental Synchronous Area of Europe. Consequently, the requirements implemented in Germany can be implemented in Hungary as well. It is important that the role of artificial inertia will increase with the growing number of renewables in the Hungarian grid. Although artificial inertia capability is not a requirement at the moment, it is likely to be included in the requirements later. That is why new renewable based PPMs should think about the future control and stability of the grid.

Acknowledgement

We would like to thank the contribution in this project to Bence Bereczki, Dr. András Dán, Dr. Bálint Hartmann and István Táczi.

References

[1] R. Wilson, R. Woodward, Requirements for Generators (RfG) – Review of banding thresholds, National Grid, London, 2014,
[2] M. Ali, E. Makki, C. Cazal and Y. Ayadi, Implementation of the Network Code on Requirements for Grid Connection of Generators, Directorate-General for Energy, European Commission, Brussels, FGH GmbH, February 2021,
[3] S. Schulz, Technische Anschlussbedingungen der 50HERTZ Transmission GmbH, 50 HERTZ Transmission GmbH, Heidestaße 2, 10557 Berlin, 11. June 2019,
[4] Fact Sheet, Requirements for Generators (RfG), National Grid, 2. June 2018,
[5] EU Bizottság 2016/631 rendelete a termelőegységek hálózati csatlakozási követelményeire vonatkozó üzemi és kereskedelmi szabályzat létrehozásáról, European Commission, Brussels, 14. April 2016,
[6] Requirements laid down under EU regulation 2016/631 – Requirements for grid connection of Generators (RfG), articles 13-28
[7] Grid Code Specifications for Power Generating Facilities VJV2018, FINGRID unofficial translation, 16. November 2018,
[8] Draft Grid Code – Grid Forming Converter Specification, 3. September 2020,
[9] M. A. Pelletier, M. E. Phethean and S. Nutt, Grid code requirements for artificial inertia control systems in the New Zealand Power System, IEEE Power and Energy Society Meeting, 22-26 July 2012,
[10] U. Tamrakar, D. Shrestra, M. Maharjan, B. P. Bhattarai, T. M. Hansen and R. Tonkoski, Virtual Inertia: Current Trends and Future Directions, Applied Sciences 2017, 7(7), 654, USA.