FAULT RIDE THROUGH REQUIREMENTS BY GRID CODES: TRANSIENT ANALYSIS AND SOLUTIONS FOR A MW RANGE ORC

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ABSTRACT

Up to recently, it was rather usual that any grid disturbance outside certain limits (like a short grid fault causing a deep voltage sag) implied a small size (hundreds of kW or megawatts range) electricity production unit, as an ORC is, to be disconnected from the grid and stop.
The increasing share of renewable plants, compared to the overall generated power in a grid, forced the utilities to take into account the problem that a sudden shut-off of many generators could even cause a major grid black-out, possibility that would be negligible if the contribution to the overall power of the disconnected generator/s was minor.
For this reason, more recently many International grid codes ask the generators connected to the grid to remain connected when a voltage sag, within a specified voltage-time profile, occurs.
The paper lists and analyzes the grid codes requirements of some European countries and shows the results of a detailed study carried out on a 770 kW ORC unit, considering the transient behaviour of the system during a grid fault from an electrical point of view and taking into account the dynamic response of the ORC unit as a whole.
The analysis is carried out considering to drive either an asynchronous generator or a synchronous one. Furthermore, some considerations are added to explain which solutions should be adopted in the design and selection of the electric generator driven by the turbine as well as of the main auxiliaries of the ORC (for example the frequency converter powering the feed pump) and other ancillary systems to avoid a shutdown of the unit during a short-circuit grid fault.

1 INTRODUCTION

The EU Regulation 2016/631, Requirement for Generators (RfG) states that the generating units shall be capable of remaining connected to the national grid during a voltage dip as specified in the regulation. This capability is also called Fault Ride Through (FRT) to suggest the ability of the unit to withstand a fault in the grid and to continue to work stably after the fault has been cleared. Depending on the size of the unit, it could be also required to inject reactive power during such a fault. This section describes the FRT requirement and briefly compares the technical specifications of some European grid codes; then it explains the physical effects on the turbogenerator and proposes a solution to control the turbine power during such faults.

1.1 European regulations for generators

The EU RfG regulation specifies a general voltage-against-time-profile as shown in *Figure 1*, which represents the lower limit of a voltage profile (phase-to-phase voltage) at the connection point before, during and after a fault, expressed as the ratio of its actual value and its reference 1 per unit (pu) value. The RfG defines a general minimum requirement which must be considered by each single EU country. The single countries can adapt the RfG voltage profile to the characteristics of the local electricity network, therefore they can move the profile inside the ranges defined by the RfG regulation. This voltage profile represents the voltage applied to the point of coupling between the plant and the electricity grid. The voltage inside the plant depends on the additional voltage drops due to the electrical equipment (cables, transformers, etc.) and the currents.

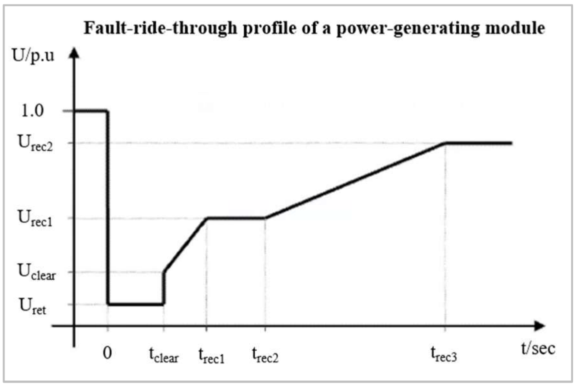

Figure 1: Fault-ride-through profile of a power-generating module according to RfG.

At a national level, each Transmission System Operator (TSO) defines the applicable voltage-profile in its country or part of the country. As example, some of the rules applicable to the medium voltage distribution network in Europe are: the VDE-AR-N-4110 in Germany, the CEI 0-16 in Italy, the G99 in UK and the RES 64E in France.

Figure 2, on the left, shows the comparison between the RfG, the German and Italian rules for the synchronous generator type. On the right it shows a similar comparison for the asynchronous generator type. The FRT diagrams of the specific countries often overstep the RfG general diagram and this represents a worse condition than the one required in the European regulation. The final effect of the FRT depends on the depth and the time duration of the fault. Minor faults have a limited impact on the machine and the generator could easily pass the fault with a small disturbance. Major faults, which correspond to deep voltage drops, can thoroughly stress the machine.

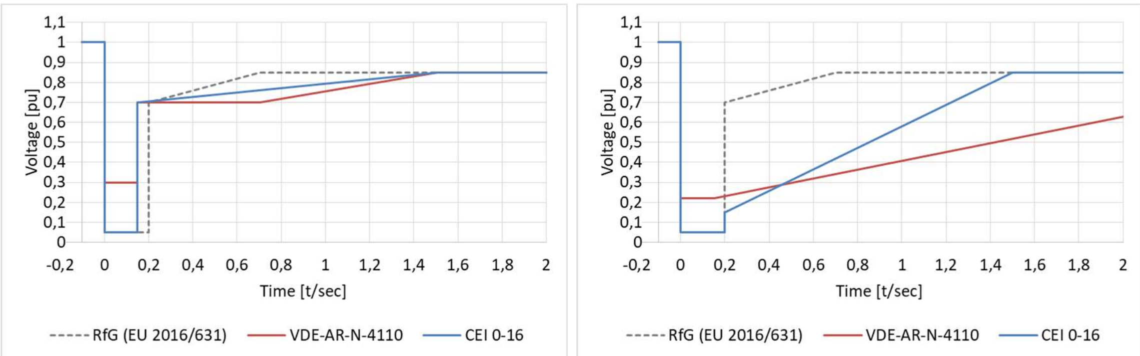

Figure 2: Fault-ride-through (FRT) limit curve for synchronous (on the left) and asynchronous (on the right) generators; comparison between RfG, German, Italian, English and French rules

Figure 2, on the right, shows that the profile for the asynchronous generator is more demanding in terms of the stress which the machine shall withstand. As shown, the recovery voltage increases quite slowly compared to the synchronous profile therefore it is more difficult to fulfil the FRT requirement with an asynchronous generator.

1.2 Effects on ORC turbogenerators

The behaviour of the generator unit during a grid fault depends on the prime mover, whether it is for example a diesel engine, a gas engine or an ORC turbine. From the electric point of view, a voltage dip causes a reduction of the active power that the electric generator can produce, thus of the resistive active torque on the rotor. The mechanical torque of the prime mover is no more balanced by the resistive torque on the generator, thus the rotor starts accelerating. If nothing changes in the ORC control system, the turbine continues to accelerate and could eventually reach the over speed trip threshold. The dynamics of the turbine speed depends on the total inertia of the turbogenerator, the accelerating torque and the reaction time of the control system. In most ORC turbines, turbine valves are installed at some

"distance" from the turbine nozzles, hence some overspeed cannot be eliminated due to the fluid volume between the control valves and the turbine, which is a characteristic imposed by the mechanical design of the machine.
A proper control strategy must be implemented in order to mitigate the overspeed during such FRTs.

1.3 Turbine valves control

A solution has been designed to help limiting the overspeed of the turbogenerator in case of a FRT. The proposed solution is called "fast valving" and consists in a rapid closing of the turbine inlet valve and the simultaneous opening of the turbine by-pass valve in case of a voltage drop below a specific threshold. The trigger of this mechanism is activated by an electric protection relay which monitors the generator voltage; in case the voltage drops below the threshold, the protection relay activates the "fast valving" control in the ORC control system. The minimum delay after which the speed begins to slow down depends strongly on the closing/opening time of the valves and the time delay caused by the residual vapor volume which flows into the turbine after closing the inlet valve. This minimum delay is about 600 ms, therefore this logic can be used only for long FRT with a small voltage drop. It is not effective for very short FRT with a deep voltage drop.

2 TRANSIENT ANALYSIS

The FRT problem cannot be approached by simple steady state calculations, but a time-domain RMS[1] transient analysis is necessary to properly evaluate the phenomenon. In literature, other studies have previously evaluated similar topics, for example Giulivo et al. studied fault tolerance focusing on the detailed electrical generator design from an electromagnetic point of view. Instead, starting from the electrical features and data of the generator provided by the manufacturer, the simulations described hereby focus on analyzing the behaviour of the whole ORC turbogenerator (electrical generator plus turbine and related control system).
The present section describes the model used for the simulations, the conditions, the assumptions and the evaluated parameters. The aim of the simulations is to show the effects of a FRT on the ORC turbogenerator and to demonstrate the ability of the machine to withstand the faults. The model and the simulations have been developed in a commercial software for this kind of analysis, in particular DIgSILENT PowerFactory 2019 SP3.

2.1 System description

The system modeled for the simulations is a real Turboden's ORC turbogenerator installed in an industrial plant in the city of Brescia, Italy. The industrial plant is connected to the public network at a voltage level of 15 kV. The relevant grid code is the CEI 0-16, applicable to the Italian medium voltage public network.
The medium voltage internal distribution is made by two power transformers, which reduce the voltage level down to 400 V. The ORC Generator is connected to a power cabinet downstream these transformers. The asynchronous generator is equipped with a power factor compensation cabinet, which is considered as a scenario variable.
The whole model contains the sub-models and related parameters of the main electrical components, such as power transformers, power cables, generator, motors and loads. Not every single load is represented, only the bigger loads are included as a specific load, while smaller loads are grouped in lumped loads.
During the FRT transient analysis, the voltage regulator on the primary side of the power transformers (tap changer) is neglected because the time response of such devices is much slower than the FRT dynamics. Similarly, all other type of regulators are neglected, such as the power factor regulator of the automatic compensation cabinet.

[1] RMS: Root Mean Square

2.2 Components models

DIgSILENT PowerFactory permits to do transient simulations in the time domain and provides components predefined dynamic models in its library. All the electrical components (generator, transformers, cables, external grid, etc.) have been represented with these predefined models.
The generator Automatic Voltage Regulator (AVR) has been modeled with the corresponding IEEE AC8b model as defined in IEEE 421.5-2016.
The turbine, the turbine valves, the governor and the upstream ORC thermal process are represented by a single model, which neglects the transient of the thermal process because that dynamic is significantly slower than electrical phenomena. The turbine power during an FRT can be changed by the turbine valves only. Given the specific ORC cycle conditions, the turbine power is evaluated with another calculation software that calculates the whole ORC thermodynamic cycle. This power is an input to the simulations described hereby. The non-linear effect of the valves is represented by a look-up table describing the relation between valves closing angle and turbine power. The vapor buffer between the valves and the turbine is modeled as a time delay in the effect of the valves. The governor is simply a PI (Proportional+Integral) control loop.
The type of simulation in DIgSILENT PowerFactory is a symmetrical electromechanical transient (RMS), which combines the electrical and mechanical physical phenomena. Time domain simulations are initialized by a load flow and the initial conditions are calculated for all the power system elements and represented by the steady-state operating point at the beginning of the simulation.

2.3 Model hypothesis

The model developed for the simulations is valid under the following conditions:

- The short circuit power at the Point Of Connection (POC) is at least 325 MVA (corresponding to a short circuit current of 12.5 kA).
- The ratio between the total reactance and resistance of the grid equal to 0.1.
- The grid voltage before the fault is the nominal one.
- The ORC model is a simplified model derived from a complete thermodynamic model of the ORC thermal process. The aim of the present analysis is to evaluate the turbogenerator behaviour during transient grid faults, which are much shorter than the ORC thermal process time response, therefore it is not worth to include the whole thermodynamic model in the FRT model.
- The fault simulated in each single simulation is not the complete voltage-against-time-profile, but it is a step-profile voltage drop as required by the simulation rules described in the relevant grid code.

Note about model validation:
The model and corresponding results discussed hereby have not been validated with physical tests on the real machine because not possible on the installation site. However the simulation model has been previously validated on other machines of the same size of the one described hereby. In particular, both the FRT simulation model and the turbine governor model have been validated, respectively in "Validation of the FRT simulation model with field measurements on Traunreut Geothermal power plant" and "Validation of ORC turbine simulation model for power system and stability studies".

2.4 Electric generator and turbine data

The present paragraph summarizes the data of the generator and the turbine. The data of the other components (power transformer, cables, etc.) are not shown for shortness.

The analysis is carried out considering the turbine to drive either an asynchronous or a synchronous generator whose data are summarized in Table *1*.

Table 1: Rated data of the asynchronous and synchronous generator

Description	Unit	Asynchronous	Synchronous
Rated power	kW	770	770

Rated voltage	V	400	400
Frequency	Hz	50	50
Number of poles	-	2	4
Rated speed	rpm	3016	1500
Rated current	A	1235	1389
Inertia (MR^2)	$kg*m^2$	7.3	25.9

The turbine data are summarized in Table *2*.

Table 2: Rated data of the ORC turbine

Description	**Unit**	**Value**
Rated power	kW	770
Inertia (MR^2)	$kg*m^2$	26.4

2.5 Fault types

The analysis is done for a turbogenerator installed in Italy, therefore the FRT simulation cases have been taken from the Italian grid code CEI 0-16. The grid code asks the generators to overcome different types of fault (three-phase, phase-to-phase, phase-to-ground), anyway the paper shows the results only for the worst type of fault (in terms of turbogenerator stress), which is the three-phase fault.
The fault cases are summarized in Table *3*.

Table 3: Fault cases list

FRT type	**Residual voltage [%]**	**Duration [ms]**
FRT 1	5%	220
FRT 2	20%	420
FRT 3	45%	870

2.6 Control functions

During short-circuit fault transients, the ORC turbine power is not limited because the time response of the complete control loop (instruments, acquisition system, Programmable Logic Controller (PLC) hardware, actuators, vapor buffer) is longer than the fault duration. Instead, in case of longer faults, more than 600 ms, the control system activates a power limitation function, which reduces the turbine power in order to limit the overspeed. This function is considered only for asynchronous generators, which is the one that has to overcome longer faults by CEI 0-16. This function is named "Fast valving". The simulations are carried out both with and without the power factor compensation system, in order to understand possible effects of this component on the generator behaviour during and immediately after the faults.

2.7 Simulation cases

The various cases are summarized in Table *4*.

Table 4: Simulation cases

Case list	**Generator type**	**FRT type**	**Power factor**	**Fast valving**
Case 1	Synch	FRT 1	N/A	No
Case 2	Synch	FRT 2	N/A	No
Case 3	Synch	FRT 3	N/A	No
Case 4	Asynch	FRT 1	No	No
Case 5	Asynch	FRT 2	No	No
Case 6	Asynch	FRT 3	No	No
Case 7	Asynch	FRT 1	Yes	No
Case 8	Asynch	FRT 2	Yes	No

Case 9	Asynch	FRT 3	Yes	No
Case 10	Asynch	FRT 3	Yes	Yes

2.8 Comparison criteria

The parameters considered to compare the simulation cases are summarized here:

- Generator voltage vs grid voltage
- Generator current
- Generator active power
- Generator speed

The key indicators to compare the behaviour of the turbogenerator during faults are the followings:

- *Voltage recovery time*, that is the time required for the generator voltage to return at least at 90% of the nominal value after the fault. The shorter is the voltage recovery time, the better is the behaviour of the plant in case of a FRT. There is not a generally valid maximum value under which the plant can be considered compliant with the technical regulation. As long as the voltage recovery is stable (no undamped oscillations, no uncontrolled voltage profile, etc.), the behaviour of the generator can be considered positive. There are other factors to take into account and that cannot be deduced from the generator voltage graph, such as the consequences of the voltage drop on the auxiliary systems. In particular the pumps or fans under Variable Frequency Drive (VFD) can be sensitive to voltage drops. In this case, additional considerations shall be done on a case by case basis.
- *Maximum overspeed*, which shall always stay below the trip threshold.
- *Maximum overcurrent*, which can be a critical issue for the protection relays. The current peaks shall stay below the tripping curve of the protection relays, which are defined on a case by case basis.
- *Maximum load angle*, which shall stay below the dynamic stability limit. The theoretical dynamic stability limit is 180 deg but it is necessary to keep a suitable safety margin due to the transient effects. Therefore the practical dynamic stability limit usually is between the static stability limit (which is equal to 90 deg) and the theoretical dynamic stability limit (which is 180 deg). The exact value shall be defined on a case by case basis.

3 ANALYSIS RESULTS

3.1 Results summary

The main results are summarized in Table *5* in terms of the comparison criteria. The columns "Voltage recovery time" and "Max overspeed" contain both the absolute value (in s or in p.u.) and the relative difference (%) compared to the equivalent case with the synchronous generator.

Table 5: Simulation results

Case list	Voltage recovery time [s]	Max overspeed [p.u.]	Max Overc. [kA]	Max load angle [deg]
Case 1	0.347	1.017	7.74	60.7
Case 2	0.757	1.031	6.55	115.7
Case 3	1.147	1.008	4.57	56.9
Case 4	0.522 (+34%)	1.034 (+2%)	4.84	N/A
Case 5	0.972 (+22%)	1.064 (+3%)	5.28	N/A
Case 6	1.702 (+33%)	1.076 (+6%)	5.08	N/A
Case 7	0.490 (+29%)	1.033 (+2%)	4.89	N/A
Case 8	0.922 (+18%)	1.063 (+3%)	5.33	N/A
Case 9	1.582 (+27%)	1.073 (+6%)	5.12	N/A
Case 10	1.432 (+20%)	1.026 (+2%)	4.05	N/A

The following figures show the results in a graphic format, where:

- Vgen indicates the generator voltage expressed in per unit (pu)
- FRT indicates the grid voltage expressed in pu
- Igen indicates the generator current expressed in kA
- Pgen indicates the active power transferred from the generator to the grid, expressed in pu
- Speed indicates the generator speed expressed in pu
- Ptur indicates the active power transferred from the turbine to the generator, expressed in pu

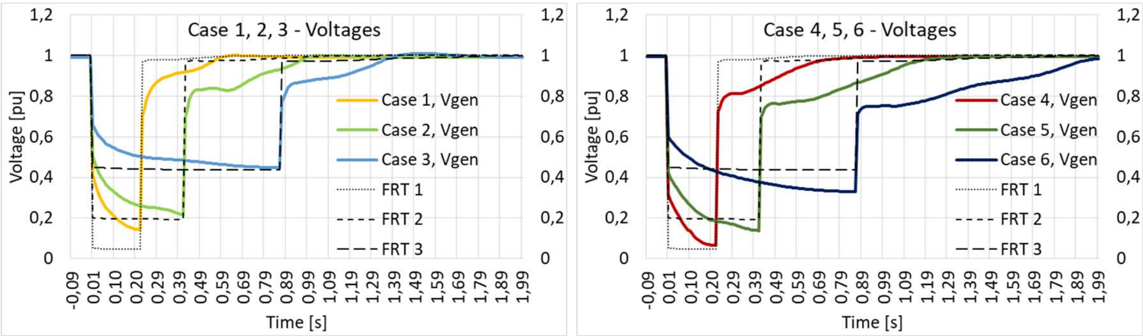

Figure 3: Comparison of voltage profiles between synchronous (left) and asynchronous (right) generators

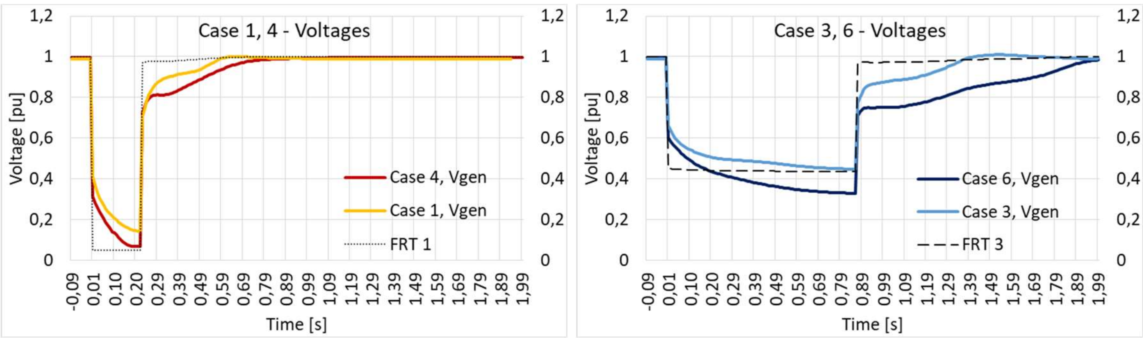

Figure 4: Comparison of voltage profiles between synchronous (case 1, 3) and asynchronous (case 4, 6) generators

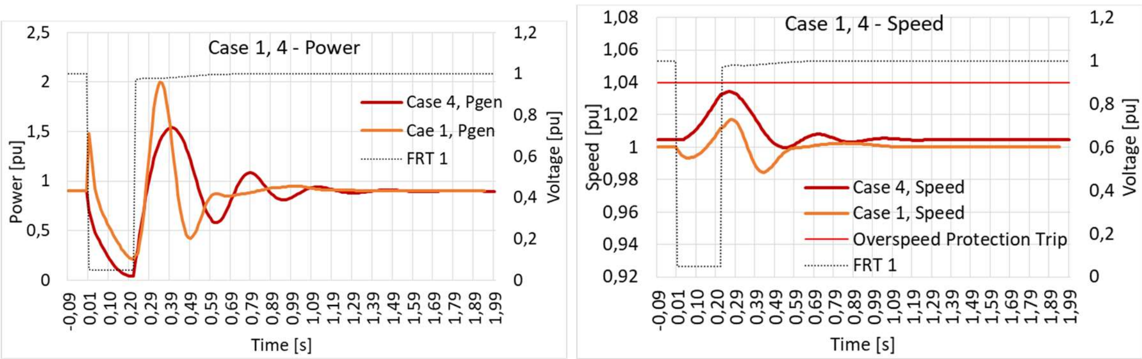

Figure 5: Comparison of power and overspeed between synchronous (case 1) and asynchronous (case 4) generators

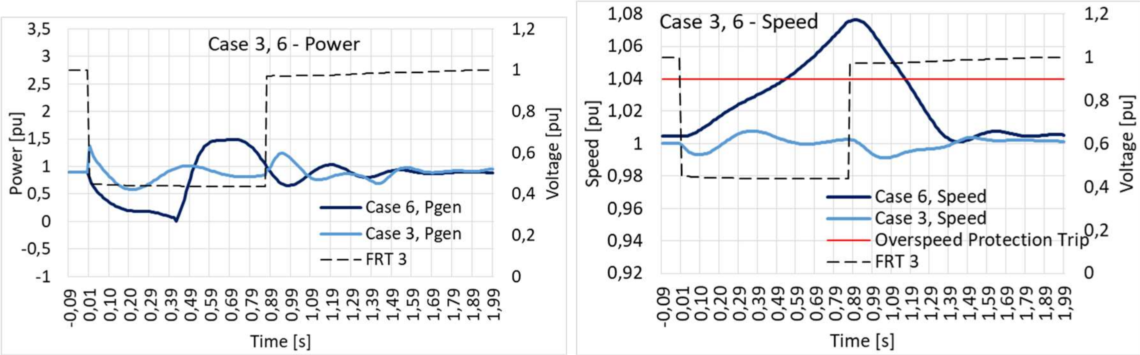

Figure 6: Comparison of power and overspeed between synchronous (case 3) and asynchronous (case 6) generators

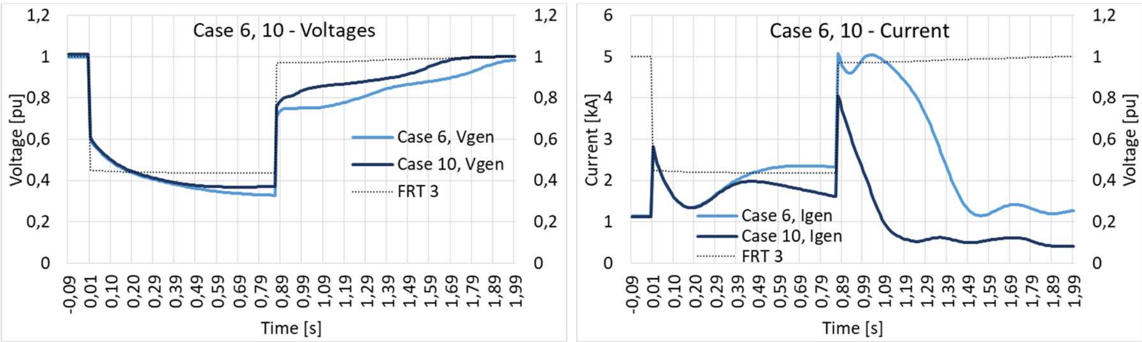

Figure 7: Comparison of voltage and current on an asynchronous generator with fast valving (case 10) and without fast valving (case 6)

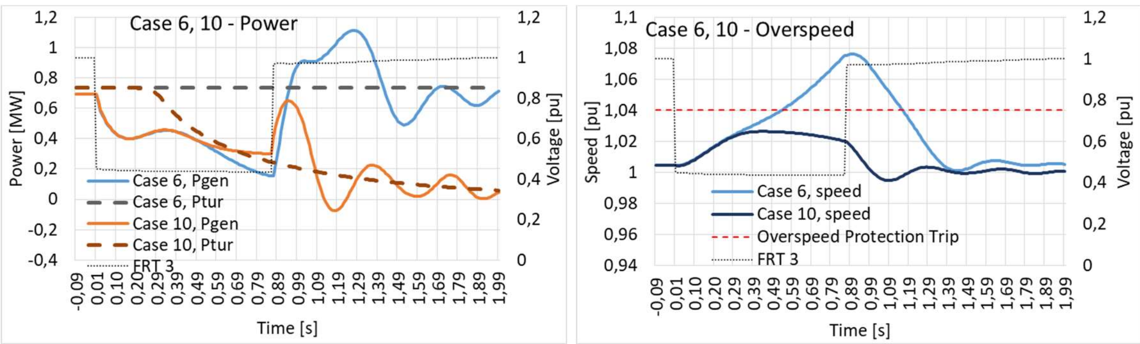

Figure 8: Comparison of power and overspeed on an asynchronous generator with fast valving (case 10) and without fast valving (case 6)

3.2 Voltage recovery time

As described in the previous paragraphs, there is not a generally valid maximum value of the recovery time under which the plant can be considered compliant with the technical regulation. As long as the voltage profile is stable, the behaviour of the generator can be considered positive. In all the above graphs the voltage profile is stable, the only difference is the recovery time, which is longer with the asynchronous generator. In particular, the asynchronous generator shows a recovery time between +18% and +34% compared to the synchronous generator, as reported in Table 5. The power factor correction permits to reduce the gap by 5% but does not reduce the gap totally. The fast valving control permits to reduce the gap by another 7%.

The generator is not the only equipment subjected to the voltage drop, also the auxiliary systems shall withstand the FRT. The shorter the voltage recovery time, the better are the possibilities for the auxiliary systems to not trip or shut down due to an excessive voltage drop. This evaluation shall be done on a case by case basis with additional calculation of the voltage profile at the auxiliary systems terminals.

3.3 Overspeed
The overspeed is the biggest problem for an asynchronous generator coupled to an ORC turbine. The threshold of the turbine overspeed protection is set to 4% but the real overspeed is always over this value except with the shorter FRT, which is the only case that permits to pass a fault. The fast valving control permits to reduce the overspeed below the trip threshold but it can be used only for faults longer than about 600 ms and with a limited depth, as FRT 3.

3.4 Overcurrent
The overcurrent profile is divided in two separate phases: the first peak during the voltage dip and a second peak during the voltage recovery. Typically, the first peak is higher for the synchronous generator (due to the reactive power contribution to the grid to sustain the voltage) while the second one is higher for the asynchronous generator (which must re-magnetize the iron core after demagnetization). Anyway, the current profiles both for the asynchronous and synchronous generator can be tolerated by a protection relay without causing unwanted trips.

3.5 Load angle
The load angle analysis is valid only for the synchronous generator and is below stability limits in all the simulated cases.

3.6 Inlet valves control
Figure 8, on the left, shows the turbine mechanical power and the generator electrical power comparison with and without the fast valving control. The dotted curves represent the mechanical power, while the continuous curves represent the generator electrical power. The fast valving effect can be seen on the orange curves (case 10) where there is a reduction of the turbine mechanical power after about 300 ms thanks to the valve closing controlled by the PLC. *Figure 8*, on the right, shows the final effect of the fast valving control on the overspeed. The blue curve (case 10) represents the turbine speed, which is limited thanks to the mechanical power reduction, which eventually limits the turbine acceleration during a FRT. Unfortunately this control can be used only for long FRT with a small voltage drop, otherwise it is not effective due to the long time delay to start reducing the turbine mechanical power.

3.7 Considerations about the ORC auxiliaries
During the grid faults, the voltage on the Low Voltage (LV) auxiliary cabinets follows the voltage profile at the generator terminals, thus, to maintain the ORC in operation, particular care shall be put in the design of the ORC auxiliaries.
Critical components, such as the control and safety PLCs and the lubrication system of the turbine, shall be fed by an Uninterruptible Power Supply (UPS).
Other auxiliary components, such as the Air Cooled Condenser (ACC) motors and the motor heaters, can slow down or be switched off for the duration of a FRT. When the power supply is restored, the motors re-start and the system returns in the normal operating condition.
The feed pump Variable Frequency Drive must be equipped with the Power Loss Ride Through function, which keeps the drive ON during the FRT, using the kinetic energy of the pump and of the process fluid inertia to keep the motor rotating and generating power to the drive. The speed of the pump decreases, but the drive remains active. Once the voltage is restored, the drive shall restart automatically the control of the motor according to the process operating conditions.

4 CONCLUSIONS

The paper describes an approach to the evaluation of the compliance of ORC turbogenerators to the Fault Ride Through requirement, present in many European grid codes, and shows the results of a detailed study carried out on a 770 kW ORC unit installed in Italy. The results have been compared for a synchronous and an asynchronous generator, on the base of selected comparison criteria.
The results show a difference between the behaviour of ORC turbogenerators when equipped with a synchronous or an asynchronous generator. The main comparison criteria (voltage recovery time and

overspeed) are better fulfilled with a synchronous generator, which represent a better electrical machine when grid code compliance is an important driving factor.
The use of an asynchronous generator coupled to an ORC turbine is not forbidden in the grid codes but the results show that it cannot comply with all the requirements on the FRT. In particular, the most critical problem is the overspeed limitation below the trip threshold. A fast valve control has been implemented but it is not suitable for all the types of faults, particularly for those similar to FRT 2. The synchronous generator, instead, is capable to withstand all the grid faults that have been simulated.
The present study focuses on the generator analysis but other considerations are necessary to evaluate the whole plant behaviour, particularly for the auxiliary systems.
In bigger plants, with medium voltage generators, the grid code compliance studies present similar issues. The ratio between turbine power and inertia is higher (because the turbine inertia increases less than its rated power), thus the overspeed is more critical compared to smaller plants, while the voltage drop inside the plant usually is easier to manage thanks to the medium voltage level.

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