

# Exposé

für die Durchführung einer Masterarbeit

am DLR-Institut für Vernetzte Energiesysteme e. V.

<b>Title of Master Thesis:</b>	“Determination of the required Power Response of Inverters to provide fast Frequency Support in Power Systems with low Synchronous Inertia”
<b>Student:</b>	Alejandro Rubio
<b>Program:</b>	Postgraduate Program Renewable Energy (PPRE)
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<b>Registration Number:</b>	4565447
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<b>First Supervisor:</b>	Prof. Dr. Carsten Agert Tel: +49 441 99906-100 c.agert@uni-oldenburg.de
<b>Second Supervisor:</b>	Dr. Stefan Geißendörfer Tel: +49 441 99906-238 stefan.geissendoerfer@dlr.de
<b>Technical Supervisor:</b>	Holger Behrends Tel: +49 441 99906-416 holger.behrends@dlr.de

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## Abstract

Decommissioning of conventional power plants and the installation of inverter-based renewable energy technologies decreases overall power system inertia. This reduction in system inertia has an impact in the power system frequency response when an unbalance between generation and load occurs, increasing the rate of change of frequency of the system. In a future scenario where renewables are predominant in power systems and due to the natural variability of the resource, unbalances of 40 percent or more are prompt to happen, which combined with low inertia may lead to frequency collapse. The requirements of inverters to provide an effective fast reserve response are investigated. In this way, inverters are intended to reduce the rate of change of frequency so enough time is provided to activate the primary power reserve. Needed power rate under different inverter time responses and different rates of change of frequency is analyzed.



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## Introduction

As part of the international efforts set to counteract global warming, the deployment of renewable energies in the electric sector has been considered an energetic priority as a measure to reduce CO<sub>2</sub> emissions. This objective is also reflected in the regulatory energy policies and plans of some countries. For instance, in Germany the transformation of the electricity sector through renewables, known as “*Energiewende*”, contemplates to achieve a share in electricity consumption from renewables of 80 percent. As part of it, the renewable energy act, “*Erneuerbare Energien Gesetz*”, regulates the expansion of renewables and convectional generation decommissioning.

Even though power systems have grown in size and complexity, frequency control has been always performed through power balancing between generation and demand due to synchronous generator characteristics. The variation of load during a given period of time is followed by a change on the prime mover power of the synchronous generator. When an unbalance occurs, the excess or lack of power is injected to or released from the kinetic energy in the rotor. Therefore in synchronous grids, the magnitude of the rate of change of frequency (ROCOF) during an unbalance is inversely proportional to the system's inertia.

Decommissioning of convectional generating power plants and its replacement with inverter-based renewables power plants has as a consequence a reduction of system inertia and consequently increasing values of ROCOF. The relevance of system inertia is to avoid rapid changes in frequency as load-generation unbalance occurs; in this way enough time is given to the activation of primary power reserve to recover balanced stable conditions.

Therefore the need of new frequency control strategies is evident in this context, where inverter-based generation has a significant share in the grid. Due to the expected higher values of ROCOF, load shedding due to low frequency may occur faster than nowadays grid configuration. In this Master Thesis the required power rate (ROCOP) and triggering time of inverters to supply fast reserve response will be investigated. With these results is expected to aim which technological improvements must be performed in order to allow participation of renewables in frequency control in low inertia grids.

## State of the Art

No matter the size or composition of the power system, a reliable and properly designed power system should fulfill some fundamental requirements (Kundur):

- The power system must have the capability of meeting the changing required load throughout time.
- Reduce costs and environmental impact.
- Ensure power quality and system stability (Voltage, frequency and level of reliability)

In conventional power systems, power balancing and frequency regulation is established through the control of synchronous machines power output. Although power systems capacities have increased along with their complexity for control and study, frequency control is implemented in the same way in any conventional grid.

### Conventional Frequency Control and Stability

The balance between generation and load must be maintained so rotor speed and electric frequency are kept constant as described by the swing equation (Kundur; Anderson and Fouad). In order to achieve the before cited system conditions, a number of control devices and strategies must be implemented. Such controls must allow the system to remain in operation after small or severe events (change in loads, loss of generation units, faults...) maintaining frequency and voltage excursions under certain levels during transient conditions until steady conditions are reached.

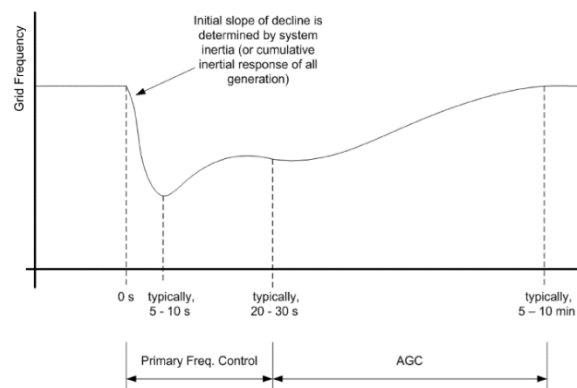
$$\frac{df}{dt} = \frac{f_o(P_{mech} - P_{elec})}{2HS_B}$$

**Equation 1:** Swing equation, where  $f_o$  is the nominal system frequency,  $P_{mech}$  is the mechanical power from prime mover,  $P_{elec}$  is the electrical power demand,  $H$  is machine inertia constant and  $S_B$  is nominal power of the machine

Power balancing in synchronous generating units is performed by the governor of the prime mover coupled to the shaft of the generator.

As depicted in figure 1; conventional frequency control is comprised by three stages (Hansen et al. 2016):

- Inertia response: Subsequent to a power unbalance, power is subtracted or injected to the rotating mass of the rotor, creating a deaccelerating or accelerating torque in the shaft. This torque will decrease or increases rotor speed and frequency. The change in frequency will be given by the amount of energy stored in the rotating masses (proportional to its inertia).
- Primary reserve: In a multi-machine system, all synchronous units contribute according to its capacity and droop characteristic. After the unbalance, the response time depends on governor control time. Once steady conditions are reached, an offset from the nominal frequency will remain as a consequence of the droop characteristics of the governors.
- Secondary reserve or Automatic Generation Control (AGC): This is coordinated from a central command (Transmission System Operator). Nominal frequency is restored from the deviation resulted from primary reserve implementation. This reserve do not necessarily comprises all connected generating units.



**Figure 1:** Frequency control in power systems (Aho et al. 2012)

## Frequency Control with Distributed Energy Resources

Distributed Energy Resources (DER) in power system are mainly comprised by renewable energy resources. Currently one of the challenges in the implementation of DER as frequency control support is the lack of inertia response from them. As it was previously pointed out, inertia response is the first natural measure against the change in frequency when an unbalance occurs. In the case of PV systems, the generation of power is given by the photoelectric effect and no rotating masses are involved, having no inertia.

Additionally, given the inherent variability of renewable resources and technology characteristics (Asynchronous generation in variable speed wind turbines and DC power generation in PV), such technologies need the implementation of power converters which

transform the unsuitable power output from the DER generators into suitable power to be injected into the grid. The power converter to be connected between the generator and the grid is in all cases an inverter; since it will convert the DC output of PV into AC synchronized power. In the case of variable speed wind turbines, the AC power with variable frequency is first converted to DC by rectifiers and then it is converted from DC to AC synchronized power output. This AC-DC-AC transition inhibits the wind turbine to react to grid disturbances. In general, it could be stated that the inertia of a power system is a measurement of its robustness, which means the higher the system inertia, the lower the rate of change of frequency (ROCOF) for a given system unbalance

Since the most prevailing inverter technology in grid connected DER is the grid-following type, frequency and voltage from the system are followed by the inverter, acting as a current source that operates at maximum power point, decoupling in this way the DER power production from the grid dynamics and disabling the participation of renewables without storage in power balancing and frequency regulation.

It is expected that grids with high penetration of DER to have a lower system inertia, leading to higher values of ROCOF. This high value of ROCOF can provoke big frequency excursions, having as possible consequence load shedding or even total system black out (ENTSOE 2016). Frequency is maintained in power system under very strict limits because sustained values out of the nominal range can cause severe mechanical damages in turbines and deterioration due to thermal effects and saturation in generators and transformers.

As synchronous machines installed capacity diminishes, not only the inertia of the system is reduced but also the contribution of synchronizing torque during disturbances. This can create small signal stability as well as frequency stability problems (Kroposki et al. 2017).

Several novel approaches may be found in the literature for implementation of renewables in frequency regulation and inertia contribution. The main inertia control strategies are synthetic inertia and fast reserve power (Dreidy et al. 2017).

- Synthetic inertia: This control strategy applies only to wind turbines. This approach attempts to extract the kinetic energy from the rotating blades of the wind turbine when a disturbance occurs. Typically the control loop releases the kinetic energy based on the ROCOF and frequency deviation.
- Fast reserve power: In contrast to synthetic inertia, fast reserve power injects a constant amount of power during a certain amount of time through the control of rotor speed set point.

For frequency regulation, techniques such de-loading and droop control have been studied:

- De-loading: Wind turbines and PV plants typically operate at their maximum power point. That means obtaining the most of power from the primary resource (wind or solar irradiation), therefore when lack of generation occurs they cannot contribute to primary reserve for frequency regulation. In this approach the generators do not operate at their maximum power point but at a lower than maximum in order to allow the generator to operate at maximum when more power is required by the load.
- Droop control: Similarly to droop governors in synchronous machines, the control loop in wind turbines emulates the power-frequency dependency, allowing the turbine to react to changes in frequency with change in power output.

### **Continental European Frequency Stability Criteria**

In the Continental European interconnected system the normal operation is between 50,2 and 49,8 Hertz. When this limits are exceed the system enters in an alarm state and actions to reestablish the allowed nominal operation must be executed. In the case that frequency exceeds 50,2 Hertz, all generating units must be capable of reduce power production (non-synchronous generators as well) with a droop in the range of 2-12% (ENTSOE 2018). At 49 Hertz automatic load shedding is activated, at this point a cascading effect may occur that could also cause a total black out in the system. If frequency reaches values of 51,5 or 47,5 Hertz total system black out is unavoidable. Additionally the European Network for Transmission System Operators for Electricity (ENTSOE) establishes that every generating unit, including renewables must remain connected in the same range of frequency (ENTSOE 2018).

Under normal operation ENTSOE has reported values of ROCOF in the range of 5-10 mHz/s for power outages of 1 GW in the current interconnected power system. If an unbalance event of more than 3 GW (reference interconnected case) occurs with depleted primary reserve, extraordinary values of frequency and ROCOF might be reached. After serious disturbances the Continental European Power System has experienced ROCOF between 100 mHz/s and 1 Hz/s. Unbalances of 20% or more along with ROCOF greater than 1 Hz/s have been determined by experience to be critical (ENTSOE 2016).

Due to the expected increase of non-synchronous generation in the future, ENTSOE estates in its split reference scenario that the power system must be capable of withstanding unbalances greater than 40% with ROCOF of 2 Hz/s or higher. Under these circumstances the island must avoid load shedding.



## Research Questions

- 1) What is the required power rate response of inverters to provide frequency stability support as ancillary service in power systems with low synchronous inertia?
  - a) What would be the ROCOF and critical time with high penetration of inverter based generation?
  - b) What is the influence of the selected synchronous primary reserve type?
  - c) What is the minimum time for measuring, filtering and processing the frequency signal and ROCOF estimation?
  - d) Would renewable without storage be able to sustain the required power rate in the test case model?
- 2) How can the proper power rate be delivered on time through the implementation of power electronics?
  - a) Could current inverters, measuring devices and storage technologies provide such power response?
  - b) What is missing or what must be improve of today's technology to achieve this power rate?

## Methodology

### Theory

Reduction of synchronous generators share in the grid will have as a consequence the unavoidable reduction of the system inherent inertia response. This reduction of system inertia can provoke higher rates of change of frequency in the grid even for small system unbalances when compared to a conventional grid completely supply by synchronous generators. These high rates of ROCOF can rapidly lead to out of range transient values of frequency, causing load shedding when primary frequency response is not enough in terms of time and response. Therefore, along with the deployment of DER in the modern power systems, new approaches must be implemented to tackle with this problem.

It has been demonstrated in theory that the implementation of some flexibilization techniques permits the application of renewable in grid ancillary services such inertia response and frequency regulation (Gevorgian and Zhang 2017; Aho et al. 2012). Synthetic inertia control along with de-loaded wind turbines were simulated in (Gevorgian and Zhang 2017) as inertia response and primary frequency response. As main result it can be highlighted the improvement of overall frequency response in a scenario with 80% of wind penetration. In this scenario the under frequency load shedding is reached when no frequency support is given by the wind turbines. In the contrary, when the described frequency support is applied, frequency response improved not only in regards of the minimum value and recovery time but also in the recovered steady frequency.

Inverter's over frequency response was evaluated in (Hoke 2018) since the investigated distributed inverters counted only with downward frequency response. It was identified the relevance of certain parameters such: speed response, droop curve and inverter dynamic response as well as the importance of the characteristics of the grid. Reaction time was not estimated, for the conditions of the grid, investigated inverters responded fast and properly.

Therefore, it can be stated that independently of the selected support strategy technology, this techniques must fulfill certain requirements in order to successfully act as inertia support

and/or frequency regulation according to the specific grid characteristics and disturbance nature. As per (ENTSOE 2016) it is foreseen in future scenarios the possibility of power unbalances of more than 40% with associated ROCOF of 4 Hz/s or more to be present in power systems with predominance of non-synchronous generation.

Due to all these reasons, it will be investigated in this research the power rate and reaction time required for inverters and controllers to provide inertia response and frequency regulation under different shares of renewables (system inertia) and different power unbalances. With this current frequency measurements current inverter's power rates can be assessed respect future grid dynamic conditions and areas for improvement can be identified.

The IEEE 9 bus model is taken as base case due to its topological simplicity for further implementation in the real time simulator and the availability of dynamic characteristics of the synchronous generators (Jayawardena et al. 2012). The addition of renewables and decrease of synchronous generators capacities will be performed to estimate system inertia under those conditions; additional unbalances will be simulated to account system frequency response.

### **Data collection**

Due to the influence of synchronous primary reserve in system frequency response, the dynamic models of the synchronous generators are required for carrying out the simulations. Typical inertia, reactances and time constants for transient and sub-transient states according to generator capacity will be used (Jayawardena et al. 2012).

The selected governor model is the WSCC type G and the selected exciter model is the IEEE type 1 (DC1A). Similarly as machine parameters, typical values can be obtained from (Anderson and Fouad).

The required time for frequency measurement with modern technologies has to be defined or estimated. In that way, areas for future improvement can be analyzed and the needed inverter power response can be obtained.

## Methods of Analysis

As a first step the impact of non-synchronous generation is evaluated. To do so, the IEEE 9 bus system is considered. Different levels of penetration will be simulated. The simulations will be run for each scenario with power unbalances up to 40%. The maximum ROCOF will be accounted as well as the alert time, when frequency reaches the value of 49,8Hz and low frequency load shedding time when frequency reaches the value of 49Hz. The impact of controls of synchronous machines along with their inertia in system frequency respond will be evaluated.

After the frequency measuring time with current technology and techniques has been determined, it will be used as upper limit for inverter reaction time. Different inverter reaction times will be simulated, from activation at the moment of the unbalance event to this upper limit. Required power rates will be obtained for each scenario. In the worst case scenarios where low frequency load shedding limit is reached, the addition of the inverter power rate response should be enough to avoid this limit. It is expected to find a mathematical expression relating reaction time, ROCOF and inverter power rate.

Additionally, the obtained results will be verified with the simulation of the IEEE 9 bus system in the Real Time Simulator in the Grid Laboratory with the implementation of inverters providing inertia response according to the obtained results.

From these results, the capability of current inverters will be investigated in order to determine whether current frequency measuring techniques and power electronics are able to meet future grid needs.

## Schedule of Activities

	April					May					June					July					August					September				
	1-7	8-14	15-21	22-28	29-30	1-5	6-12	13-19	20-27	27-31	3-9	10-16	17-23	24-30	1-7	8-14	15-21	22-28	29-31	1-4	5-11	12-18	19-25	26-31	2-8	9-15	16-22	23-30		
<b>DETERMINATION OF INVERTER ROCOP</b>																														
Simulation of scenarios with different RE penetration on IEEE 9 bus system																														
Investigation of measuring, filtering and processing frequency signal time																														
Power rate estimation to avoid frequency collapse																														
Analysis of renewables response as frequency support																														
<b>SIMULATION IN GRID LAB</b>																														
Getting to know the equipment (Specsheets)																														
Grid simulation and comparisson of results																														
<b>POWER ELECTRONICS</b>																														
State of the art in regards reaction time and power rate delivery																														
Identification of areas for improvement																														
<b>WRITING MASTER THESIS</b>																														
First draft Submission																														
Final Submission																														

Critical priority

Optional

No Critical

■ Critical priority  
■ Optional  
■ No Critical

## Organizational Issues

Date for oral presentation and thesis defense will be arranged with First and Second Supervisors.

The regularity of progress reports will be determined by the First Supervisor.

Weekly meetings to treat about progress and/or challenges associated with the investigation will be hold with the Technical Supervisor. Additionally, working group meetings will take place twice a month.

After the thesis has been finished, contract and residence permit extension would be needed for further activities related with publication of paper on the investigated topic.

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