The Role of Inertia in Frequency Stability and The Implementation of Virtual Inertia in RES-based Power Plants

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Abstract

For economic and environmental reasons, the power system is changing. From having all the electric power production from large power plants based on fossil fuels to distributed generation based on renewable energy sources. This change results in a significant reduction in the system's inertia, challenging the existing frequency control. This work presents the frequency response of a three-area power system with two power plants based on renewable energy sources and a thermal power plant in order to study the role of inertia for frequency responses. Namely, the implementation of virtual inertia devices in the RES-based power plants is simulated and analysed to conclude about its impact on the power system.
Keywords: Power System Control, Frequency Control, Virtual Inertia, Virtual Synchronous Generator

1. Introduction

The electric power system is changing, [16]. The power generation from synchronous machines is decreasing, while the power production from RES-based power plants is increasing. With this evolution, the power system is losing its inertia, which is tied to the synchronous generator functioning, that contributed to the power system's frequency stability.

This work aims to study the effects caused by the high penetration level of RES. Namely, how this change on the power grid can influence the power system's frequency and what is the role that inertia plays in the frequency response when facing external perturbations. The installation of virtual inertia in power plants based on RES will also be the part of the main scope of the work, as it allows us to further understand the importance of the inertia in the power system.

In order to study the role of virtual inertia, a model of three interconnected areas will be modelled. The three areas consist in an area constituted by a thermal power plant, with a classical generator operating, and load, the second area has a wind park as well as its load, and finally, the third area has a PV power plant and also a load.

The area 1 is the central area and is connected to both other areas 2 and 3. The area's connection, established through transmission lines, allows the electric power to flow from one area to another, enabling compensation between areas.

The developed model should represent as accurately as possible the system described above while keeping analytical simplicity. The area 1 model should represent the operation of a thermal power plant connected to a load and two other areas. The areas 2 and 3 models should represent the operation virtual inertia device built-in the power plant based on wind and PV, respectively, as well as its loads and connections to area 1.

Once the model is developed, it will be implemented as a MATLAB program to produce simulation results. The program enables the simulation of different perturbations and outputs figures representing not only the frequency behaviour in the three areas but also the power exchanged between them.

Having the system's frequency responses to different perturbations makes it possible to analyse, with a decent level of detail, what happens in the system and what variables contribute to each part of the system behaviour. Therefore, it will possible to analyse the role of the virtual inertia on the system and to draw conclusions from it.

2. Background

2.1. Literature Review

For economic, technical and environmental reasons, the share of inverter-based generators is growing and is foreseen further growth. From large-scale power plants to small distributed generation points the penetration level of these new generation methodologies is increasing [5]. Whether these new generation units are based on solar energy, using the photovoltaic technology, on the wind power its behaviour will, typically, be different from the synchronous generator.

Some authors have also studied the effects of DG in the power system, [6] and [16]. The authors identified not only the advantages and disadvantages of introducing distributed generation but also the impact that different penetration levels of DG can have on the power system, namely on the frequency. These authors concluded that, for a high level of DG penetration, it is necessary to add some energy compensation means in order to keep frequency stability.

The proposed solution by many literature sources, which will be explored and analysed throughout this work, consists in making the converter-based power plants contribute with inertia to the frequency perturbations in the power system, [17], [13]. As the power plants based on renewable energy sources are converter-based, having a solution that makes possible these power plants behave as the classical synchronous generators would simplify the introduction of RES.

The inertia can be installed in the RES-based power plants through a virtual synchronous generator, [17]. The virtual synchronous generator is based on conventional inverter hardware controlled in a way that emulates the energy release and absorption. This behaviour allows the converter to counteract the system frequency perturbations once they are detected. The main advantages of this topology are its simple implementation and the capacity of changing the parameter values of the inertia constant, H, and damping factor, D, which are explained in the following section [17].

This solution has been studied and tested in the VSYNC project which was developed between January 2007 and December 2010, aims to implement a virtual inertia system in a real operating power system. This European project had various participants such as the Delft University of Technology and the University Politehnica of Bucharest being led by the Energy Research Centre of the Netherlands, producing research articles, [?, 11, 3, 15, 2, 1, 8, 7], that support the utilization of virtual inertia technologies to improve power system's stability.

Other authors have studied the application of virtual inertia to PV power plants, [5], [14] and [13], and wind parks, [10], and [12]. These studies resulted in similar conclusions: the implementation of VSG improves frequency stability. Therefore, this technology will be used in this work's simulations, in order to understand the importance and role of inertia in the power system.

3. Three interconnected areas model

In order to obtain simulation results, one needs to model the system. The system under analysis consists of three areas interconnected. The fist area presents a thermal power plant connected to the other two areas. Area 2 has a wind park and the load, and it is connected to area 1, through a transmission line. Finally, area 3 contains a PV power plant, a load and is also connected to the area 1. The thermal power plant has the double of the capacity, 200 MW, of the other two areas. Also, the power plants based on renewable energy sources present a VSG which will be used in some experiments, to conclude about its importance.

Having defined the system that is desired to be modelled, it is now relevant to identify the variables that are interesting to relate in order to produce simulation results. To analyse a frequency response, it is interesting to relate the frequency deviations when facing miss-matches between the produced power and the demand.

The classical models relating the variables under study for thermal power plants have already been defined and studied by many authors, [9]. A simplified version of this model, which will be used for simulation purposes, is presented in 1.

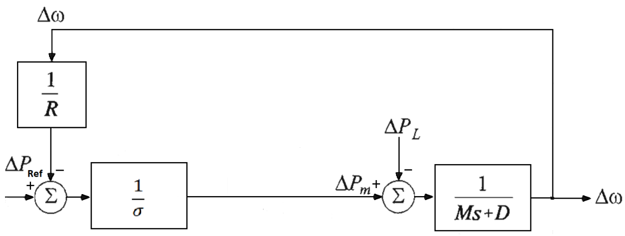

Figure 1: Block diagram for the steam power plant.

The model for the power plants based on renewable energy sources is based on the work developed in [4]. This work presents a model for the VSG implemented in a RES-based plant and it is represented in 2.

Combining the two models presented in 1 and 2 and considering that the interconnections are made through transmission lines, the model for the entire system is obtained, 3.

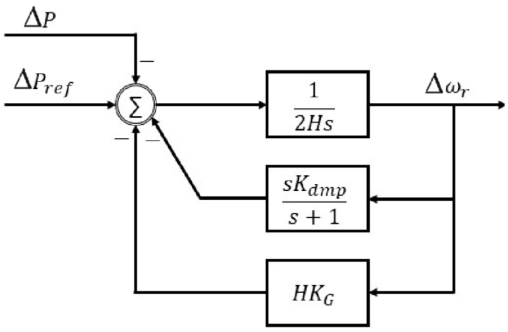

Figure 2: Block diagram for the voltage synchronous generator [4]

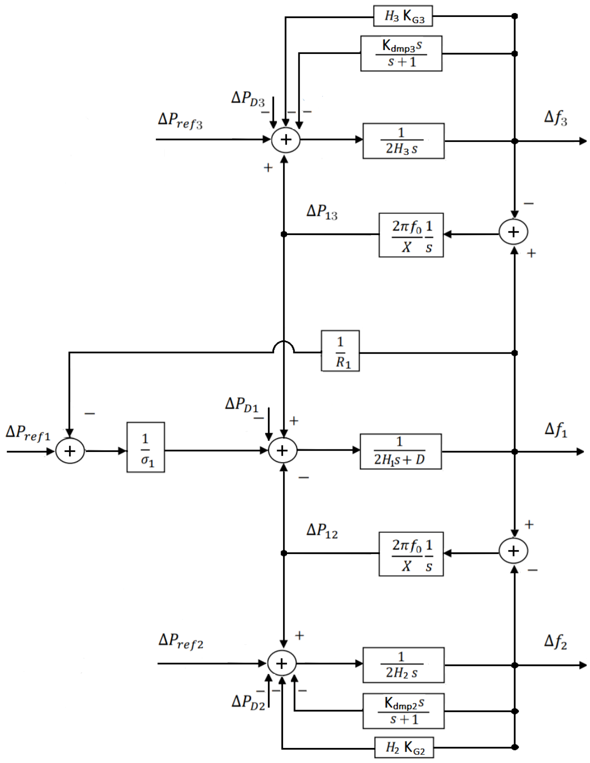

Figure 3: Three interconnected areas block diagram.

4. Results

4.1. Methodology

Having defined the model, the state model approach will be applied to the problem in order to obtain simulation results. The state model approach is based on:

$$\dot{x} = Ax + Bu + \Gamma p. \tag{1}$$

Where x represents the vector containing the state variables, $\dot{x}$ is the vector with the first-order derivative of the state variables, u is the control vector,p is the perturbation, A is the state the matrix, B is the input matrix and Γ is the perturbation matrix.

Analysing the block diagram of the three are system, represented in 3, it is possible to write equations that can be arranged as 1. The state variable vector used along this work is defined as:

$$x = \begin{bmatrix} \Delta f_1 \\ \Delta f_2 \\ \Delta f_3 \\ \Delta P_{12} \\ \Delta P_{13} \end{bmatrix}. \tag{2}$$

The control vector, u, is constituted by the reference powers relative to all the different areas:

$$u = \begin{bmatrix} \Delta P_{ref1} \\ \Delta P_{ref2} \\ \Delta P_{ref3} \end{bmatrix}. \tag{3}$$

The perturbation vector is then defined as follows,

$$p = \begin{bmatrix} \Delta P_{D1} \\ \Delta P_{D2} \\ \Delta P_{D3} \end{bmatrix}. \tag{4}$$

The matrices A, B and Γ can be written as presented in Appendix.

In order to obtain the response from the system in the time domain, a change of variables should be applied to the state model matrices. The change of variables is used because it is desirable to operate with a diagonal matrix, so, the following change of variables is applied,

$$x(t) = Mq(t), \tag{5}$$

where M is the modal matrix. It can also be written as,

$$q(t) = M^{-1}x(t). \tag{6}$$

Applying the variable change 5 to **??** the following is obtained,

$$M\dot{q} = AMq(t) + Bu(t) + \Gamma p(t). \tag{7}$$

Solving 7 in order to $\dot{q}$, we obtain,

$$\dot{q} = M^{-1}AMq(t) + M^{-1}Bu(t) + M^{-1}\Gamma p(t). \tag{8}$$

In a more compact way,

$$\dot{q} = Jq(t) + B^{norm}u(t) + \Gamma^{norm}p(t). \tag{9}$$

The matrix M is the modal matrix, i.e., the matrix containing the eigenvectors of the A. The J matrix is the diagonal matrix with the eigenvalues of the matrix A in its diagonal. In order to simulate a perturbation to the system, the desired variation should be inserted in either vector u or p, depending on the desired simulation.

In the end, one must return to the initial variable, using 6. This methodology will allow us to obtain the time response of the system when introducing any perturbation. It can be useful not only to analyse the importance and the impact of each variable but also to dimension certain values for the PV emulations, namely the emulated inertia and the damping factor.

The values for each simulated parameter are presented in table 1. However, it is important to consider that for some specific simulations the value may be different from the presented.

Table 1: Parameter values used for simulation [9], [4]

H_1	10 s
H_2	3 s
H_3	3 s
D	1
K_{G2}	55
K_{G3}	55
K_{dmp2}	1
K_{dmp3}	1
σ	0.1
R	0.04
X_{12}	0.1
X_{13}	0.1

4.2. Results

A computer program was developed in MATLAB, applying the methodologies described in the previous section, to obtain the frequency deviations and the power flowing between areas when facing a perturbation. Five distinct simulations where performed, to conclude about the impact of having different inertia values when facing perturbations.

The first case study, simulates an increase of 0.3 p.u. in area 3, while the RES-based power plants present inertia provided by the VSG. In this case the frequency in the area where the perturbation occurred dropped around 1%, 4. The other two areas supported the area 3, providing power 4, and avoiding further frequency drop.

The second case study aims to study how the system will respond when faced with the same perturbation while having no inertial contribution from area 3. This time, the frequency in area 3 dropped 4.5%, 5, and it also dropped more in the other areas when compared to the first experiment. The power flowing into area 3 is also higher because it requires total support from the other areas, 5. This suggests that having areas with low or no inertia can lead to

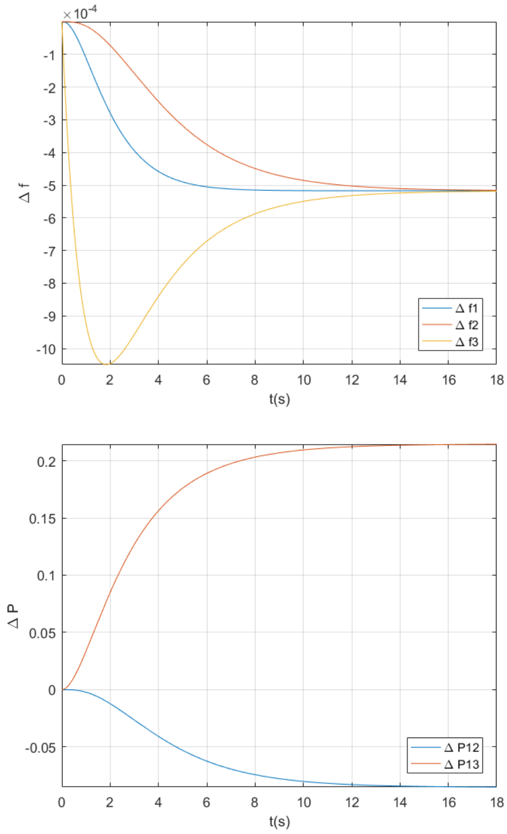

Figure 4: Frequency variation response and transmitted power variation response to a 30% increase in power demand in area 3, respectively.

frequency instability.

The third case study considers that area 3 is operating in island mode, with no connection to other areas, while facing the same perturbation as the two experiments before and having a VSG able to output an inertial response. As expected, only the frequency from area 3 was affected, dropping 1.8%, 6. The power exchanged between areas is zero, 6, because there is no connection to the area affected by the perturbation. Therefore, the other two areas operate in steady-state.

The fourth case study is similar to the third: the perturbation is the same, and area 3, where the perturbation occurs, is disconnected from the other areas. However, in this experiment, the PV power plant based in area 3 does not present inertial response. One can observe that the frequency collapsed in this experiment, 7. Without power injected from other areas to compensate the demand increase, the frequency keeps dropping until it collapses.

This case study highlights how an isolated area cannot operate without connection to power plants that present inertia. The inertia contributes to counteract the perturbation, holding the frequency

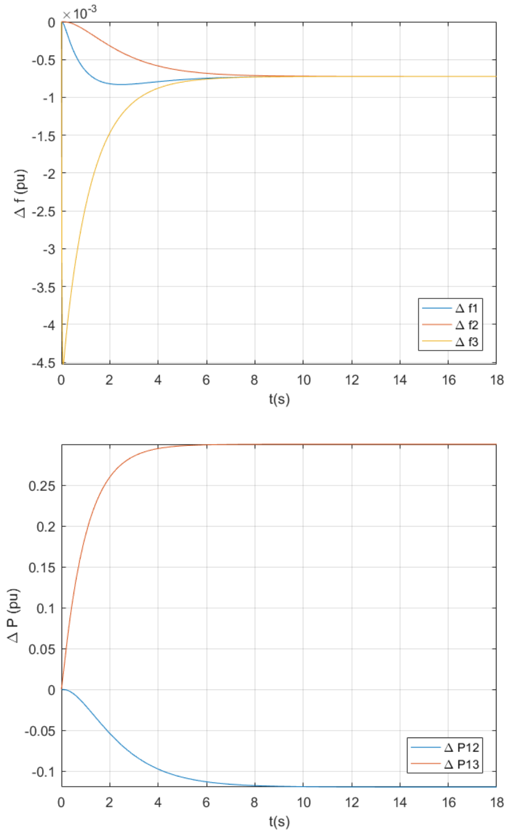

Figure 5: Frequency variation response and transmitted power variation response to a 30% increase in power demand in area 3, without inertial contribution from area 3, respectively.

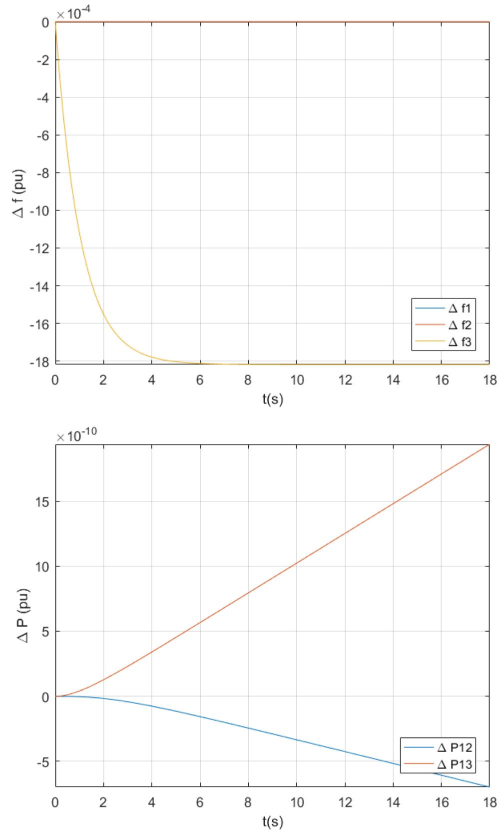

Figure 6: Frequency variation response and transmitted power variation response to a 30% increase in power demand in area 3, without interconnection to any other area, respectively.

value closer to its rated value. When the inertia is lacking the perturbation is not counteracted and the frequency ends up collapsing.

The fifth and final case study simulates the system behaviour when, due to weather conditions, the PV power plant drops 30% of its production. This is simulated considering that the PV plant presents a VSG contributing to the inertial response.

As one may have expected, the results are exactly equal to the first case study. The drop of 0.3 pu in power production produces the same effect as an increase of 0.3 pu in power demand. Therefore, the frequency response, 8, and the power flowing between areas, 8, behave the same way as in the first experiment.

5. Conclusions

From the simulation results, it is possible to conclude that, when the RES-based power plants were operating without the virtual inertia compensation, its frequency response was insufficient, being harmful to the system's frequency, 5. When testing a perturbation on an area fully dependent on the RES-based power plant, without external compensation nor virtual inertia contribution, the frequency collapsed, 7.

The obtained results suggest that it is not possible to fully rely on the production from power plants based on renewable resources without any compensation in order to produce the desired frequency response. Therefore, to achieve a high penetration level of these power plants it is required an inertial contribution to counteract the frequency perturbations. VI devices, such as VSG, can provide the desired compensation to keep frequency stability.

The future of the electric power system is moving towards a high level of penetration of RES-based power plants, as high as possible while reducing the thermal power plants' presence. Therefore, a more ecological and sustainable power system will take the role of the old pollutant system.

The future system must still meet the power quality standards and it must also present a stable behaviour, avoiding blackouts. In the previous section, it was stated that virtual inertia can make possible the system operation while having a high level of RES-base power plants penetration. Despite trying to mimic the operation of thermal power plants,

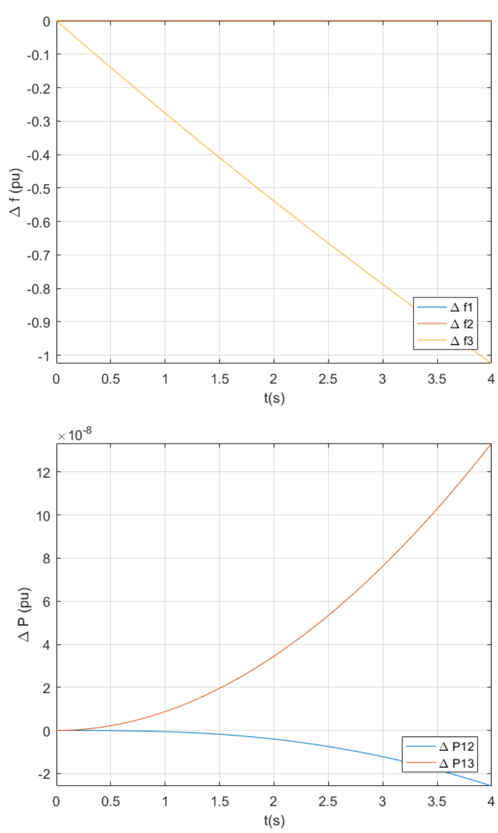

Figure 7: Frequency variation response and transmitted power variation response to a 30% increase in power demand in area 3, without interconnection to other areas and without inertial contribution from area 3, respectively.

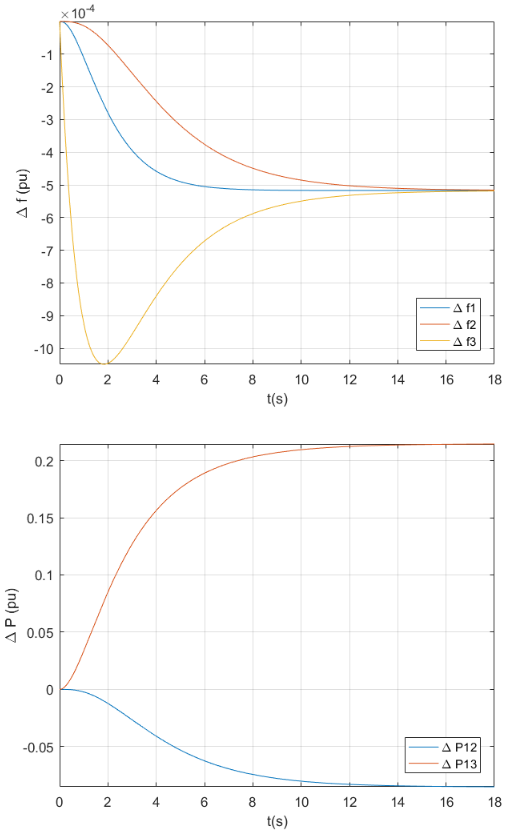

Figure 8: Frequency variation response and transmitted power variation response to a 30% decrease in power production in area 3, respectively.

virtual inertia is different in nature and scale resulting in differences between the power system dominated by thermal power plants and the future power system.

The new way to introduce inertia to the system, the virtual inertia, relies on energy storage devices, such as flywheels, which will globally represent a lower value of inertia than the synchronous machines. Therefore, the system will present inertia, enabling an initial inertial response to the frequency perturbations, however, it will be lower than before. This results in a more accentuated drop in frequency, or, as referred to in the literature sources, a higher ROCOF.

As long as the system is not only adapted to support a slightly higher drop in the frequency but also able to have just enough inertia to counteract the frequency perturbations, the power system will be able to operate reliably, as it has been for centuries.

References

[1] M. Albu, M. Calin, D. Federenciuc, and J. Diaz. The measurement layer of the virtual synchronous generator operation in the field test. In *2011 IEEE International Workshop on Applied Measurements for Power Systems (AMPS)*, pages 85–89, 2011.

[2] M. Albu, J. Diaz, V. Thong, R. Neurohr, D. Federenciuc, M. Popa, and M. Calin. Measurement and remote monitoring for virtual synchronous generator design. In *2010 IEEE International Workshop on Applied Measurements for Power Systems*, pages 7–11, 2010.

[3] M. Albu, K. Visscher, D. Creanga, A. Nechifor, and N. Golovanov. Storage selection for dg applications containing virtual synchronous generators. In *2009 IEEE Bucharest PowerTech*, pages 1–6, 2009.

[4] O. BAHWAL. Implementation of virtual synchronous machine to allow high penetration of converter connected generation, CHALMERS UNIVERSITY OF TECHNOLOGY, Gothenburg, Sweden 2018.

[5] H. Bevrani, T. Ise, and Y. Miura. Virtual synchronous generators: A survey and new per-

spectives. *International Journal of Electrical Power Energy Systems*, 54:244–254, 2014.

[6] D. Dulau, M. Abrudean, and D. Bica. Effects of distributed generation on electric power systems. *Procedia Technology 12*, pages 681–686, 2014.

[7] V. Karapanos, S. de Haan, and K. Zwetsloot. Real time simulation of a power system with vsg hardware in the loop. In *IECON 2011 - 37th Annual Conference of the IEEE Industrial Electronics Society*, pages 3748–3754, 2011.

[8] V. Karapanos, S. W. H. de Haan, and K. H. Zwetsloot. Testing a virtual synchronous generator in a real time simulated power system. In *International Conference on Power Systems Transients IPST 2011*, volume Delft, Netherlands, 2011.

[9] P. Kundur. *Power System Stability And Control.* McGraw-Hill, 1994.

[10] G. Lalor, J. Ritchie, S. Rourke, D. Flynn, and M. J. O'Malley. Dynamic frequency control with increasing wind generation. In *IEEE Power Engineering Society General Meeting, 2004.*, pages 1715–1720 Vol.2, 2004.

[11] T. Loix, S. De Breucker, P. Vanassche, J. Van den Keybus, J. Driesen, and K. Visscher. Layout and performance of the power electronic converter platform for the vsync project. In *2009 IEEE Bucharest PowerTech*, pages 1–8, 2009.

[12] J. Morren, J. Pierik, and S. de Haan. Inertial response of variable speed wind turbines. In *Electric Power Systems Research*, volume 76, pages 980–987. ELSEVIER, 2006.

[13] D. Remon, A. M. Cantarellas, M. A. A. Elsaharty, C. Koch-Ciobotaru, and P. Rodriguez. Equivalent model of a synchronous pv power plant. *2015 IEEE Energy Conversion Congress and Exposition*, pages 47–53, 2015.

[14] P. Rogrigues, I. Candela, and A. Luna. Control of pv generation systems using synchronous power controller. *2013 IEEE Energy Conversion Congress and Exposition*, pages 993–998, 2013.

[15] V. Van Thong, A. Woyte, M. Albu, M. Van Hest, J. Bozelie, J. Diaz, T. Loix, D. Stanculescu, and K. Visscher. Virtual synchronous generator: Laboratory scale results and field demonstration. In *2009 IEEE Bucharest PowerTech*, pages 1–6, 2009.

[16] Vu Van Thong, D. Van Dommelen, and R. Belmans. Penetration level of distributed energy resources with anti-islanding criteria and secure operation of power system. In *2006 IEEE Power Engineering Society General Meeting*, pages 7 pp.–, 2006.

[17] K. Yap, C. Sarimuthu, and J. Lim. Virtual inertia-based inverters for mitigating frequency instability in grid-connected renewable energy system: A review. *Appl. Sci. 9*, 2019.

Appendix

$$A = \begin{bmatrix} \frac{-1}{2H_1\sigma R} & 0 & 0 & \frac{-1}{2H_1} & \frac{-1}{2H_1} \\ \frac{T_{12}}{2H_2+K_{dmp2}+H_2K_{G2}} & -\frac{T_{12}+H_2K_{G2}}{2H_2+K_{dmp2}+H_2K_{G2}} & 0 & \frac{1}{2H_2+K_{dmp2}+H_2K_{G2}} & 0 \\ \frac{T_{13}}{2H_3+K_{dmp3}+H_3K_{G3}} & 0 & -\frac{T_{13}+H_2K_{G3}}{2H_3+K_{dmp3}+H_2K_{G3}} & 0 & \frac{1}{2H_3+K_{dmp3}+H_3K_{G3}} \\ T_{12} & -T_{12} & 0 & 0 & 0 \\ T_{13} & 0 & -T_{13} & 0 & 0 \end{bmatrix}$$

$$\mathrm{B} = \begin{bmatrix} \frac{1}{\sigma 2H_1} & 0 & 0 & 0 & 0 \\ 0 & \frac{1}{2H_2+K_{dmp2}+H_2K_{G2}} & 0 & 0 & 0 \\ 0 & 0 & \frac{1}{2H_3+K_{dmp3}+H_2K_{G3}} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

$$\Gamma = \begin{bmatrix} \frac{1}{\sigma 2H_1} & 0 & 0 & 0 & 0 \\ 0 & \frac{1}{2H_2+K_{dmp2}+H_2K_{G2}} & 0 & 0 & 0 \\ 0 & 0 & \frac{1}{2H_3+K_{dmp3}+H_2K_{G3}} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$