Methodological Framework for Stability Analysis, Control Design and Verification in Hybrid Power Plants

Lennart Petersen*†, Florin Iov*, German C. Tarnowski†, Karthikeya B. Raghuchandra †
*Department of Energy Technology, Aalborg University, Denmark.
†Vestas Wind Systems, Denmark
Email: lepte@vestas.com, fi@et.aau.dk, getar@vestas.com, kablr@vestas.com

***Abstract*—This paper addresses the assessment of voltage and frequency stability in hybrid power plants (HPPs) and how to design, to tune and to verify the control system. Firstly, the benchmark off-grid HPP used in this study is described. Additionally, an overview of the general requirement specifications for the HPP controller is presented. A brief classification of stability phenomena in off-grid HPPs is given and the implications on the required detail of small-signal modeling are explained. Secondly, it is ascertained that the state-space method is most suitable for analysis of voltage and frequency stability and likewise serves as a tool for control design and tuning. The main part of this paper is to propose the model-based design approach as a generic guidance for stability analysis, control design including tuning and verification for HPPs. This methodological framework can be applied for both on-grid and off-grid HPPs, independent of plant topology and power management strategy.**

***Index Terms*—Hybrid power plant; model-based design; state-space model; voltage stability; frequency stability; control tuning; wind power; solar photovoltaic; battery energy storage; generator set;**

I. INTRODUCTION

ONE of the trends in modern energy systems is to explore potentialities for combining multiple distributed energy resources (e.g. wind power, solar PV, biomass power) and energy storage, forming so-called hybrid power plants (HPPs). In the case of grid integrated HPPs, hybridization is justified by complementarity of renewable resources (wind, solar) and hence a better utilization factor of the electrical infrastructure (balance of plant). Moreover, synergies in development, installation and service as well as enhanced grid ancillary serviceslead to an increased business case certainty [1], [2]. In emerging and frontier markets, a significant trend is to be expected towards stand-alone hybrid solutions (i.e. off-grid HPPs) to ensure rural electrification and supplying remote industrial sites (e.g. mining areas) [3], [4], [5].

Certain power management strategies and a pre-defined control architecture are required in order to enable stable operation of HPPs, in this way ensuring e.g. voltage and frequency regulation. In grid integrated HPPs a centralized control architecture is commonly utilized, as grid code requirements need to be fulfilled at one particular point in the grid, i.e. the Point of Common Coupling (PCC) [1], [2]. In the case of off-grid HPPs, many studies are found proposing various microgrid control architectures that can be classified as centralized or decentralized (e.g. [6], [7]). Several publications are identified elaborating on small-signal stability in microgrid and subsequent optimization of DER controllers (e.g. [8], [9], [10]). Another cluster of papers focuses on the development and assessment of advanced control algorithms for specific microgrid system architectures (e.g. [11], [12]). However, no study is found that casts light on the entire process of 1) assessing system stability with DER controls, 2) proposing mitigation techniques in case of stability problems, 3) designing and tuning the entire HPP controller (HPPC) for various operating conditions and 4) test its performance towards high technology readiness level (TRL). The aim of this paper is to provide a practical approach for voltage and frequency stability analysis and development of the HPP controller, independent of the actual plant topology or the defined power management strategy.

Section II describes the off-grid HPP used as a benchmark case in this study as well as the general requirement specifications for the HPP controller. In section III a brief classification of stability phenomena in these off-grid systems is given, before elaborating on modeling and methods for small-signal analysis. Finally, a generic guidance for stability analysis, control design including tuning and verification in HPPs is proposed in section IV.

II. SYSTEM DESCRIPTION AND REQUIREMENT SPECIFICATIONS

A. System Characterization of Benchmark HPP (Off-Grid)

For the purpose of this study an off-grid HPP supplying a rural community is used as a benchmark system. In [4] the composition of various plant components and the electrical infrastructure is defined to enable modularity and scalability of the HPP. The described balance of plant as in Fig. 1 allows an installed capacity of the renewable energy system (RES) up to 900 kW, being sited with a maximum distance of 4 km towards the PCC of the HPP. Upscaling towards MW scale HPPs requires an enhanced voltage level for the MV lines between RES subsystem and PCC to account for power losses and the permitted voltage drops. The application of off-grid HPPs in the MW range is targeted e.g. for energy-intensive industry (mining, pulp mill, cement kiln) or military bases [4]. Wind turbines (WTGs), PV and battery systems are grid interfaced via back-to-back converters, such having the capability of contributing actively to voltage / reactive power

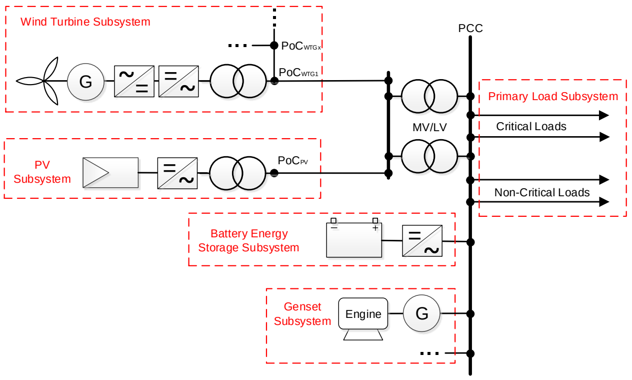

Figure 1. Generic single line diagram of the benchmark hybrid power plant [4]

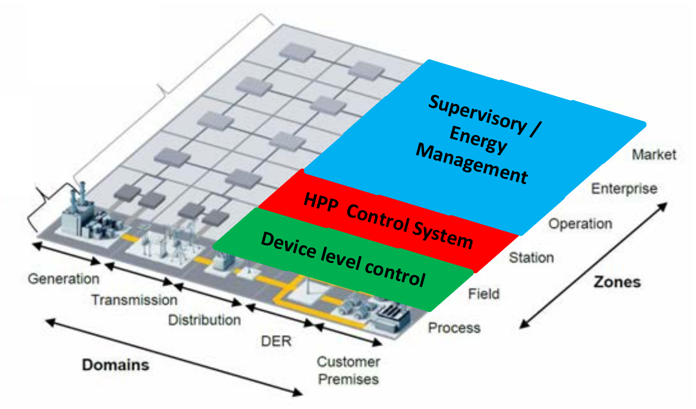

Figure 2. Scope of *IEEE Draft Standard for Specification of Microgrid Controllers* [13]

control. Gensets consist of the diesel or gas engine itself and a synchronous generator. The generator is implemented with an automatic voltage regulator and speed governor system. In this study, the primary load subsystem including critical loads (e.g. hospital) and non-critical loads (e.g. residential) is considered as an aggregated electrical load that the system shall meet in order to avoid power shortage.

B. Requirement Specifications for HPP Controller

It is challenging to detect and apply relevant grid codes for such off-grid HPPs due to the unique characteristics of islanded power systems. However, a generic guidance on the required control functions to be implemented is given by the *IEEE Draft Standard for Specification of Microgrid Controllers* [13]. It describes the core level functions of the *microgrid control system* (in this paper referred to *HPP control* system) as transition between various operating modes and dispatch of command signals to the individual DERs. Fig. 2 illustrates the scope of the standard [13] using the well-known Smart Grid Architecture Model (SGAM) framework [14]. The device level functions refer to voltage/frequency control and active/reactive power control on DER level, while energy management functions are not regarded in this standard either. Based on the content in [13], a list of functional requirements including their features and performance metrics is given in Tab. I.

III. METHODS FOR SMALL-SIGNAL STABILITY ANALYSIS

A. Classification of Stability - Microgrids vs. Conventional Power Systems

First, it is essential to provide a brief overview of the unique features of stability in microgrids / off-grids / islanded power systems in comparison to conventional power systems. In [15] the stability phenomena are classified as illustrated in Fig. 3. While in conventional power systems the major stability concerns are categorized by voltage, frequency and rotor angle stability [16], some new types of stability issues are observed in microgrids. Power supply and balance stability refers to the phenomena associated with the physical characteristics of the microgrid. Frequency stability is a major concern due to low system inertia and a high share of intermittent renewable power generation. Conventional frequency control techniques may not be sufficient due to rapid frequency changes which are not observed in power systems with relatively high share of synchronous generation. Regarding voltage stability, in conventional power systems the key problems are linked with long transmission lines (power transfer limit) and short-circuit power levels. In microgrids, unacceptable system voltages (steady-state and dynamic) may occur due to DER capacity limits, fluctuating power generation and consumption as well as poor reactive power sharing caused by low X/R ratio of the lines and load voltage sensitivities [15]. Moreover, the short-circuit ratio (SCR) as a metric to determine the relative strength of the system is not directly applicable in microgrids due to high share of inverter based DERs [17].

Table I
FUNCTIONAL REQUIREMENTS - FEATURES AND PERFORMANCE METRICS [13]

Elements of the function	**Features**	**Performance metrics**
DER dispatch	Implementing a DER dispatch table or (optimization) algorithm	HPP controller response accuracy, settling time
Frequency regulation	Grid-forming control, Real-time power dispatch, Generation curtailment, Load shedding / curtailment	f, P, Q, dynamic response (rise time, settling time, overshoot), steady-state error
Voltage regulation	Grid-forming control, Static & dynamic voltage support, Real-time power dispatch	V, P, Q, dynamic response (rise time, settling time, overshoot), steady-state error
Load management	Demand response, Load shedding, Load curtailment	P, Q, V, f , dynamic response (rise time, settling time, overshoot), steady-state error
Transition to new operating condition	Change in DER/load dispatch orders (as required)	P, Q, V, f , dynamic response (rise time, settling time, overshoot), steady-state error
Controller re-tuning, new device settings	Look-up table or equivalent	Compile responses, deviations in steady-state and transients

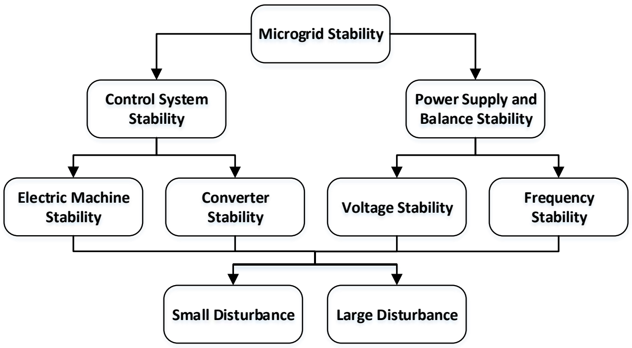

Figure 3. Classification of stability in microgrids[15]

In [15] it is proposed to further add stability phenomena caused by equipment control systems due to the increased complexity of power electronic controls. Here, a major concern is the converter stability, i.e. stable operation of inner voltage and current control loops in combination with LCL filters, control of power electronic switches, phase-locked loop etc. Electric machine stability aspects in conventional power systems are related to synchronizing / damping torque issues as part of the classic rotor angle stability phenomena [16]. In microgrids, the stability problems are dominantly associated with poor tuning of exciters and governors in co-operation with inverter based DERs [15]. It is worth emphasizing that many of the described stability phenomena in microgrids are valid for modern bulk power systems with increasing penetration of inverter based DERs, too.

For all stability phenomena it is distinguished between small and large disturbances (Fig. 3). Large-signal stability is affected by short-circuits, loss of generation units and unplanned transitions between operating modes. Small-signal stability being in scope of this paper is a measure of stability during normal operating conditions. Any stability problem occurs in the form of sustained oscillations of some system variables. These principles are not different to conventional power systems.

B. Implications on Small-Signal Modeling of Distributed Energy Resources

The level of detail for modeling the system components is dependent on the power system characteristics as well as the type of stability phenomena in scope of the particular analysis. One of the small-signal stability issues is associated with harmonic resonances caused by grid impedances and converter controls. High bandwidth EMT models (kHz range) are required to investigate harmonic stability which is not in the responsibility of the HPPC. With regards to voltage and frequency stability, the conventional method to design control systems of large power plants is to apply low bandwidth RMS models (e.g. < 5 Hz) [18]. However, this is not sufficient in low inertia and low short-circuit strength systems such as microgrids. Concerning inverter based DERs it is necessary to fully represent all inner and outer control loops, e.g. current, voltage, active/reactive power control. In order to reduce the complexity, it can be sufficient to apply average models to represent power converters [15]. This type of model does not represent harmonics, while preserving the average voltage dynamics necessary to design controls.

C. Benchmarking Methods for Small-Signal Stability Analysis

Small-signal stability is widely studied using either state-space models or impedance-based models [19]. State-space models are developed in time domain. However, the analysis of state-space models can be performed in frequency domain by using transfer functions. Meanwhile, the impedance-based model is developed and analyzed only in frequency domain. The impedance-based approach works by defining the in- and output impedances of each main component of the power system. The main advantages and disadvantages of impedance-based models are as follows [19]:

+ It is straightforward to obtain a model in a linear form. It is thereby a simple method with linear assumptions and easy to apply as only impedance characteristic is needed;
+ Adding or removing system components or changing their operation mode is achieved by only modifying one new element of the system impedance;
+ If the impedance of the system cannot be obtained analytically, there is the possibility to obtain it experimentally;
- It is difficult to define evaluation criteria for stability assessment, as the stability margins can vary depending on a specific busbar;
- It is not straight forward to find the root cause and purpose the mitigation method, if the system is unstable.

The state-space model uses state variables to describe a system by a set of first-order differential equations, rather than by one or more n-th order differential equations. The main advantages and disadvantages of state-space models are as follows [16], [20]:

+ Modular and configurable approach: Each plant component is modeled separately, then merged according to the balance of plant;
+ Decoupled approach: Plant components and controller components are separated to perform small-signal analysis individually;
+ Stepwise stability analysis:
    1) Eigenvalue analysis allows to determine damping and frequency;
    2) Participation factor analysis allows to define the root cause of instability. This can help in finding the most optimal mitigation measure by controller tuning;
+ Sensitivity analysis: Model linearization around various operating points and control parameters enables to assess sensitivity of system stability;
+ Unified control tuning: Multiple-Input-Multiple-Output (MIMO) models and transfer functions for

  specific in-/output pairs are utilized to tune and verify controls;
- Complex mathematical formulation: Everything must be linearized and modelled in state-space form. Moreover, the dynamic state variables need to be selected thouroughly.

In this work, it is taken advantage of the benefits to develop and merge individual state-space models as well as to perform root cause analysis of instability problems.

D. Features of State-Space Models

The approach of state-space modeling is to describe the in- and output dynamics of the system by a set of state-space equations. Thus, not only the dynamic behaviour of the in- and output variables, but also of the internal state variables of the considered system are regarded. Therefore, a linearization of the non-linear system has to be performed around one operating point. The linearized state-space form is given by Eq. 1, where only the change of the corresponding variables is regarded at a certain operating point. [16]

$$\begin{aligned} \triangle\mathring{\mathbf{x}} &= \mathbf{A}\triangle\mathbf{x} + \mathbf{B}\triangle\mathbf{u} \\ \triangle\mathbf{y} &= \mathbf{C}\triangle\mathbf{x} + \mathbf{D}\triangle\mathbf{u} \end{aligned} \tag{1}$$

The dynamics of the state variables $\mathring{\mathbf{x}}$ are obtained by linking the system state matrix $\mathbf{A}$ with the state vector $\mathbf{x}$ and the input matrix $\mathbf{B}$ with the input vector $\mathbf{u}$. The output vector $\mathbf{y}$ is calculated likewise by the output matrix $\mathbf{C}$ and feedforward matrix $\mathbf{D}$.

The main part of small-signal analysis is evaluating the Eigenvalues (EVs) λ of the state matrix $\mathbf{A}$. The EVs are generally an indication of system stability for the particular linearized system. Different operating points yield in different EVs. Furthermore, the EVs are capable of identifying poorly damped or unstable modes in dynamic systems. [16]

Furthermore, the participation factors (PFs) $\mathbf{p_{ki}}$ of the matrix $\mathbf{P_i}$ are obtained by Eq. 2, where the right (Φ_{ki}) and left (Ψ_{ik}) eigenvectors of the system matrix $\boldsymbol{A}$ are used. The magnitudes of $\mathbf{p_{ki}}$ provide a measure of the relative participation of the *k*th state variable in the *i*th dynamic mode and vice versa. Thus, such PF analysis is capable of determining the origin of any unstable mode in the system. [16]

$$\mathbf{P_i} = \begin{bmatrix} \mathbf{p_{1i}} \\ \mathbf{p_{2i}} \\ \vdots \\ \mathbf{p_{ni}} \end{bmatrix} = \begin{bmatrix} \mathbf{\Phi_{1i}\Psi_{i1}} \\ \mathbf{\Phi_{2i}\Psi_{i2}} \\ \vdots \\ \mathbf{\Phi_{ni}\Psi_{in}} \end{bmatrix} \tag{2}$$

Then, when having an expression of the system in state-space, it is straightforward to achieve an overall transfer function of the system. The transfer function is a mathematical representation used to describe the in- and output behaviour of the system. It can be derived from Eq. 1, which finally leads to a set of transfer functions for the system described by Eq. 3. [16]

$$G(s) = \frac{\triangle y(s)}{\triangle u(s)} = \mathbf{C}(s\mathbf{I} - \mathbf{A})^{-1}\mathbf{B} + \mathbf{D} \tag{3}$$

Transfer functions are important for the control design and tuning stage, as they fully describe a control system. Nyquist and Bode plots can be obtained from open loop transfer functions.

IV. GENERIC METHODOLOGY FOR STABILITY ANALYSIS, CONTROL DESIGN / TUNING AND VERIFICATION

In this section, a step-by-step guidance is proposed in order to tackle the overall problem of voltage and frequency regulation in HPPs. By using the model-based design approach, sections A - D explain the required s-domain studies for stability analysis, control design and tuning. The final stage is control verification in a Real-Time Hardware-in-the-Loop (RT-HIL) co-simulation environment (section E).

A. Modular Approach for State-Space Modeling

First, each system component is modelled separately in state-space form. The dynamics of each subsystem (i.e. each DER) are described by its state vector $\mathbf{x}$. Interfaces with other subsystem are defined by input vector $\mathbf{u}$ and output vector $\mathbf{y}$. The validity of each linearized small-signal model shall be evaluated by means of an initial EV analysis and the performance shall be verified with the aid of time-domain models. At this stage, it is recommended to develop in parallel discrete-time domain models to account for various sampling times of each subsystem, thus being prepared for operating in RT simulation environment. A verification of discrete-time domain models can be performed against the continuous-time domain models.

Subsequently, all grid components and the individual DER state-space models are connected by linking in- and output variables. All models shall be represented in a local synchronous rotating reference frame (SRRF), as all state variables are DC values. Then, it is important to transform all dq-variables in the local reference frame to DQ-variables in the global reference frame of the HPP. The technique of merging individual state-space models is depicted in Fig. 4, representative for the HPP topology in Fig. 1. The RES subsystems are not illustrated to reduce the complexity of the figure. As a result an overall state-space model of the HPP is obtained containing reference input variables (e.g. V^*, ω^*, P^*, Q^*) and user defined output variables that are to be assessed (e.g. ω_g, V_{PCC}). The modular approach for the model development allows to evaluate system stability and to re-tune controllers for various operating states (e.g. diesel generator on/off). Stability analysis and control tuning for various operating points (e.g. power generation and consumption levels) is realized by using respective initial conditions for the model linearization.

B. Eigenvalue- and Participation Factor Analysis

The global system state matrix $\mathbf{A}$ of the HPP model is utilized for EV and PF analysis. First, matrix $\mathbf{A}$ is updated for m potential operating points, i.e. initial voltage levels (e.g. $V_{nom} \pm 10\,\%$) and frequency levels (e.g. $f_{nom} \pm 2\,\mathrm{Hz}$) as well as power generation and consumption levels (e.g. $P = 0...1\,\mathrm{pu}$). The EVs of all matrices $\sum_{i=1}^{m} \mathbf{A}$ are illustrated in the complex

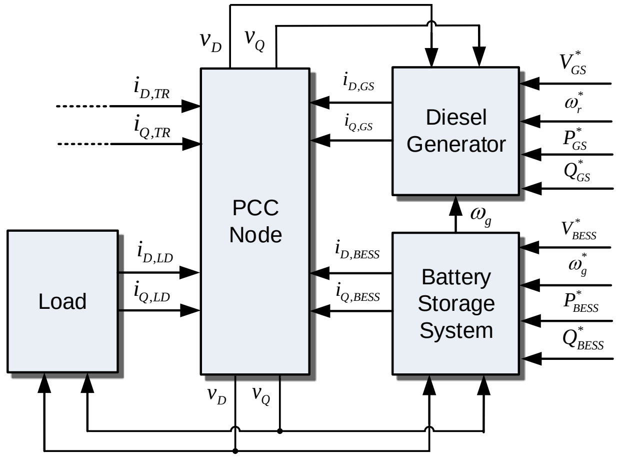

Figure 4. Functional diagram of hybrid power plant model used for state-space representation

plane as shown in Fig. 5. Absolute stability is obtained if all EVs are located in the left-half plane (positive real part of EVs). Subsequently, a list of EVs as well as their Eigenfrequencies and damping ratios provides a more analytical representation of the stability problem. Such table is completed by adding the dominant state variables, ascertained by using the PF analysis (see example in Tab. II). Relative stability of the system is assessed by observing the damping ratio of a certain EV. Dynamic modes with relatively low Eigenfrequency are likely to be visible as oscillations in grid frequency and/or voltages. Hence, any kind of power oscillations shall have adequate damping and the target damping ratio can be e.g. $\zeta \geq 0.05$ [21]. The dominant state variables for the representative EV pair in Tab. II refer to rotor speed / angle dynamics of the genset as well as active power / frequency control of the BESS.

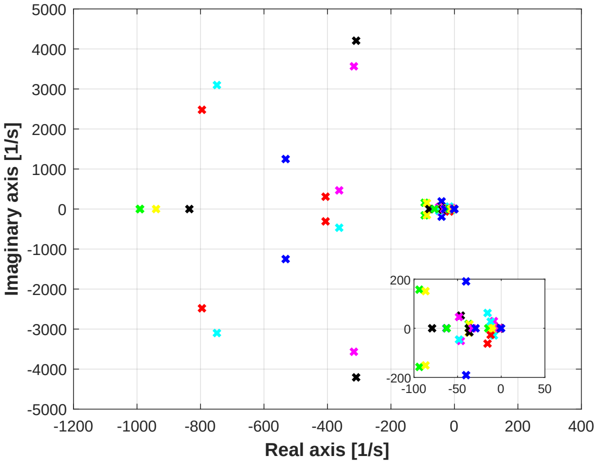

Figure 5. Representative Eigenvalue map of HPP state-space representation (stable case)

Table II
EIGENVALUES, FREQUENCY, DAMPING RATIO AND DOMINANT STATE VARIABLES

EV #	Frequency f [Hz]	Damping ratio ζ	Dominant state variables
...	...	...	...
48/49	10.23	0.24	$\omega_{r,GS}$, $\delta_{r,GS}$, $P_{c,avg,BESS}$, $P_{avg,GS}$, $T_{m,GS}$, $\varphi_{G2,GS}$
...	...	...	...

C. Sensitivity Analysis

In this particular control architecture, genset and BESS are sharing the grid-forming task by droop regulation. In this context, it is reasonable to evaluate the sensitivity of EV #48/49 to various P/f droop characteristics. Fig. 6 demonstrates the impact of various droop gains $m_p = 2...12\,\%$ on the damping ratio ζ of dynamic mode #48/49. In this case, attention needs to be paid at very large droop gains (e.g. $m_p = 12\,\%$), as the damping ratio is approaching the limit of $\zeta = 0.05$.

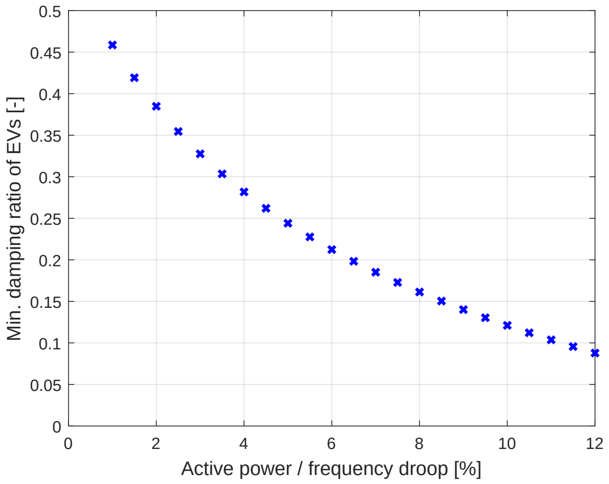

Figure 6. Damping ratio ζ of EV pair # 46/47 for various active power / frequency droop gains $m_p = 2...12\,\%$

D. Tuning of DER Controllers

While the previous section has exclusively focused on the absolute and relative stability by evaluating EVs, the design and tuning stage (section C. and D.) is achieved by evaluating the system in time-domain and in frequency-domain by using transfer functions. Following up on previous example, one objective for tuning DER controllers is to determine an optimum value for the droop gain m_p. One approach can be to observe the change of grid frequency after losing the largest power generation unit in the HPP. Fig. 7 shows the step response characteristic, still using state-space models. Considering a threshold for the permissible frequency change of $\Delta f_{g,th} = -2\,\text{Hz}$, it is feasible to apply any droop gain between $m_p = 2...6\,\%$. One shall include some safety margin, as the linearized models cannot accurately represent the frequency deviation Δf_g during large-perturbation signals.

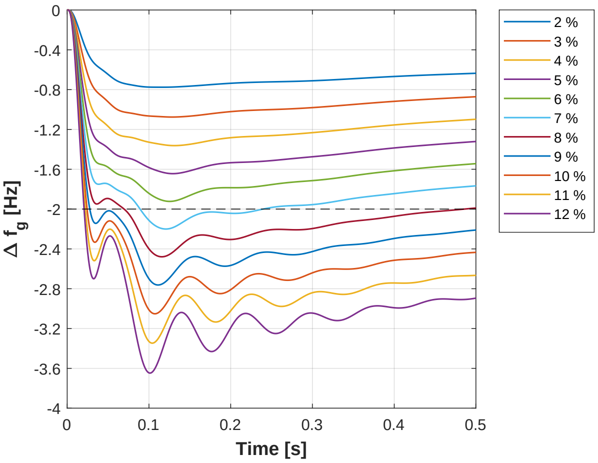

Figure 7. Grid frequency response of BESS and genset during the loss of the largest generation unit for various P/f droop gains m_p

E. Design and Tuning of HPP Controller

Droop regulation by DERs will leave a steady-state error in grid voltage and frequency measured at the PCC (see Fig. 1). A central HPPC can be utilized to eliminate the steady-state error and restore voltage and frequency to nominal values. At this stage, only some key recommendations are given of how to use the state-space models for designing the HPPC. A representative control architecture for frequency control is shown in Fig. 8, where the plant transfer function $G(s)$ includes the dynamics of DERs and their device level controllers as well as the HPP internal grid. $G(s)$ is obtained by converting the respective SISO state-space expression by using Eq. 3.

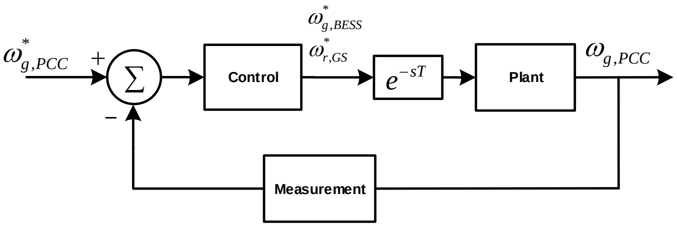

Figure 8. Control architecture for frequency control with HPP controller

The plant transfer function is a high-order system due to the vast number of involved state-variables. This can be challenging for the control design and tuning stage. However, adequate model order reduction can be applied so that only the dominant poles and zeros of the overall plant system are regarded.

In this example, the central controller dispatches commands ($\omega^*_{g,BESS}$, $\omega^*_{r,GS}$) to various DERs, resulting in multiple plant transfer functions. The plant system having the smallest bandwidth shall be regarded in order to respect the speed of the inner loop controllers (DER level) when designing the outer loop controller (HPP level). Moreover, it is essential to account for any time delays introduced by the communication and sampling process (e^{-sT}).

F. Control Verification by Real-Time Hardware-in-the-Loop Co-Simulation

Verifying control algorithms on HPPs requires testing of the controller platform connected to a RT model of the power system including DERs, i.e. WTGs, PV system, BESS, gensets. Moreover, for realistic testing a RT model of the communication networks shall be used. Thus, the controller platform including the developed algorithms can be assessed in realistic conditions. Grid events that cannot be measured in real life can also be replicated in a controlled environment while data traffic associated to specific communication network technologies is captured properly without actually involving the real technologies [22].

One may argue that on-site testing of off-grid HPPs can be realized as being independent of any external grid parameters. However, it seems impracticable and cumbersome to deploy and test HPPCs on-site for remote applications, before gaining further confidence by extensive testing and verification in a controlled system environment. The existing facilities in the Smart Energy Systems Laboratory at Aalborg University allow all the above design and verification procedure. The architecture of this platform is shown in Fig. 9.

V. CONCLUSIONS AND OUTLOOK

This paper presents a methodological guidance of how to approach voltage and frequency stability analysis in HPPs as well as the design and tuning stage of the HPPC with final testing of control performance. An off-grid HPP, designed and configured to supply a rural community, is used as a study case. Therefore, the specifics of microgrid stability and requirement specifications for the HPP operating in off-grid conditions are described. Note that the stability phenomena caused by low SCR and inertia are increasingly observed in modern bulk power systems, too. The state-space method is ascertained as the most suitable tool for small-signal analysis of hybrid power systems, as it enables a modular approach for setting up the HPP model. Other key benefits are the possibility to detect root causes of instabilities as well as the preparation of plant transfer functions for the control development stage. Based on the example of off-grid HPPs, the required s-domain studies for stability analysis, control design and tuning are outlined. A detailed presentation will be given in another publication. In the final stage of model-based design approach, the control algorithms need to be tested in a RT-HIL system environment. Preparing discrete-time domain models in the early stage of development enables to validate linearized state-space models as well as to verify control performance in RT [23]. It is worth mentioning that the proposed generic methodological framework is applicable for HPPs independent on plant topology, the overall power management strategy and operating conditions (on-grid or off-grid).

ACKNOWLEDGMENT

This work was carried out as part of the PhD project “Proof-of-Concept on Next Generation Hybrid Power Plant Control”. The authors acknowledge Innovation Fund Denmark for financial support through the Industrial PhD funding scheme.

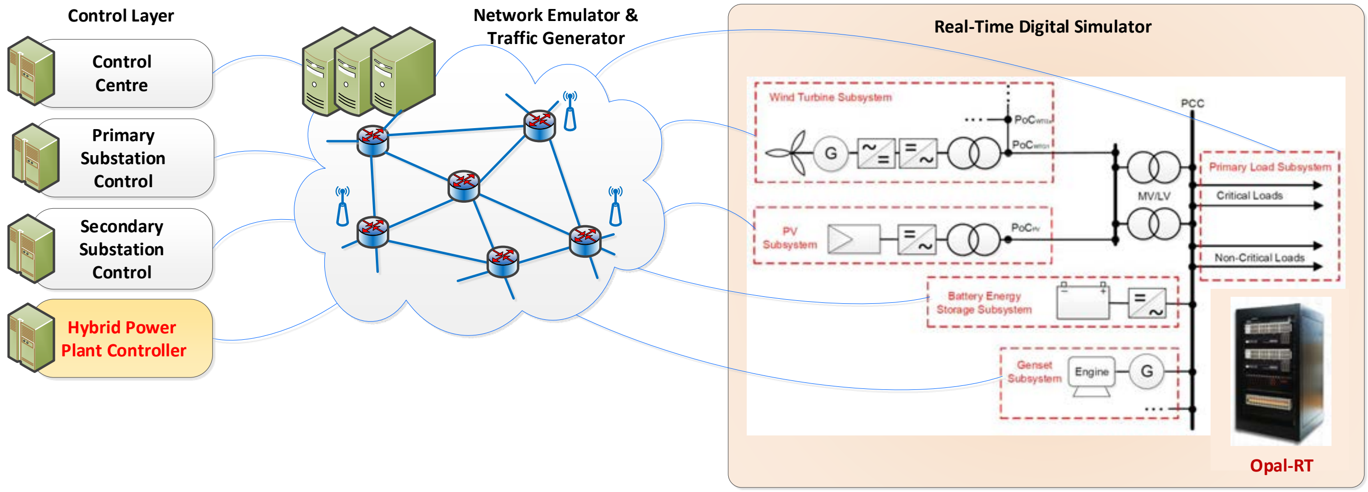

Figure 9. Real-Time Hardware-in-the-Loop Co-Simulation Architecture in Smart Energy Systems Laboratory [23]

REFERENCES

[1] Lennart Petersen, Roberto M Borsotti-Andruszkiewicz, German C Tarnowski, Bo Hesselbæk, Antonio Martinez, Nathan Steggel, and Dave Osmond. Vestas Power Plant Solutions Integrating Wind, Solar PV and Energy Storage. In *3rd International Hybrid Power Systems Workshop*, 2018.

[2] Alin George Raducu, Nikolaos Styliaras, Jonas Funkquist, Claudiu Ionita, and Vattenfall Ab. Design and Implementation of a Hybrid Power Plant Controller. In *3rd International Hybrid Power Systems Workshop*, 2018.

[3] Mohamed Mamdouh Elkadragy, Manuel Baumann, Nigel Moore, Marcel Weil, and Nicolaus Lemmertz. Contrastive Techno-Economic Analysis Concept for Off-Grid Hybrid Renewable Electricity Systems Based on comparative case studies within Canada and Uganda. In *3rd International Hybrid Power Systems Workshop*, 2018.

[4] Lennart Petersen, Florin Iov, German C Tarnowski, and Carlos Carrejo. Optimal and Modular Configuration of Wind Integrated Hybrid Power Plants for Off-Grid Systems. In *3rd International Hybrid Power Systems Workshop*, 2018.

[5] Hamideh Bitaraf and Britta Buchholz. Reducing energy costs and environmental impacts of off-grid mines. In *3rd International Hybrid Power Systems Workshop*, 2018.

[6] Josep M. Guerrero, Juan C. Vasquez, José Matas, Luis García de Vicuna, and Miguel Castilla. Hierarchical Control of Droop-Controlled AC and DC Microgrids - A General Approach Toward Standardization. *IEEE Transactions on Industrial Electronics*, 58(1):158–172, 2011.

[7] Josep M. Guerrero, José Matas, Luis Garcia de Vicuna, Miguel Castilla, and Jaume Miret. Decentralized Control for Parallel Operation of Distributed Generation Inverters Using Resistive Output Impedance. *IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS,*, 54(2), 2007.

[8] Xisheng Tang, Wei Deng, and Zhiping Qi. Investigation of the dynamic stability of microgrid. *IEEE Transactions on Power Systems*, 29(2):698–706, 2014.

[9] F. Katiraei, M. R. Iravani, and P. W. Lehn. Small-signal dynamic model of a micro-grid including conventional and electronically interfaced distributed resources. *Generation, Transmission & Distribution, IET*, 1(2):324, 2007.

[10] Aris Gkountaras. *Modeling techniques and control strategies for inverter dominated microgrids*. 2017.

[11] S. Mishra, G. Mallesham, and A.N. Jha. Design of controller and communication for frequency regulation of a smart microgrid. *IET Renewable Power Generation*, 6(4):248, 2012.

[12] Yun Su Kim, Chul Sang Hwang, Eung Sang Kim, and Changhee Cho. State of charge-based active power sharing method in a standalone microgrid with high penetration level of renewable energy sources. *Energies*, 9(7), 2016.

[13] IEEE Standards Department. P2030.7/D11 Draft Standard for Specification of Microgrid Controllers. Technical Report August, 2017.

[14] CEN-CENELEC-ETSI Smart Grid Coordination Group. Smart Grid Reference Architecture. *Online: http://ec. europa. eu/energy/gas_electricity/*, 2012.

[15] Claudio A. Cañizares. Microgrid Stability Definitions, Analysis and Modeling. (April):113, 2018.

[16] Prabha Kundur. *Power System Stability and Control*. McGraw-Hill, Inc., 1993.

[17] North American Electric Reliability Corporation. Integrating Inverter-Based Resources into Low Short Circuit Strength Systems. Technical Report December, 2017.

[18] National Grid Electricity Transmission NGET. The grid code. *National Grid Electricity Transmission*, (5), 2017.

[19] Jian Sun. Small-signal methods for AC distributed power systems–a review. *Power Electronics, IEEE Transactions on*, 24(11):2545–2554, 2009.

[20] Lennart Petersen and Fitim Kryezi. *Wind Power Plant Control Optimisation with Incorporation of Wind Turbines and STATCOMs*. PhD thesis, 2015.

[21] Eirgrid. Operating Security Standards. (April):1–10, 2010.

[22] Florin Iov, Kamal Shahid, Lennart Petersen, and Rasmus Olsen L. D5.1 - Verification of ancillary services in large scale power system. *RePlan Project*, www.replan, 2018.

[23] Smart Energy Systems Laboratory at Aalborg University. www.et.aau.dk/laboratories/power-systems-laboratories/smart-energy-systems, 2019.