A Vector-Based Flexible-Complexity Tool for Simulation and Small-Signal Analysis of Hybrid AC/DC Power Systems

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***Abstract*—VFlexP is an open-source tool for simulating and analysing hybrid AC/DC power systems using MATLAB-Simulink, based on a vectorised formulation of all variables. Its main contributions are allowing flexible-complexity representations of devices, easy inclusion of new models and the analysis of the state variables' relevance, aiding in model simplification. It ensures fast initialisation from power-flow analysis and features a user-friendly interface that groups similar power system elements together. This makes VFlexP ideal for detailed, non-linear time simulations of hybrid power systems, despite its current limitation to balanced power systems in d-q representation.**

***Index Terms*—Flexible complexity, model reduction, small-signal analysis, vector-based**

I. INTRODUCTION

As countries transition to low-carbon energy systems, renewable energy sources (RESs) are becoming more important, transforming power system operations. RESs present challenges such as being non-dispatchable, requiring inverter-based interfaces (IBRs), and being distributed across the grid as distributed energy resources (DERs) [2]. Hybrid AC/DC systems, enabled by advances in DC/AC converters, can improve grid flexibility, stability, and resilience.

Conventional tools for AC power system analysis include static analysis (power flow and optimal power flow) and dynamic analysis (time-domain simulation and small-signal analysis) [3]. Time-domain simulators include Transient Stability (TS) Simulators, which study synchronous generator dynamics, and Electromagnetic Transient (EMT) simulators, which use detailed models for fast transients [4], [5], [6]. Small-signal analysis (SSA) evaluates system stability and dynamic response to small disturbances [7]. The increasing presence of IBRs raises questions about time-scale separation between generators and the grid [8], highlighting the need for more flexible tools.

This paper presents VFlexP, an open-source tool for hybrid AC/DC power system analysis and simulation built on MATLAB/Simulink. Component data are input via a MATPOWER-like file, and the system is described using a d-q reference frame with Simulink dynamic blocks. Static analysis can be performed using a modified version of MATPOWER [9]. VFlexP supports SSA for hybrid systems with high IBR penetration, quantifies state relevance in dynamic systems, and accommodates flexible modelling with varying detail levels. EMT simulation is the default, but simplified models allow less cumbersome simulation. Simulations can use the original non-linear model or a linearised approximation, with options for full-order or reduced-order models.

Compared to other tools, the contributions of this tool are:

- Accurate calculation of the operating point of the full system starting from PF results of MATPOWER, avoiding unrealistic and time-consuming transients when starting a simulation and enabling precise linearisation.
- Linearised versions of most blocks in the Simulink workspace, with those not in the library linearised using a Taylor expansion and stored for subsequent use, avoiding finite differences calculations.
- Analysis of the relevance of all state variables in the input-output response of the non-linear system, aiding in model order reduction.
- Representation of all devices of the same type and detail level in a single Simulink block, reducing computational effort through vectorisation of differential equations.
- Hosting several levels of detail for a given component in each device block, with easy selection via a GUI, implementing flexible complexity and improving computation efficiency.

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This paper is a summarised version of [1].

The paper is structured as follows: Section II explains the vector-based and flexible-complexity approach used in VFlexP for hybrid power systems. Section III covers the SSA and simulations after system initialisation. Section IV presents SSA and simulation results, comparing VFlexP with another tool and validating a reduced-order model of a large power system. Finally, Section V concludes the paper.

II. VECTOR-BASED MODELLING OF HYBRID POWER SYSTEMS WITH FLEXIBLE COMPLEXITY

A. Scalable and Vectorisable Modelling of power systems

The simplest components included in VFlexP's library are inductors (L-R series connected) and capacitors (C-R parallel connected). The differential equations governing the behaviour of a series RL in a synchronous d-q frame are typically written as follows in per unit (pu):

$$v_d = \frac{1}{\omega_{base}} L \frac{di_d}{dt} - \omega L i_q + R i_d, \tag{1}$$

$$v_q = \frac{1}{\omega_{base}} L \frac{di_q}{dt} + \omega L i_d + R i_q, \tag{2}$$

where v_d and v_q are the d- and q-axis voltages, respectively, across the RL element, i_d and i_q are the d- and q-axis currents, respectively, ω_{base} is the base frequency of the system (in rad/s), ω is the angular speed of the synchronously rotating frame, and R and L are the resistance and inductance values of the series RL element, respectively. If v_d and v_q (inputs) are known, differential equations (1) and (2) can be integrated to calculate i_d and i_q (outputs and state variables). These differential equations can be easily built using elementary Simulink blocks (integrators, sums, and gains with the parameters), and they can be included in a user-defined block. However, a power system is bound to have a large number of RL elements as part of power lines and/or loads, for example, and including a block for each line in Simulink's workspace is not practical. Instead, a single block can be used to contain all the elements of the system with equations like (1) and (2), if those equations are vectorised as follows:

$$\mathbf{v_d} = \frac{1}{\omega_{base}} \mathbf{L} \odot \frac{d\mathbf{i_d}}{dt} - \omega \mathbf{L} \odot \mathbf{i_q} + \mathbf{R} \odot \mathbf{i_d}, \tag{3}$$

$$\mathbf{v_q} = \frac{1}{\omega_{base}} \mathbf{L} \odot \frac{d\mathbf{i_q}}{dt} + \omega \mathbf{L} \odot \mathbf{i_d} + \mathbf{R} \odot \mathbf{i_q}, \tag{4}$$

where voltages, currents and each type of parameter are grouped in vectors (i.e., $\mathbf{v_d}$, $\mathbf{v_d}$, $\mathbf{i_d}$, $\mathbf{i_q}$, $\mathbf{L}$, and $\mathbf{R}$); and multiplications and sums are carried out element-by-element (i.e., Hadamard product $\odot$).

Similarly, all elements included so far in VFlexP (capacitors, loads, synchronous generators, electronic power converters, etc.) can be represented in vector form. Therefore, only one block needs to be included in Simulink's workspace to contain all elements of the same type and model.

B. Flexible-complexity models for power systems

In traditional power systems, the slow electromechanical dynamics of synchronous generators could be decoupled from the fast response of inductors and capacitors [8]. However, the fast response of electronic-based generation or IBRs challenges this separation, and not all fast dynamics can always be simplified. VFlexP addresses this by allowing each element to be included with different levels of detail. For example, if the dynamics of some inductors can be neglected ($di_{dq}/dt = 0$), their equations can be simplified into algebraic equations. Each block in VFlexP's library offers multiple levels of detail, but within the Simulink workspace, each block must contain elements of the same type at the same level of detail.

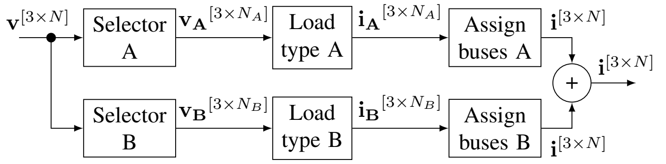


Fig. 1. Loads, selectors and assignments. Array dimensions are indicated in square brackets. All arrays have 3 rows, direct (d), quadrature (q) and homopolar (neglected for the time being) components. N is the number of buses in the system, N_A, N_B and N_C are the number of Loads of type A, B and C in the system, respectively.

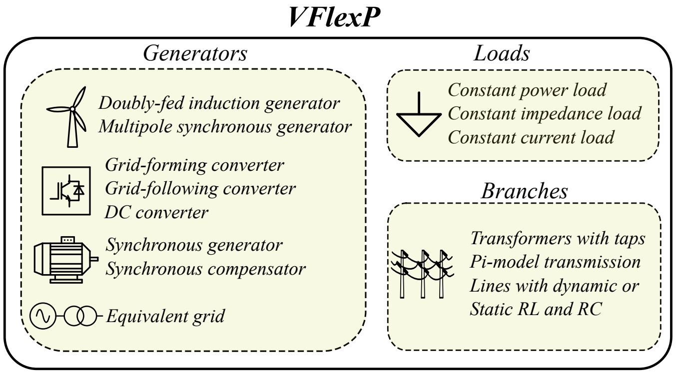


Fig. 2. Summary of elements included in VFlexP.

Selector and assignment blocks are used to choose the level of detail for each component model. Voltage and current vectors are structured with three rows, representing the direct, quadrature, and homopolar components (see Fig. 1). For instance, the notation $\mathbf{v}_A^{[3\times N_A]}$ and $\mathbf{i}_A^{[3\times N_A]}$ designates the dimensions of the voltage and current array corresponding to type A loads across N_A buses. The current vector through each load is calculated from its parameters and voltage vector. To consolidate the currents of all load types into a single current array $\mathbf{i}^{[3\times N]}$, an assignment block is employed. This block assigns each load type's current at a given bus k to the corresponding position in $\mathbf{i}^{[3\times N]}$. This approach to array assignment applies similarly to other elements in VFlexP, such as generators, transmission lines, and both AC and DC loads.

A descriptive list of the models included in VFlexP, detailing components like generators and converters, is provided in Figure 2, highlighting the modularity and flexibility of VFlexP's modelling framework.

III. SIMULATION OF HYBRID POWER SYSTEMS AND SSA

This section describes VFlexP capabilities to simulate and analyse hybrid power systems. VFlexP runs a power flow to initialise the state variables accurately, which is needed for non-linear time-domain simulations and SSA. With respect to SSA, VFlexP derives a linear approximation of the non-linear system included in the Simulink workspace, and it can carry out a comprehensive eigenvalue analysis of the resulting linear system. The tasks corresponding to these capacities are addressed in the following sections.

A. Powerflow and Initialisation

Before linearising a Simulink model, the target steady-state operation point must be calculated, i.e., the initial values of all the state variables of the system must be determined. This can be done directly with the original tools in MATLAB/Simulink (e.g., *findop*), but they are not very efficient when dealing with large dynamic systems. Alternatively, VFlexP uses the following strategy:

1) Grid currents and voltages are initialised by running a power-flow algorithm based on MATPOWER [10], which is a well-known open-source MATLAB tool originally developed to be applied on AC power systems, only. This tool has been extended with the flexible universal branch model (FUBM) [9] to seamlessly deal with hybrid AC/DC power systems.
2) Generators state variables can be calculated automatically using a gradient-based optimisation in MATLAB for each one of the blocks in the Simulink workspace. The results of the PF run are the restrictions to be satisfied by the optimisation process. In addition, for simple blocks, the equations to calculate the initial conditions can be calculated manually in advance and stored in the block for future use.

B. Linearisation

For linearisation, VFlexP uses the MATLAB function `linearize(mdl, io, op)`, where `mdl` is the Simulink model name, `io` is the set of inputs and outputs for the linear model (set using the `setlinio` function), and `op` is the operation point for linearisation. MATLAB calculates the input and state values for each block at the operating point and requests its Jacobian. VFlexP primarily uses Simulink basic blocks (*e.g.,* integrators, products, sums, switches), which have predefined Jacobians for linearisation. For more complex blocks, the Jacobian at the operating point is provided. Simulink then computes the complete linear model of the system by considering the connections between blocks. The final linear system obtained is of the form:

$$\left\{ \begin{array}{l} \dot{x} = \mathbf{A}x + \mathbf{B}u \\ y = \mathbf{C}x + \mathbf{D}u \end{array} \right. \tag{5}$$

where x is the system state column vector, u is the input vector, y is the output vector, and $\mathbf{A}$, $\mathbf{B}$, $\mathbf{C}$ and $\mathbf{D}$ are the system matrices.

C. Small signal analysis

The mode-in-state participation factors normalised as in [3] and [11] (based on [12]) are used here:

$$p_{ji} = \frac{|w_{ij}|\,|v_{ji}|}{\sum_{\forall k} |w_{ik}|\,|v_{ki}|} \tag{6}$$

where p_{ji} is the normalised mode(i)-in-state(j) participation factor in a linear system, v_{ji} is the element of the $j-th$ row and $i-th$ column of matrix $\mathbf{V}$ of right column eigenvectors of $\mathbf{A}$ and w_{ij} is the element of the $i-th$ row and $j-th$ column of matrix $\mathbf{W}$ of left row eigenvectors of $\mathbf{A}$ calculated as $\mathbf{W} = \mathbf{V}^{-1}$.

The state relevance presented in [13], included in this tool, measures the importance of the dynamics of each state in the input-output response of the system. This algorithm uses the balanced transformation of the linearised system, presented in [14] and implemented using `balanced_system = balreal(linear_system)` command in MATLAB. The state relevance is calculated as:

$$\hat{\mathbf{R}}_x = \mathbf{P} \cdot \left([g_1, \cdots, g_n] \cdot \bar{\mathbf{P}} \right)^T \tag{7}$$

where g_i is the Hankel singular value of state i, $\mathbf{P}$ is the participation matrix of the original system and $\bar{\mathbf{P}}$ is the participation matrix of the balanced system. The state relevance can be normalised as:

$$\mathbf{R}_x = [R_x(x_1), \ldots, R_x(x_n)]^T = \hat{\mathbf{R}}_x / \sum_{\forall i} \left(\hat{R}_x(x_i) \right) \tag{8}$$

D. Simulation of non-linear and linear models

VFlexP models each element of hybrid power systems using basic Simulink blocks like sums, products, and integrators to define differential equations, leveraging all native Simulink capabilities. Variable-step solvers are particularly useful when the steady state is reached, as variables of a balanced three-phase power system remain constant in the d-q reference frame. Simulink solvers for stiff differential equations can speed up simulations, especially given the different time scales involved in system dynamics. Simulink also supports real-time simulation on most RT boxes, including OPAL-RT [15].

Linearised models are simulated using MATLAB's `lsim (linearised_system,u,t)` command, where `u` is the system input and `t` is the time vector.

IV. CASE STUDIES USING VFLEXP

This section demonstrates the main features of VFlexP through case studies on small and large hybrid AC/DC power systems. The performance is compared with the Simplus Grid Tool [16], a recently presented open-source tool also based on MATLAB-Simulink. Two test systems are analysed, focusing on voltage and frequency responses, and power delivery. VFlexP's ability to handle non-linearities and SSA is demonstrated. The usefulness of the concept of state relevance for model-order reduction without compromising accuracy is also discussed.

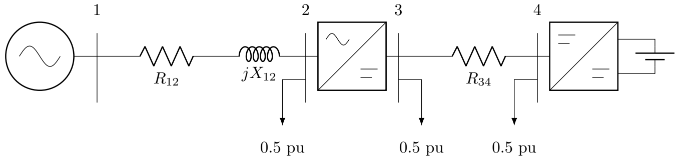


Fig. 3. Single-line diagram of the 4-bus hybrid AC-DC system in [17].

A. *Case study: A small power system*

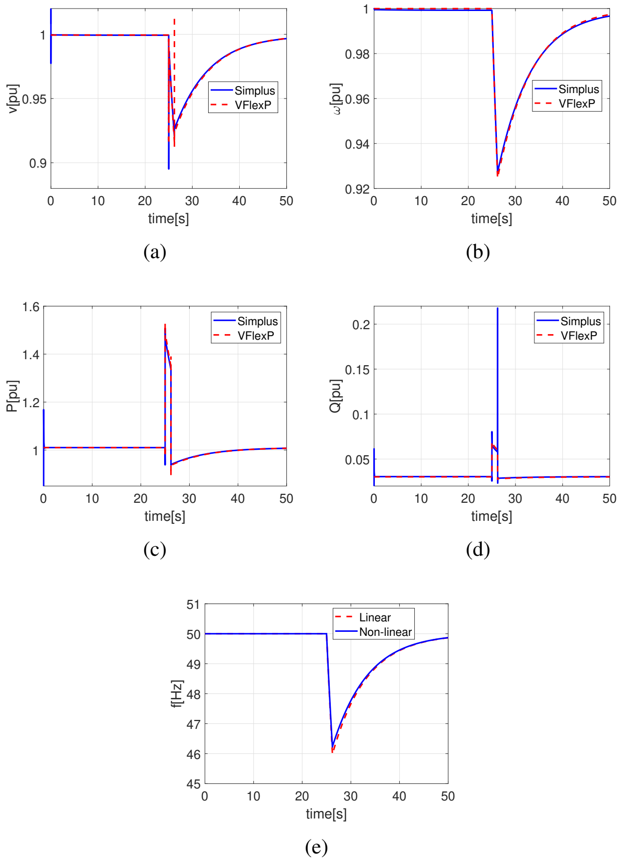
This section explores the application of VFlexP in the 4-bus hybrid AC/DC power system presented by Zheng et al. in [17] (see Figure 3). A synchronous generator is connected to bus 1 (AC side), a buck converter is connected to bus 4 (DC side), and AC and DC sides are connected by a grid-following interface converter placed between buses 2 and 3 with a PI current controller, and an inductance as output filter. The generator and the two electronic converters in Fig. 3 feed three active power loads. All the parameters for the system shown in Figure 3 can be found in the examples in SimplusGT repository [16]. For comparison, a 50-second dynamic simulation was carried out in the system, starting from an operating point determined by the load values shown in Figure 3. The load in the system was increased between 25 and 26.2 seconds. Simulation results for the two simulation tools applied to the system were recorded, and voltage, speed, active, and reactive power of the synchronous machine are shown in Fig. 4, comparing SimplusGT (blue line) with VFlexP (red dotted line).

Fig. 4 shows the behaviour of this system when using Simplus and VFlexP. Figures from 4-(a) to 4-(d) demonstrate the close agreement between the simulation results using Simplus and those using VFlexP. In addition, Fig. 4-(e) shows that the simulations of the non-linear system and its linear approximation carried out using VFlexP agree closely.

The computation times (CT) required for both tools to perform the dynamic simulations are calculated using MATLAB commands `tic` and `toc`. All simulations were performed on an Intel Core i7 PC with a 2.8 GHz processor. The difference for this test system is clear, where VFlexP requires only 11.687 seconds, compared to 103.84 seconds required by Simplus (i.e., a reduction of about 89%).

B. *Case study: A large hybrid AC/DC power system*

1) Exploring reduced order models for a large hybrid power system: To validate the performance of the proposed tool on large hybrid AC/DC power systems, the hybrid power system introduced in [18] was implemented only in the proposed tool, as it is challenging to implement such a large system in Simscape with EMT modelling. Figure 5 shows the schematic diagram of that power system, automatically generated by the tool, consisting of two AC areas connected through two DC grids by means of several DC/AC converters. VFlexP includes in this graph the active and reactive power generated by units and consumed by loads at every bus, resulting from the power flow calculation.



(a) (b) (c) (d) (e)

Fig. 4. (a) Bus-1 voltage, (b) Speed of the synchronous generator in pu, (c) Active power, (d) Reactive power and (e) Frequency in the non-linear and linearised simulations of the system in Fig. 3.

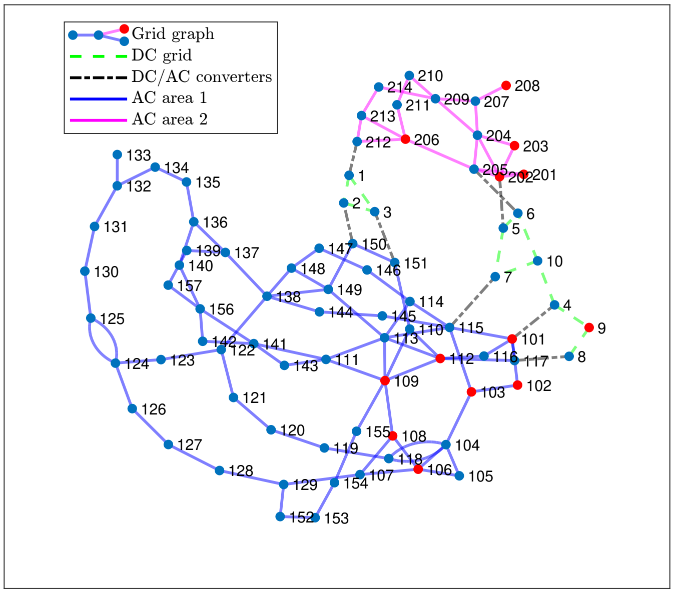


Fig. 5. Graph representing the grid used for the case study. Buses highlighted in red include generation.

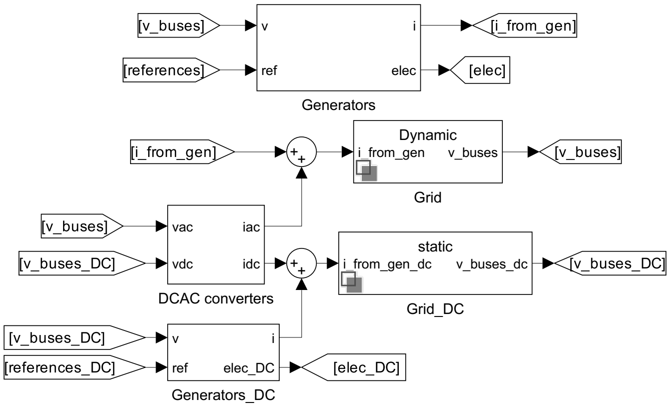


Fig. 6. Screenshot of the Simulink workspace for the hybrid system implemented in VFlexP.

AC area 1 is the IEEE 57-bus system, and AC area 2 is the IEEE 14-bus system, with generator buses highlighted in red. Static data for the test case were sourced from [18], and the generator model and parameters for bus 9 of the DC grid are from [17]. Generators on the AC grids are modelled as grid-forming converters with traditional droop control, PI voltage and current controllers in cascade, and an LCL output filter. Details of the converter control structure are in [19].

Figure 6 illustrates the advantages of vectorisation in VFlexP, showing a Simulink workspace screenshot of the hybrid system. The blocks used for the large hybrid system in Figure 5 are the same as those for the small hybrid system in Figure 3, except the synchronous generator block is replaced by the grid-forming block. Although the system in Figure 5 is larger, the number of Simulink blocks remains the same.

The system was linearised in the operating point calculated by the initialisation of all variables from the results of the power-flow analysis given by [9] with the set-points of [18]. Then, the state relevance of each state of the linear system in the system input-output response is calculated as described in [13] and grouped by type of element as shown in Figure 7. The inputs chosen for the linear model are current injections on each AC bus, and the outputs are the frequencies of all grid-forming converters.

As shown in Figure 7, the dynamics of all DC elements, load dynamics and some dynamics of the grid-forming converters (GFrs) have very little contribution to the input-output response of the linear system. However, some dynamics of the GFrs, branches and buses can not be neglected because they have a considerable contribution to the input-output response (*i.e.,* not negligible state relevance).

To show the usefulness of the state relevance measure, the following scenario is proposed: the system in this large case study is modified by changing the voltage controller of DG1.

Figure 8 shows the evolution of the state relevance of the voltage and current controllers for all converters of the system under study when increasing the integrator gain of the voltage controller of DG1 from its initial value (the value of the integrator gain of the voltage controller of all other DGs) to 10 times its initial value. Clearly, the state relevance of the states of the voltage and current controllers of DG1 increase with the integrator gain of the voltage controller of DG1. This result can be understood by considering that the varying control system is approaching instability. However, the state relevance of the states of the voltage and current controllers of DG2 also increase with the integrator gain of the voltage controller of DG1. This is due to the fact that DG2 is close to DG1 in terms of electrical distance.

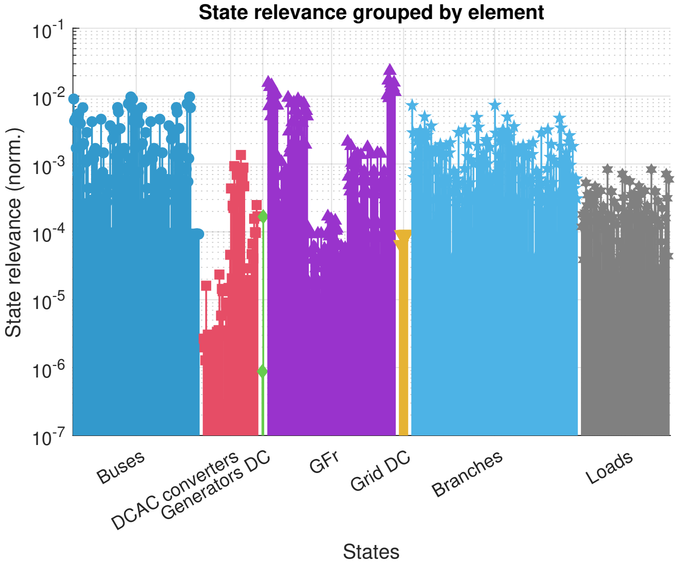


Fig. 7. State relevance of the linearised system. The state variables are grouped by element (buses, branches, loads, generators, ...), normalised to sum one and shown in a logarithmic scale for clarity.

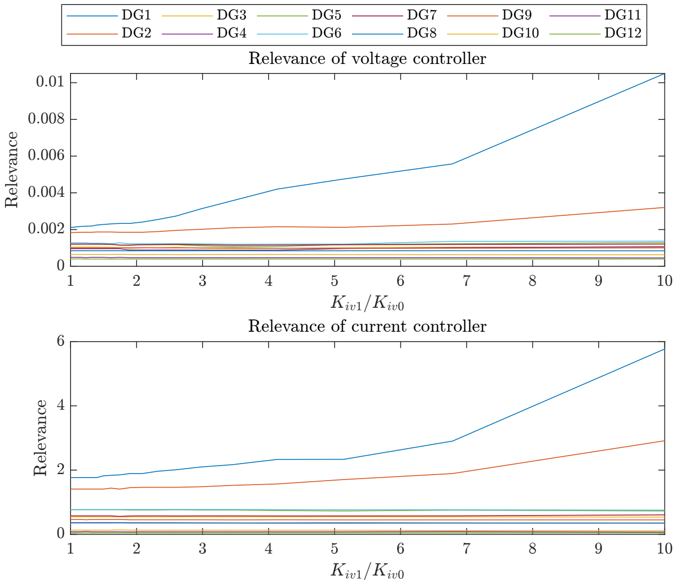


Fig. 8. Evolution of the state relevance of the voltage and current controllers for all converters of the system under study when varying the voltage controller of converter DG1. In K_{iv1}/K_{ivO}, K_{iv1} is the varying gain of DG1 and K_{ivO} is its initial value.

To further validate the state relevance analysis, the response

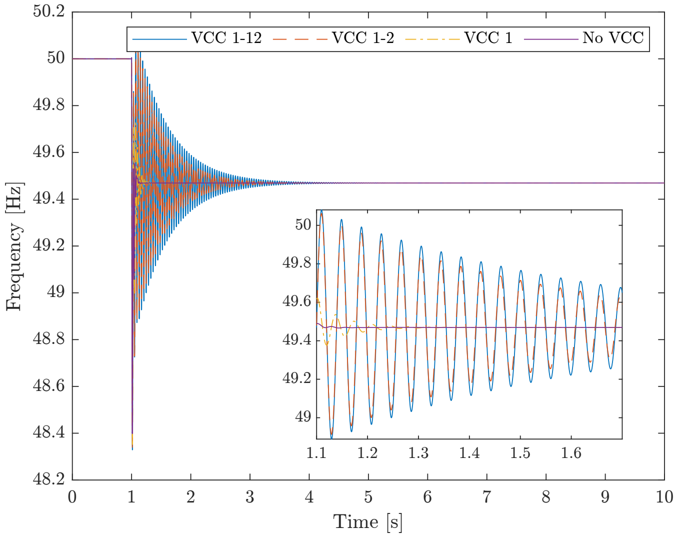


Fig. 9. Response of the frequency of DG1 to a load change. Comparison between the complete model and different reduced-order non-linear models.

of the complete non-linear system to a load change is compared with the response of several non-linear systems with different levels of complexity reduction. The dynamics of AC branches, loads and grid-forming converter voltage and current controls with state relevance below are all considered on "VCC 1-12", the ones with state relevance below 0.0012 and 0.004 are neglected in "VCC 1-2" and "VCC 1", respectively, and all are neglected in "No VCC".

Figure 9 shows the comparison of the complete and reduced models to a load increment in bus 10. The variable compared is the frequency of DG1 (grid-forming converter at bus 101). Clearly, the frequency of DG1 has a lightly damped oscillation when the load change is applied. This oscillation is only properly captured when the dynamics of the states with relatively high relevance are not neglected. In any reduced-order model, the dynamics of the states with higher state relevance must be conserved.

V. CONCLUSION

The paper introduces VFlexP, a MATLAB/Simulink-based tool for simulating and analysing hybrid AC/DC power systems. VFlexP includes steady-state analysis via MATPOWER-FUBM, non-linear electromagnetic simulation, accurate linearisation, eigenvalue analysis, and a unique tool for assessing state-variable dynamics. System data can be input via a MATPOWER-compatible spreadsheet, and the user interface allows intuitive complexity selection. Compared to other existing tools, VFlexP offers more accurate initialisation, more precise linearisation results, and more efficient modelling, as proved by simulation. Future extensions will address unbalanced systems as described in [20].

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