A Digital Twin Framework for the Preventive Mitigation of Adverse Converter–Grid Interactions Considering Black-Box Models

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I. Introduction

The grid impedance is one of the primary factors in ensuring the stable operation of a grid-connected inverter-based resource (IBR) [1]. The extensive range of power converter controllers facilitates undesired interactions to occur at frequencies that are not typically subject to monitoring, thereby inducing voltage oscillations [2].

Techniques for estimating power grid impedance can be broadly categorised into Fourier-based methods and regression-based methods. Both approaches rely on linear system identification principles [3] to characterise the dynamic response of the grid to known perturbations. The application of system identification techniques to power systems is challenging. The presence of noise in the measurements can mask the true system response, leading to inaccurate impedance estimates [4]. One solution is to perturb the system with a higher amplitude signal, however it may involve the excitation of non-linear behaviours. Furthermore, the system must remain at the same operating point during data collection process, which is unrealistic in a real system. Finally, the data must be sufficiently informative to capture a full dynamic range, however deliberate signal injection may be restricted or infeasible due to regulatory or operational constraints.

In order to identify the potential undesirable interactions that may emerge within the system while circumventing the aforementioned issues in obtaining the equivalent impedance of the grid and the IBR, this study proposes a tool embedded in a Digital Twin (DT) of the power system. We assume that an up-to-date and accurate digital model of the power grid is available, but only black box models of the IBRs connected to the grid are accessible. This limits the use of analytical techniques so analyses are performed using data-driven methods.

The advantages of the DT approach are that the grid conditions are controlled, noise-free measurements, and the power quality of the real system is not compromised. Furthermore, the synchronisation of the measurements is implicit in the process. This approach also enables different operating points to be analysed. Therefore, the algorithm's scope of application is extended to grid design tasks by allowing the analysis of interactions between converters that are not currently connected to the grid.

II. Methodology

The methodology proposed in this work for the analysis of the small-signal stability of an IBR connected to the power system consists of two stages. Firstly, data-driven techniques are utilised to determine the equivalent impedance model of the electrical network (observed from a designated bus) and that of the IBR connected to that same bus. Then, the impedance models are employed to ascertain the stability of the system within the bandwidth permitted by these models.

Equivalent models are obtained by running multiple EMT simulations in parallel within the DT. The IBR model is obtained by simulating its operation against an infinite voltage source, and measuring the voltage and current at the connection point. The same case is simulated at the same operating point, but including Random Binary Signals noise in the voltage. For the network model, a similar procedure is followed, with the IBR being replaced by a current source. Note that these simulations can be run in parallel. The low amplitude of the noise implies that the difference between the base cases and the disturbed cases provides the linear models of the IBR and the network. This is achieved by employing ARX models, which are fed with the resulting time series.

The Positive Mode Damping technique is used to determine interactions, based on the network's and converter's impedance models. This technique assesses the stability of systems in the frequency domain and is particularly suitable for systems with high converter penetration [5].

III. Results

The interaction detection tool will be evaluated using a numerical simulation. The system consists of an IBR connected to a network. The case study will involve sweeping the parameters of the IBR's different control stages to determine whether interactions occur and at what frequency. An EMT simulation will then be run to demonstrate these interactions.

References

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